

Bovine TB: The Scientific Evidence

A Science Base for a Sustainable Policy to Control TB in Cattle

An Epidemiological Investigation into Bovine Tuberculosis

**Final Report of the
Independent Scientific Group on Cattle TB**

**Presented to the Secretary of State for Environment, Food and Rural Affairs
The Rt Hon David Miliband MP, June 2007**



Robert Koch
(1843-1910)

Proved that human TB was caused by
a mycobacterium

– *Mycobacterium tuberculosis*

Koch expressed doubt that bovine TB (*Mycobacterium bovis*) could infect man, but acknowledged that he had little evidence upon which to base his opinion.

“A Royal Commission was quickly set up to explore the situation. In an unprecedented move, it was charged with conducting its own research, rather than simply collecting evidence from supposedly independent, but usually biased, witnesses.

The Commission, which published an interim report in 1904, demonstrated transmission of the organism from cow to man, and called for urgent legislation to combat the menace.” *

*Taken from *The White Death – a History of Tuberculosis*
Thomas Dormandy, Hambledon Press 1999

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18 June 2007

Dear Secretary of State,

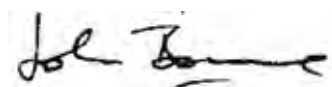
FINAL REPORT OF THE INDEPENDENT SCIENTIFIC GROUP ON CATTLE TB

I have pleasure in enclosing the final Report of the Independent Scientific Group on Cattle TB (ISG). After nearly a decade's work, I believe that the ISG has fulfilled its original objective and can now provide you with a comprehensive picture of TB epidemiology in cattle and badgers. Further research will doubtless improve the knowledge base, but I believe that the work described in this Report will allow you to develop future policies based on sound science.

The ISG's work – most of which has already been published in peer-reviewed scientific journals – has reached two key conclusions. First, while badgers are clearly a source of cattle TB, careful evaluation of our own and others' data indicates that badger culling can make no meaningful contribution to cattle TB control in Britain. Indeed, some policies under consideration are likely to make matters worse rather than better. Second, weaknesses in cattle testing regimes mean that cattle themselves contribute significantly to the persistence and spread of disease in all areas where TB occurs, and in some parts of Britain are likely to be the main source of infection. Scientific findings indicate that the rising incidence of disease can be reversed, and geographical spread contained, by the rigid application of cattle-based control measures alone.

Our Report provides advice on the need for Defra to develop disease control strategies, based on scientific findings. Implementation of such strategies will require Defra to institute more effective operational structures, and the farming and veterinary communities to accept the scientific findings. If this can be achieved, the ISG is confident that the measures outlined in this Report will greatly improve TB control in Britain.

The ISG remains grateful to you and your colleagues for your continued support and encouragement to see our work brought to a successful conclusion.



F J BOURNE

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(i) CHAIRMAN'S OVERVIEW

1. Bovine TB is a serious infectious disease of cattle. It has public health implications, has major economic consequences for Government and the farming industry, and causes distress to farmers and their families.
2. From the outset of our work we recognised that controlling cattle TB would require a broad understanding of the complex issues involved in the epidemiology of the disease in both cattle and badgers. Control policies adopted since the 1970s have failed, and a new approach is clearly needed.
3. Believing that future control policies would need to be multidisciplinary, we identified the need for reliable scientific evidence on the contribution that badger culling could make to the control of cattle TB, as well as on the potential for improving cattle-based controls. Meeting these needs required a broad but sound scientific base, which up to now has been lacking. After nearly a decade's work, we believe that we have fulfilled our original aims and are now able to provide a comprehensive appreciation of the overall problem; this report reflects this wide-ranging approach. Our findings have been surprising – and occasionally unwelcome – to some, but they are biologically consistent with one another and with the results of other studies conducted in Britain and overseas.
4. In accordance with good scientific practice, we have worked to clear protocols and prioritised publishing our findings in leading peer reviewed scientific journals. Our practice has been to concurrently release all relevant data in order that a full assessment of our work could be made by any interested member of the scientific community. All aspects of the Randomised Badger Culling Trial (RBCT), including field work, data handling, and data analysis, were subjected to an ongoing audit independently of ourselves and of Defra. All audit reports have been published (see Appendix E for details).
5. Implementation of the RBCT progressed mostly as was anticipated in our early reports, apart from the interruption of field operations because of the foot-and-mouth disease epidemic in 2001. Although this did not affect the trial conclusions it did delay the completion of the work. The numbers and proportions of badgers removed were consistent with our published predictions. Analyses revealed no evidence that interference or noncompliance with field activities materially influenced the outcome of the trial. Ultimately, the RBCT provided estimates of the effect of badger culling on cattle TB at the level of precision predicted by initial sample size calculations and in the predicted time frame of 50 triplet-years.
6. Reactive culling was included in the RBCT as the most likely future policy option, being both logistically and politically implementable. However, RBCT results showed that reactive culling increased, rather than reduced, the incidence of TB in cattle, making this unacceptable as a future policy option. The failure of reactive culling to control cattle TB appears to be an outcome of complex badger ecology and behaviour linked to the social disturbance of badgers brought about by culling. These matters are fully discussed in the report, and may help to explain the failure of past badger culling policies to control cattle TB.
7. As expected, proactive culling reduced TB incidence in cattle in culled areas. However, as described in the report, this beneficial effect on cattle breakdowns was offset by an increased incidence of the disease in surrounding un-culled areas. As in reactive areas, this detrimental effect appears to reflect culling-induced changes in badger ecology and behaviour. We have given careful consideration to culling approaches that might be

adopted that would overcome the detrimental effects of altered badger social behaviour, but we conclude that this is not achievable on any useful or practicable scale.

8. The results of the RBCT are consistent with those from similar studies carried out elsewhere, notably in the Republic of Ireland. While the 'Four Areas Trial' in the Republic has received particular attention for having reported greater reductions in cattle TB incidence than were apparent in the RBCT, we have advised Ministers that the claim that these findings could be replicated in GB are unsubstantiated and must be treated with considerable caution. The Four Areas Trial differed from the RBCT in a multitude of ways, including trial objectives, trial design, farming practice, environmental conditions, badger ecology, capture methods, and social attitudes (particularly towards badger welfare); these differences help to explain the differing conclusions drawn from the two studies and mean that conclusions drawn from the Four Areas Trial cannot be extrapolated to Britain. Further, while the medium term culling strategy in the Republic is to eliminate, or virtually eliminate, badgers from 30% of the land mass, the ISG was directed by Ministers at the outset of the RBCT that the elimination of badgers from large tracts of the countryside was politically unacceptable, and that badger welfare issues must be taken into account.

9. After careful consideration of all the RBCT and other data presented in this report, including an economic assessment, we conclude that badger culling cannot meaningfully contribute to the future control of cattle TB in Britain.

10. The research programme on cattle pathogenesis, implemented in parallel with the RBCT, has been particularly rewarding and informative in providing the basis for more effective future control policies, as is reflected in the report. Studies have shown that a number of undiagnosed, TB-infected, cattle frequently remain following tuberculin testing, particularly in some heavily infected herds. This has serious implications for the maintenance and persistence of disease in infected herds, and for the spread of the disease to neighbouring herds and to other parts of the country. Improving ability to diagnose *M. bovis* infection in cattle is crucial if future control policies are to succeed. In this respect, the value of the interferon- γ (IFN) test to complement the tuberculin skin test in some situations has been clearly established. Although some concerns have been expressed about the sensitivity and specificity of the IFN test, work described in this report show such concerns to be unwarranted.

11. Defra has recently tightened its TB control measures by the introduction of compulsory pre-movement testing and more rigid adherence to planned testing intervals. While this necessary development must be welcomed, we advise that further and stronger measures are needed. Priority should be given to the adoption of wider strategic use of the IFN test, and enhanced control of cattle movement. We advise that the highest priority should be given to avoiding further geographical spread of the disease, but consider that elimination in high disease incidence areas is realistic only in the very long term. We recommend that control measures adopted in these areas, while continuing to bear down on the level of herd breakdowns, be proportionate to allow farms to continue trading, even if not definitively clear of infection. Efforts in these high risk areas should focus in particular on the prompt and effective detection of positive animals and on rigorous movement testing with the objective of achieving a major reduction in incidence.

12. Our results indicate that while badgers contribute significantly to the disease in cattle, cattle-to-cattle transmission is also very important in high incidence areas and is

the main cause of disease spread to new areas. The key aspects of reducing cattle-to-cattle transmission are improved surveillance through more reliable, and possibly more frequent, testing and control measures limiting spread through the movement of cattle between herds. This is consistent with data from cattle pathogenesis and field studies. Our modeling work indicates that implementation of cattle control measures outlined in this report are, in the absence of badger culling, likely to reverse the increasing trend in cattle disease incidence that has been a feature in GB for decades. It is also possible that more effective cattle controls will lead to a decline of the disease in badgers, although the timescale for this is likely to be slow.

13. The ISG recognises the difficulties faced by Government in implementing control strategies without full industry cooperation. It is unfortunate that agricultural and veterinary leaders continue to believe, in spite of overwhelming scientific evidence to the contrary, that the main approach to cattle TB control must involve some form of badger population control. It is our hope that Defra will embrace new scientific findings, and communicate these to stakeholders in ways that encourage acceptance and participation.

14. We also hope that Defra will expand the role of scientists and other relevant experts in developing evidence-based policies. The strength and quality of scientific expertise already available to Defra through its Executive Agencies means that it is well placed to adopt this approach, but we have been aware of some considerable reluctance to accept and embrace scientific findings. We have therefore recommended how structures could be changed to introduce a much needed vigour into policy development and implementation.

15. The objective of our work over the past decade – outlined in this scientific report – has been to provide clarity on the major issues that need to be considered for gaining control of cattle TB. Some scientific questions remain unanswered. Further work will address some of these; that is the nature of scientific enquiry. Ministers clearly have demanding policy questions to address, but we believe that they now have sufficiently robust and extensive evidence to enable informed decisions to be made.

Acknowledgements

16. Following such a long period of study involving so many areas of investigation it is inevitable I want to express my gratitude to a large number of individuals and organisations who have helped and encouraged our work.

17. I am particularly indebted to the various Ministers who over the last decade have continually provided their support and guidance. It is necessary to express my appreciation to Defra's TB scientific advisors, in particular Miss Fiona Stuart, who have made valuable contributions to our work.

18. I am also particularly grateful to members of the farming community, and their representatives, whose cooperation made this study possible, and for the many friendships developed.

19. It is with the greatest of pleasure that I express a massive debt to, and appreciation of, the field and administrative staff, and trial managers, of Defra's Wildlife Unit (WLU). Often operating under very difficult and demanding conditions and circumstances they have collectively responded to our many demands, have met all RBCT design objectives, and carried out their work with great skill and dedication. I wish to extend this recognition of

debt also to staff members of Defra's State Veterinary Service (now Animal Health) who provided professional in-depth, collateral support, for the field work and provided much invaluable advice along the way, in particular to disease diagnosis and the design and completion of risk analysis surveys. I am also grateful to our independent auditors who have provided a much valued and essential input.

20. Much of the cattle pathogenesis and badger ecology research was dependent upon scientific expertise at the Veterinary Laboratories Agency (VLA), DARDNI Laboratories in Northern Ireland, the Institute for Animal Health, Compton and from the Central Science Laboratory (CSL). Staff from these internationally acclaimed laboratories made seminal contributions to the science programme. In addition scientists from the University of Warwick, in particular Professor Laura Green, and the University of York made significant contributions to the research and enlightened our scientific discussions.

21. I wish to acknowledge the contribution made by Dr. Richard Clifton-Hadley (VLA) and Dr. Chris Cheeseman (CSL, Woodchester Park) and their respective teams who have worked closely with the ISG from the outset. The collaboration and contribution of Andy Mitchell of the VLA team and of Professor Glyn Hewinson and Dr Martin Vordermeier, and other members of the TB research group at VLA has been central to much of our work.

22. The ISG has also been strongly supported by a large number of scientists who have contributed to scientific sub-groups of the ISG; I am indebted for their contribution.

23. We have enjoyed research discussions with scientists from a number of countries including the Republic of Ireland, Australia and New Zealand, and I wish to acknowledge the contribution that they have made to our work by their observations and shared experiences.

24. The level of service from the ISG Secretariat team since its inception in 1998 has been outstanding. Successive Secretaries and their teams have given us sound advice and guidance. They have provided the necessary interface with Defra and I have at all times been grateful for their dedicated and enthusiastic support. I would wish to acknowledge the individual contributions made by Steve Coleman and Dr. Alan Patey who have worked with us for almost the entire period of our work.

25. Defra senior policy advisors have come and gone throughout the process, and their levels of engagement with and support for our work have varied, dependent largely on the nature of the individuals concerned, and their understanding of the issues involved in scientific enquiry. I extend my sincere thanks to those who shared our desires to successfully complete our work.

26. We have experienced two sad events. The deaths of Professor Jo Colston and Dr. John Pollock, who were close friends and colleagues, came as a great shock. They were leading international figures in tuberculosis research and made significant contributions to our own science programme and to our discussions and deliberations. I am grateful for their large contribution. They are sorely missed.

27. It would be remiss not to mention my genuine gratitude to our vociferous critics who, through various media, have expressed their views, some perceptive, others misinformed. Their criticisms were listened to, have been to a large extent beneficial having impacted

on our deliberations, influenced some of our working practices and reinforced our need to vigorously address a range of questions.

28. My appreciation goes to our research assistants, Dr. Tom Johnston, Dr. Andrea Le Fevre, Miss Helen Jenkins, Mr Peter Gilks and Dr. Gao Wei. They have responded positively and enthusiastically to our ever increasing needs, and the demands made of them, as research data have accumulated.

29. Finally, it gives me enormous pleasure to acknowledge that it has been a particular privilege for me to work so closely with my fellow members of the ISG. They are individually talented scientists, all with demanding scientific careers and of international standing, who have given unstintingly of their time. They have withstood the strains of a demanding workload that has put unrealistic pressure on their professional and academic activities, and also on their family lives. Their commitment has ensured the well-being of this project. They have collectively provided a dynamic environment in which to work and it is to their credit that they were determined to see this extensive programme of work brought to a successful conclusion. I shall remain ever grateful.

PROFESSOR JOHN BOURNE

(ii) SUMMARY OF SCIENTIFIC FINDINGS

Background

1. Bovine tuberculosis (TB) is a serious disease of cattle that has re-emerged as a major problem for British farmers. Badgers (*Meles meles*) are implicated in spreading the infectious agent (the bacterium *Mycobacterium bovis*) to cattle. Hence, between 1973 and 1998, cattle-based TB controls were supplemented by various forms of badger culling.
2. A scientific review of the issue, chaired by Professor John Krebs and completed in 1997, concluded that there was “*compelling*” evidence that badgers were involved in transmitting infection to cattle. However, it noted that the development of TB policy was hampered because the effectiveness of badger culling as a control measure could not be quantified with data then available. Krebs’ team therefore recommended establishment of a large-scale field trial of the effects of badger culling on cattle TB incidence, to be overseen by a group of independent experts.
3. The Independent Scientific Group on Cattle TB (ISG) was formed in 1998 and recognised the need for a broader remit than that anticipated by Krebs. In addition to designing and overseeing the Randomised Badger Culling Trial (RBCT), the ISG identified and initiated a broad array of research related to the diagnosis, pathogenesis, dynamics and control of TB in cattle and badgers. This report – the ISG’s 6th and final, formal report – describes the outcome of this research, which provides a previously unavailable scientific basis for the design of future TB control policy.

The Randomised Badger Culling Trial

4. The RBCT was conducted in 30 areas of England, each located in a high-risk area for cattle TB and measuring approximately 100km². The 30 areas were grouped into 10 sets of three, each called a ‘triplet’. Within each triplet, one area was subjected to approximately annual culling across all accessible land (‘proactive culling’), and in one area the badgers were culled locally on and near farmland where recent outbreaks of TB had occurred in cattle (‘reactive culling’). The remaining area received no culling (‘survey-only’) and acted as an experimental control with which the culling treatments could be compared. Treatments were assigned to trial areas at random (Chapter 2).
5. At the start of the RBCT badgers lived in territorial social groups, and *M. bovis* infections were found to be strongly clustered on scales of 1-2 km. However, removing badgers by culling was found to disrupt their social organisation, causing remaining badgers to range more widely both inside and around the outside of culled areas. Probably as a result the proportion of badgers infected with *M. bovis* rose markedly in response to repeated culling, and infections also became less spatially localised. Hence, although proactive culling reduced badger activity by approximately 70%, reductions in the density of infected badgers were much less marked, and infections became more widely dispersed (Chapter 4).
6. Culling affected the incidence of cattle TB in ways that were consistent with the patterns observed in badgers. Inside proactive areas, the prevalence of infection in badgers was increased, but badger densities were greatly reduced, so infectious contact with cattle appears to have been reduced overall. Culling was associated with an estimated 23% reduction in cattle TB incidence inside the proactive areas. This indicates that the level of

TB reduction in cattle was not linearly correlated with the reduction in badger density. This is equivalent to an estimated 116 confirmed cattle herd breakdowns prevented inside ten 100km² areas subjected to proactive culling over a five-year period (assuming an underlying incidence rate of 10 confirmed breakdowns per area per year) (Chapter 5).

7. Just outside proactive areas, however, data suggest that opportunities for badger-to-cattle transmission would have been increased by culling. Badger numbers were only slightly depleted yet ranging behaviour – and hence potentially infectious contacts with other badgers and with cattle – was increased. Proactive culling was associated with a 25% increase in the incidence of cattle TB on neighbouring un-culled land. This is equivalent to an estimated 102 confirmed cattle herd breakdowns induced in the vicinity of ten circular 100km² areas subjected to proactive culling over a five-year period (again, assuming an underlying incidence rate of 10 confirmed breakdowns per area per year) (Chapter 5).

8. Both the beneficial and detrimental effects of proactive culling changed over time, with the detrimental effect dominating initially: only after the fourth annual cull did the estimated number of breakdowns prevented by proactive culling consistently exceed the estimated number induced, but the overall gains, in terms of reduced herd breakdowns, were small (Chapter 5).

9. Reactive culling was associated with a roughly 20% increase in cattle TB incidence. Culling prompted changes in the ecology and behaviour of badgers in reactive areas which were similar to those observed just outside proactive areas; hence this detrimental effect of reactive culling was consistent with the pattern observed in and around proactive areas. Reactive culling was suspended by Ministers in November 2003; there was no evidence of either a long-term detrimental effect or a delayed beneficial effect after the suspension (Chapters 4 and 5).

10. Badger culling, as conducted in the RBCT, required substantial effort by a large and dedicated team of skilled staff. For example, proactive culling entailed over 160,000 trap nights, conducted over 4-7 years per area. Simple economic analyses reveal that a culling policy based on cage trapping as in the RBCT would incur costs that were between four and five times higher than the economic benefits gained inside a proactively culled area of 100km². If the predicted detrimental effects in the surrounding areas are included, the overall benefits achieved would fall to approximately one-fortieth of the costs incurred. Reactive culling involved approximately 25,000 traps nights and generated no economic benefits, only costs (Chapter 9).

11. The RBCT yielded some evidence of transmission of *M. bovis* infection from cattle to badgers. The majority of cattle TB testing was suspended during a nationwide epidemic of foot-and-mouth disease in 2001; hence infected cattle remained able to transmit infection rather than being identified and removed. The prevalence of *M. bovis* infection in badgers rose markedly during this period, and declined again after cattle testing was resumed (Chapter 4).

Analysis of Farm Level Risk Factors

12. No farm level risk factors have been found to be consistently correlated with the risk of a herd breakdown over time and across geographical regions. Instead a variety of farm management, wildlife, and environmental factors have been observed suggesting the risk of breakdown is multifactorial. Factors amenable to management associated with herd breakdowns include cattle movements, herd contacts, housing, fertiliser usage, feeding practices and badger contact. Account should therefore be taken of these factors (Chapter 6).

Cattle Pathogenesis

13. Although the tuberculin test is a critical component of TB control policy in Britain, recent research shows that this test fails to identify a significant number of infected animals. In heavily infected herds the IFN test diagnosed 27% more animals with confirmed infection (visible lesioned and culture positive) than were diagnosed by the disclosing tuberculin skin test (Chapter 7).

14. This has serious implications for the persistence of the disease in infected herds, for the spread of infections within the herd and locally, and for the spread, by cattle movement, to geographically distant parts of the country. Research provides evidence that improved diagnosis of the disease in cattle and more effective animal movement controls would have an appreciable effect on the epidemic (Chapter 7).

Conclusions and recommendations

15. Detailed evaluation of RBCT and other scientific data highlights the limitations of badger culling as a control measure for cattle TB. The overall benefits of proactive culling were modest (representing an estimated 14 breakdowns prevented after culling 1,000km² for five years), and were realised only after coordinated and sustained effort. While many other approaches to culling can be considered, available data suggest that none is likely to generate benefits substantially greater than those recorded in the RBCT, and many are likely to cause detrimental effects. Given its high costs and low benefits we therefore conclude that badger culling is unlikely to contribute usefully to the control of cattle TB in Britain, and recommend that TB control efforts focus on measures other than badger culling (Chapter 10).

16. In contrast with the situation regarding badger culling, our data and modelling suggest that substantial reductions in cattle TB incidence could be achieved by improving cattle-based control measures. Such measures include the introduction of more thorough controls on cattle movement through zoning or herd attestation, strategic use of the IFN test in both routine and pre-movement testing, quarantine of purchased cattle, shorter testing intervals, careful attention to breakdowns in areas that are currently low risk, and whole-herd slaughter for chronically affected herds (Chapters 7 and 10).

17. Continued research will be critical to refine cattle-based TB control strategies. Further refinement and field experience of the IFN test, more detailed interrogation of existing data, particularly cattle testing and tracing data, will be of value. The involvement of independent expert scientists, as a complement to the excellent scientific expertise already available to Defra through its Executive Agencies, will ensure the application of the most appropriate and up-to-date approaches and is likely to generate the most effective control strategies.

(iii) RECOMMENDATIONS AND CONCLUSIONS

General Conclusions

1. On the basis of our careful review of all currently available evidence, we conclude that badger culling is unlikely to contribute positively, or cost effectively, to the control of cattle TB in Britain (10.48 and 10.92).

2. We conclude that there is substantial scope for improvement of control of the disease through the application of heightened control measures directly targeting cattle. Therefore, we recommend that priority should be given to developing policies based on more rigorous application of control measures to cattle, in the absence of badger culling (10.57 and 10.93).

Options involving badger management

3. It is highly unlikely that reactive culling – as practised in the RBCT – could contribute other than negatively to future TB control strategies (10.3 – 10.4).

4. Proactive culling – as practised in the RBCT – is unlikely to contribute effectively to the future control of cattle TB (10.5 – 10.7).

Adaptations of proactive culling

5. Improvements in culling efficiency are unlikely to generate benefits substantially greater than those recorded in the RBCT (10.10 – 10.14).

6. Different configurations of culling operation, alternative to that used in the RBCT, would confer no advantage and could lead to further detrimental effects (10.15).

7. Culling over larger areas would be unlikely to develop net benefits in economic terms (10.16 – 10.18).

8. Areas with boundaries impermeable to badgers could contribute to TB control only on a local scale, as few areas exist with appropriate natural boundaries (10.19 – 10.21).

9. Culling in areas adjoining land with low or zero TB risk is likely to achieve no greater overall benefits than the RBCT (10.22 – 10.23).

10. Preventing re-colonisation by destroying setts is likely to involve high costs and the potential benefits appear small (10.24).

Adaptations of reactive culling

11. Improving culling efficiency is very unlikely to generate overall beneficial effects from localised culling (10.25 – 10.26).

12. Reactive culling over larger areas is unlikely to generate overall benefits for the control of cattle TB (10.27).

13. Repeated reactive culling is likely to increase, rather than decrease, the detrimental effect associated with localised culling (10.28).

14. Reactive culling conducted more rapidly after detection of infection in cattle offers little promise of an effective control strategy for cattle TB (10.29 – 10.31).

Culling badgers under licence

15. Culling badgers under licence not only could fail to achieve a beneficial effect, but could increase the incidence of cattle TB and increase the geographical spread of the disease, irrespective of whether licences were issued to individual farmers or to groups (10.33 – 10.36).

Other approaches to badger culling

16. Culling in response to detection of infection in road-killed badgers may not target areas of high cattle TB risk and is likely to generate the detrimental effect of reactive culling (10.38).

17. Selective culling of infected badgers is very unlikely to reduce the prevalence of *M. bovis* infection in badgers substantially and might increase overall infection rates (10.39 – 10.42).

18. Culling of ‘hospital setts’ is a highly speculative approach appearing to have little or nothing to contribute to future control strategies (10.43).

19. Badger culling combined with vaccination is likely to reduce any advantage gained by vaccination (10.44).

Approaches to badger management other than culling

20. Separating cattle and badgers by badger-proof fencing might occasionally be appropriate for some farms. More generally, common sense measures could be applied in some circumstances to keep badgers out of buildings and feed stores. We recommend that research effort into ways of keeping badgers and cattle apart be continued (10.49 – 10.56).

Options based on cattle controls

Control of cattle movement

21. More rigorous control measures aimed at preventing spread of infection by cattle movement are necessary. Pre-movement testing protocols involving the parallel use of the tuberculin skin test and the IFN test should be used. Isolation of purchased animals prior to introduction into the herd and re-testing (post-movement testing), by combined use of the tuberculin skin test and the IFN test, would also be desirable in some situations. These measures could be reinforced by categorising herds or regions of the country as high or low risk and preventing cattle movement from high to low risk farms/regions (10.64).

Disease control in low risk areas

22. High priority should be given to preventing introduction of infection into low risk areas by imposing strict animal movement control, as proposed in recommendation 21 (10.65).

23. The elimination of infection from all breakdown herds should be addressed by parallel use of the tuberculin skin test and the IFN test (10.66 – 10.67).

Disease control in high risk areas

24. Elimination of infection in high risk areas is unrealistic in anything other than the very long term; control measures should therefore be proportionate to avoid prolonged restrictions being imposed on farms (10.69 – 10.70).

25. Spread between herds should be prevented by animal movement controls, as specified in recommendation 21 (10.71),

26. In breakdown herds with one or two reactors at the disclosing skin test and no recent history of infection, the aim should be to eliminate infection by parallel use of the tuberculin skin test and the IFN test (10.72).

27. The objective in multiple reactor herds in high risk areas should be to reduce the weight of infection, in the first instance by removing as many infected animals as possible but limiting the period of restriction imposed on herds (10.73). This could be accompanied by restricting movement of animals (other than to slaughter) only to herds of similar disease status, subject to pre-movement testing as proposed in recommendation 21 (10.75).

28. Where a hard core of multiple reactor herds, with a previous testing history of persistent disease, is revealed, slaughter of the whole herd or cohorts within the herds should be considered (10.74).

Measures relating to high and low risk areas

29. Surveillance should be heightened by more frequent testing of herds in low risk areas and by ensuring that annual testing is applied to all herds in high risk areas (10.68 and 10.76).

30. The justification and need for these more rigorous testing procedures should be communicated by Defra to the farming and veterinary communities. Veterinary advice should be sought by farmers on herd biosecurity and re-stocking policies following whole herd slaughter or clearance of infection (10.77).

Mathematical Modelling

31. Analysis of a simple mathematical model suggests that rigorously enforced movement testing would halt the epidemic and indeed produce some steady decline in incidence. If testing of enhanced sensitivity were used the decline is predicted to be appreciably more rapid (10.60).

Refinement of diagnostic tests and testing procedures

32. Based on available scientific evidence and on the need for rapid removal of infected animals from breakdown herds, consideration should be given to applying more rapid follow-up testing upon identification of a herd breakdown and to speeding up procedures for confirmation of infection (10.78).

33. Continued support should be provided for research on the development and field testing of improved versions of the IFN test (10.79).

34. Collection of reliable and informative field data on the use of the IFN test is required to advise on its value in a range of potential policy options (10.79).

35. Defra should continue to give high priority to research on *M. bovis* genotyping and should integrate the use of genotyping into disease control strategies (10.80).

36. The causes of unconfirmed breakdowns and their epidemiological impact should be investigated (10.81).

Analyses and presentation of data

37. Defra should revise the presentation of the current statistical data on breakdowns to provide an accurate indication of trends in TB incidence that is independent of changes in testing regime (10.83 – 10.84).

38. Herd breakdown data should be published in a format that allows some regional comparisons (10.83 – 10.84).

39. Procedures should be established to provide, at a relatively local level, information about the potential development of the disease in current low risk areas (10.83 – 10.84).

Effective use of data to address policy needs

40. Effective use of data to address policy issues requires greater effort to be devoted to analysis of cattle data (10.82 and 10.85).

41. A group of external scientists with appropriate expertise should be established to advise on data collection and analysis, and their systematic use for designing and assessing the impact of changes of disease control policy (10.86).

Formulation and implementation of disease control policy

42. Most urgent consideration should be given to ensuring that scientific expertise, particularly that available at VLA and CSL, is used more effectively to develop and implement TB control strategies. Effective TB control will only be achieved by assembling a small but focused, dedicated, informed team, to establish a clearly defined disease control strategy, which can be implemented and communicated to stakeholder groups (10.87 – 10.88).

43. Specific attention should be directed towards the economic evaluation of possible long- and short-term impacts of control strategies, their wider economic implications and distributional effects (10.88).

EU legislation

44. Issues with respect to EU legislation will need to be addressed and the case for changes made on the basis of strategic needs and scientific evidence (10.89).

Vaccines

45. While endorsing the need for continued research on vaccine development, we recognise that substantial obstacles need to be overcome in developing an effective vaccine and therefore advise that vaccination, of either cattle or badgers, should be considered only as a longer term option (10.90).

Need for 'ownership' of the disease

46. Farmers need to take 'ownership' of the TB disease problem in their cattle herds, rather than leaving it largely to Government to resolve (10.91).

1. INTRODUCTION

Background: TB in cattle and badgers

1.1 Bovine tuberculosis is caused by the bacterium *Mycobacterium bovis*. It has long been a persistent problem in cattle farming in the UK and has been the focus for concern and control for generations. It was the widespread disquiet in the late 19th century over the dangers to human health from infected meat that initiated the first of what has been since then a series of government inquiries in the search for appropriate policies to ameliorate the problem. Despite this it remains, in the words of the current Chief Veterinary Officer, “the most difficult animal health problem we face in Great Britain” (Reynolds, 2006).

1.2 Notwithstanding the attention it had received and a variety of specific Government Orders, little obvious progress was made in reducing the incidence of the disease in cattle, or its damaging effects on human health, until the mid-1930s – at which time it was estimated that 40% of all domestic cattle were infected (Proud, 2006). The report of the Gowland Hopkins Committee in 1934 (Economic Advisory Council, 1934) is credited with ultimately being the catalyst for things to change. It recognised explicitly that milk, not meat, was the prime source for human infection, and initiated actions that led progressively to effective control and virtual eradication of bovine tuberculosis in the following 25 years. This period saw the widespread establishment of milk pasteurisation and enhanced meat inspection procedures at slaughterhouses – practices which remain today as the principal defences against human infection, and have resulted in the disease no longer in practice representing a threat to human health. (The Health Protection Agency report 39 cases of human *M. bovis* infection in the UK in 2005 (HPA, 2006) – and some of these originated with other humans (Evans *et al.*, 2007) – compared with over 2,500 deaths per year attributed to bovine TB in the 1930s). The other major element of control was to create explicit differentiation between ‘clean’ and infected cattle herds, along with the introduction of an incentive scheme for the ‘attestation’ of herds based on the regular tuberculin testing of cattle and the removal of reactors so as to progressively reduce the incidence of the disease in the cattle population. Cattle movement into attested herds was strictly controlled and other disease biosecurity measures, such as double fencing between farms, were adopted. This proved to be remarkably effective, and by 1964 the prevalence of infection in cattle had fallen to 0.06% (Proud, 2006) and the disease was considered from a national standpoint to have been virtually eradicated.

1.3 Underneath this comforting picture, however, was a nagging concern. The statistics showed that the annual incidence of infected herds nationally (i.e. the proportion of herds that revealed a reactor to the regular skin tests) had fallen to below 0.5% in the early 1960s and continued to fall until the early 1970s. But the incidence in the South West of England was inexplicably at least five times higher and, more worryingly, was showing no evidence of decline. A special intensive field study of the problem was undertaken by Ministry of Agriculture, Fisheries and Food (MAFF) veterinarians in West Cornwall, where the infection rate was more than double the South West regional average; but their report (Richards, 1972) concluded mainly that fences were generally in a poor state (allowing easy contact and disease spread between cattle on neighbouring farms) and overall standards of livestock husbandry and management were poor.

1.4 A new insight appeared in 1971 following examination of a dead badger (*Meles meles*) found on a Gloucestershire farm in an area where cattle TB breakdowns were very common. It was diagnosed as being severely infected by *M. bovis* and this led to an

investigation to measure the prevalence of infection in badgers, in the light of which MAFF concluded in 1973 that action was required to deal with infected badgers where they posed a threat to the health of cattle. This seemed to be a logical step given that the density of badgers was regarded as particularly high in the South West where the level of TB amongst cattle was also so much higher. Badgers were a protected species under The Badgers Act 1973, but the Minister was empowered to issue licences for the killing of badgers for the purpose of preventing disease spread. Initially MAFF merely gave advice to farmers on killing (by trapping, shooting or snaring) badgers on their own land where badgers were considered a threat to cattle health; but in the face of the considerable public disquiet that this caused it took over responsibility itself for culling operations in 1975, which it implemented by gassing badgers in their setts using cyanide gas. Under this policy gassing operations were conducted in a total of 166 areas, averaging 7km², throughout the South West of England (Wilesmith, 1986). A particular and frequently quoted episode of this period was a clearance programme where setts were intensively and repeatedly gassed over an area of some 100km² near Thornbury in Gloucestershire. Gassing continued from 1975 until 1982 and, with the badger population effectively eliminated, was followed by a period of 10 years with no confirmed breakdowns (Clifton-Hadley *et al.*, 1995-b).

The search for solutions

1.5 Continuing public concern over gassing led to a review of this policy being undertaken by Lord Zuckerman, during which time gassing was suspended pending his investigation. In his report (Zuckerman, 1980) he concluded that badgers represented a significant ‘reservoir’ of *M. bovis* infection and recommended that gassing be resumed, but subject to investigations into the efficacy of cyanide gas in killing badgers quickly and humanely. However, from the results of these experiments the Minister of the day concluded there were strong doubts as to whether badgers in a gassed sett did die humanely and decided the method should no longer be used. It was replaced by culling based on cage trapping badgers and then shooting them – a method not only considered more humane but also bringing the advantage that it yielded carcasses for scientific examination. The so-called ‘clean ring’ culling policy that followed was based on the hypothesis that *M. bovis* infection among badgers occurred in ‘pockets’ of infected social groups. Subject to certain clear criteria, a TB herd breakdown that had been confirmed by detection of visibly lesioned organs and/or laboratory culture of *M. bovis* from tissues of the slaughtered reactor cattle provided a case for badger removal. After their territories had been mapped, a number of badgers from the social groups using the land of the infected farm were trapped, killed, examined and cultured for *M. bovis* infection (there being no live test). If at least one infected animal was found the social groups were removed, and a second round of testing and trapping of all contiguous social groups was undertaken. This process continued outwards until a clean ring of social groups was encountered in which no infection could be identified, at which point the ‘pocket’ was considered to have been eliminated.

1.6 Virtually all cattle herd breakdowns in the South West thought to be associated with badgers were subjected to culling in this way, but the policy was clearly both expensive and time consuming. In 1984 a further group was established to review the problem of badgers and bovine TB. Its report (Dunnet *et al.*, 1986) concluded that, on the basis of careful statistical analyses of the time path of herd incidence over the previous 20 years, there was not sufficient evidence to say that gassing had had any discernible effect in reducing TB breakdowns. It observed that a significant drop in incidence that was apparent in the South West just after the gassing programme had commenced (and was attributed by

many to be an effect of that programme) had also occurred nationally, and had coincided with restrictions on cattle imports from Ireland, along with a change in the tuberculin test which would result in fewer false positives. (A similar fall in incidence was also recorded in Northern Ireland, where no badger culling took place.) In the light of these doubts, unconvinced by the ‘pocket theory’ and bolstered by the fact that a cost-benefit analysis showed the high cost of the clean ring policy could not be economically justified, Dunnet *et al.* recommended an ‘interim’ strategy in which culling was to be undertaken only where infection could be reasonably attributed to badgers, and was to be restricted to the land occupied by the breakdown herd. They also recommended for the first time that farmers themselves should take some responsibility for controlling the disease by taking action to keep badgers and cattle apart. Recognising the lack of information to guide policy formulation and assessment they recommended a major focus on targeted research, and in particular on the development of a diagnostic test for *M. bovis* in live badgers which could then radically alter the approach to badger culling by allowing selective removal (and until which time their recommendations were ‘interim’).

1.7 As is often the nature of these things the Dunnet interim strategy – foreseen as lasting for only five years – continued for ten. A live test for badgers had been developed and subject to trial from 1994-96, but its sensitivity was much poorer than had been hoped, successfully detecting only about 40% of infected badgers (Clifton-Hadley *et al.*, 1995-a, Woodroffe *et al.*, 1999); consequently, it appeared not to offer any advance in terms of cattle disease control while being more costly than the interim strategy. By this time the annual herd incidence of TB, having reached its lowest point in both the South West and nationally in 1979 (at 4.0 and 0.4 breakdowns per 100 herds per year respectively), had shown itself to be on an exponentially rising path and back up beyond the levels of the 1960s. Voices in the farming and veterinary communities were again expressing serious concern.

1.8 So, in 1996 yet another review of the problem was instituted, with badger culling operations in response to new herd breakdowns being suspended while it deliberated. This group, under the chairmanship of Professor John Krebs, was more substantial in size and remit than any of its forerunners and was given a specific task, *inter alia*, to assess the scientific evidence for the links between TB in cattle and in badgers. Its enquiries ranged widely, and the group finally declared that “the control of TB in cattle is a complex problem and there is no single solution”. The group’s report (Krebs *et al.*, 1997) made a large number of recommendations designed to further understand the causes of herd breakdowns, evaluate the effectiveness of current control strategies, develop improved strategies and to foster more and better research. With respect to the role of badgers it concluded that they were a significant source of infection but, importantly, noted that “most of the evidence is indirect, consisting of correlations rather than demonstrations of cause and effect”. In reviewing the various policy actions that had been implemented against badgers the Krebs report emphasised the fundamental point that it was not possible to compare their relative effectiveness, nor to compare their impact with that of not killing badgers, because there had been no proper experiments.

The question to be resolved

1.9 This latter statement crystallised the essence of why, despite its long history, there has remained so much controversy and uncertainty over the issue of badger culling. That badgers are a potential source of TB in cattle is undisputable. The fact that badgers are

found to have tuberculous lesions caused by *M. bovis* demonstrates that they are clearly another host species. In principle it could be that they are solely a ‘spillover’ host, but if they are a primary host (i.e. infection can be transmitted between badgers and maintained in the population) then it means they may amplify the infection and pass it to other species. If this is the case then the presence of infected badgers logically represents a potential risk of infection for cattle (and equally, the presence of *M. bovis* infected cattle represents a potential risk of infection for badgers). Consequently, if badgers were completely eliminated from an area of farmland and repopulation prevented, it follows that this should eliminate completely that source of infection risk on that land. It is on this logic that badger culling was implemented as a key element of TB control policy for over 20 years.

1.10 However, the situation is more complicated than this. First, as Krebs pointed out, the evidence of an *association* between *M. bovis* infection in badgers and in cattle, which is undisputed, is not the same as evidence of *transmission* from badgers to cattle. This therefore injects considerable uncertainty into how effective badger culling will be in reducing the risk of TB breakdowns – uncertainty which is exacerbated by the fact that to remove every badger and maintain that zero population over time on any reasonable areal scale would be extremely difficult in Great Britain. Added to this, the magnitude of risk reduction resulting from badger removal may not be simply proportional to the quantitative importance of badger infection as a risk factor. The dynamics of the disease may involve two-way interactions between infection in badgers and in cattle. The badger culling policies of the past have been based on the implicit assumption that, in those areas where the incidence of TB breakdowns is high, it is infected badgers that have been the main source of continuing cattle infection, discounting the possibility that it could be transmitted in multiple directions and, in particular, from cattle to badgers. So, if the assumption about the contribution of badgers is wrong and, despite an obviously infected badger population, the actual transmission of the disease to cattle is in fact relatively low then the impact of badger culling, however effectively conducted, in reducing the risk to cattle would be similarly low.

1.11 The upshot of all these considerations is clear. Examinations of infection rates in cattle and in badgers, theoretical explanations of the possibilities of infection transmission between the two species, evidence of transmission under experimental conditions, circumstantial evidence of links between herd breakdowns and badger populations, and anecdotes and documented cases of where badger culling has ‘worked’, do not amount to a sufficient scientific basis upon which to build a generalised disease control policy. In the last analysis policy must be constructed on clear evidence of what is feasible in practice and predictable in outcome. And this, in turn, highlights the fundamental question that needs to be resolved: What effect, in practice, is badger culling likely to have in reducing the number of herd breakdowns in an area?

The origins of the ISG

1.12 The Krebs report confronted this question directly in one of its key recommendations. In discussing the various large scale clearances of badgers that have taken place (Thornbury in Gloucestershire, Steeple Leaze in Dorset, Hartland in Devon and East Offaly in Ireland) and which are often quoted as evidence of the effectiveness of culling in controlling cattle TB, the report notes that “badger removal might have caused the observed falls in herd breakdown rates, but the possibility remains that some other unidentified factor could have been responsible” (Krebs *et al.*, 1997, p30). There is an important functional difference

between those local intensive culling operations and the more general culling approaches applied across the South West from 1975-96 in response to herd breakdowns, but in both cases the observed outcomes do not constitute dependable scientific findings because of the lack of the necessary comparable control areas to act as the baseline against which to measure effects. This criticism strikes at the heart of all the previous assertions and expectations about badger culling because these all lack the necessary scientific rigour. The Krebs report concluded that “a proper experimental assessment is the only way to test rigorously the effectiveness... of different strategies to provide a sound basis for future policy”. It therefore recommended that: (a) a randomised field experiment be put in place to determine the impact and effectiveness of two alternative types of badger culling strategy, as compared to specific no culling areas; and (b) an independent expert group be formed to oversee the experimental design and to monitor progress. This expert group was set up in early 1998 as the Independent Scientific Group on Cattle TB (hereafter the ISG), and the experiment it designed and oversaw became known as the Randomised Badger Culling Trial (RBCT or ‘the trial’). The rest of this report develops and presents the work of the ISG and the conclusions that have emerged from its long and detailed programme of activity.

1.13 The logic of the Krebs recommendation was immediately apparent. We live in a world in which, to be rational, actions to resolve complex problems need to be guided by information and analysis, not by opinion and casual inference. It is established scientific method that provides the only reliable framework for developing the required information in a clear, rigorous and dependable fashion and in so doing confers credibility on it. The Department for Environment, Food and Rural Affairs (Defra) has committed itself to the principle of basing its decisions on ‘sound science and evidence ... to ensure that animal health policy is based on sound scientific evidence’ (Defra, 2004a, page 30). Because of the complexity of the biological system in which it has to function, the control of bovine TB requires, perhaps more than in most other areas, the clarity, precision and rigour that science brings to problems. The relatively crude policies for TB control seemed to be satisfactory in the past when it was a gross problem in a relatively static cattle population in established production systems, such that a tolerably effective method of identifying and isolating infected herds and removing the reactor animals (or sometimes whole herds) could make major improvements. But when herd incidence had fallen to low levels, and complications in the overall system grew due to the recognition of wildlife sources, the increasing scale and intensity of cattle management systems, the dynamics of trade and wider geographical livestock movements, the pressures of financial constraints and issues of public awareness became a consideration, much greater precision and fine tuning of interventions became increasingly necessary. All this imposed greater pressures on the technology for disease management and the information requirements to achieve the desired levels of control. The weakness of the existing information and conceptual base for policy development becomes clear when it is realised that the procedures for the tuberculin skin test were initially developed in the 1930s and, apart from a change in the tuberculin used in the 1970s, are largely unchanged since then; that the possibility of cattle-to-cattle transmission of TB was assumed unlikely to impede the control effort because of the confidence placed in the efficacy of cattle testing; and the knowledge that badgers were susceptible to *M. bovis* infection led directly to the presumption that culling them would automatically reduce the occurrence of herd breakdowns.

1.14 The ISG recognised these complexities from the beginning of its work. While accepting a prime responsibility to design and implement the RBCT so as to provide, for the

first time, rigorous assessments of the power of badger culling to reduce herd breakdowns, it also realised the need to adopt a wide-ranging and integrated approach to the problems of managing TB within a modern, commercial and geographically dispersed cattle sector. Thus, its Terms of Reference (see Appendix B) included a final and crucial component that directed it to consider the problem of cattle TB more widely than simply the delivery of ultimate findings from a scientifically designed and implemented RBCT.

1.15 The outline structure of the trial was firmly based on the scientific method. It was to measure the effects of two different approaches to badger culling ('the experimental treatments') applied across large and appropriately selected areas, and to compare these with the measured effects of no culling across comparable areas ('the experimental controls'). The trial was to be conducted in areas of high incidence of herd breakdowns in order to maximise the ability to capture any significant effects that were to be found. The way in which this proposal was to be interpreted, refined, developed, implemented, guided and monitored constituted the primary task of the ISG in the early stages of its work, and is discussed in detail in the next Chapter.

2. DEVELOPMENT AND IMPLEMENTATION OF THE RBCT

Background considerations

2.1 Although the origins of the RBCT lay in the Krebs report's declaration of the need for "a proper experimental assessment...to test rigorously the effectiveness...of different (badger culling) strategies" (Krebs *et al.* 1997, page 128), the ISG recognised very early in its deliberations the necessity of pursuing a wider programme of research than designing, managing and analysing a field trial along the lines proposed by Krebs. It was evident from past experience and previous reviews of the link between badgers and TB in cattle herds that the interrelationships were complex and poorly understood. Consequently, the ISG realised that clarifying the role of badger culling, while necessary, would not in itself be sufficient for determining an effective control policy. Indeed, concentrating solely on the badger dimension in what was clearly a multidimensional and dynamic system of disease spread would be to fail to learn the lessons of previous experience.

2.2 So the ISG believed it essential to adopt a wide-ranging approach to its inquiry from the outset, viewing the problem of TB in cattle and its potential control from a broad-based and integrated standpoint on the grounds that future control policies would need to be based on the application of a range of measures. Furthermore, the ISG was conscious of the fact that, despite TB policies having been in force for many years, there remained important gaps in knowledge and areas of uncertainty concerning the epidemiology and pathogenesis of the disease in both cattle and badgers. Consequently, the ISG interpreted its remit as being to develop a wide-ranging epidemiological investigation into TB in cattle and badgers that extended well beyond the culling trial. In doing so, while confirming its commitment to the scientific approach, the ISG identified its core aim as being "to present Ministers with a range of scientifically based policy options which will be technically, environmentally, socially and economically acceptable" (Bourne *et al.*, 1998, page 4).

2.3 Meeting this aim would lead us into reviewing the state of scientific knowledge about *M. bovis* and its transmission, the diagnosis of TB in cattle, the dynamics of infection in both the badger and cattle populations, the risk factors facing cattle herds, and the prospects for novel control and protection methods such as vaccination and targeted farm biosecurity. And this in turn implied the need for us to recommend a carefully constructed programme of research that MAFF should put in place, along with support for a series of studies which would broaden the information base available for taking a fully considered approach to control policy.

SETTING UP THE TRIAL PROCEDURES

Establishing the Randomised Badger Culling Trial

2.4 The first detailed task, however, was to design and initiate the RBCT. The Krebs report emphasised the need for research "to quantify the contribution of badgers to the risk of TB in cattle" (Krebs *et al.*, page 33), and many presumed it was information of this nature that the trial would yield. However, such quantification would have required the total removal of badgers from at least some of the culled areas and prevention of any subsequent immigration, so that the change in cattle TB incidence when badgers were absent could be measured. A qualifying statement from the Krebs report (page 89) states that "Analysis of the data from the proactive strategy, and comparing this with the data from the no cull strategy, will allow the estimation of the maximum possible impact of badger management

on herd breakdown rates.” The ISG recognised that an objective to quantify ‘the badger contribution’ implicitly assumes that there is simply a one-way transfer of infection, from badgers to cattle; whereas in reality there is interchange of infection between the two species with disease transfer in both directions, so the contribution of badgers is not independent of the feedback from cattle. It was therefore clear that the trial could not provide anything quite as precise as a quantitative estimate of “the contribution of badgers to the risk of TB in cattle” and could directly measure only the contribution that particular forms of culling could make.

2.5 The proposed structure of the trial was to compare, within a framework of scientific experimentation under field conditions, the relative impact on herd breakdowns of two different approaches to badger culling as compared to not removing badgers at all – i.e. three distinct experimental ‘treatments’. As such the ISG understood that it would be, in practice, comparing three potential policies of TB control based on different levels of intervention in badger populations. The ISG thus consistently referred to this aspect of its work as being “a trial of alternative culling policies”. The aim was to achieve the rigour of a scientific approach by following well tested principles of investigation, but (apart from the greater detail of data collection) approximating the procedures and performance that could be reasonably achieved in everyday field operations.

2.6 The trial was also designed and implemented to ensure that it provided an additional wealth of epidemiological data in both cattle and badgers – data that could not be gained in any other way.

The culling treatments

2.7 The two types of badger culling in the trial, labelled as ‘proactive’ and ‘reactive’ respectively, were to be compared with the measured effects in comparable areas where no culling took place; these latter areas were labelled as ‘survey-only’ (rather than ‘no culling’, because as well as being uncultured control areas, important survey data were collected on signs of badger activity throughout all trial areas).

2.8 The aim in proactive culling areas was to remove at the outset as large a proportion as possible of the badgers resident in the trial area (while paying due attention to animal welfare considerations) and to maintain this population suppression throughout the period of the trial by regular follow-up culling operations. In the reactive areas badger culling was to be undertaken only on the occurrence of a confirmed herd breakdown and with the aim of removing all social groups of badgers having access to the breakdown farm, but (in contrast with past policies) with no specific consideration given to whether or not badgers were implicated in the breakdown. The survey-only areas played an important role in providing the benchmark against which the impacts of the two culling programmes were to be assessed, thereby acting as the ‘experimental control’. As well as trialling possible culling approaches as TB control measures, the proactive and reactive treatments were designed to yield a fund of badger carcasses for scientific examination to provide previously unavailable information on the prevalence, genetic type and pathology of TB in a large sample of badgers in areas of high cattle incidence.

2.9 The ISG invested considerable time in defining, characterising and explaining the three treatments. The reactive treatment had many similarities with what had been the standard badger intervention approach during the 10 years of the Dunnet interim strategy (Dunnet *et al.* 1986), and in this respect was closest to being a formal assessment of a

previously accepted policy. Some observers had questioned the appropriateness of trialling the proactive treatment, since it was not perceived as being widely applicable in practice, and there was concern over the high number of badgers that might be killed in the process – though the Krebs report (page 94) had estimated this might be little different from the numbers killed in the latter years of the interim strategy. The ISG argued that the proactive treatment was essential because it might well form a component of future policy, it would demonstrate the maximal effect that the selected culling approach could achieve and, importantly, it would provide otherwise unobtainable information on the epidemiology of TB in badgers. The inclusion of the survey-only treatment allowed the RBCT to be scientifically robust in estimating the impact of culling strategies on TB incidence in cattle. Such estimates were unavailable for all previous culling policies, whether based on gassing or trapping.

Trial design

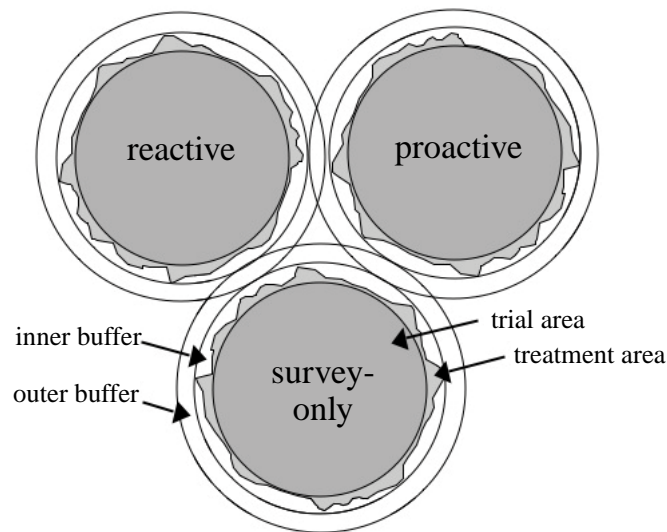
2.10 The formal design of the trial required the specification of the method of treatment allocation, the number of farms to be enrolled and the timescale of the trial. (See Appendix H for further information.)

Trial areas and treatment allocation

2.11 The three strategies could in principle have been allocated individually to herds enrolled in the trial, but some badger social groups might have had territories overlapping the land areas associated with more than one herd, and would thus be potentially subject to more than one treatment. To avoid this and, furthermore, to reduce the interference between different culling treatments, all of the farms in relatively large trial areas (roughly 100 km²) were assigned the same treatment.

2.12 After careful consideration the ISG decided that rather than adopting the Krebs report's suggestion of using 10km x 10km squares, it was more appropriate to apply the treatments within broadly circular areas of approximately 100km² (10,000 hectares or 24,710 acres). Circles would minimise the length of boundary (and hence any boundary effects) associated with each trial area. An important consideration was to ensure the trial areas in a triplet, while desirably as similar as possible in location, were sufficiently separated so that treatments would not overlap. The same consideration was necessary to ensure appropriate separation of triplets. This was achieved by defining a 1km wide zone around each 100km² trial area (the 'inner buffer zone') and then a further 1km wide 'outer buffer zone'; 1km represents approximately the maximum likely ranging distance of a badger (see Chapter 4 for details on the scale of badger movements), so the defined buffer zones should also ensure no overlap of badger territories between treatments. Outer zones were allowed to overlap but not inner buffer zones, meaning that the boundaries of nearby trial areas would never be less than 3km apart. 'Treatment areas' were defined to encompass trial areas, as well as any land within the inner buffer judged to be occupied by badgers using farms inside the trial area (Figure 2.1).

Figure 2.1: Schematic representation of trial areas in a triplet



2.13 These trial areas were to be identified in groups of three ('triplets') which were as similar as possible in terms of location and agricultural characteristics, the three treatments to be allocated randomly to the areas within each triplet to avoid any bias in selection. The randomisation procedure was to be conducted at the latest possible stage so that neither the level of consent given by landholders, nor the determination of treatment area boundaries, nor the intensity of surveying for signs of badger activity across the areas concerned, would be influenced by prior knowledge of the culling to be applied.

Statistical power

2.14 The statistical power of the trial was the probability of it being able to detect a reduction, if it existed, in the incidence of TB in cattle. It depended primarily on the total number of TB breakdowns (i.e. the cumulative incidence) in the survey-only (control) areas and the percentage reduction in the breakdown rate in the culling (proactive and reactive) areas.

2.15 The statistical power calculations for the trial, originally presented in the Krebs report (Krebs *et al.*, 1997) and adopted by the ISG to determine the size of the RBCT, were based on the simple but reasonable assumption that the variability of numbers of observed cattle TB breakdowns is essentially that found in the Poisson distribution, the statistical distribution governing the count of events occurring totally at random. Based on the historical incidence of TB in cattle across Great Britain between 1992 and 1996 inclusive, the Krebs report had recommended that a minimum of thirty 100km² areas should be included in the trial. The ISG accepted this view but, in its early deliberations, considered the possibility that additional triplets might become necessary to deliver the required statistical power.

2.16 Based on the statistical power calculations it was suggested in the Krebs report that if the incidence of TB in cattle remained at the level observed over the previous five years, then a reduction in TB incidence as low as 20% in the trial areas subject to culling should be detectable within five years of observation in 10 triplets (i.e. with the accumulation of data amounting to 50 'triplet-years'). Higher TB incidence in the trial areas (but the

same ratio of incidence rates between treatments) would reduce the number of triplet years required to detect a difference.

Assumptions

2.17 The assumption that TB breakdowns occur totally at random will tend to underestimate the variability to be encountered in practice. For example, there is some evidence of clustering of TB breakdowns in space and time (Woodroffe *et al.*, 2005c). The final analysis of variation is based on the observed consistency of the ratios of breakdown rates (for example, the ratio within a triplet of the TB incidence in the proactive area divided by the TB incidence in the survey-only area) between triplets, adjusted for herd and cattle numbers and possibly other features.

2.18 While 10 is the minimum number of triplets advisable for effective error control, the viability of the trial did not, as such, depend on the validity of the original power calculations. For later discussion the emphasis was placed not on detecting a real difference but rather on estimating the magnitude of any effect with adequate precision. The implications for the size of the trial were identical.

2.19 It was recognised that non-compliance with the trial through interference with culling operations, denial of access for survey or culling teams (particularly in the proactive and reactive areas) and illegal killing of badgers (especially in the survey-only area) could all reduce the differences between treatment areas. Depending on the circumstances, such factors could serve to mask the true effect of culling treatments, but the statistical power of the trial was sufficient to deal with the levels of non-compliance encountered.

Analysis strategy

2.20 The primary outcome of the RBCT, on which its empirical findings were to be based, was to be the data on the incidence of TB over the period of the trial among cattle herds in the triplet areas that had been subjected to proactive culling, reactive culling and no culling. From the outset, and long before the ISG examined any data, it established an analysis strategy (see Appendix 3, Bourne *et al.*, 1998) and agreed that interim analyses of the data emerging from the trial would be undertaken at appropriate intervals to ascertain whether significant findings were emerging. These analyses were to be conducted by the two statistician members of the ISG, but with the results remaining known only to them and to the independent statistical auditor (Professor Denis Mollison of Heriot-Watt University). The method for the interim comparison of outcomes from the three treatments was formulated by the ISG and then approved by the independent statistical auditor when the first interim analysis was undertaken in late 2000 (Mollison, 2000). The next analysis was delayed due to the lack of cattle testing during the foot-and-mouth disease epidemic in 2001, and was not conducted until 2002. Interim analyses continued then to be undertaken and reported to the statistical auditor every six months.

2.21 What is later referred to as the ‘primary analysis’ of treatment effects was to be a comparison of the number of confirmed cattle herd breakdowns associated with each culling strategy (i.e. within the relevant trial areas) with the number associated with the no-cull survey-only strategy. The commencement of the trial in each triplet (i.e. the date it became ‘active’) was timed from the end of its initial proactive cull, and breakdowns occurring after this date in any of the three triplet areas thus contributed to the analysis. Data relating to each herd breakdown were to be obtained from the animal health information

system VetNet, which holds information on all cattle herds in Great Britain (covering size, type, breakdown history, etc.), and also on their disease management including TB tests conducted by the State Veterinary Service (now Animal Health).

2.22 In analysing the comparison between treatments, adjustments were to be made for triplet effects, as well as for baseline variables and characteristics associated with each trial area, effects due to time or interactions between variables. The details of all the analyses are explained in Chapter 5.

Geographical location of triplets

2.23 The trial was to be located in the TB ‘hotspot’ regions of West and South West England since the impact of culling that the trial was designed to measure would be most easily detected in areas where the incidence of herd breakdowns was highest. In these hotspot regions most cattle herds were already subject to annual TB tests, and given the history of breakdowns there were many areas that had also been subject to badger removal at some time in earlier years (details in Chapter 4). The specific criterion for identifying the locations of potential trial areas was the incidence of confirmed herd breakdowns over the three years prior to selection, with the additional evidence of a continuing breakdown problem in the most recent year. Although ideally the three areas in each triplet would be as nearly identical as possible in terms of numbers and types of cattle holdings, breakdown histories, surface area, landscape characteristics, badger population density, etc., this was not feasible in practice – nor, indeed, essential given the ability of the planned statistical analyses to accommodate the inevitable variability in the trial findings.

Surveying the trial areas

2.24 Once the location of a triplet was specified, the first task was to undertake a detailed field survey of the three constituent areas to record the location, activity and size of all badger setts plus other field signs of badgers such as latrines and paths. GPS facilities were not available at the outset, so the locations of field signs were mapped as precisely as was feasible using 1:10,000 paper maps. The information derived from these surveys was recognised to be critical for both the operation of the trial and many of the analyses of the results. These enabled estimates to be made of badger activity prior to the commencement of culling, permitted the mapping of social group territories to assist delineation of the appropriate boundaries for removal operations and, importantly, provided guidance for the subsequent siting of traps in areas that received the culling treatments.

2.25 The ISG appreciated that not all landowners and occupiers within a designated trial area would agree to collaborate in the trial. When a triplet location was defined, all identified landholders were contacted and, without it having been determined at that stage which of the three treatments would eventually be allocated to their area, asked if they would participate in the trial. A large but variable proportion in each trial area did agree to offer full co-operation, some agreed to allow their land to be surveyed for badger activity but refused permission to cull, and some declined access for any of the trial’s procedures. It was evident that, except in the case of large individual landholdings, the areas of land unavailable for inclusion in the trial were likely to be mostly relatively small and scattered and, although the incompleteness of co-operation was less than ideal, it was not unexpected and trial operations could be adjusted to minimise the constraints that this incomplete access imposed. Furthermore, given that this was a trial of potential culling policy options, such restrictions reflected a reality that would be encountered in practice anyway. Statistical

analyses of the level of consent granted, and their changes over time, are presented in paragraphs 2.49 and 2.50 and Appendix G, respectively.

Culling strategy

2.26 The ultimate aim in the proactive areas was to be able to determine whether suppressing and then maintaining the badger population at as low a level as was reasonably practical had a detectable and worthwhile effect on the incidence of herd breakdowns in the region. The aim in the reactive areas was more limited, namely to assess whether removing as large as possible a proportion of the badgers geographically associated with confirmed herd breakdowns had a measurable effect on future breakdowns in the region. In line with experimental objectives, follow-up culling was necessary across a proactive area to reinforce and maintain the level of clearance, whereas after a reactive cull the necessary action against the badgers was assumed to have been taken and no repeat removals were appropriate. In each case, for the two treatments to be relevant as practical policies, the requirement was for the culling to be as efficient as possible in removing the target populations but balanced against considerations of animal welfare and cost.

2.27 Mindful of general public attitudes towards the destruction of wildlife, and to the badger in particular, the ISG considered very carefully what culling method to adopt. Given that wildlife, by definition, is not under managerial control total removal was unlikely to be achievable. Added to this, the ISG had been given a very explicit declaration by Ministers at the outset that elimination of badgers over large tracts of the countryside was not acceptable as future policy. A further consideration involved in implementing the RBCT related to the legality of widespread culling of a protected species. In December 1998, while the ISG was still planning the trial procedures, the Standing Committee of the Bern Convention on the Conservation of European Wildlife and Natural Habitats (to which the UK is a signatory) recommended that the trial be postponed pending an opinion on whether it was in breach of the Convention. The Convention prohibits “the use of all means capable of causing local disappearance of, or serious disturbance to, populations (of badgers)” (Council of Europe, 1979). The ISG assisted and supported MAFF in making the case that, in the light of the severity of the cattle TB problem in the country and the explicitly scientific motivation underlying the planned culling activities, the trial did not breach either the letter or the spirit of the Convention. (See <http://www.defra.gov.uk/animalh/tb/publications/bern/bern.htm>). Twelve months after it had raised the issue, the Standing Committee agreed with this argument and closed its file on the matter, MAFF agreeing to provide it with regular updates both on the RBCT and on the wider TB control programme. In assessing the effectiveness of badger culling as a practical policy option the trial’s aim was not total depopulation of an area; rather it was to achieve the maximum level of removal that was reasonably attainable in practice and, importantly, defensible in environmental, welfare and political terms. In its first report (Bourne *et al.*, 1998) the ISG discussed in detail the alternative capture methods and the reasons why the ISG concluded that cage trapping should be adopted. The ISG recognised that the effectiveness of this method was strongly influenced by season and weather, was demanding of resources, and that a proportion of the badger population is ‘trap-shy’ (Tuytens *et al.*, 1999). Nevertheless, the ISG considered that, if implemented intensively enough with a large number of traps laid relative to the anticipated badger population, and continued for long enough (the ISG anticipated at the outset that about two weeks of continuous trapping would be sufficient) – trapping would effectively capture the majority of the badgers in the area. Gassing was considered to be out of the question for a variety of reasons, not least its political unacceptability as reflected in the ministerial decision to abandon this culling method in 1982. The main alternative method

of capture, snaring, was recognised to be possibly more efficient in terms of capture rate and cost. However, it had potentially severe disadvantages in terms of animal welfare to both badgers and non-target species that might also be caught, and the public image of snaring was strongly negative.

Animal welfare considerations

2.28 Badger welfare was taken into account in the design of RBCT methods. Not only were there legitimate concerns that some trapping methods would entail suffering for badgers, but also methods perceived to involve cruelty could attract widespread public criticism and jeopardise both the RBCT and any decision about culling policy in the future. This was a concern in relation to the treatment of lactating female badgers during the RBCT culling operations. Under the previous ‘clean ring’ and ‘interim’ strategies, trapping had been conducted year-round but lactating females were released to avoid leaving dependent cubs underground to starve. Both the Dunnet and Krebs reports (Dunnet *et al.*, 1986; Krebs *et al.*, 1997) asserted that this practice was inconsistent in the context of a disease control strategy. The ISG considered the arguments carefully and concluded that meeting the concerns over badger welfare was essential to the integrity of the trial, both as an experiment and as an assessment of a potential policy. It was decided to impose a 3-month ‘closed season’ on all culling, from 1 February to 30 April (inclusive) every year. Given the typical times of births and weaning these dates would avoid taking badgers at a time when there were most likely to be dependent cubs underground (Woodroffe *et al.*, 2005a). This moratorium was thought unlikely to affect the efficacy of proactive culls, for which there was flexibility in scheduling initial and follow-up culls – and cage trapping was known to be far less effective in the winter months anyway (Woodroffe, 1995). However, it might be more disadvantageous for reactive culling where there was considered to be a need to minimise any delay between a herd breakdown being confirmed and initiating the consequent cull of badgers.

2.29 A second and significant welfare issue related to the way in which badgers were killed once captured in a cage trap. The appropriate method was to kill by gunshot, but the skill and the precision with which this was administered was critical to ensure that death was instantaneous, with minimal stress to the badger and no suffering – not to mention the safety of the staff in the field. This would not always be easy to attain in field conditions, perhaps in harsh weather and with the animal not presenting itself conveniently. It was evident that careful guidance and specific training needed to be given to field staff to ensure welfare of badgers and human safety. Similarly it was necessary to minimise the levels of stress and injury suffered by badgers while confined within a cage trap, and procedures were defined to ensure inspection of all traps as early as practicable in the morning after these were set. In addition, detailed procedures were established for handling and release of non-target species that would inevitably be captured in some of the traps. Finally, in order to feel reassured that its procedures were appropriate and defensible in welfare terms the ISG further decided to instigate careful data collection to enable analyses of badger welfare to be undertaken during the trial. (See paragraphs 2.60 to 2.66 for results of these investigations.)

Administrative and operational matters

2.30 All the field activities involved in the trial were to be undertaken by staff of MAFF’s Wildlife Unit (WLU) under the guidance and management of a National Trial Manager who was to work closely with the ISG and participate in its meetings. The WLU staff operated from two centres, in Cornwall and in Gloucestershire, and were highly experienced in

most aspects of the trial operations having been responsible for implementing previous badger culling policies. The ISG recognised that triplets would have to be enrolled in sequence and that it would take some time before the whole trial was up and running (the original expectation had been that all 10 triplets would be in place by the end of 1999). The WLU had to have the capacity to undertake a sequence of initial proactive culls, maintain a programme of follow-up proactive culls, and be capable of responding rapidly when reactive culls were called for. This clearly imposed substantial demands on them, and the ISG therefore stressed the need for planning the provision and mobilisation of sufficient extra resource, and for additional staff to be recruited and trained to accomplish the rising level of trial tasks. These tasks included initial field surveys of badger activity; the siting and setting of traps; the humane killing of badgers; the sampling, labelling and delivery of carcasses, with recording of each capture location, to the laboratories for post mortem examination; and the subsequent monitoring of badger activity in all trial areas. The ISG was conscious from the outset of its dependence on the skill and co-operation of WLU staff, and were reassured by their professional approach and commitment to their role. The ISG understood the need to work closely with them, and ensured arrangements were in place whereby the ISG and WLU staff could exchange information and feedback on experiences as the trial progressed.

2.31 In addition to fieldwork capability, the trial was to make substantial demands on laboratory capacity within the Veterinary Laboratories Agency (VLA), who were to undertake the post mortem examination of badger carcasses as rapidly as possible after they became available from culling operations, along with tissue sampling, culturing and genetic typing of *M. bovis* infection when discovered. This in turn necessitated the provision of additional resources, not only of laboratory staff but also the appropriate facilities required by health and safety regulations. Thus, the required support structure for the RBCT was of considerable magnitude, and the ISG devoted much attention to initiating and co-ordinating its availability.

2.32 As part of this framework of arrangements the ISG, in association with MAFF (and subsequently its successor, Defra), developed a series of detailed Standard Operating Procedures (SOPs) for all aspects of the trial, which were to be kept under constant review and updated with experience. The SOPs were conceived as ensuring the clarity, rigour and consistency essential in a science-based information gathering process, and were to provide a valuable reference point for subsequent analyses of trial outcomes. The procedures detailed included surveying for badger activity, delineation of trial area boundaries, trapping, humane dispatch of captured animals, post mortem protocols, and laboratory culture procedures for *M. bovis*. A list of all the SOPs developed is contained in Appendix F.

2.33 The initiation of the trial had received much publicity among farming and rural communities, and it was realised that the culling operations were potentially an emotive and high profile issue. The ISG therefore held a public meeting in the vicinity of each triplet around the time that landholder consent was being sought, with the aim of explaining the trial and its objectives to local communities. Nevertheless, much opposition had been declared by badger interest groups and direct interference from animal rights activists had been volubly threatened. In the light of these concerns, and notwithstanding its belief in the principle of open government, the ISG advised MAFF/Defra to give only the most basic of information concerning the location of triplets and issue no advance information about the areas to which culling treatments had been allocated (though it recognised this

would rapidly become well known as soon as WLU staff were in the field to start laying and pre-baiting traps). It was necessary to give full advance information to the police forces in those areas where culling was to take place, taking security advice from and working closely with those forces, to ensure adequate protection of WLU staff and to minimise as far as possible physical interference with field personnel and traps and disruption of the trial operations.

Independent audit arrangements

2.34 A further issue to which the ISG attached considerable importance from the beginning was the need for formal independent audits of core aspects of the trial to be undertaken and repeated at appropriate intervals. This was seen as essential to give the ISG confidence that the work being undertaken on its behalf was done to the highest standards, and to reassure external observers of the objectivity with which the trial was being pursued. An auditor was appointed initially to review the field procedures of surveying, social group delineation and badger removal, followed by a second auditor to evaluate the welfare aspects of the way trapped badgers were killed. The programme of audits was to be developed as the RBCT progressed, and in recognition of the importance of the laboratory-based services on which the findings would be dependent the need for audits of post-mortem protocols and bacteriological culture procedures was identified. Finally, the ultimate value of the trial was to be embodied in the strength and validity of its empirical findings. This highlighted how essential it was to audit fully all aspects of the data collection and handling processes as well as statistical aspects of the trial. Auditors were to be given free rein to enquire into all aspects that fell within their remit and were expected to write full reports, along with any recommendations they considered appropriate, with their reports to be made public when completed. Appendix E lists the programme of audits undertaken throughout the trial, along with summaries of any subsequent action taken, and provides references to access the various audit reports.

2.35 After the RBCT was established, culling had commenced and data were accumulating, Defra instituted an over-arching audit of the objectives and operation of the trial. The review group set up for this purpose (formally the Independent Scientific Review of the Randomised Badger Culling Trial and Associated Epidemiological Research) considered the design and implementation of the trial, the epidemiological studies the ISG had initiated (see paragraphs 2.39 to 2.46) and explored some of the scientific issues needed to underpin a badger control policy. The review group's report (Godfray *et al.*, 2004) recommended continuing support for the work of the ISG and its work programme and offered Defra specific advice. The ISG response is available at <http://www.defra.gov.uk/animalh/tb/isg/pdf/isgresp.pdf>.

Communication, confidentiality and data release

2.36 From the outset the ISG recognised the need for the objectives and scientific credentials of the RBCT to be clearly presented to interested parties, with accurate and accessible information about the work to be disseminated as it developed. This was not only an important reflection of the Group's philosophical stance of openness and objectivity, but it also had relevance for practical reasons. Since participation in the trial was entirely voluntary, maximising the co-operation of landowners and occupiers would to a large extent be influenced by how well the trial's aims were communicated and understood. In this sense it was important that landholders recognised the RBCT as an essential practical

step in the search for a sustainable approach to the long running and so far seemingly unresolvable problem of TB in cattle, and so perceived the importance of the contribution they could make.

2.37 Clearly some aspects of the trial would need to remain confidential, at least in the first instance. This included the identities of landholders and their agreement to participate and, in the light of predicted interference by animal rights activists, the locations and timing of planned culling operations. The ISG believed also that premature release of data on the incidence of herd breakdowns within trial areas could jeopardise the viability of the whole investigation by undermining compliance with the regimes proposed. It was feared that in the initial phases, for example, before a full database had built up, that any apparent changes in the number of breakdowns might appear, due to random fluctuations, to suggest conclusions not confirmed by subsequent data. The ISG felt strongly that merely issuing warnings against ‘over-interpretation’ would be ineffectual in this context, and so considered it essential that the incidence data be kept strictly confidential until the ISG advised that reasonably firm conclusions could be drawn and reported to Ministers accordingly. Such information restrictions are consistent with accepted practice in the conduct of clinical trials and, notwithstanding the keen interest of both stakeholders and members of the research community, the ISG considered confidentiality to be of paramount importance. Indeed, this principle was rigorously applied within the ISG, too, to avoid any danger of unreliable information unwittingly affecting its collective thinking. As data accumulated and trial findings started to emerge from the regular interim analyses, the results were to remain exclusively confidential to the two members responsible for the analyses and the statistical auditor; other ISG members, including the Chairman, were to be informed only when statistically significant effects were detected. This is in accord with standard practice in, for example, randomised clinical trials involving human patients.

2.38 Nevertheless, the ISG declared a basic policy of being as open as possible (giving due consideration to practicality) and specified a long list of data that it believed should properly be made available to any interested parties at the earliest opportunity. We prioritised publishing our findings in leading peer reviewed scientific journals with concurrent release of all relevant data in order that a full assessment of our work could be made by any interested member of the scientific community. In addition, it was anticipated that public ‘open’ meetings would be arranged, and members were ready to participate in meetings with a wide range of stakeholders to explain and update information about the trial. The ISG’s general communications to the Minister, as well as the periodic formal reports the ISG would prepare, were all intended to become openly available. We have instructed Defra that all papers relating to our work be released into the public domain.

The associated research programme

2.39 From the start of its work the ISG has been conscious of the complexity of the cattle TB situation, and has continually stressed that the problem will be resolved only by taking a wide-ranging approach to assembling the information and understanding essential to develop predictably effective control policies. Thus, as well as designing and putting in place the RBCT, the ISG gave considerable thought to the areas and priorities for targeted studies to which MAFF/Defra should direct its research funding.

2.40 The ISG undertook to design and analyse a major epidemiological survey (called the TB99 survey) to investigate risk factors associated with herd breakdowns and to seek

conclusions about any actions that farmers themselves could take to defend against the disease. (Results from the studies undertaken are summarised in Chapter 6 of this report.)

2.41 The ISG also advised on the merits of undertaking a structured survey of badger carcasses recovered from road traffic accidents (RTAs) to establish if a survey of this kind could provide useful information on TB prevalence in badgers outside of trial areas. Some discussion of the findings from these RTA surveys are given in Chapter 4, while the full results and analyses are available at <http://www.defra.gov.uk/animalh/tb/isg/publications/isg1607.pdf>.

2.42 The ISG strongly supported a continuing programme of research to develop more effective vaccines, with potential for badgers as well as cattle, as a longer term goal and conducted a vaccine scoping study (Bourne *et al.*, 2003) to facilitate this line of inquiry. The outcome of that study is summarised in Chapter 8.

2.43 The ISG saw a critical need for, and proposed, a number of research initiatives to provide a better understanding of the pathogenesis and epidemiology of the disease in cattle, and its dynamics, and in particular to improve its diagnosis. The ISG believed this had not been sufficiently addressed in the past, with the result that the potential role and importance of cattle-to-cattle transmission had been underestimated.

2.44 The ISG's consideration of needed research also addressed gaps in understanding of badger ecology and behaviour, the consequences of badger removal for TB dynamics, the potential role of other wildlife species in maintaining *M. bovis* infection, and the environmental impact of removing badgers from ecosystems. Finally, in the light of the fact that selection of appropriate disease control strategies and the manner in which these are applied are dependent, not only on their predicted technical effectiveness but also necessarily involving economic considerations, the ISG outlined a number of economic studies designed to enable the economic evaluation of policy options.

2.45 The research needs identified by the ISG were incorporated into MAFF/Defra's research requirements documents which MAFF/Defra published prior to each round of research funding, and initiated a series of relevant studies which have considerably enlarged the formal evidence base for developing and managing TB control policy.

2.46 A list of MAFF/Defra-funded RBCT-related research projects appears in Appendix P and the summary reports are available on the Defra website. Where they link in directly with ISG analyses and recommendations, some of the detailed results of these research studies are discussed in subsequent Chapters of this report.

THE PROGRESS OF TRIAL ACTIVITIES

Enrolment of triplets

2.47 After selection of specific geographic locations for the three trial areas in a triplet and preliminary mapping, the precise boundaries of each trial area were subject to marginal adjustment in the light of relevant features (such as urban boundaries, major roads and rivers) and then finalised by the ISG. All identified landholders were then contacted in writing, informing them their land was included in a trial area (though treatments had not yet been allocated) and their participation requested. Surveying of the land then commenced. Based on this, final precise boundaries for each 'treatment area' (the area within which all

culling would occur if the trial area was later allocated to the proactive treatment) were delineated so as to encompass whole farms and their associated badger social groups (see Figure 2.1). The treatments were then randomly allocated to the three areas. The first triplets enrolled were A and B in 1998 (see Table 2.1), and subsequent triplets were then enrolled as resources allowed and the schedule of initial proactive culls could be planned. The enrolment and initiation of culling in successive triplets extended over a longer period than had been anticipated, and was hampered by resource and logistic problems – and not least the interruption due to the nationwide foot-and-mouth disease epidemic in 2001 (see paragraphs 2.67 to 2.71).

2.48 Table 2.1 shows how activity unfolded across the 10 triplets as the trial operations progressed and triplets were brought into being over a period of 29 months. The table gives the key information about the dates for the mapping, beginning of surveying for signs of badger activity, the initial proactive cull and the first reactive badger cull. Figure 2.2 shows the geographic locations of all thirty trial areas.

Table 2.1: Dates of key operations in establishing and implementing triplets.

Triplet	Dates				
	Initial mapping of trial areas	Beginning of surveying	Treatment allocation	Completion of the initial proactive cull	Completion of the first reactive cull
A Gloucs/Hereford	11-Jun-98	08-Aug-98	20-Apr-99	28-Jan-00	Jul-00
B Cornwall/Devon	11-Jun-98	28-Aug-98	11-Nov-98	13-Dec-98	Jun-99
C East Cornwall	10-Mar-99	30-Mar-99	13-Sep-99	29-Oct-99	May-00
D Hereford	19-Mar-99	04-May-99	11-Nov-02	18-Dec-02	Sep-03
E North Wiltshire	05-Oct-99	08-Nov-99	27-Mar-00	26-May-00	Jun-02
F West Cornwall	04-Nov-99	05-Jan-00	24-May-00	18-Jul-00	Aug-02
G Derbys/Staffs	15-Mar-00	06-Jun-00	03-Oct-00	10-Nov-00	Aug-02
H Devon/Somerset	15-Mar-00	10-May-00	20-Oct-00	15-Dec-00	Jan-03
I Gloucestershire	10-Nov-00	05-Dec-00	13-Sep-02	08-Oct-02	May-03
J Devon	10-Nov-00	29-Nov-00	06-Sep-02	18-Oct-02	–

Note: no reactive culling took place in triplet J.

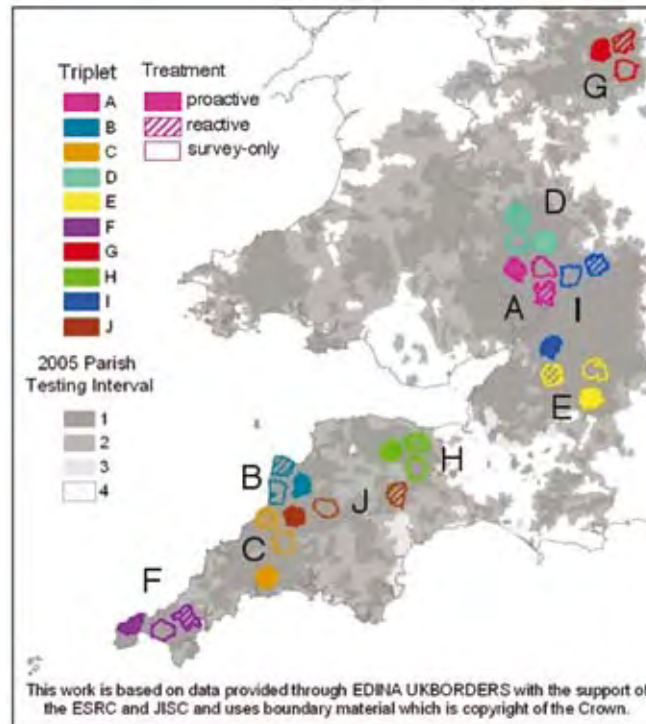


Figure 2.2: Map of proactive (shaded), reactive (hatched) and survey-only (open) trial areas of the RBCT. Grey shading indicates parish testing intervals, which give an approximate index of local TB incidence; parishes with the lowest incidence are assigned four yearly testing (white) and highest incidence are assigned annual testing (dark grey). Testing was conducted annually inside all trial areas.

Taken from Supplementary Information of Donnelly et al., 2006.

Land access

2.49 The ISG were conscious that the effectiveness of badger removal was dependent on the ability to set traps to target badger social groups across the designated culling areas. Because of landholders' rights to participate or not, as they chose, in the trial, culling could be conducted only on land to which they had formally granted access. As explained, landholders were contacted as soon as trial area locations had been designated, but in some instances access was denied, or the ownership of land parcels could not be determined, and so those areas had to be regarded as 'inaccessible'. Across the 10 proactive treatment areas, some 70% of the land inside proactive treatment areas was directly accessible for culling (Table 2.2). Of the remaining land, 73% (amounting to 22% of the total proactive area) fell within 200m of accessible land. Wherever possible, traps were set at appropriate locations along the boundaries of inaccessible land in proactive areas to try to remove the badgers resident in the inaccessible land parcels (Donnelly *et al.*, 2007). Because of the typical nature of badger ranging, this land should have been readily targeted by the culling conducted along its boundaries. See paragraphs 2.57 to 2.59 for a discussion of the impact of land access on badger removal rates.

Table 2.2: Percentages of land accessible for culling within proactive treatment areas. Data relate to consent status at the outset of the trial (Donnelly *et al.*, 2007); see Appendix G for details on how consent levels changed over the course of the trial.

	Proactive trial area										
	A	B	C	D	E	F	G	H	I	J	All
% of treatment area accessible for culling	79%	87%	81%	73%	66%	50%	65%	67%	64%	75%	70%
% of inaccessible land $\leq 200\text{m}$ from accessible land	80%	82%	82%	79%	79%	66%	83%	59%	62%	74%	73%

2.50 The issue of land access was not a major consideration in relation to reactive culling operations. This was because reactive culling was restricted to the home ranges of badger social groups, judged on the basis of field surveys, to include land occupied by cattle herds that had experienced recent TB breakdowns.

Culling operations within the RBCT

2.51 In each triplet, an initial proactive cull was conducted as soon as possible after allocation of trial areas to treatments; as Table 2.3 shows, in most cases this proactive cull was completed (thereby defining the effective start of the treatments) within one or two months of treatment allocation, but in one case took as long as 8 months because of special difficulties. ‘Follow-up’ culls to maintain the reduction in the badger population were repeated approximately annually thereafter. Table 2.3 shows the dates of the sequence of culls in each of the proactive areas in the different triplets, and Table 2.4 shows the numbers of badgers taken. Proactive culls covered all the land accessible across entire trial areas (roughly 100km^2). Of 51 proactive culls, 47 covered the entire area in a single operation. The other four (all follow-up culls, in three trial areas) were conducted in several large ‘sectors’ over periods of several months. This sector-based “maintenance culling” was adopted because it was thought likely by WLU staff that this would reduce the logistical difficulties of culling large areas; however, this turned out not to be the case and the approach was then abandoned. The average initial cull captured 314 badgers (range 55-605), and the average follow-up cull captured 141 badgers (range 48-369).

2.52 The reactive treatment involved a series of localised culls carried out in response to specific cattle TB breakdowns. When TB was confirmed in a cattle herd within a reactive trial area, field staff mapped the land used by the affected herd. Survey data were then used to estimate the likely home ranges of badgers using this land, and to identify their setts (sometimes on neighbouring properties). Areas targeted for culling in this way often coalesced where multiple cattle herds in the same vicinity were affected by TB; hence the 169 confirmed breakdowns which prompted reactive culling were covered by 76 culling operations. The average reactive culling operation captured badgers within an area of 5.3km^2 .

2.53 Table 2.5 shows the dates of reactive culling operations in each triplet, and Table 2.6 presents the numbers of badgers taken by MAFF/Defra. The years shown are ‘culling years’ and are the period between 1 May and the following 31 January; the intervening months of February-April being the closed season adopted by the ISG. The average reactive operation captured 27.2 badgers (range 2-87). The median time lag between the first cattle slaughter

date of reactor cattle on a breakdown (a proxy for the date infection was confirmed in cattle), and the date the first badger was culled on the associated reactive operation was 211 days (inter-quartile range 146-323 days). When breakdowns are divided into clusters (with each cluster prompting a single culling operation), the median time lag between the earliest slaughter date of cattle in the cluster and the first badger cull date was 254 days (inter-quartile range 166-453 days). In principle, any lag between the confirmation of infection in a herd and the consequent reactive culling of the farm's badger population is undesirable if the objective is to curtail further spread of infection from badgers to cattle, and if badgers were the initial cause of the breakdown. However, the practical realities of implementing a culling policy result in unavoidable delays while the breakdown is confirmed, badger territories are then mapped and field operations organised and implemented. Additionally reactive culls were sometimes delayed while tuberculin tests were conducted on herds contiguous with the index herd, to ensure that culling operations covered all affected farms within a cluster. The delays to culling experienced in the reactive treatment of the RBCT were similar to those characteristic of past culling policies (Woodroffe *et al.*, in review).

Table 2.3: Dates of initial and follow-up culls in proactive areas, by triplet. Proactive areas received between four and seven successive culls.

Triplet	Initial cull	Second cull	Third cull	Fourth cull	Fifth cull	Sixth cull	Seventh cull
A	Jan 2000	May 2002	Nov 2003	May 2004	Oct 2005		
B	Dec 1998	Nov–Dec 1999	Aug 2000–Jan 2001*	Nov–Dec 2002*	Jun 2003	Jul–Aug 2004	Oct 2005
C	Oct 1999	Jan 2001	Aug–Nov 2002*	Oct 2003	Jun 2004	Sep 2005	
D	Dec 2002	May 2003	Sep 2004	May 2005			
E	May 2000	Jan 2001	Jun 2002–Jan 2003*	Jun 2003	Jul 2004	Sep 2005	
F	Jul 2000	May 2002	Dec 2003	Sep 2004	Jun 2005		
G	Oct–Nov 2000	Jul 2002	Jul 2003	Jun 2004	Jun 2005		
H	Dec 2000	Jun–Jul 2002	Sep 2003	May 2004	Jul–Aug 2005		
I	Sept–Oct 2002	Sep–Oct 2003	Oct–Nov 2004	Jul 2005			
J	Oct 2002	Jul–Aug 2003	Oct–Nov 2004	May 2005			

*Culling was performed in sectors between these times

Table 2.4: Total numbers of badgers (of all age classes) culled in proactive areas, by triplet and culling year (defined to run from 1 May – 31 January). (Includes 19 badgers found dead in proactive areas.)

Triplet	1998	1999	2000	2002	2003	2004	2005	Total
A		55		149	52	58	48	362
B	239	85	74	49	172	111	58	788
C		247	111	126	132	187	163	966
D				293	369	211	182	1055
E			747†	96	258	214	148	1463
F			452	249	103	220	155	1179
G			427	205	144	103	117	996
H			162	231	71	75	54	593
I				219	176	93	173	661
J				442	187	109	109	847
Total	239	387	1,973	2,059	1,664	1,381	1,207	8,910

†Combined total for initial and follow-up cull completed in the same year

Table 2.5: Approximate dates of reactive culling, by triplet and culling year (defined to run from 1 May – 31 January). Reactive culling operations occurred between the dates indicated. Triplet J was eligible for reactive culling in 2003 but no culls had been performed when the reactive treatment was suspended in November 2003.

Triplet	1999	2000	2002	2003
A		Jul-Nov 2000	Jan 2003	May 2003
B	May-Dec 1999	Aug-Sep 2000	Sep 2002-Jan 2003	May-Jul 2003
C		May-Aug 2000	Jul 2002-Jan 2003	May 2003
D				Aug-Sep 2003
E			Jun 2002-Jan 2003	Jul-Oct 2003
F			Jul 2002-Jan 2003	Jun-Sep 2003
G			Aug 2002-Jan 2003	Sep-Oct 2003
H			Jan 2003	Sep-Oct 2003
I				May-Sep 2003
J				

Table 2.6: Total numbers of badgers (of all age classes) culled in reactive areas, by triplet and culling year (includes 3 badgers found dead in reactive areas). Triplet J was eligible for reactive culling in 2003 but no culls had been performed when the reactive treatment was suspended in November 2003

Triplet	1999	2000	2002	2003	Total
A		34	47	36	117
B	73	34	84	110	301
C		179	115	101	395
D				122	122
E			62	126	188
F			145	291	436
G			172	84	256
H			17	143	160
I				94	94
J				0	0
Total	73	247	642	1,107	2,069

Trapping procedures and capture rates

2.54 Trap deployment at each capture site (usually a sett) was determined by the level of badger activity detected at the time, with the number of traps set intended to exceed the number of badgers that experienced field staff expected to capture. Traps were placed (but not set) and pre-baited with peanuts for 1-2 weeks, and were then set in the late afternoon, and visited next morning. Standard operating procedures prescribed that initial proactive culling operations be conducted over 11 consecutive nights; however, as an exception, security concerns in Triplet A dictated a discontinuous eight-night initial proactive cull. ‘Follow-up’ proactive culls and reactive culls were conducted over eight nights. Badgers captured were dispatched by gunshot (see paragraphs 2.60 to 2.66); captured animals other than badgers were released wherever possible, or dispatched humanely if deemed too badly injured for release.

2.55 The numbers of traps placed at each sett exceeded the total number of badgers that experienced field staff expected to capture there so as to avoid constraining capture rates by forcing badgers to compete for traps. Over the whole period of the RBCT, proactive culling involved an estimated 160,893 trap nights conducted over 51 operations, with an average of 298.5 traps deployed per night on each operation (Table 2.7; Woodroffe *et al.*, in press). This represented an average ‘capture effort’ of 40 trap-nights/km²/year over periods of 4-7 years. There were 62 reactive culling operations for which data on trapping effort were available, and these comprised a total of 21,109 trap nights with an average of 42.6 traps being deployed per night on each operation (Table 2.8, Woodroffe *et al.*, in press).

2.56 Not every trap that was set on every night in the culling operations was available to catch a badger. This is because some traps captured species other than badgers, or (despite the strong support provided to WLU staff by the local police) were disturbed by people protesting at the operations of the RBCT. Occasionally, interference and capture of non-target species together meant that no traps were available to badgers at a particular sett,

even though traps had been placed there. On an average trap night, 6.1% of trapped setts in proactive areas, and 3.4% of those in reactive areas, were affected in this way. After accounting for such factors, on the first night of culling operations badgers were found in 20.1% of traps in proactive areas and in 30.2% of traps in reactive areas (Woodroffe *et al.*, in press). Capture rates declined rapidly after the first night, averaging 6.1% in proactive areas (Table 2.7), and 8.8% in reactive areas over the whole trapping period (Table 2.8).

Table 2.7: Capture rate, and interference with trapping, on culling operations conducted in **proactive** areas, summarised by triplet. Data from Woodroffe *et al.* (in press)

Triplet	Number of operations	Total trap nights	Number (%) animals caught		Number (%)¶ trap nights disrupted	
			<i>Badgers</i> †	<i>other species</i> ¶	<i>badgers released</i>	<i>other interference</i>
A	5	10,751	362 (3.9%)	176 (1.6%)	12 (0.1%)	1,232 (11.5%)
B	7	26,806	787 (3.1%)	181 (0.7%)	28 (0.1%)	1,276 (4.8%)
C	6	22,111	964 (4.7%)	120 (0.5%)	36 (0.2%)	1,637 (7.4%)
D	4	13,841	1,052 (8.4%)	160 (1.2%)	12 (0.1%)	1,177 (8.5%)
E	6*	19,773	1,459 (8.2%)	44 (0.2%)	22 (0.1%)	1,922 (9.7%)
F	5	14,653	1,177 (9.9%)	124 (0.8%)	68 (0.5%)	2,581 (17.6%)
G	5	13,624	995 (8.0%)	87 (0.6%)	54 (0.4%)	1,047 (7.7%)
H	5	16,023	590 (3.9%)	465 (2.9%)	15 (0.1%)	480 (3.0%)
I	4	10,887	659 (6.6%)	226 (2.1%)	7 (0.1%)	710 (6.5%)
J	4	12,424	846 (7.3%)	36 (0.3%)	23 (0.2%)	713 (5.7%)
Total	51	160,893	8,891 (6.1%)	1,619 (1.0%)	277 (0.2%)	12,775 (7.9%)

† percent capture rate calculated as the number of badgers caught and dispatched per available trap per night, where available traps are defined as those not disturbed and not occupied by another species.

¶ percentages calculated as the proportion of all trap nights affected.

*includes two operations conducted in one culling year.

Table 2.8: Capture rate, and interference with trapping, on culling operations conducted in reactive areas. (No reactive culling was performed in Triplet J.) Data from Woodroffe *et al.* (in press).

Triplet	Number of operations‡	Total trap nights	Number (%) animals caught		Number (%)† trap nights disrupted	
			<i>Badgers</i> †	<i>other species</i> †	<i>badgers released</i>	<i>other interference</i>
A	7	1,600	83 (5.3%)	29 (1.8%)	1 (0.1%)	1 (0.1%)
B	5	3,457	194 (6.0%)	56 (1.6%)	0 (0.0%)	169 (4.9%)
C	13	2,595	216 (9.5%)	12 (0.5%)	8 (0.3%)	312 (12.0%)
D	4	1,600	122 (7.7%)	7 (0.4%)	0 (0.0%)	2 (0.1%)
E	10	2,468	188 (7.7%)	22 (0.9%)	1 (0.0%)	14 (0.6%)
F	10	3,967	435 (11.8%)	9 (0.2%)	14 (0.4%)	271 (6.8%)
G	6	2,549	256 (10.4%)	14 (0.5%)	1 (0.0%)	82 (3.2%)
H	4	1,898	159 (9.1%)	75 (4.0%)	2 (0.1%)	73 (3.8%)
I	3	975	94 (10.0%)	10 (1.0%)	2 (0.2%)	19 (1.9%)
Total	62	21,109	1,747 (8.8%)	234 (1.1%)	29 (0.1%)	943 (4.5%)

‡ ‘number of operations’ refers to the number of reactive culling operations for which capture effort data were available, not the total number of operations performed.

† rates calculated as in Table 2.7.

2.57 In proactive treatment areas, badgers were trapped only on land where landholders had given consent to culling. However, efforts were made to capture badgers resident on inaccessible land by placing traps on nearby accessible land. To assess the effectiveness of these efforts, the ISG analysed capture rates within 200m of inaccessible land within trial areas. This involved comparing the badger removal rate on accessible land (less the 200m zones around inaccessible land) with that in the 200m zones, and with that in the inaccessible land and 200m zones combined.

2.58 Data on capture rates suggest that substantial numbers of badgers were removed from inaccessible land by trapping in the surrounding 200m zones. If badger density was uniform across trial areas and no badgers were taken from inaccessible land then, based on the relative area of accessible land, inaccessible land, and 200m zones, 44% fewer captures would be expected per km² in 200m zones plus inaccessible land, than on the remaining accessible land. In fact, on initial culls, only 28% fewer badgers were taken from each km² of 200m zones plus inaccessible land, with the 95% confidence interval (8% to 43% fewer, $p=0.007$ for the hypothesis of no difference between capture rates) indicating a removal rate significantly greater than expected (44% fewer, $p=0.033$, Donnelly *et al.*, 2007). This effect differed (interaction $p=0.014$) between initial and follow-up culls; on follow-ups there was no difference in removal rate between land types with different accessibility (3% fewer on inaccessible land plus 200m zones; 95% CI: 17% more to 20% fewer; $p=0.74$).

2.59 These patterns suggest that trapping around the boundaries of inaccessible land successfully removed substantial numbers of badgers from this land, particularly on follow-up culls (Donnelly *et al.*, 2007).

Badger welfare

2.60 Badger welfare was an issue of concern to the ISG from the beginning of its consideration of the trial, and several measures were taken to minimise welfare costs for the badgers targeted by culling. Independent auditors reviewed carefully the trapping procedures and methods by which the badgers captured were killed (by gunshot) and in every case deemed the dispatch method “humane”. Defra made several small improvements to methods and staff training in response to auditors’ suggestions (Kirkwood, 2000; Ewbank, 2003; Ewbank, 2004; Anderson, 2005; Anderson, 2006).

2.61 All badgers were closely examined at post mortem and a number of observable characteristics of their condition recorded. These data then allowed detailed studies to be undertaken to assess the level and extent of trap-related injuries the animals had sustained. The substantial majority of badgers (87%) showed no evidence of detectable injuries as a result of confinement in the trap (see Table 2.9). Of the injuries that were recorded, most (69%) were minor skin abrasions. The incidence of trap-related injuries of this nature declined over the course of the RBCT, partly as a result of improvements to trap design (Woodroffe *et al.*, 2005b).

Table 2.9: Summary of trap-related injuries recorded in the RBCT. Data are restricted to badgers not contaminated with mud (which may conceal minor injuries) and are taken from Woodroffe *et al.*, (2005b) and Woodroffe *et al.*, (2007b).

Injury type	Count					Percentage (%)				
	Culling year					Culling year				
	2000	2002	2003	2004	2005	2000	2002	2003	2004	2005
Injury to teeth or jaw	22	56	55	17	10	1.3	2.4	2.1	1.4	0.9
Cuts or serious abrasions	15	61	62	29	18	0.9	2.6	2.4	2.3	1.6
Minor abrasions	206	178	236	83	71	12.1	7.6	9.2	6.6	6.5
No injury	1,455	2,033	2,212	1,128	994	85.7	87.3	86.2	89.7	90.9
Total	1,698	2,328	2,565	1,257	1,093	100	100	100	100	100

2.62 An additional cause for concern about the welfare of badgers subjected to culling involves killing mothers with dependent cubs which cannot themselves be captured (Woodroffe *et al.*, 2005a). Badger cubs are born underground, and do not emerge from the sett until they are around 6-8 weeks old. Killing a breeding female badger during this period of dependency will therefore leave her cubs to die of starvation or dehydration below ground. This gives cause for concern since such a death is likely to involve suffering. By contrast, once cubs are moving regularly outside the sett, they are easily captured in cage traps and can be dispatched humanely.

2.63 To limit the numbers of cubs missed by culling operations, the ISG instituted a three-month closed season covering the months of February, March and April; no trapping was conducted at this time (Woodroffe *et al.*, 2005a). The ISG undertook detailed analyses of the age and reproductive status of the badgers that had been captured in the months before and after the closed season, in order to assess the outcomes of this welfare-protecting measure. From these analyses the ISG conclude that the closed season appeared highly

effective at limiting the numbers of females caught that had dependent cubs: of 4,617 adult females captured in 2000-5, only 171 (3.7%) were actively lactating. For comparison, in high density populations around one-third of adult females raise cubs each year (Neal and Harrison, 1958; Cresswell *et al.*, 1992; Woodroffe and Macdonald, 1995). The ISG assessed the capacity of RBCT culling operations to capture the offspring of actively lactating females in the months of January (immediately before the closed season) and May (immediately after the closed season, Woodroffe *et al.*, 2005a) in 2000-5. No actively lactating females were caught in January (Woodroffe *et al.*, 2007a); data from May are shown in Table 2.10.

Table 2.10: Numbers of actively lactating mothers, and their associated cubs, caught during the month of May (immediately after the closed season) in 2000-5. Data from May 1999 are excluded because the methods used to identify breeding females were not consistent with those applied in subsequent years. The expected number of litters captured equals the number of mothers; the expected number of cubs assumes an average litter size of 2.36, derived from Neal & Cheeseman (1996). The numbers of litters and cubs assumed missed by trapping are numbers caught, subtracted from the numbers expected. Data are from Woodroffe *et al.* (2005a) and Woodroffe *et al.* (2007a).

Year	Caught			Expected		Missed	
	<i>mothers</i>	<i>litters</i>	<i>cubs</i>	<i>litters</i>	<i>cubs</i>	<i>litters</i>	<i>cubs</i>
At setts							
2000	4	3	7	4	9.4	1	2.4
2002	12	8	15	12	28.3	4	13.3
2003	26	19	41	26	61.4	7	20.4
2004	8	4	11	8	18.9	4	7.9
2005	6	1	1	6	14.2	5	13.2
<i>Total at setts</i>	<i>56</i>	<i>35</i>	<i>75</i>	<i>56</i>	<i>132.2</i>	<i>21</i>	<i>57.2</i>
Away from setts							
2000	0	0	0	–	–	–	–
2002	2	2	4	2	4.7	0	0.7
2003	3	0	0	3	7.1	3	7.1
2004	6	1	1	6	14.2	5	13.2
2005	11	0	0	11	26.0	11	26.0
<i>Total away from setts</i>	<i>22</i>	<i>3</i>	<i>5</i>	<i>22</i>	<i>52</i>	<i>19</i>	<i>47</i>
Grand total	78	38	80	78	184.2	40	104.2

2.64 Data in Table 2.10 suggest that the numbers of cubs suffering starvation through culling of their mothers in the course of the RBCT was small, relative to the total number of badgers culled. Between May 2000 and May 2005, the litters of 40 actively lactating females – approximately eight per year on average – were estimated to have been missed by culling operations conducted at, and away from, badger setts. Taking into account the possibility that incomplete litters may have been captured on some occasions, if each lactating female is assumed to have had a litter of average size for the region, the total annual estimate of the number of dependent cubs orphaned by culling operations is approximately 21 per year.

2.65 The data in Table 2.10 give two causes for potential concern, however, which would need to be addressed if badger culling were to form any part of a future TB control policy. First, a comparatively large number of cubs appear to have been missed by trapping operations conducted away from setts. Trapping away from setts was implemented particularly where access to badger setts was restricted by protestors or by lack of landholder consent. However, this practice appears to have had the potential welfare cost of allowing culling of breeding females, but not their unweaned cubs which have much more restricted movements. A second cause for concern is that the relative number of cubs estimated to have been missed by culling operations at setts appears to have increased in 2004-5 relative to 2000-3. The reasons for this are uncertain (Woodroffe *et al.*, 2007a).

2.66 The ISG recognises that any culling procedure is likely to entail some risk of leaving cubs to starve when their mothers are killed. However, the data currently available suggest that a careful review of the humaneness of capture protocols – particularly the practice of trapping away from setts – would be appropriate if badger culling were to be continued by Defra, or under its auspices.

Interruptions caused by the 2001 foot-and-mouth disease epidemic

2.67 Following the diagnosis of foot-and-mouth disease (FMD) in February 2001, RBCT field work in the trial areas was suspended until December 2001 as part of MAFF's FMD management strategy. The end of this suspension was just prior to the start of the next closed season (1 February – 30 April 2002) and preparations were therefore undertaken for the culling season commencing in May 2002.

2.68 The suspension of field activity resulted in effectively a year's delay in completing trapping operations. However, because proactive culling had already been completed in 7 out of the 10 triplets, 70% of the overall proactive study area was effectively engaged in the trial and so data on the effects of badger removal were accumulating throughout 2001. The primary impact of the FMD suspension was essentially therefore simply to put back the enrolment of the last three triplets into the trial and not to bring it to a halt. Recognition of this fact is important in viewing the integrity of the RBCT over its seven years of culling operations, and to appreciate its scientific strengths.

2.69 When, after the resumption of field activities, follow-up proactive culling was undertaken in those seven proactively culled triplets (A, B, C, E, F, G and H), it was clear that in five of these, badger populations had stayed relatively low throughout the period of suspension, and were probably not markedly higher than they would have been had culling continued as planned (see Table 2.4). This is an important finding in providing confidence that the trial has remained robust in these areas despite the suspension of direct activity. In the other two active trial areas, badger populations had been less markedly suppressed by initial culls

2.70 Three triplets (D, I, J) in which initial culling had not taken place at the time of the FMD epidemic, although delayed, were not otherwise affected by the suspension in field activity.

2.71 While the FMD epidemic entailed some disruption of trial activities, it is worth noting that this unexpected event ultimately generated extremely valuable insights into the dynamics of *M. bovis* infection in both cattle and badgers (Cox *et al.*, 2005; Woodroffe *et al.*, 2006b).

3. TB IN CATTLE

Current methods of surveillance

3.1 Monitoring of the cattle population for infection with *M. bovis* relies primarily on a national programme of herd testing, which involves subjecting animals in most cattle herds to a diagnostic test at prescribed intervals. The frequency of herd testing is determined by the recent incidence, at a local parish level, of herds with confirmed TB, and ranges from annual testing for herds in parishes with an incidence of 1% or more, to 4-yearly testing for herds in parishes with an incidence of 0.1% or less. The categories of animals tested also varies according to the type of test being applied (see Defra 2007a for full details). For example, all animals over 6 weeks of age must be tested in herds subject to annual testing whereas only breeding animals and animals intended for breeding are required to be tested in herds on 2-, 3- or 4-yearly testing. The inspection of carcasses of all animals sent for slaughter provides an additional means of surveillance. Recently these measures have been supplemented by the introduction of pre-movement testing of all animals over 6 weeks of age moved from one farm to another.

Herd testing

3.2 Routine testing of cattle herds is conducted using the single intradermal comparative cervical tuberculin test (SICCT or ‘tuberculin skin test’). The tuberculin skin test involves injecting purified protein derivative (PPD) from *M. bovis* into the skin of the animal at one site on the neck, and injecting PPD from *M. avium* at another. Three days later the test is interpreted based on the size of reaction in the skin. If the reaction to *M. bovis* is more than 4mm (under so-called standard interpretation) or more than 2mm larger than the reaction to *M. avium* (or any positive reaction to *M. bovis* in the absence of a response to *M. avium*) (under severe interpretation), then the animal is categorised as a ‘reactor’. The herd is placed under movement restrictions, all reactors are compulsorily slaughtered and subject to post mortem examination, and tissue samples cultured for *M. bovis*. This event is known as a herd breakdown. Culture of tissue samples is undertaken in order to confirm bovine TB in those herds in which none of the reactor animals have visible lesions typical of TB, and to obtain molecular typing information on *M. bovis* isolates obtained from all herds; the recommended numbers of animals sampled are up to five for each epidemiological group of animals in a herd showing no visible lesions and up to three for groups with one or more animals showing visible lesions. If either lesions characteristic of TB are identified at post mortem or the *M. bovis* organism is cultured, the breakdown is classified as ‘confirmed’ and the severe interpretation of the skin test applied to remaining members of the herd. Otherwise breakdowns are classed as ‘unconfirmed’.

3.3 Herds in which reactor animals are confirmed as infected are re-tested at minimum intervals of 60 days until they have had two consecutive clear tests, based on severe interpretation of the test. They are re-tested again after a minimal interval of 6 months and after a further 12 months, applying standard interpretation. All reactors removed prior to the second clear 60 day test are attributed to the breakdown incident and animal movement restrictions remain in place throughout this period.

3.4 Herds in which infection is not confirmed in reactor animals are also placed under animal movement restrictions and are retested after 42 days. If this test is clear, restrictions are lifted and the herd returns to the routine testing cycle.

3.5 Confirmation of a herd breakdown also triggers testing of contiguous herds (i.e. any herd with a common boundary with the breakdown herd) and herds from which reactor animals have been purchased during the period extending back to two months before the previous herd test (i.e. approximately 14 months for annually tested herds). Any animals sold by the breakdown farm to other herds during the same period are also tested. Identification of animals and herds that require testing makes use of the computerised National Cattle Tracing System.

Slaughterhouse carcass inspection

3.6 The Meat Hygiene Service inspects the carcasses of all cattle sent for slaughter and any suspected cases of TB are reported to Animal Health (previously the State Veterinary Service). Tissue samples collected from such cases are submitted for culture and, in the event of a positive culture, the farm of origin of the animal is subjected to a herd test. These incidents contribute to the recorded incidence of TB breakdowns, i.e. all herds from which a confirmed infected slaughterhouse animal originates are classified as confirmed breakdowns irrespective of whether or not further infected animals are detected at the follow-up test.

Pre-movement testing of cattle

3.7 An increasing awareness of the risk of spreading TB through movement of cattle in the periods between routine herd tests led to the introduction in 2006 of a requirement to test cattle that are moved between herds. Initially testing was applied to animals over 15 months of age from herds on one- or two-yearly testing (with some specific exemptions), but since March 2007, the lower age limit for these herds was extended downwards to 6 weeks of age. Animals must be tested using the tuberculin test no more than 60 days before they move to the purchasing farm. The test is applied at standard interpretation, but if a reactor is detected, all movements from the farm are prohibited and herd breakdown procedures commence.

The incidence and distribution of the disease

3.8 By the mid-1980s the national herd testing and surveillance programme had reduced the number of cattle herds affected by TB in Great Britain to less than 100 per year, with 500-700 reactor animals slaughtered each year. However, since the late 1980s there has been a progressive increase in incidence of the disease culminating in 3,512 breakdowns and the slaughter of 19,963 reactor animals in 2006 (Figures 3.1 and 3.2). This increase in incidence has resulted in a larger proportion of herds being subjected to annual testing, so that currently more than 5 million cattle are tested annually compared to around 2 million in the mid-1980s.

Figure 3.1: Number and rate of tuberculin test reactors disclosed annually in Great Britain.
(Reproduced from Report of the Chief Veterinary Officer 2006, Defra 2007).

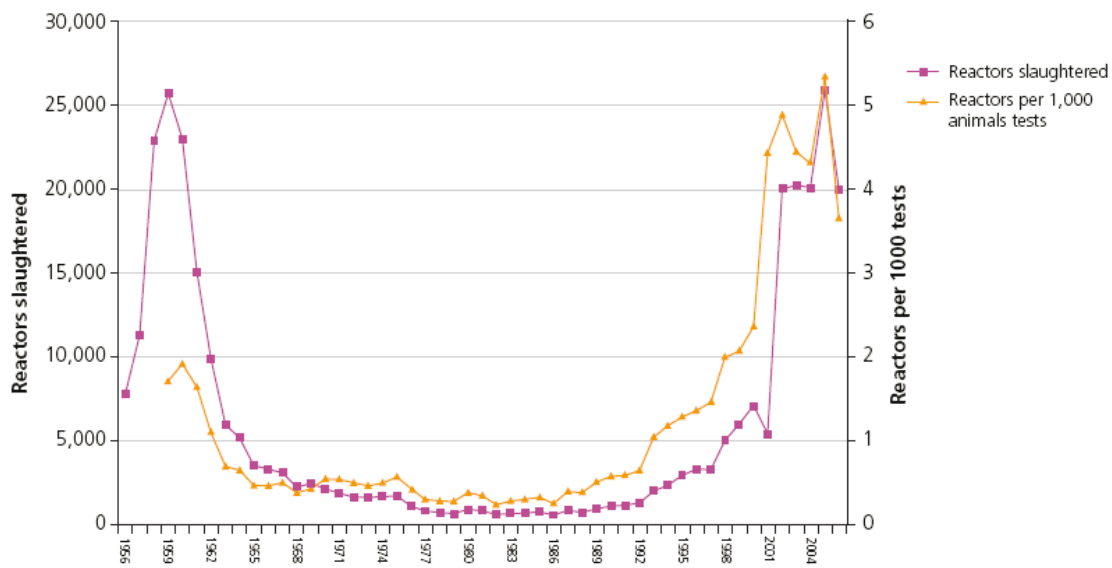
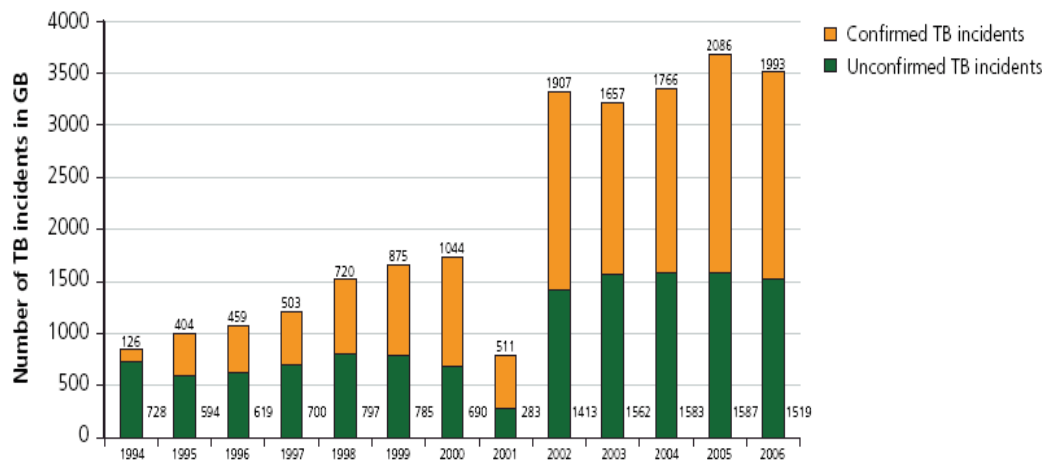


Figure 3.2: Evolution in the number of TB incidents disclosed annually in Great Britain since 1994.
(Note: The marked fall in 2001 is due to drastic restrictions in national TB testing during the Foot and Mouth Disease outbreak). (Reproduced from Report of the Chief Veterinary Officer 2006, Defra 2007).



3.9 Details of the numbers of herd breakdowns and reactor cattle detected in herds subjected to testing at different time intervals, for the year 2005 (the most recent year for which full details are available), are presented in Table 3.1. Herd breakdowns occurred in 11.2% of the (32,569) herds tested in 2005 and an average of 5.1 animals were slaughtered from each breakdown. Infection with *M. bovis* was confirmed in 52% of the reactor cattle and in 65% of the breakdown herds, the latter representing 6.9% of all herds tested. A large majority of the confirmed breakdowns (80%) were in the regions subjected to annual testing.

Table 3.1: Cattle herd testing figures for Great Britain in 2005.

Testing interval	Total herds	Herds tested*	Herds with reactors	Reactors slaughtered	Herds with confirmed reactors	Confirmed reactors slaughtered
1 year	22,461	17,812	2,744	15,146	1803	8,180
2 years	12,501	5,461	582	2,799	299	1,165
3 years	661	218	31	95	10	18
4 years	55,931	9,078	284	580	135	364
Total	91,554	32,569	3,641	18,620	2,247	9,727

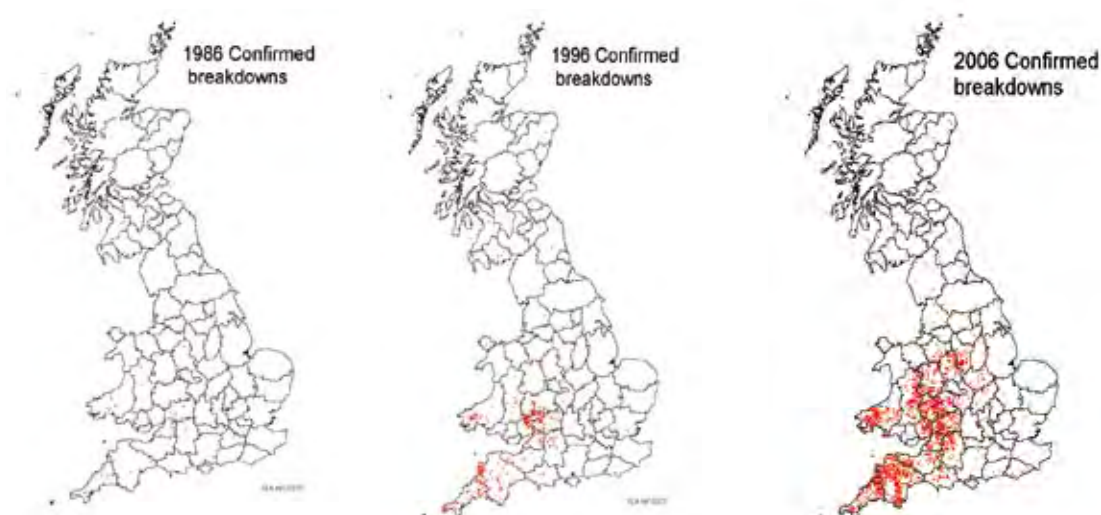
(Source, VLA)

Data were derived from VLA (2006; Tables 5.1, 5.8 and 5.9).

* The numbers of herds in each testing interval category were derived from records of the status of the herds in the period between 1st July and 30th September 2005. The data include tests in which all eligible animals in the herd were tested (i.e. excluding tests of inconclusive reactors or follow-up tests of cattle sold from reactor herds).

3.10 The disease is not evenly distributed throughout the country, but rather is focused in particular regions, notably in the South West of England, South West Wales and parts of Staffordshire and Derbyshire (Figure 3.3). The same regions have been affected over the last 20 years, but there has been local spread of the disease and a progressive increase in the local incidence of breakdown herds.

Figure 3.3: Geographical distribution of TB breakdowns 1986, 1996 and 2006.



3.11 Molecular methods have been developed which allow the identification of different strains of *M. bovis* (Smith *et al.*, 2006). A method known as spacer oligonucleotide typing (spoligotyping) identifies 34 genotypes (i.e. genetically distinct strains) in Great Britain,

although some occur at a much higher frequency than others. A second method, known as variable number tandem repeat (VNTR) typing, identifies further genetic diversity within some of the most common genotypes identified by spoligotyping. Use of these methods to type a large number of *M. bovis* isolates obtained from reactor cattle across the country has revealed a strong geographical clustering of *M. bovis* genotypes to particular regions (Figure 3.4; Smith *et al.*, 2006). This has been taken as evidence of a high rate of local transmission of infection (cattle-to-cattle and/or wildlife-to-cattle). These typing methods are also being used to trace the origins of infection in herd breakdowns arising from cattle movements (see Chapter 7).

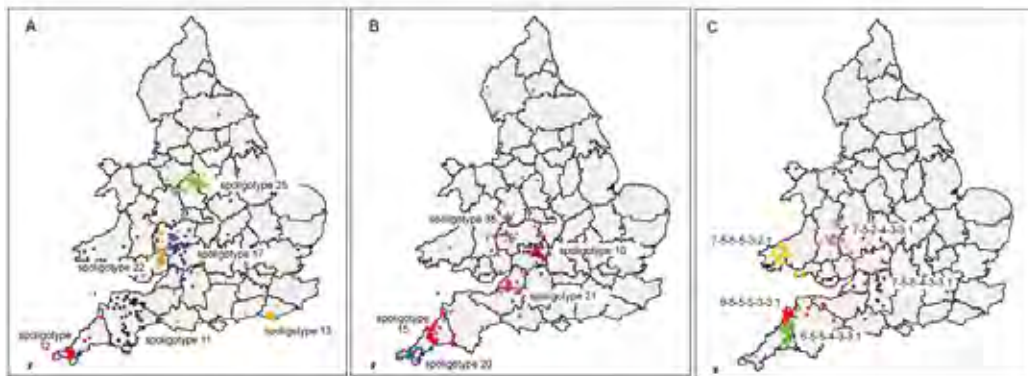


Figure 3.4: The geographical localisation of *M. bovis* genotypes in Great Britain: Panels A and B show the locations of 50 isolates randomly selected from each of the 11 most common spoligotypes (excluding spoligotype VLA type 9) found in Great Britain. Panel C shows the locations of 5 of the most common genotypes identified by VNTR typing within spoligotype VLA type 9, which account for 87% of all type 9 isolates.

Modified from: Smith *et al.*, (2006).

Specificity versus sensitivity of the tuberculin skin test

3.12 Routine testing of thousands of cattle for infection with *M. bovis* requires a test with high specificity (defined as the percentage of truly uninfected animals that are correctly identified) in order to avoid frequent detection of false positives and unnecessary imposition of herd restrictions. The tuberculin skin test is based on detection of a specific cellular immune response to *M. bovis* in infected animals. However, cattle are exposed to other species of mycobacteria (Pollock and Andersen, 1997), which can stimulate immune responses that cross-react with *M. bovis*. For this reason, *M. avium* antigen is used in the tuberculin test in an attempt to exclude these cross-reactive responses. The skin thickness measurement readings that define a positive reaction at standard interpretation of the tuberculin test are deliberately set to provide a high level of specificity. Two studies, which involved testing of 10,305 and 1,007 animals, respectively, from TB-free herds, reported specificity levels of 99.2% and 100%, although the former represented an underestimate, as the positive animals included an unspecified number of inconclusive reactors (Lesslie and Herbert, 1975; Neill *et al.*, 1994a). However, high specificity is achieved at some cost to sensitivity (defined as the percentage of truly infected animals correctly identified). Therefore, to increase sensitivity, a severe interpretation of the test is applied once infection

has been detected in a herd. Although a number of workers have published figures for sensitivity of the tuberculin test (reviewed in Monaghan *et al.*, 1994), the ISG considers that these do not provide an accurate measure of the true sensitivity and that most are likely to have overestimated sensitivity. The principal reason for this, in most cases, is the lack of a sufficiently large and representative sample of in-contact tuberculin-negative animals for post-mortem examination, to allow reliable measurement of the number of infections that remain undetected. Moreover, many of the datasets on which the figures for sensitivity were based did not specify the relative proportions of the slaughtered reactors that were identified at standard or severe interpretation of the tuberculin test. Where such data were available, the numbers of animals examined were small and often were obtained from slaughter of whole herds suffering large TB breakdowns, which are unlikely to be representative of the wider population of infected cattle. The issue of test sensitivity will be discussed further in Chapter 7.

Alternative diagnostic tests

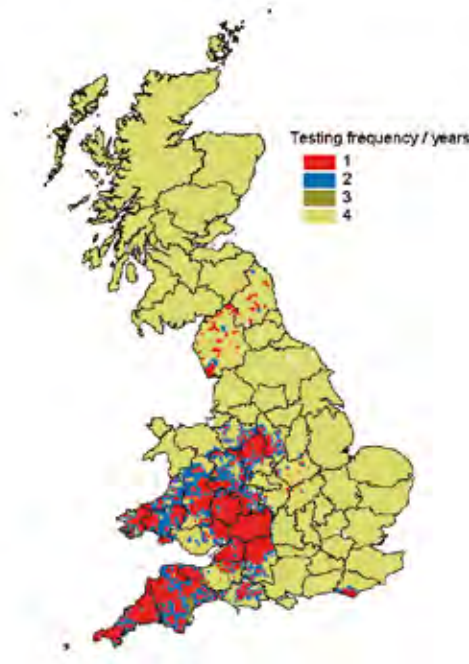
3.13 The limitation in sensitivity of the tuberculin skin test has stimulated research into development of alternative diagnostic tests. One such test, known as the interferon- γ (IFN- γ) test (or IFN test), was developed in Australia and used in that country to assist in their bovine TB eradication programme (Wood *et al.*, 1992; Wood and Rothel 1994). The test involves incubation *in vitro* of blood samples with PPD from *M. bovis* and *M. avium* and measurement of the release of IFN- γ in the culture supernatant after 24 hours. As with the tuberculin skin test, a positive result is based on detecting a differential response to *M. bovis* PPD and the cut-off readings that define positivity can be adjusted depending on how the test is being applied, with high specificity being achieved at the cost of reduced sensitivity. Field trials of the IFN test in Australia and Ireland, using reading cut-off levels that optimised the trade-off between sensitivity and specificity, have shown that levels of sensitivity comparable to, or higher than, that of the tuberculin skin test can be achieved (Wood *et al.*, 1991; Wood *et al.*, 1992; Neill *et al.*, 1994b; Monaghan *et al.*, 1997). However, the levels of specificity (96-99%) were generally lower than those obtained with the tuberculin skin test. Importantly, the two tests have been shown to identify a slightly different population of *M. bovis*-infected cattle (Neill *et al.*, 1994b; Vordermeier *et al.*, 2006), such that by combining the tests it is possible to further enhance sensitivity. Although the limitation in specificity of the IFN test has curtailed its use as a primary surveillance tool, the test is currently used in several countries in conjunction with the tuberculin test to enhance detection of infected animals in herds suffering a TB breakdown. A field trial to evaluate the performance of the IFN test under UK conditions has recently been completed; the main findings of this trial and their implications for control policy will be discussed further in Chapter 7 (also see Appendix I). Defra have announced their intention for wider use of this test.

Disease surveillance

3.14 In areas of the country at high risk of disease, the majority of herds, but not all, are subjected to annual herd testing aimed at controlling the disease. Detection of disease in other areas considered to be at lower risk, based on the recent incidence of herd breakdowns, relies on strategic surveillance involving testing of herds at prolonged intervals of up to four years. Thus, approximately 50%, 33% or 25% of herds are subjected to testing each year in different regions according to the level of risk, representing herd testing intervals of 2-, 3- and 4-years respectively (Figure 3.5). Testing of all herds in a parish in the same year is adopted, giving a patchwork pattern of testing. This appears to have been adopted

for ease of administration rather to provide better surveillance. Surveillance also includes identification and testing of cattle in herds that have traded animals with the breakdown herd in the period extending back to 2 months before the previous herd test (see paragraphs 3.1 to 3.7).

Figure 3.5: Parish testing intervals in Great Britain, January 2005.



3.15 Routine inspection of carcasses for evidence of TB in slaughterhouses is carried out primarily to protect public health, but also provides an additional means of surveillance to detect infected herds. Of more than 4 million cattle slaughtered in Great Britain in 2005 out of a total population of over 8 million, 774 cattle carcasses were reported by meat inspectors as having suspect TB lesions, of which 516 were confirmed with *M. bovis* infection by bacterial culture. This led to follow-up testing of 335 herds not already under restriction, from which these animals were derived, and detection of further infected animals in 144 of these herds. These incidents account for a relatively small proportion (14% in 2005) of the total confirmed breakdowns recorded in Great Britain, and a substantial majority of them (272, i.e. 81%) arise in the higher risk areas subject to 1- or 2-yearly testing. The efficiency of detection of infected animals in slaughterhouses is discussed further in Chapter 7 (paragraph 7.17).

Cattle population structure and mobility

3.16 The cattle industry in the UK has undergone substantial change since the 1970s when the incidence of TB was at its lowest level. Of particular relevance with respect to TB control, have been increases in herd size and cattle movement. The gradual increase in average number of animals per herd over this period, exemplified by an increase in dairy herd size from 46 to 107 animals between 1975 and 2005 (Milk and Dairy Council, 2006), has important implications for the ability to remove all infected animals from breakdown herds, using a diagnostic test with incomplete sensitivity (see discussion in Chapter 7). This is compounded by the large number of cattle movements and the distances over

which such movements occur (Mitchell *et al.*, 2005). A system to record and trace cattle movements in the UK, introduced in response to the BSE epidemic, and made compulsory in 2001, has provided a valuable resource both to quantify and analyse cattle movements and to trace potential sources of infection suspected to have arisen from cattle movement. Movement of cattle from infected herds in the periods between routine herd tests has long been recognised as a cause of new herd breakdowns, and it is generally accepted that most of the sporadic herd breakdowns in relatively disease-free areas of the country result from movement of infected animals. The increasing number of such breakdowns, associated with the progressive increase in TB incidence nationally, has raised concern about the risk of these incidents leading to introduction of infection into local wildlife populations and establishment of new foci of endemic infection. While cattle movement undoubtedly also contributes to local spread of infection between herds in areas continuously affected by TB, this has been difficult to quantify. However, the large numbers of cattle movements coupled with the observation that 43% of movements in the south west of the country occur over a distance of less than 20km (Mitchell *et al.*, 2005), highlight the potential for substantial local dissemination of infection through animal movement. Pre-movement testing of cattle moving from farms in high risk areas in England and Wales has been introduced in an attempt to address these concerns.

4. ECOLOGY OF BADGERS IN RBCT AREAS, AND THE EPIDEMIOLOGY OF *MYCOBACTERIUM BOVIS* IN BADGERS

Introduction

4.1 As explained in Chapter 1, at the start of the RBCT there was substantial anecdotal evidence to suggest that badgers were an important source of *M. bovis* infection for cattle, and badger culling had therefore formed a component of British TB control policy for many years. To understand the relationship between infections in these two host species, and to devise management strategies to limit spread from badgers to cattle, it is important to understand the ecology of the infection in badgers. This chapter therefore provides information on badger ecology in the agricultural landscape, and reviews the effect of culling on badger populations. It then characterises the prevalence and distribution of *M. bovis* infection in badgers, and discusses the effects of culling on these patterns. Finally, it outlines some of the more recent evidence linking *M. bovis* infections in badgers and cattle. Data are taken mainly from RBCT areas, but comparisons are drawn with other studies where appropriate. Implications of these findings for the future control of cattle TB are detailed in Chapter 10.

Density and structure of badger populations prior to RBCT culling

Past culling in RBCT areas

4.2 All RBCT areas were placed in areas of high TB risk to cattle. For this reason, most (26 out of 30) had been subjected to badger culling under earlier national policies. Table 4.1 shows the numbers of badgers culled within each area under the ‘interim strategy’ which ran from 1986-1998 (see Chapter 1), immediately before the start of the RBCT.

Table 4.1: The number of badgers culled under the ‘interim strategy’ (between 1986 and 1998) on land that subsequently fell inside RBCT areas.

Treatment	Triplet										Total
	A	B	C	D	E	F	G	H	I	J	
Proactive	115	399	199	67	203	480	0	55	385	78	1,981
Reactive	300	314	168	64	455	357	0	126	35	94	1,913
Survey-Only	186	342	319	14	239	240	0	31	38	0	1,409

Relative densities of badgers prior to RBCT culling

4.3 Before they were allocated to culling treatments, all RBCT areas were surveyed for signs of badger activity; Table 4.2 gives the dates of all surveys. Because badgers are active at night, and rest by day in underground dens (setts), they are difficult to count, especially over large areas. However, there are broad correlations between the densities of badgers and the densities of field signs such as setts and latrines (Tuytens *et al.*, 2001; Wilson *et al.*, 2003; Sadlier *et al.*, 2004), suggesting that these measures give a reasonable indication of true badger densities. Initial surveys of field signs revealed that badgers were widespread in all areas, and appeared to occur at comparable densities across the areas subsequently allocated to different treatments prior to RBCT culling (Table 4.3).

Table 4.2: Dates of successive surveys conducted in RBCT areas. Surveys were conducted across all three areas in each triplet. The first survey of each triplet covered all accessible land; later surveys covered proportions of the total as indicated. Each survey was conducted without reference to earlier survey data. In some triplets, initial surveys were interrupted by events (e.g. the 2001 FMD epidemic).

Triplet	First (pre-cull) survey	Second survey	Third survey	Fourth survey	Fifth survey
A	Aug 1998–May 1999	Mar–Apr 2002†	Jan 2004†	Nov–Dec 2004†	Feb–Mar 2006‡
B	Aug–Nov 1998	Jan–Feb 2002†	Jan 2004†	Jan 2005†	Feb–Mar 2006‡
C	Mar–Sep 1999	Feb 2002†	Jan 2004†	Dec 2004–Jan 2005†	Nov–Dec 2005‡
D	May 1999–Oct 2002	Nov 2003–Jan 2004†	Feb 2005†	Jan–Feb 2006†	
E	Nov 1999–Apr 2000	Jan–Feb 2003†	Feb–Mar 2004†	Dec 2004–Jan 2005†	Nov 2005–Jan 2006‡
F	Jan–Jul 2000	Feb 2003†	Jan–Mar 2004†	Nov–Dec 2004†	Jan–Mar 2006‡
G	Jun–Oct 2000	Feb–Mar 2003†	Feb–Mar 2004†	Jan 2005†	Nov–Dec 2005‡
H	May–Dec 2000	Feb–Mar 2003†	Jan–Apr 2004†	Nov–Dec 2004†	Nov–Dec 2005‡
I	Feb 2000–Jul 2002	Nov–Dec 2003†	Nov–Dec 2004†	Feb–Mar 2006†	
J	Jan 2001–Oct 2002	Jan–Apr 2004†	Dec 2004–Jan 2005†	Jan–Feb 2006‡	

†covered approximately 20% of each trial area;

‡covered approximately 30% of each trial area.

Table 4.3: The numbers of active badger setts (including ‘main’ and ‘other’ setts) and latrines recorded per km² of land accessible for surveying, in the course of initial pre-cull surveys. Statistical analyses (log-linear regressions adjusting for triplet and log-transformed land area available for surveying) revealed no significant differences between proactive and survey-only areas in sett ($p=0.31$) or latrine ($p=0.39$) densities before these areas were allocated to treatments (Donnelly *et al.*, 2006).

Treatment	Triplet										Mean
	A	B	C	D	E	F	G	H	I	J	
<i>Active setts per km²</i>											
Proactive	1.45	3.82	2.65	4.02	4.24	3.18	3.82	4.58	3.91	4.49	3.62
Reactive	2.67	1.59	1.89	2.71	3.16	3.83	4.38	6.68	3.00	7.41	3.32
Survey-only	2.18	1.01	3.78	2.51	4.15	3.61	3.31	7.61	1.47	2.95	3.26
<i>Latrines per km²</i>											
Proactive	4.97	8.32	8.95	10.04	8.84	13.26	8.96	5.84	4.30	9.23	8.27
Reactive	8.08	6.47	5.27	6.80	8.68	13.89	10.64	10.95	3.89	14.89	8.30
Survey-only	7.75	2.89	8.77	8.19	11.21	13.13	8.69	14.11	2.60	7.18	8.45

4.4 A minimum estimate of badger density in RBCT areas prior to culling can also be obtained from the numbers of animals taken on initial proactive culls. These numbers need to be interpreted with caution since the proportions of badgers resident within a trial area that were captured on a particular initial cull varied according to local conditions such as season, weather, and disruption by protestors (Smith and Cheeseman, 2007). Nevertheless these numbers do give a minimum estimate of badger numbers, albeit measured inconsistently across triplets. Density estimates derived from these numbers – presented in Table 4.4 – are comparable with those recorded previously in agricultural areas of Britain (Cheeseman *et al.*, 1981; Kruuk and Parish, 1982; Cheeseman *et al.*, 1985a; Tuytens *et al.*, 2000b).

Table 4.4: Numbers, densities (numbers per km² of land accessible for culling within treatment area) and sex ratios of badgers taken on initial proactive culls. Data from Donnelly *et al.*, (2007) and Woodroffe *et al.*, (2005c).

Age class	Triplet										All
	A	B	C	D	E	F	G	H	I	J	
Area (km ²)	82.2	88.2	98.2	75.9	77.9	55.8	74.0	77.5	84.0	83.0	796.8
Adults: number	55	230	236	278	440	337	410	145	170	396	2,697
density	0.67	2.61	2.40	3.66	5.65	6.04	5.54	1.87	2.02	4.77	3.39
% male	64%	55%	35%	55%	42%	47%	42%	50%	44%	39%	45%
Cubs: number	0	9	7	15	162	109	15	16	49	46	428
density	0.00	0.10	0.07	0.20	2.08	1.95	0.20	0.21	0.58	0.55	0.54
% male	–	11%	14%	47%	42%	49%	33%	50%	49%	54%	45%
Total: number	55	239	243	293	602	446	425	161	219	442	3,125
density	0.67	2.71	2.47	3.86	7.73	7.99	5.74	2.08	2.61	5.33	3.92

16 badgers of undetermined age or sex have been excluded.

Structure of badger populations at the start of RBCT culling

4.5 Data from initial culls provide information on population structure at the start of RBCT culling. The proportions of cubs in the populations were highest on culls conducted in early summer, shortly after cubs' first emergence in spring (Woodroffe *et al.*, 2005c); the lower numbers of cubs caught later in the year is to be expected since cub mortality is high in the first year of life (Cheeseman *et al.*, 1987; Harris and Cresswell, 1987; Woodroffe and Macdonald, 1993). Sex ratio varied substantially between triplets (Table 4.4) but overall there were more females than males, as in most other badger populations (Cheeseman *et al.*, 1987; Harris and Cresswell, 1987).

4.6 These data from initial proactive culls can also be used to derive minimum estimates of the sizes of badger social groups. The approximate disposition of badger home ranges can be estimated from field signs such as setts and latrines (Woodroffe *et al.*, 1999; Cresswell, 2001). Badgers' capture locations relative to these home ranges can then be used to assign them, tentatively, to social groups (Woodroffe *et al.*, 1999). Table 4.5 shows the sizes of social groups estimated in this way using data from initial proactive culls. Once again, group sizes are comparable with those recorded on more intensive studies of badgers in agricultural areas of Britain (Cheeseman *et al.*, 1981; Kruuk and Parish, 1982; Cheeseman *et al.*, 1985a; Tuytens *et al.*, 2000b).

Table 4.5: Minimum estimates of group size (mean and standard deviation (SD)) of badgers taken on initial proactive culls. These estimates exclude 11% of animals as these could not be uniquely allocated to a single social group.

Age class	Triplet										All
	A	B	C	D	E	F	G	H	I	J	
Adults: mean	2.75	4.19	4.84	4.16	5.69	5.24	5.50	3.74	3.27	5.31	4.72
SD	2.22	4.06	3.12	3.59	4.31	3.42	3.85	2.63	2.15	3.14	3.53
Cubs: mean	0.00	1.00	1.40	1.27	3.22	2.39	1.17	1.40	1.87	1.47	2.10
SD	–	0.00	0.55	0.65	2.36	1.86	0.39	0.70	1.49	0.73	1.76
Total: mean	2.75	4.38	5.02	4.39	7.62	6.92	5.63	4.18	4.02	5.94	5.44
SD	2.22	4.25	3.32	3.98	5.92	4.63	4.08	2.83	2.95	3.40	4.27

Home range sizes

4.7 Badger home range sizes were not measured directly prior to culling. However, during spring in 2004-5 home range sizes were measured in uncultured survey-only areas within 16km² study areas in four triplets (Woodroffe *et al.*, 2006a), using a technique called bait marking (Kruuk, 1978; Delahay *et al.*, 2000a). The resulting home range size estimates, shown in Table 4.6, are comparable with those recorded in other studies of badger ecology in agricultural areas of Britain (Cheeseman *et al.*, 1981; Kruuk and Parish, 1982; Cheeseman *et al.*, 1985a; da Silva *et al.*, 1993; Woodroffe and Macdonald, 1993; Tuytens *et al.*, 2000a).

Table 4.6: Badger home range sizes estimated by bait marking in survey-only areas. These estimates exclude home ranges derived from <8 bait returns. SD indicates the standard deviation.

Triplet	Home range size (ha)	
	mean	SD
B	65.5	60.5
D	42.5	33.1
G	28.9	13.7
H	34.4	18.3

Effects of RBCT culling on badger ecology and behaviour

Effects of culling on badger population density

4.8 Effects of repeated culling on badger populations in proactive areas became apparent in the course of conducting the culls. Capture rates declined on successive culls and, at the same time, an increasing proportion of badgers were captured close to trial area boundaries, suggesting that badgers were moving in from neighbouring land to recolonise culled areas (Woodroffe *et al.*, in press). The pattern of captures around inaccessible land likewise changed between initial and follow-up proactive culls, suggesting that badgers were moving out of inaccessible land and being caught nearby (Donnelly *et al.*, 2007).

4.9 Culling clearly reduced badger population density (Woodroffe *et al.*, in press). Although surveys revealed comparable densities of badger field signs within triplets before culling (see Table 4.3 above), by the fourth post-cull survey, the mean density of active holes in proactive areas ($2.83/\text{km}^2$) was 69% lower than that in survey-only areas ($9.18/\text{km}^2$), and the density of latrines ($2.49/\text{km}^2$) was 73% lower than that in survey-only areas ($9.14/\text{km}^2$). At the same time, the density of active holes in reactive areas ($7.23/\text{km}^2$) was 26% lower than that in nine matched survey-only areas ($9.81/\text{km}^2$), and latrine density ($7.09/\text{km}^2$) was 26% lower than that in survey-only areas ($9.56/\text{km}^2$), (Woodroffe *et al.*, in press). Likewise, the density of faecal deposits retrieved on bait-marking studies (see paragraph 4.7) was 64% lower inside proactive areas than in matched survey-only study areas (range 36-76% lower), and 76% lower than that in adjoining un-culled areas (range 75-77%), (Woodroffe *et al.*, in press). Reactive culling was associated with a 53% reduction in bait return density. Finally, the average density of road-killed badgers retrieved inside proactive culling areas ($0.029/\text{km}^2$) was 73% lower than that recorded in survey-only areas ($0.105/\text{km}^2$), and 58% lower than that recorded in the 5km zone surrounding proactive areas ($0.068/\text{km}^2$), (Woodroffe *et al.*, in press). The average density of road-killed badgers was 9.8% lower inside reactive areas ($0.061/\text{km}^2$) than in matched survey-only areas ($0.068/\text{km}^2$), (Woodroffe *et al.*, in press).

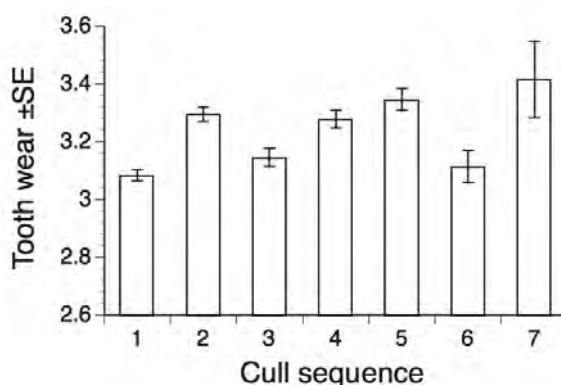
4.10 Taken together, these studies indicate that proactive culling caused substantial reductions in badger density. Since the badgers detected on such surveys are likely to have been a combination of animals missed by culling, animals immigrating into culled areas from outside, and cubs born since the last culling operation, the proportion of animals removed by each cull is likely to have been somewhat larger than the density reduction achieved (Woodroffe *et al.*, in press), and is consistent with trial design estimates (Bourne *et al.*, 1998).

4.11 Reactive culling caused a smaller reduction in badger density than did proactive culling. Interestingly, by early 2006 there was still little evidence of population recovery following the suspension of reactive culling in late 2003 (Woodroffe *et al.*, in press).

Effects of culling on badger population structure

4.12 Proactive culling appeared not to influence the gender or age structure of badger populations. As would be expected (since badger births are highly seasonal), the proportion of badgers captured which were cubs varied between culls according to the season. After accounting for this seasonal variation, there was no difference in cub proportion between successive culls. Among adults, there was statistically significant variation in tooth wear – a measure of age (Neal and Cheeseman, 1996) – between successive culls but no clear increasing or decreasing trend (Figure 4.1). There was likewise no trend in adult sex ratio across culls. This lack of any clear trend in demographic structure is surprising: a substantial reduction in density could be expected to either increase breeding success (by making more resources available) or reduce it (by disrupting social organisation), but neither effect seems to dominate. Likewise, there are known effects of gender and age on dispersal behaviour (Cheeseman *et al.*, 1988; Woodroffe, Macdonald and da Silva, 1995) which might be expected to influence the structure of populations likely to contain a high proportion of immigrant animals.

Figure 4.1: Variation in badger tooth wear (a measure of age) on successive proactive culls. These data are least squares means, calculated after adjusting for effects of triplet and sex (unadjusted means and standard errors are very similar to these, however). There is no consistent trend relating tooth wear to cull sequence



Effects of culling on badger behaviour and movements

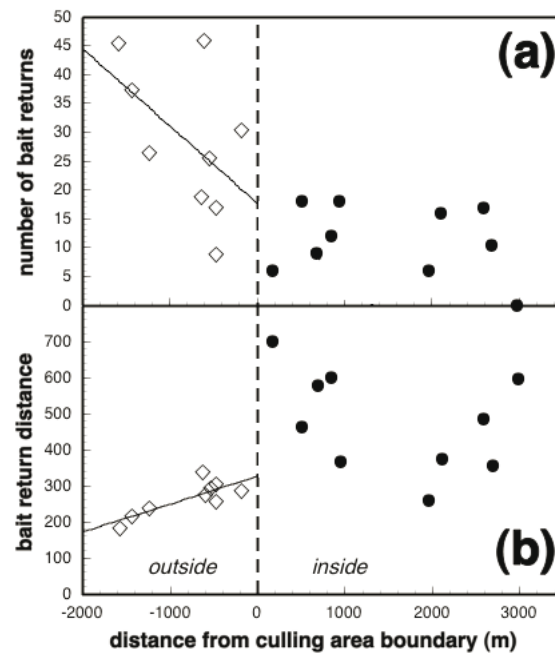
4.13 As well as reducing population densities, culling profoundly altered badger spatial organisation. In undisturbed populations, badger social groups defend more-or-less exclusive territories (reviewed in Woodroffe and Macdonald, 1993), and a similar pattern was observed in survey-only areas where no culling was conducted (Woodroffe *et al.*, 2006a). In culled areas, however, badgers' home ranges were significantly expanded, and overlap with neighbouring ranges was also affected suggesting that territoriality had been greatly reduced (Woodroffe *et al.*, 2006a). Summary data are presented in Table 4.7.

Table 4.7: Effects of culling detected by bait marking (Kruuk, 1978; Delahay *et al.*, 2000a) studies conducted in five RBCT triplets (data from Woodroffe *et al.*, 2006a). The number of bait returns per sett gives an index of badger density, and median return distance is a measure of home range size. The mean number of neighbouring home ranges found to overlap each range is also given.

Triplet	Treatment	n	Mean returns per sett	Median return distance (m)	Mean overlaps per home range
B	inside proactive	15	13.8	421	1.23
	outside proactive	7	37.1	282	1.75
	reactive	14	11.8	460	0.40
	survey-only	17	18.8	367	1.18
C	inside proactive	12	25.3	463	2.20
	outside proactive	23	35.7	239	2.79
D	inside proactive	16	17.3	370	1.00
	outside proactive	20	31.2	259	0.90
	reactive	16	23.4	538	0.44
	survey-only	27	31.6	222	0.79
G	inside proactive	17	9.8	598	0.56
	outside proactive	3	30.0	338	1.00
	reactive	17	16.9	324	0.00
	survey-only	23	28.9	304	0.32
H	inside proactive	14	7.8	300	0.50
	outside proactive	9	23.8	240	0.57
	reactive	17	14.4	275	0.25
	survey-only	23	22.0	225	0.38

4.14 Bait marking revealed that the effects of culling on badger density and spatial organisation were not restricted to the areas actually culled. Density was also somewhat reduced, and ranging behaviour expanded, up to 2km outside the proactive culling areas, with effects most marked close to culling area boundaries (Figure 4.2). This probably occurred because, as described above, badgers living close to culling areas expanded their ranging behaviour to occupy vacated space, or immigrated into the cleared areas, and were themselves subjected to culling. While bait marking detected these changes in behaviour over distances of 1-2km, studies of badger population genetics suggest that movements of individual badgers expanded over much greater distances (>5km, Pope *et al.*, 2007).

Figure 4.2: Effects of proactive culling on badger populations inside and outside culling areas, in five triplets. The number of bait returns per sector (a) gives an index of badger density, and median bait return distance (b) is a measure of ranging behaviour. These graphs show how reduced density and expanded ranging inside proactive culling areas were also observed on neighbouring uncultured land. The sloping lines indicate statistically significant relationships. Reproduced with permission from Woodroffe *et al.* (2006a). Copyright Blackwell Publishing.



Effects of badger culling on populations of other wildlife species

4.15 In addition to its effects on badgers themselves, proactive culling in particular had impacts on other wildlife species. Numbers of foxes (*Vulpes vulpes*) increased in proactive areas, in comparison with survey-only areas and, perhaps as a result, numbers of hares (*Lepus europaeus*) declined (Trewby *et al.*, in review). Before culling, hedgehogs (*Erinaceus europaeus*) were rare in parts of RBCT areas where badgers were abundant (Young *et al.*, 2006), and badger culling increased their numbers (G. Wilson, personal communication).

Patterns of *M. bovis* infection in badgers

*Issues concerning diagnosis of *M. bovis* infection in badgers*

4.16 In interpreting patterns of *M. bovis* prevalence in badgers, it is important to note that diagnostic methods used in the RBCT (rapid necropsy followed by culture and Ziehl-Neelsen staining) were not 100% sensitive. Statistical analyses revealed that the probability of detecting infection varied according to the laboratory at which the necropsy was detected and also, to a much lesser extent, on the culture laboratory (Woodroffe *et al.*, 2006b). These laboratory effects did not influence overall conclusions, since the same laboratories were used across all triplets, and also because statistical analyses adjusted for these effects. Likewise, storage of carcasses (almost always frozen) for >7 days before necropsy reduced

the probability of detecting infection; this affected about 10% of carcasses overall and, once again, all analyses of *M. bovis* prevalence in badgers accounted for this effect. A sample of 205 necropsies conducted under lesser time constraints than was possible for the majority of RBCT badgers (which included sampling of more tissue for bacteriological culture and incubation of cultures for longer periods of time) revealed substantially more infected animals than did standard necropsy of the same animals (Crawshaw *et al.*, in review). This indicates that the prevalence values reported below are likely to be under-estimates. However, since all RBCT badgers were necropsied according to the same standard operating procedures, this under-estimation of prevalence is expected to be consistent across triplets, treatments and years and should not, therefore, influence the interpretation of patterns of *M. bovis* prevalence.

Prevalence of M. bovis infection in RBCT badgers

4.17 Evidence of *M. bovis* infection was found in all RBCT areas where culling was conducted. Overall patterns of prevalence, i.e. the proportion of badgers found to be *M. bovis* infected, are shown in Table 4.8. Prevalence was higher in adults than in cubs (Woodroffe *et al.*, 2005c; Woodroffe *et al.*, 2006b; Woodroffe *et al.*, in review). Among adults, prevalence was higher in males than in females, and was also somewhat higher in animals with higher tooth wear scores (indicating greater age, Woodroffe *et al.*, 2005c; Woodroffe *et al.*, 2006b; Woodroffe *et al.*, in review). Baseline prevalence appeared higher in reactively culled badgers than in proactive areas (Woodroffe *et al.*, in review). There was also substantial variation in *M. bovis* prevalence between triplets and years (Table 4.8). Table 4.9 presents minimum estimates of the densities of infected badgers recorded on each proactive cull.

4.18 Data from initial proactive culls suggest that, prior to culling, infection was clustered within badger populations (Woodroffe *et al.*, 2005c). This is consistent with patterns detected elsewhere, where the territories of social groups with high *M. bovis* prevalence have been found to abut those of uninfected groups (Cheeseman *et al.*, 1981; Cheeseman *et al.*, 1985a; Cheeseman *et al.*, 1985b; Delahay *et al.*, 2000b). Clustering was particularly close for badgers infected with the same strain type of *M. bovis* (Woodroffe *et al.*, 2005c).

4.19 The prevalence of infection on initial culls was higher in the inner regions of proactive treatment areas (≥ 2 km inside the boundary) than in the outer areas (Woodroffe *et al.*, 2006b); this is not surprising as trial areas were centred on areas of high TB risk.

Table 4.8: Overall prevalence of *M. bovis* infection (all age classes combined) in RBCT culling areas. Numbers of badgers presented in parentheses, years indicate ‘badger years’, running from 1st February – 31st January. Data exclude 20 animals (18 proactive, 2 reactive) for which no data on infection status were available. No reactive culling was performed in Triplet J.

		1998		1999		2000		2002		2003		2004		2005	
		Prevalence (n)		Prevalence (n)		Prevalence (n)		Prevalence (n)		Prevalence (n)		Prevalence (n)		Prevalence (n)	
Proactives															
A	–	–	14.5%	(55)	–	–	–	30.1%	(146)	34.6%	(52)	15.5%	(58)	6.3%	(48)
B	5.5%	(238)	6.0%	(83)	8.1%	(74)	20.4%	(49)	9.4%	(170)	15.3%	(111)	17.2%	(58)	
C	–	–	1.6%	(244)	4.5%	(111)	7.1%	(126)	18.9%	(132)	14.4%	(187)	12.3%	(163)	
D	–	–	–	–	–	–	34.6%	(292)	22.5%	(369)	27.5%	(211)	31.3%	(182)	
E	–	–	–	–	5.9%	(747)	10.4%	(96)	13.2%	(258)	14.0%	(214)	14.9%	(148)	
F	–	–	–	–	2.9%	(452)	8.4%	(249)	6.8%	(103)	6.8%	(220)	6.5%	(155)	
G	–	–	–	–	6.8%	(426)	9.3%	(204)	7.6%	(144)	8.7%	(103)	12.0%	(117)	
H	–	–	–	–	7.4%	(162)	10.8%	(231)	15.5%	(71)	16.0%	(75)	18.9%	(53)	
I	–	–	–	–	–	–	37.2%	(218)	11.4%	(176)	29.0%	(93)	22.5%	(173)	
J	–	–	–	–	–	–	14.7%	(442)	7.6%	(185)	17.4%	(109)	33.9%	(109)	
Reactives															
A	–	–	–	–	29.4%	(34)	25.5%	(47)	25.0%	(36)	–	–	–	–	
B	–	–	4.1%	(73)	5.9%	(34)	15.5%	(84)	9.1%	(110)	–	–	–	–	
C	–	–	–	–	10.1%	(179)	14.8%	(115)	21.8%	(101)	–	–	–	–	
D	–	–	–	–	–	–	–	–	25.4%	(122)	–	–	–	–	
E	–	–	–	–	–	–	21.0%	(62)	8.0%	(125)	–	–	–	–	
F	–	–	–	–	–	–	14.5%	(145)	10.7%	(291)	–	–	–	–	
G	–	–	–	–	–	–	12.9%	(171)	10.7%	(84)	–	–	–	–	
H	–	–	–	–	–	–	11.8%	(17)	18.9%	(143)	–	–	–	–	
I	–	–	–	–	–	–	–	–	31.9%	(94)	–	–	–	–	

Table 4.9: Numbers of infected badgers captured per km². Since not all badgers were captured on each cull, and not all infected badgers are likely to have been detected, these are minimum estimates.

Triplet	area (km ²)	Number (n) and density (n km ²) <i>M. bovis</i> infected badgers captured on each cull													
		first		second		third		fourth		fifth		sixth		seventh	
		n	n km ²	n	n km ²	n	n km ²	n	n km ²	n	n km ²	n	n km ²	n	n km ²
A	103.8	8	0.08	44	0.42	18	0.17	9	0.09	3	0.03	–	–	–	–
B	101.8	13	0.13	5	0.05	6	0.06	10	0.10	16	0.16	17	0.17	10	0.10
C	121.2	4	0.03	5	0.04	9	0.07	25	0.21	27	0.22	20	0.17	–	–
D	104.1	101	0.97	83	0.80	58	0.56	57	0.55	–	–	–	–	–	–
E	118.8	29	0.24	15	0.13	10	0.08	34	0.29	30	0.25	22	0.19	–	–
F	110.8	13	0.12	21	0.19	7	0.06	15	0.14	10	0.09	–	–	–	–
G	114	29	0.25	19	0.17	11	0.10	9	0.08	14	0.12	–	–	–	–
H	116	12	0.10	25	0.22	11	0.09	12	0.10	10	0.09	–	–	–	–
I	131.4	81	0.62	20	0.15	23	0.18	39	0.30	–	–	–	–	–	–
J	110.5	65	0.59	14	0.13	19	0.17	37	0.33	–	–	–	–	–	–
Total	1132.4	355	0.31	251	0.22	172	0.15	247	0.22	110	0.14	59	0.17	10	0.10

Prevalence of M. bovis infection in road-killed badgers

4.20 During the RBCT, patterns of *M. bovis* infection were also investigated in badgers killed in road traffic accidents through the Road Traffic Accident Survey (see <http://www.defra.gov.uk/animalh/tb/isg/publications/isg1607.pdf> for more details). This survey was concentrated in seven counties, chosen to represent either high, or historically low but increasing, TB risk to cattle (Bourne *et al.*, 1998). Table 4.10 presents the prevalence of infection recorded in these seven counties, for each year of the survey.

Table 4.10: Prevalence of *M. bovis* infection among badgers killed in road traffic accidents in seven counties by calendar year.

County	Percent road-killed badgers infected with <i>M. bovis</i> (sample size)			
	2002	2003	2004	2005
Cornwall	12% (86)	13% (77)	16% (191)	12% (328)
Devon	7% (115)	5% (178)	10% (172)	11% (204)
Dorset	10% (31)	11% (72)	3% (40)	9% (77)
Gloucestershire	26% (187)	19% (223)	25% (244)	20% (222)
Herefordshire	20% (60)	28% (58)	11% (66)	29% (59)
Shropshire	27% (26)	3% (34)	10% (78)	13% (56)
Worcestershire	11% (38)	8% (75)	11% (124)	18% (117)

4.21 The overall prevalence of *M. bovis* infection in road-killed badgers (15%) was similar to that recorded in proactively culled badgers during the same time period (16.6%; data in Table 4.8). There was substantial variation in prevalence between counties and between years, probably relating to the comparatively small numbers of animals collected over large areas.

4.22 One aim of the Road Traffic Accident Survey was to determine whether this approach could be used to estimate the prevalence of infection in badgers in localised areas. While estimates were derived for counties, it was not possible to estimate prevalence accurately at smaller spatial scales because of the small numbers of animals collected. For example, despite considerable effort to locate and collect carcasses, only a single badger was collected each year from most parishes (around 60% of the total), and the overwhelming majority of parishes (97%) yielded 5 or fewer badgers each year. This illustrates the limited ability of a survey of this kind to provide precise estimates of prevalence in small areas.

Pathology of tuberculosis in badgers

4.23 Not all badgers found to be infected with *M. bovis* by bacteriological culture had lesions indicative of TB disease (Table 4.11). Although *M. bovis* infection occurred less frequently in cubs than in adults, among infected animals the prevalence of lesions was higher for cubs (Jenkins *et al.*, in review-a).

Table 4.11: Proportions of *M. bovis* infected badgers with visible lesions suggestive of TB. In the RBCT, neither the prevalence nor the severity of lesions differed between proactive and reactive areas. Data are from Jenkins *et al.* (in review-a) and Woodroffe *et al.* (in review).

	Adults		Cubs	
	proactive	reactive	proactive	reactive
Sample size:	1,020	247	146	42
% with visible lesions	38.5%	41.7%	55.5%	40.5%
% with >1 body compartment lesioned*	14.7%	12.6%	28.1%	26.2%
% severely lesioned [†]	10.5%	7.7%	23.3%	14.3%

* body compartments are: head, lungs, chest, abdomen, peripheral (Jenkins *et al.* in review-a);

[†] animals with lesion severity scores ≥ 8 calculated using methods presented in Jenkins *et al.* (in review-a).

4.24 The distribution of lesions indicative of TB disease is shown in Table 4.12. The majority of lesions were associated with the respiratory tract (78.5% of 496 lesioned, *M. bovis* infected, adult badgers had lesions in the head or thorax). This is consistent with previous studies and suggests that most infections are acquired via the respiratory route (Gallagher and Clifton-Hadley, 2000).

Table 4.12: Distribution of lesions indicative of TB disease in badgers. Data indicate the number and proportion of lesioned, *M. bovis* infected, adult badgers that had lesions at different sites in the body. Data are from Jenkins *et al.* (in review-a) and Woodroffe *et al.* (in review).

Body compartment	Site	RBCT treatment	
		proactive	reactive
Head	Retropharyngeal lymph node	96 (24.4%)	25 (24.3%)
	Submaxillary lymph node	40 (10.2%)	10 (9.7%)
	Any head lesion	109 (27.7%)	29 (28.2%)
Lungs	Lungs	126 (32.1%)	36 (35.0%)
Chest	Bronchial lymph node	135 (34.4%)	29 (28.2%)
	Mediastinal lymph node	98 (24.9%)	22 (21.4%)
	Pericardium	14 (3.6%)	2 (1.9%)
	Any chest lesion	176 (44.8%)	43 (41.7%)
Abdomen	Gastric lymph node	8 (2.0%)	0 (0.0%)
	Hepatic lymph node	22 (5.6%)	1 (1.0%)
	External Iliac lymph node	11 (2.8%)	1 (1.0%)
	Internal Iliac lymph node	10 (2.5%)	1 (1.0%)
	Mesenteric lymph node	8 (2.0%)	0 (0.0%)
	Renal lymph node	9 (2.3%)	2 (1.9%)
	Kidney	51 (13.0%)	15 (14.6%)
	Liver	28 (7.1%)	4 (3.9%)
	Any abdominal lesion	105 (26.7%)	20 (19.4%)
Peripheral	Axillary lymph node	37 (9.4%)	6 (5.8%)
	Inguinal lymph node	23 (5.9%)	2 (1.9%)
	Popliteal lymph node	39 (9.9%)	6 (5.8%)
	Prescapular lymph node	64 (16.3%)	11 (10.7%)
	Any peripheral lesion	110 (28.0%)	21 (20.4%)
Total		393	103

4.25 It has been proposed in the past that severely lesioned badgers could be highly infectious and play an important role in TB dynamics (Gallagher and Clifton-Hadley, 2000). However, the number of such severely lesioned infected badgers was very low (only 166 animals out of 9,919 scored in 1998-2005, Jenkins *et al.*, in review-a; Woodroffe *et al.*, in review). This suggests that animals with only mild (or no detectable) pathology may be able to transmit infection, as has been demonstrated recently in cattle (McCorry *et al.*, 2005).

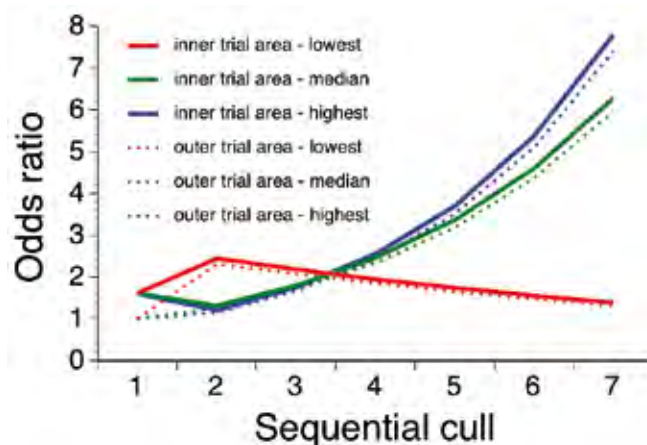
Effects of culling on M. bovis infection in badgers

4.26 Culling profoundly altered the prevalence and distribution of *M. bovis* infection in badgers. Statistical analyses adjusting for variables such as age, sex, triplet, and various measures relating to the probability of detecting infection, revealed that prevalence rose on successive proactive culls (Woodroffe *et al.*, 2006b). Overall, by the fourth cull the prevalence of infection was approximately double that recorded on the initial cull (odds ratio 1.92, 95% confidence interval 1.51-2.45) after adjusting for other factors (Woodroffe *et al.*, 2006b). Because of this rise in prevalence, the reduction in the density of badgers achieved by proactive culling was not associated with an equivalent reduction in the density of infected badgers (see Table 4.9).

4.27 The rise in prevalence associated with repeated proactive culling was particularly great following four proactive culls that were conducted in a piecemeal manner over a period of several months ('maintenance culling'), rather than in a single operation (Woodroffe *et al.*, 2006b).

4.28 The effect of proactive culling on *M. bovis* prevalence was particularly marked in trial areas where geographical conditions meant that badgers could easily recolonise the cleared area; the rise was much smaller, or absent, where coastline, major rivers or motorways blocked immigration routes around a high proportion of the trial area boundary (Figure 4.3, Woodroffe *et al.*, 2006b).

Figure 4.3: Effects of proactive culling on the prevalence and distribution of *M. bovis* infection in badgers. The y axis denotes a measure of *M. bovis* prevalence in adult badgers, after adjusting for covariates such as triplet, age, sex, and variables relating to the probability of detecting infection. Effects are shown for badgers captured in inner (>2km inside, solid lines) and outer (<2km inside, dashed lines) regions of proactive treatment areas. Coloured lines indicate the observed variation in the permeability of treatment area boundaries for immigrating badgers (lowest permeability red; median permeability green; highest permeability blue). Reproduced with permission from Woodroffe *et al.* (2006b). Copyright National Academy of Sciences, USA



4.29 As well as influencing the prevalence of *M. bovis* infection, proactive culling also affected its spatial distribution. As described above, on initial culls the prevalence was lower close to (<2km inside) trial area boundaries than in trial area cores (≥ 2 km inside); this difference is shown in Figure 4.3 as the first cull in the sequence. This difference disappeared on subsequent culls, however (Figure 4.3), indicating that prevalence had risen more rapidly close to trial area boundaries than deeper inside. This pattern is consistent with the finding of increased capture rates of badgers immediately inside trial area boundaries on follow-up culls, indicating immigration (see paragraph 4.12, Woodroffe *et al.*, in press), and also with the finding of reduced badger densities and disrupted territorial behaviour immediately outside the boundaries (see paragraphs 4.13 to 4.14, Woodroffe *et al.*, 2006a). Taken together, these pieces of evidence strongly suggest that proactive culling provoked increased immigration, greater contact rates among badgers and, as a consequence, increased transmission of *M. bovis* infection among badgers.

4.30 Proactive culling likewise influenced the distribution of *M. bovis* infection relative to other badgers. On initial culls, infection was strongly clustered on scales of 1-2 km (see paragraphs 4.17 to 4.19). However, these clusters became significantly more diffuse over successive culls, although some degree of clustering persisted (Jenkins *et al.*, in review-b). This is consistent with the observation that badgers became less territorial and more wide-ranging in the conditions of low population density generated by culling (see paragraphs 4.13 to 4.14). These behavioural changes probably encouraged contact between badgers originating at greater distances from one another, breaking up the clusters observed in high density, territorial populations.

4.31 The patchy and episodic nature of reactive culling, along with limited sample size, hindered detailed analysis of *M. bovis* prevalence in reactively culled badgers. However, there was evidence to suggest that repeated reactive culling of the same land parcels was associated with increased prevalence (Woodroffe *et al.*, in review). It is likely that ecological and epidemiological conditions in and around areas subjected to reactive culling would have been somewhat similar to those experienced close to the edges of proactive culling areas, and in proactive areas subjected to piecemeal ‘maintenance culling’. Hence, the finding that *M. bovis* prevalence may have been elevated by reactive culling is consistent with observations from proactive areas.

4.32 There is no evidence to suggest that repeated proactive culling influenced the severity of TB lesions detected in *M. bovis* infected badgers (Jenkins *et al.*, in review-a).

Comparison of RBCT findings with data from the Republic of Ireland

4.33 Data from the RBCT may be compared with information from a similar study conducted in the Republic of Ireland, the ‘Four Areas Trial’ (Griffin *et al.*, 2005).

Badger density

4.34 Two datasets suggest that the baseline density of badgers was substantially lower in the ‘Four Areas’ than in the RBCT culling areas. First, initial surveys conducted in the two studies indicate lower badger activity in the Republic of Ireland: prior to culling, overall sett density in the Irish areas was only about 40% as high as that in RBCT areas (Table 4.13). The difference in main sett density was less marked, but RBCT data indicate that main sett density is likely to be less closely correlated with overall density than is total sett density (Woodroffe *et al.*, in press).

Table 4.13: Comparison of pre-cull sett densities in study areas of the Republic of Ireland's Four Areas Trial and the RBCT. Data indicate the numbers of setts recorded per km² on initial (pre-cull) surveys. "Widespread culling" refers to the Irish "removal" and "buffer" areas combined, and to the RBCT proactive treatment areas; "localised culling" refers to the Irish "reference areas" and the RBCT reactive treatment areas. There were no survey-only areas in the Four Areas Trial. Data on the Four Areas Trial are from Griffin *et al.* (2003).

Area	Widespread culling		Localised culling		Survey only		Average	
	all setts	main setts	all setts	main setts	all setts	main setts	all setts	main setts
Four Areas Trial								
Cork	3.62	0.66	2.16	0.55	–	–	3.04	0.62
Donegal	2.45	0.47	2.44	0.42	–	–	2.45	0.44
Kilkenny	2.32	0.52	2.02	0.51	–	–	2.19	0.51
Monaghan	1.87	0.40	3.15	0.57	–	–	2.42	0.47
Average	2.53	0.51	2.44	0.51	–	–	2.49	0.51
RBCT								
A	3.24	0.48	4.05	0.54	4.21	0.38	3.85	0.47
B	6.65	0.49	3.70	0.47	2.73	0.36	4.50	0.45
C	5.15	0.53	3.76	0.51	6.87	0.49	5.30	0.51
D	6.50	1.09	4.59	0.72	3.93	0.73	4.95	0.84
E	7.03	0.69	4.84	0.50	6.49	0.68	6.15	0.62
F	4.87	0.39	5.69	0.63	5.07	0.61	5.20	0.54
G	6.99	0.98	6.82	1.00	6.70	0.83	6.84	0.94
H	8.23	0.45	11.96	0.55	11.23	0.56	10.49	0.52
I	6.17	0.90	4.53	0.78	2.19	0.51	4.41	0.74
J	8.23	0.70	11.42	0.69	5.41	0.55	8.45	0.65
Average	6.34	0.67	6.23	0.65	5.56	0.57	6.05	0.63

4.35 Comparison of badger capture rates provides further evidence of comparatively high badger density in RBCT areas. Table 4.14 presents data on the numbers of badgers culled per unit area in the RBCT and the Four Areas Trial. The Irish study used snares to capture badgers, a method which appears more efficient (but may have been somewhat less humane, Woodroffe *et al.*, 2007b) than the cage traps used in the RBCT. Also, while RBCT proactive culls were repeated approximately annually, two or three rounds of snaring were conducted each year in the Four Areas Trial (Griffin *et al.*, 2003). Despite this potentially more intensive capture effort, the numbers of badgers captured per km² per year of culling were significantly lower in the Four Areas Trial than in the RBCT, both in the first year (with means of 0.87 (Four Areas) and 3.10 (RBCT)) and averaged across all years (with means of 0.34 (Four Areas) and 1.83 (RBCT)). Hence, removal data strongly suggest higher background badger densities in the RBCT areas.

4.36 Lower baseline badger density in the Irish areas would influence not only the number of badgers to be removed by culling, but also the number of immigrants likely to move into areas cleared by culling. This ‘immigration pressure’ would have been further reduced in the Irish study since the ‘Four Areas’ were deliberately located so that substantial proportions of their boundaries were formed by natural barriers to badger movement such as coastline and major rivers (Griffin *et al.*, 2005).

Table 4.14: Numbers of badgers culled per unit area in the Republic of Ireland’s Four Areas Trial and the RBCT proactive treatment. Data on the Four Areas Trial refer to removal and buffer areas (both culled) and are from Griffin *et al.* (2005).

	Area (km ²)	Number of years	Badgers culled		Badgers culled/km ² /year	
			initial	total	initial	total
Four Areas Trial						
Cork	307	5	401	806	1.30	0.53
Donegal	226	5	208	342	0.93	0.30
Kilkenny	313	5	250	552	0.74	0.35
Monaghan	368	5	254	660	0.69	0.35
RBCT						
A	95.7	5	55	362	0.57	0.76
B	99.9	7	239	788	2.39	1.13
C	105.1	6	247	966	2.35	1.53
D	98.9	4	293	1,055	2.96	2.67
E	105.2	5	605	1,463	5.75	2.78
F	95.6	5	452	1,179	4.73	2.47
G	101.9	5	427	996	4.19	1.95
H	95.3	5	162	593	1.70	1.24
I	99.8	4	219	661	2.19	1.66
J	100.8	4	442	847	4.38	2.10

Prevalence of M. bovis infection

4.37 The prevalence of *M. bovis* infection in the RBCT cannot easily be compared with that recorded in the Four Areas Trial, as diagnostic methods were not standardised across the two studies. Initial *M. bovis* prevalence appeared less variable across study areas in the Four Areas Trial in comparison with the RBCT (Table 4.15); this may be partly because all of the Irish areas were recruited in the same year.

Table 4.15: Prevalence of *M. bovis* infection, and numbers of infected badgers/km², recorded in the first year of culling of the Four Areas Trial and on RBCT initial proactive culls. Both adults and cubs are included. Note that, since complete removal of badgers was not attained in the first year of either study, and diagnostic tests were not 100% sensitive, numbers of infected badgers per km² give minimum estimates of the true densities of infected animals. Data on the Four Areas Trial are from Griffin *et al.* (2003).

Area	Badgers examined	Badgers infected	Prevalence	Area (km ²)	Infected badgers/km ²
Four Areas Trial					
Cork	400	117	29.3%	307	0.38
Donegal	207	30	14.5%	226	0.13
Kilkenny	248	30	12.1%	313	0.10
Monaghan	241	54	22.4%	368	0.15
Average	1,096	231	21.1%	1,214	0.19
RBCT					
A	55	8	14.5%	103.8	0.08
B	238	13	5.5%	101.8	0.13
C	244	4	1.6%	121.2	0.03
D	292	101	34.6%	104.1	0.97
E	605	29	4.8%	118.8	0.24
F	452	13	2.9%	110.8	0.12
G	426	29	6.8%	114	0.25
H	162	12	7.4%	116	0.10
I	218	81	37.2%	131.4	0.62
J	442	65	14.7%	110.5	0.59
average (overall)	3,134	355	11.3%	1,132.4	0.31
average (pre-FMD)	2,182	108	4.9%	786.4	0.14

All badgers culled in the RBCT were subjected to post mortem. However, in this table badgers culled in the RBCT for which no data on infection status were available were excluded.

4.38 One very clear difference between the two studies is that, while prevalence rose markedly on successive culls in the RBCT (see paragraphs 4.26 to 4.32) prevalence appeared to decline through the course of the Four Areas Trial (Griffin *et al.*, 2003). This probably reflects the ecological differences between the RBCT and Irish study areas. As mentioned above, the ‘Four Areas’ were deliberately selected to be isolated from neighbouring badger populations by geographical features such as coastline and major rivers (Griffin *et al.*, 2005). Isolated areas were chosen because recolonisation of culled areas by immigrating badgers was perceived to have undermined the success of the earlier East Offaly study (Eves, 1999). In contrast, the boundaries of RBCT areas mainly followed property boundaries and were therefore easily traversed by immigrating badgers; the permeability of RBCT boundaries was found to influence the impact of repeated culling on *M. bovis* prevalence in badgers (paragraph 4.28). Additionally, the lower background badger density in the Irish areas would be expected to further reduce the ‘immigration pressure’ experienced

in the Four Areas Trial compared with the RBCT. The combination of efficient removal of badgers from the 'Four Areas', and limited subsequent immigration from surrounding areas, probably allowed culling to force badger densities to low enough levels that contact rates – and hence transmission rates – were substantially reduced.

Correlations between *M. bovis* infection in cattle & badgers

4.39 In addition to experimental data on the relationship between *M. bovis* infection in cattle and badgers (presented in Chapter 5), the RBCT provided correlational evidence of links between infections in the two species. The associated case-control studies (detailed in Chapter 6) offered an additional opportunity to evaluate such relationships.

Spatial associations between infections in cattle and badgers

4.40 Prior to the RBCT, most recent information on *M. bovis* infection in badgers came from badgers culled, or killed in road accidents, on and around breakdown farms (Krebs *et al.*, 1997). Hence, evidence of spatial associations between infections in cattle and badgers was limited by a paucity of data on badgers from farms without recent infections in cattle. The proactive culling treatment provided an opportunity to compare infection patterns among badgers at varying distances from infected cattle. Analyses from initial culls revealed that clusters of infection in badgers and cattle were indeed correlated in space, on a scale of 1-2km (Woodroffe *et al.*, 2005c). This association was particularly close for badgers and cattle sharing the same *M. bovis* strain type, suggesting that the association was due to transmission between the two species, rather than to some areas having environmental conditions conducive to *M. bovis* infection.

4.41 The close spatial association between infections in cattle and badgers that was observed on initial proactive culls became less marked on successive culls (Jenkins *et al.*, in review-b). This is consistent with the observation that badger culling caused badgers to range more widely, allowing infection to spread over greater spatial scales and hence to come into contact with cattle at greater distances from their own points of origin.

4.42 While it is very likely that these spatial associations between infections in cattle and badgers provide evidence of transmission between the two host species, the data cannot conclusively demonstrate the direction of transmission. Hence, these patterns could be generated by badger-to-cattle transmission, cattle-to-badger transmission, or some combination of the two.

Correlation of infections in cattle and badgers from reactive culling areas

4.43 Reactive culling preferentially removed badgers from the vicinity of TB-affected cattle herds. Hence, the observation that *M. bovis* infections in cattle and badgers were spatially linked in the proactive areas leads to a prediction that infection prevalence should be higher in reactively culled badgers, when compared with proactively culled badgers. As expected, prevalence was significantly higher among badgers taken on reactive culls than on initial proactive culls (odds ratio 1.81, 95% confidence interval 1.31-2.48, Woodroffe *et al.*, in review).

4.44 There was a high degree of similarity between the spoligotypes of associated cattle and badgers: the average probability that a randomly chosen reactively culled badger would share the same spoligotype as a randomly chosen bovine from the breakdown(s) that prompted culling was 80.3% (95% confidence interval 75.3-85.4%, Woodroffe *et al.*, in review-a). This provides further evidence of a link between infections in badgers and

cattle but, being correlational rather than experimental, cannot distinguish between badger-to-cattle and cattle-to-badger transmission.

Transmission of infection from cattle to badgers

4.45 The 2001 nationwide epidemic of foot-and-mouth disease (FMD) provided another opportunity to evaluate the links between *M. bovis* infections in cattle and badgers. During the FMD epidemic, the majority of routine cattle testing was suspended as veterinary resources were focused on FMD and farms were isolated to avoid spreading infection. As a consequence, most herds (including those in RBCT proactive areas) experienced a delay in cattle testing of approximately one year (Defra, 2004d; Cox *et al.*, 2005). This delayed the removal of *M. bovis* infected cattle from the environment, providing increased opportunities for them to spread infection to other cattle and, potentially, to badgers. In association with this delay, the prevalence of *M. bovis* infection in adult badgers increased substantially (odds ratio 1.70, 95% confidence interval 1.33-2.16 after adjusting for other variables such as triplet, sex, age, effects of culling and laboratory effects). A similar, albeit weaker, trend was observed in badger cubs. This rise was observed consistently across all seven proactive trial areas under observation at the time (Figure 4.4). Other explanations – for example that the change had been caused by climatic conditions, or by the temporary suspension of culling during the FMD epidemic – were not consistent with the data (Woodroffe *et al.*, 2006b). A similar pattern recorded in road-killed badgers confirms that the effect was not driven by culling itself (Woodroffe *et al.*, 2006b). Hence, this pattern provides powerful – albeit observational rather than experimental – evidence that cattle-to-badger transmission may be an important factor in TB dynamics. This suggests that cattle controls may have the capacity to influence not only cattle-to-cattle transmission but also, indirectly, the chances of reinfection from badgers through their effect on cattle-to-badger transmission.

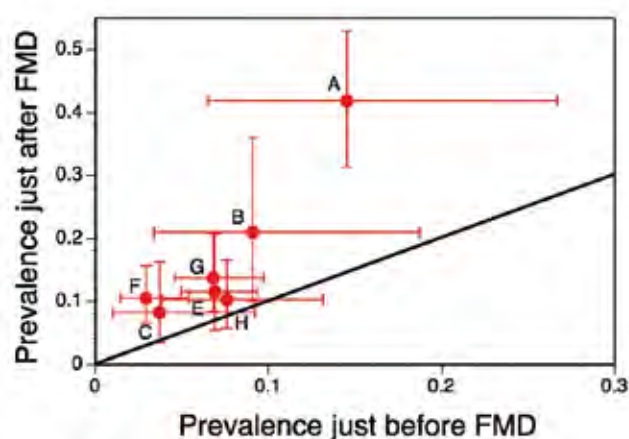


Figure 4.4: Change in *M. bovis* prevalence in proactively culled badgers, in association with the 2001 FMD epidemic in the seven RBCT proactive areas under observation at the time. Error bars give exact binomial 95% confidence intervals; the solid line indicates equal prevalence before and after FMD. Reproduced with permission from Woodroffe *et al.* (2006b). Copyright National Academy of Sciences, USA

Associations between infections in cattle and road-killed badgers

4.46 The temporal and spatial associations observed between *M. bovis* infections in badgers and cattle suggest that infected badgers might be used as sentinels for infection in cattle. This raises the possibility that TB surveillance in cattle might be improved by targeting tuberculin testing at areas where infection had been detected in road-killed badgers. To investigate this possibility, in 2003-6 the State Veterinary Service conducted a number of additional tuberculin tests on herds in the vicinity of *M. bovis* infected road-killed badgers

(Goodchild, 2006). However, such tests were, on average, less likely to detect infected cattle than were routine whole-herd tuberculin tests conducted on unrestricted herds in the same parish, and on the same parish testing interval (Goodchild, 2006). This suggests that, despite associations between infections in cattle and badgers, the presence of infection in badgers is not a reliable indicator of infection in nearby cattle.

Summary and conclusions

4.47 Overall, these findings highlight the critical importance of badger ecology and behaviour in TB epidemiology. Prior to culling, RBCT areas contained badger populations similar in all respects to those previously described for British agricultural landscapes: badgers lived at reasonably high densities, in territorial social groups, with *M. bovis* infections clustered on a scale of 1-2km. Infections in badgers were spatially associated with those in cattle, probably due to a combination of badger-to-cattle and cattle-to-badger transmission.

4.48 These patterns were profoundly disrupted by culling, however. Proactive culling substantially reduced badger population density, both on culled land and on nearby land that was either inaccessible for culling or outside the culling area. This density reduction was associated with disruption of badgers' territorial system: badgers ranged more widely, and substantial numbers immigrated into the culled areas from neighbouring lands. Probably as a result of this perturbation, *M. bovis* prevalence in badgers rose substantially in response to culling, and infection became more diffuse across the landscape. Reactive culling caused smaller reductions in density, but seems to have had similar consequences for *M. bovis* prevalence.

4.49 These findings contrast with the conventional view of culling as a tool for controlling disease transmission by reducing contact rates among hosts. Although culling, as conducted in the RBCT, markedly reduced badger density, its effect on the rate of infectious contact with cattle is difficult to predict since it also increased both the prevalence and spatial extent of infection within the badger population. These effects, which were seen consistently across RBCT areas, appear to reflect the high baseline badger density and paucity of geographical barriers to badger movement which occur in TB-affected regions of Britain.

5. THE EFFECTS OF BADGER CULLING ON CATTLE TB

Data and statistical methods

5.1 The primary outcome of the RBCT, on which its estimates of the impact of badger culling on cattle TB were to be based, was information on the incidence of TB over the period of the trial among cattle herds in the triplet areas which had been subjected to proactive culling, reactive culling and no culling.

5.2 Data relating to each herd breakdown were obtained from the animal health information system VetNet, which holds demographic information on all cattle herds in Great Britain as well as their disease management histories including TB tests conducted by the State Veterinary Service (now Animal Health).

5.3 The ‘primary analysis’ of treatment effects compared the number of confirmed cattle herd breakdowns associated with each culling strategy (i.e. within the relevant trial areas) with the number associated with the no-cull survey-only strategy. The design of the trial was such that all comparisons are made between areas within a triplet, thus comparing areas with similar environmental conditions, for example. In analysing the comparison between treatments, adjustment was made for two other effects which might influence the number of breakdowns observed in each area, obscuring any effects of badger culling. These were the baseline number of herds within the trial area, and the TB incidence in those cattle herds in a preceding three-year period, since both of these factors were expected to influence subsequent breakdown rates. Because these variables refer to occurrences before randomisation they could not have been affected by operations in the trial and this makes adjustments based on them legitimate.

5.4 The start of the trial in each triplet (i.e. the date it became ‘active’) was taken to be the end of its initial proactive cull. Breakdowns first detected after this date in any of the three trial areas within the triplet thus contributed to the analysis.

5.5 Individual cattle herd locations were taken from two alternative databases: the national animal health information system VetNet and a separate database set up specifically for the RBCT. Analyses performed using these two databases are presented separately. These databases were used to identify herds inside the boundaries of all 30 trial areas.

The effects of proactive culling within RBCT trial areas

5.6 The results described in paragraphs 5.7 to 5.36 are summarised from a recently published paper (Donnelly *et al.*, 2007), where further details can be found. This was an update and extension of the analyses first presented in Donnelly *et al.* (2006).

5.7 The cattle TB incidence data analysed here were collected from the period from the initial proactive cull in each triplet, to a date one year after culling had ceased in that triplet, when another cull would have occurred had the proactive culling treatment been continued. This time period – which totalled 55.8 triplet-years – also offered an opportunity for annual herd testing to detect any breakdowns which occurred during the culling period.

5.8 Table 5.1 presents, for each of the proactive and survey-only trial areas, the number of confirmed breakdowns during this observation period, the number of historic confirmed breakdowns and the number of baseline herds.

Table 5.1: Numbers of confirmed herd breakdowns, and important covariates, for herds within proactive and survey-only trial areas. Herds were identified based on locations recorded in the VetNet database. For comparable data based on herds identified as being in trial areas based on locations recorded in the RBCT database, see the supplementary data published electronically with Donnelly *et al.* (2007)

Triplet	Confirmed breakdowns during the observation period		Confirmed breakdowns during the historic three-year period		Number of baseline herds		Triplet-years
	Proactive	Survey-only	Proactive	Survey-only	Proactive	Survey-only	
A	40	67	33	33	71	89	6.74
B	98	70	40	27	153	133	7.88
C	34	98	15	27	107	173	6.90
D	39	49	28	30	98	108	3.40
E	42	67	25	28	116	101	6.30
F	16	64	12	34	142	190	5.92
G	83	54	26	15	245	131	5.61
H	36	42	23	22	66	129	5.63
I	38	31	30	19	107	98	3.80
J	46	40	25	18	116	124	3.56

5.9 The primary analysis demonstrated that the overall incidence of confirmed TB breakdowns in cattle was 23.2% (95% CI 12.4-32.7%; Table 5.2) lower inside proactively culled trial areas than inside survey-only areas ($p < 0.001$), using herd locations as recorded in the VetNet database. This estimate was obtained from a log-linear Poisson regression model adjusting for the number of baseline herds and historic TB incidence calculated over three years (each log-transformed) as well as triplet. This beneficial effect of proactive culling was similar across all ten proactive/survey-only trial area pairs (the test for overdispersion was not significant, $p = 0.87$). Furthermore, it achieved the level of precision predicted by the study design, specifically that the 95% confidence limits on the estimated percentage benefit, if any, should be approximately the estimate plus and minus 10% (see Appendix H).

5.10 As in previous analyses (Donnelly *et al.*, 2006), the beneficial effect of proactive culling was somewhat stronger when measured from the first follow-up cull (cull 2), rather than from the initial cull (cull 1; Table 5.2). Similar results were obtained based on cattle herd locations as recorded in the RBCT database, adjusting for historic incidence in the previous year (rather than the previous three years), using different measures of the size of the cattle population at risk and excluding from the analyses all breakdowns in herds in which cattle confirmed in the first 30 days of the breakdown had been moved into the herd in the previous year.

Table 5.2: Estimated effects of proactive culling on the incidence of confirmed cattle TB breakdowns within trial areas. Analyses adjust for triplet, baseline herds, and historic TB incidence (over three years). Taken from Donnelly *et al.* (2007).

	Proactive effect			Overdispersion*	
	estimate	95% CI	p-value	factor	p-value
<i>Using VetNet location data</i>					
From initial cull (cull 1)	-23.2%	(-32.7%, -12.4%)	<0.001	0.67	0.87
From first follow-up cull (cull 2)	-26.6%	(-36.8%, -14.8%)	<0.001	0.93	0.53
Between initial and follow-up	-7.2%	(-31.3%, 25.4%)	0.63	1.05	0.36
<i>Using RBCT location data</i>					
From initial cull (cull 1)	-17.4%	(-27.2%, -6.2%)	0.003	0.79	0.74
From first follow-up cull (cull 2)	-21.0%	(-31.6%, -8.8%)	0.001	0.86	0.64
Between initial and follow-up	1.1%	(-26.4%, 39.0%)	0.94	1.15	0.23

* The overdispersion factor was estimated as the square-root of the deviance divided by the degrees of freedom. An overdispersion factor less than or near 1, as indicated by a high p-value, indicates that the results were similar across all ten triplets. An overdispersion over 1, as indicated by a low p-value, indicates that the results were variable across the ten triplets. Confidence intervals and p-values were conservatively adjusted for extra-Poisson overdispersion by using this adjustment factor in all cases where its value was greater than 1.

5.11 For illustration, these results can be used to estimate approximately the number of confirmed breakdowns prevented by proactive culling. If we assume that a 100km² area were culled and the herd density were 1.25 per km² (roughly that seen in trial areas), then there would be 125 herds in the culling area. If the underlying incidence rate per annum throughout ten such areas were 8 confirmed breakdowns per 100 herds (again a reasonable approximation based on survey-only areas during the observation period; Table 5.1), then these results are equivalent to the saving of an estimated 116 confirmed breakdowns (10 areas × 125 herds × 8 confirmed breakdowns / 100 herds per year × 5 years × 0.232) over 5 years across the ten 100km² culling areas. The results of this and similar calculations clearly depend strongly on the size of area culled (see paragraphs 5.31 and 5.39 to 5.42).

The impact of repeated culling

5.12 Surveys for signs of badger activity indicate that badger density decreased with repeated proactive culling (see paragraphs 4.8 to 4.11, Woodroffe *et al.*, in press). Thus, if risks to cattle scale with badger density, the beneficial effect of culling would be expected to increase after repeated culls. However, data also show that the prevalence of *M. bovis* infection in badgers increased on successive culls (paragraphs 4.26 to 4.32). This effect might be expected to reduce any additional beneficial effects of repeated badger culling on cattle TB incidence.

5.13 When the incidence data were stratified based on the intervals between successive culls (initial to second, second to third, third to fourth, and after fourth), the beneficial effect of proactive culling inside trial areas appeared to increase with repeated culling (Figure 5.1 panel A). The linear trend (on the log scale) suggested an 11.2% increase in the beneficial proactive effect with each cull, although this effect was on the borderline of statistical significance at a conventional level (p=0.064).

The impact of distance from the trial area boundary

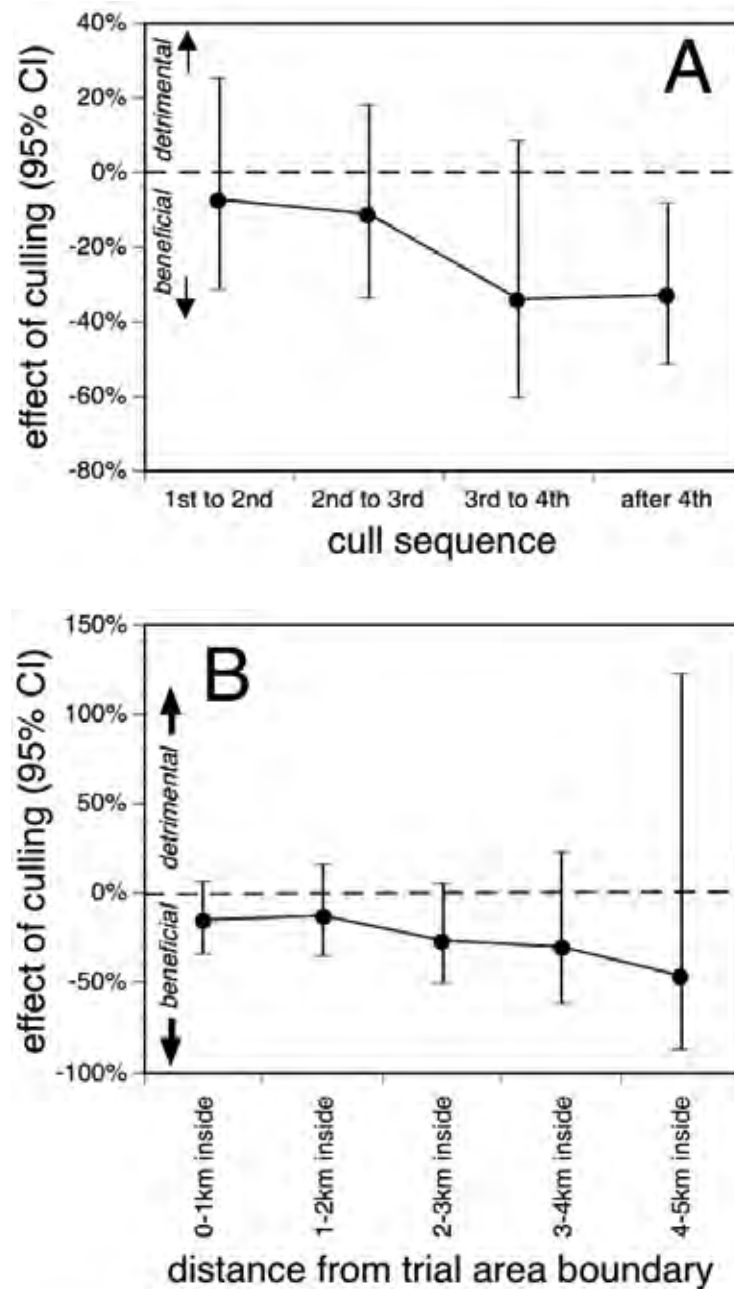
5.14 The proportion of badgers captured close to the culling area boundary increased on successive proactive culls (probably due to immigration from surrounding areas; paragraph 4.8, Woodroffe *et al.*, in press) indicating that a more thorough removal was sustained deeper inside trial areas. Furthermore, the prevalence of *M. bovis* infection in badgers rose more markedly close to culling area boundaries than deeper inside, even though prevalence was initially lower close to the boundaries (paragraph 4.29, Woodroffe *et al.*, 2006b). Both of these factors suggest that the beneficial effects of culling might be expected to vary for herds located at different distances from the trial area boundary.

5.15 The beneficial effect of proactive culling appeared to increase at greater distances inside the trial area boundary (Figure 5.1 panel B, $p=0.085$). However, there was no evidence that this dependence in the effect of culling on proximity to the boundary changed in response to repeated culling.

The impact of the permeability of trial area boundaries

5.16 An association between repeated proactive culling and increased *M. bovis* infection in badgers was found only in trial areas where landscape conditions allowed badgers to immigrate into culled areas from neighbouring land; no such effect was seen where coastline, major rivers or motorways formed a substantial proportion of trial area boundaries (paragraphs 4.26 to 4.32, Woodroffe *et al.*, 2006b). Hence, geographical barriers to badger movement might also be expected to influence the impact of badger culling on cattle TB. However, the overall effect of culling on cattle TB inside trial areas did not depend on boundary permeability inside trial areas ($p=0.73$). The finding of no evidence for such an effect may be because of limited statistical power: the RBCT was not designed to test this hypothesis and the variation among trial areas in boundary permeability was not great (Woodroffe *et al.*, 2006b). Thus, currently available data shed no direct light on whether a proactive culling policy would be more beneficial if conducted in more geographically isolated areas.

Figure 5.1: A) Variation in the beneficial effect of proactive culling by the number of repeat culls within trial areas;
 B) Variation in the beneficial effect of proactive culling at different distances inside the trial area boundary. These analyses used cattle herd locations from the VetNet database and adjusted for historic cattle TB incidence (over three years). Error bars denote 95% confidence intervals. These graphs were based on those published in Donnelly *et al.* (2007).



The impact of land access

5.17 Landholder consent was required before field staff could survey or cull badger populations. Every trial area contained land where consent was refused, and land for which no landholder could be identified. No traps were set on such land, although efforts were made to capture badgers residing in these areas by trapping around their boundaries. Nevertheless if trapping were less successful at removing badgers from inaccessible land, then the benefits of proactive culling observed on accessible land might be expected to be greater than those observed overall. See paragraphs 2.57 to 2.59 for investigation of the rates of badger culling and land access.

5.18 Comparing TB incidence in herds on accessible proactive land with entire survey-only areas indicated effects of culling comparable in magnitude and precision with those observed on proactive land as a whole (Table 5.3; Donnelly *et al.*, 2007). As the estimates from inaccessible land were of limited precision, it was unsurprising that comparisons between effect estimates based on accessible and inaccessible land showed no significant differences ($p=0.36$ using herd locations from the VetNet database).

Table 5.3: Estimated effect of proactive culling on the incidence of confirmed TB breakdowns. Analyses adjust for triplet, baseline herds, and historic TB incidence (over three years). All herds in proactive trial areas are compared with all those in survey-only trial areas, and then the comparison is stratified by consent status of land. Taken from Donnelly *et al.* (2007).

Source of herd location data	Consent status	Proactive effect			Overdispersion*		p-value for difference between accessible & inaccessible†
		Estimate	95% CI	p-value	factor	p-value	
VetNet	All						
	Proactive land	-23.2%	(-32.7%, -12.4%)	<0.001	0.67	0.87	–
	Accessible	-15.4%	(-29.9%, 2.0%)	0.080	1.33	0.009	0.36
	Inaccessible	-28.7%	(-48.6%, -1.0%)	0.044			
RBCT	All						
	Proactive land	-17.4%	(-27.2%, -6.2%)	0.003	0.79	0.74	–
	Accessible	-15.5%	(-28.1%, -0.6%)	0.042	1.25	0.034	0.82
	Inaccessible	-10.6%	(-42.4%, 38.6%)	0.615			

* See footnote to Table 5.2.

† 95% CI for the difference in the effect of proactive badger culling between herds on accessible and inaccessible land:

- VetNet: (-17.8%, 71.0%)
- RBCT: (-41.0%, 51.7%)

The impact of proactive culling on unconfirmed herd breakdowns

5.19 Our primary analyses concerned only those breakdowns that were confirmed – that is, evidence of *M. bovis* infection was detected by culture of samples from slaughtered cattle, or lesions indicative of TB disease were found at post mortem examination. However, some TB herd breakdowns which remain unconfirmed are likely, in fact, to indicate the presence of infection in cattle. One reason for the failure to confirm a breakdown may be the incomplete sensitivity of the standard protocol for the culture of *M. bovis* bacteria from cattle samples; this would be analogous to findings when a more extensive culture protocol was used for badger samples (Crawshaw, Griffiths and Clifton-Hadley, in review). This revealed that *M. bovis* could be cultured from samples declared to be negative on the basis of the standard protocol through the use of additional culture tubes and longer culture times. If unconfirmed breakdowns do, in fact, indicate the presence of *M. bovis* infection in cattle, badger culling might be expected to influence their rate of occurrence.

5.20 A second reason for investigating the effects of badger culling on the incidence of unconfirmed breakdowns is that disruptions and costs result from both types of breakdowns, although unconfirmed breakdowns are typically shorter in duration. Both confirmed and unconfirmed breakdowns result in the compulsory slaughter of reactor cattle, movement restrictions on the herd, and additional testing of cattle. Hence, from an economic point of view preventing unconfirmed breakdowns would be desirable, whether or not they indicate the presence of disease.

5.21 Table 5.4 presents, for each of the proactive and survey-only trial areas, the number of total (confirmed and unconfirmed) breakdowns during the period from the initial proactive cull in each triplet to a date one year after culling had ceased in that triplet and the number of historic total breakdowns, and Table 5.5 gives the results of log-linear Poisson regression analyses of these data. These show reduced estimates of the impacts of proactive culling, in comparison with analyses considering confirmed breakdowns only (compare Table 5.5 with Table 5.2).

Table 5.4: Numbers of total (confirmed and unconfirmed) herd breakdowns during the period of analysis and in the historic three-year period before culling within proactive and survey-only trial areas. Herds were identified based on locations recorded in the VetNet database. For comparable data based on herds identified as being in trial areas based on locations recorded in the RBCT database, see the supplementary data published electronically with Donnelly *et al.* (2007).

Triplet	Total breakdowns during the observation period (% confirmed)		Total breakdowns during the historic three-year period (% confirmed)	
	Proactive	Survey-only	Proactive	Survey-only
A	56 (71%)	90 (74%)	38 (87%)	45 (73%)
B	125 (78%)	96 (73%)	56 (71%)	33 (82%)
C	50 (68%)	143 (69%)	21 (71%)	41 (66%)
D	53 (74%)	61 (80%)	36 (78%)	40 (75%)
E	78 (54%)	87 (77%)	32 (78%)	35 (80%)
F	41 (39%)	97 (66%)	18 (67%)	54 (63%)
G	114 (73%)	63 (86%)	41 (63%)	32 (47%)
H	52 (69%)	64 (66%)	26 (88%)	29 (76%)
I	53 (72%)	61 (51%)	39 (77%)	28 (68%)
J	70 (66%)	71 (56%)	38 (66%)	26 (69%)

Table 5.5: Estimated effects of proactive culling on the incidence of all (confirmed and unconfirmed) cattle TB breakdowns within trial areas. Analyses adjusted for triplet, baseline herds and historic TB incidence (over three years). Taken from the supplementary text published electronically with Donnelly *et al.* (2007).

	Proactive effect			Overdispersion*		
	estimate	95% CI		p-value	factor	p-value
<i>Using VetNet location data</i>						
From initial cull (cull 1)	-11.7%	(-22.5%,	0.7%)	0.063	1.26	0.14
From first follow-up cull (cull 2)	-12.9%	(-25.2%,	1.5%)	0.078	1.30	0.10
Between initial and follow-up	-5.2%	(-30.6%,	29.6%)	0.74	1.36	0.073
<i>Using RBCT location data</i>						
From initial cull (cull 1)	-6.3%	(-19.2%,	8.6%)	0.39	1.43	0.045
From first follow-up cull (cull 2)	-6.0%	(-19.8%,	10.2%)	0.45	1.37	0.068
Between initial and follow-up	-5.8%	(-33.2%,	33.0%)	0.74	1.51	0.025

* See footnote to Table 5.2.

5.22 To investigate the apparently smaller impact of proactive culling on all breakdowns, in comparison with only confirmed breakdowns, we therefore examined analyses of unconfirmed breakdowns only. These analyses, which are presented in Table 5.6, revealed considerable overdispersion (indicating less consistency between triplets than was observed in the analyses of confirmed breakdowns), and estimated effects that were all consistent with no effect of proactive culling on unconfirmed breakdowns. Several estimates were in the opposite direction to the significant effects found on confirmed breakdowns, with wider confidence intervals than the estimates associated with confirmed breakdowns due to the more limited numbers of unconfirmed breakdowns in trial areas. We therefore conclude that there is no evidence of an impact of proactive culling on unconfirmed breakdowns within trial areas and focus our attention on the analyses based on confirmed breakdowns only.

5.23 We cannot determine, from these data, why there was no apparent effect of proactive culling on unconfirmed breakdowns. No effect would arise for any unconfirmed breakdowns that were genuinely uninfected herds (i.e. false positives at tuberculin testing). Furthermore, no effect would arise for any unconfirmed infections (i.e. false negative at confirmation) unrelated to badgers. Thus, if infections arising from cattle-to-cattle transmission events and/or previously unidentified infections which occurred prior to badger culling were less likely to have visible lesions, or were more difficult to confirm by culture, then the impact of proactive badger culling on unconfirmed infections would be expected to be less than the impact on confirmed breakdowns. See Chapter 7 for further discussion of unconfirmed infections in cattle.

Table 5.6: Estimated effects of proactive culling on the incidence of unconfirmed cattle TB breakdowns within trial areas. Analyses adjusted for triplet, baseline herds and historic TB incidence (over three years). Taken from the supplementary text published electronically with Donnelly *et al.* (2007).

	Proactive effect			Overdispersion*	
	estimate	95% CI	p-value	factor	p-value
<i>Using VetNet location data</i>					
From initial cull (cull 1)	-3.4%	(-28.0%, 29.5%)	0.82	1.49	0.029
From first follow-up cull (cull 2)	5.8%	(-21.6%, 42.8%)	0.71	1.35	0.076
Between initial and follow-up	-31.0%	(-57.5%, 11.9%)	0.13	1.10	0.30
<i>Using RBCT location data</i>					
From initial cull (cull 1)	11.9%	(-17.4%, 51.7%)	0.47	1.59	0.014
From first follow-up cull (cull 2)	25.4%	(-7.0%, 69.2%)	0.14	1.38	0.062
Between initial and follow-up	-28.8%	(-57.2%, 18.3%)	0.19	1.18	0.20

* See footnote to Table 5.2.

Effects on the spatial distribution of infections in cattle

5.24 Prior to badger culling, *M. bovis* infections were clustered in space, within both badger and cattle populations; infections in the two species were also spatially associated (Woodroffe *et al.*, 2005c). As discussed in paragraphs 4.30 and 4.40 to 4.42, repeated proactive culling reduced the degree of clustering of infection within badger populations, and also reduced the spatial association between infections in cattle and badgers, probably because badgers' increased ranging behaviour allowed them to come into contact with other badgers, and with cattle herds, at greater distances from their own origins (Jenkins *et al.*, in review-b). These changes in the spatial distribution of infection in badgers might be expected to cause corresponding reductions in the clustering of infection between cattle herds, if substantial badger-to-cattle transmission was occurring inside proactive culling areas. However, analyses revealed no evidence that the degree of clustering of infections within cattle populations either increased or decreased across successive badger culls within proactive areas (Jenkins *et al.*, in review-b).

The effects of proactive culling outside RBCT trial areas

5.25 Ecological studies had revealed reduced population densities and expanded ranging behaviour in badger populations studied up to 2km outside proactive areas, as well as in reactive areas (paragraphs 4.13 to 4.14, Woodroffe *et al.*, 2006a). Thus incidence data from herds up to 2km outside trial area boundaries were analysed, comparing herds outside proactive trial areas with herds outside survey-only trial areas.

5.26 Data on herd locations within the VetNet and RBCT databases were used to identify herds up to 2km outside proactive and survey-only trial areas. The VetNet database provided more complete data on herds outside trial areas, because the RBCT database was not designed to include all farms on neighbouring land. Herds within 2km of more than one trial area boundary (whether proactive, reactive or survey-only) were omitted from analyses.

5.27 Table 5.7 presents the number of confirmed breakdowns in these ‘neighbouring areas’ during the same observation periods as those used for analyses of the effects of culling inside proactive areas. Numbers of historic confirmed breakdowns and numbers of baseline herds within 2km within neighbouring areas are also provided.

Table 5.7: Numbers of confirmed herd breakdowns and important covariates for herds up to 2km outside proactive and survey-only trial areas. Herds were identified based on locations recorded in the VetNet database. For comparable data based on herds identified as being up to 2km outside trial areas based on locations recorded in the RBCT database, see the supplementary data published electronically with Donnelly *et al.* (2007).

Triplet	Confirmed breakdowns during the observation period		Confirmed breakdowns during the historic three-year period		Number of baseline herds		Triplet-years
	Proactive	Survey-only	Proactive	Survey-only	Proactive	Survey-only	
A	27	25	24	19	60	70	6.74
B	82	50	16	15	153	69	7.88
C	40	47	10	14	118	122	6.90
D	17	18	5	19	48	58	3.40
E	29	34	11	17	96	76	6.30
F	17	43	1	21	61	129	5.92
G	35	39	3	15	165	138	5.61
H	51	29	16	14	71	94	5.63
I	25	11	11	15	69	64	3.80
J	39	25	18	5	120	103	3.56

5.28 Our primary analysis revealed that, on land up to 2km outside proactive trial areas, overall cattle TB incidence was 24.5% higher (95% CI: 0.6% lower – 56.0% higher) than that on land neighbouring survey-only areas ($p=0.057$; Table 5.8). This effect was similar across all ten proactive/survey-only pairs (the test for overdispersion was not significant, $p=0.13$). Similar patterns were detected using herd locations from the RBCT database, and adjusting for one year’s historic incidence (Table 5.8).

5.29 As in the analysis of data from herds within trial areas, the TB incidence data analyses were taken from the period from the initial proactive cull in each triplet, to a date one year after culling had ceased in that triplet, when another cull would have occurred had proactive culling continued (55.8 triplet-years in total).

5.30 This detrimental effect of culling was most marked between the initial and first follow-up cull; weaker detrimental effects were detected after the first follow-up cull (Table 5.8).

Table 5.8: Estimated effects of proactive culling on the incidence of confirmed cattle TB breakdowns up to 2km outside trial areas. Analyses adjust for triplet, baseline herds, and historic TB incidence (over three years). Taken from Donnelly *et al.* (2007).

	Proactive effect			Overdispersion*	
	estimate	95% CI	p-value	factor	p-value
<i>Using VetNet location data</i>					
From initial cull (cull 1)	24.5%	(-0.6%, 56.0%)	0.057	1.26	0.13
From first follow-up cull (cull 2)	19.6%	(-10.3%, 59.5%)	0.22	1.41	0.052
Between initial and follow-up	46.8%	(-0.4%, 116.4%)	0.052	0.95	0.50
<i>Using RBCT location data</i>					
From initial cull (cull 1)	35.3%	(5.8%, 73.0%)	0.016	1.00	0.44
From first follow-up cull (cull 2)	24.9%	(-7.2%, 67.9%)	0.14	1.09	0.34
Between initial and follow-up	95.4%	(10.5%, 245.5%)	0.021	0.82	0.69

* See footnote to Table 5.2.

5.31 These results can be used to estimate approximately the number of confirmed breakdowns induced by proactive culling. If we assume that a 100km² circular area were culled, then just under 83.5km² of land would fall up to 2km outside the culling area boundary. If the herd density were 1.25 per km², then there would be 104 herds in the neighbouring area. If the underlying incidence rate throughout ten such areas were 8 confirmed breakdowns per 100 herds per year, then these results are equivalent to an estimated 102 additional confirmed breakdowns (10 areas × 104 herds × 8 confirmed breakdowns/100 herds per year × 5 years × 0.245) due to proactive culling over 5 years across the ten neighbouring areas. This may be compared with the calculation in paragraph 5.11.

The impact of repeated culling

5.32 When the incidence data were stratified based on the intervals between successive culls (initial to second, second to third, third to fourth, and after fourth), the detrimental effect of proactive culling up to 2km outside trial area boundaries appeared to decline with repeated culling (Figure 5.2 panel A), although this effect was not statistically significant. The linear trend (on the log scale) suggested a 7.3% decrease in the detrimental proactive effect with each cull (p=0.17). Similar non-significant trends were found adjusting for one year's historic incidence and using herd locations from the RBCT database adjusting for three years' historic incidence.

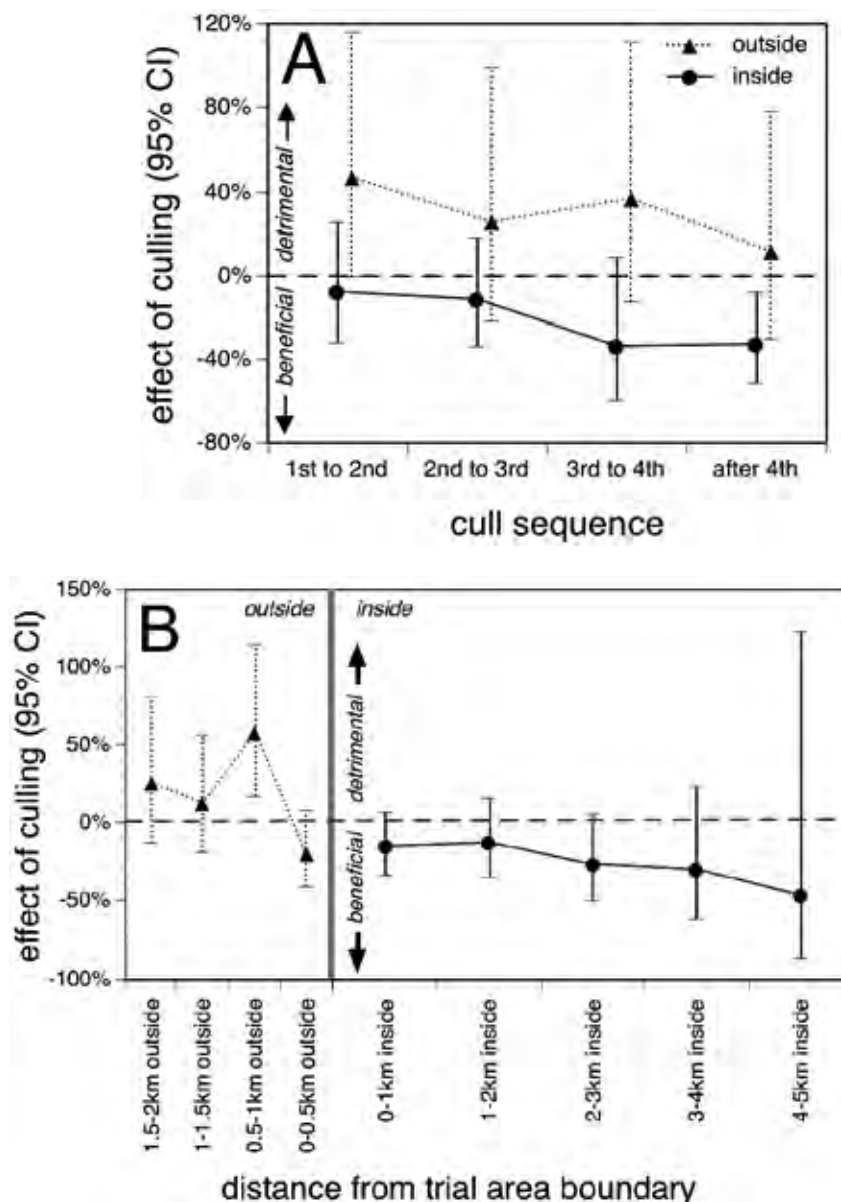
The impact of distance from the trial area boundary

5.33 Detrimental effects of culling were observed for herds 0.5-2km outside the trial area boundary, while those less than 0.5km outside the trial area boundary appeared to experience a benefit (Figure 5.2 panel B). This latter effect was unsurprising, because badger culling extended just beyond the boundaries of the trial areas to target social groups judged, on the basis of field signs, to occupy home ranges falling partially inside the trial areas (see Figure 2.1 and paragraphs 2.54 to 2.59).

The impact of the permeability of boundaries

5.34 There was no evidence that the effect of culling on cattle TB up to 2km outside trial area boundaries depended on boundary permeability ($p=0.69$). As mentioned in paragraph 5.16, the finding of no evidence for such an effect may be because of limited statistical power.

Figure 5.2: A) Variation in the effects of proactive culling by the number of repeat culls;
B) Variation in the effects of proactive culling at different distances from the trial area boundary. These analyses used cattle herd locations from the VetNet database and adjusted for historic cattle TB incidence (over three years). Error bars denote 95% confidence intervals. These graphs were published in Donnelly *et al.* (2007).



The impact of proactive culling on unconfirmed herd breakdowns

5.35 Table 5.9 presents the total number of (confirmed and unconfirmed) breakdowns during the period from the initial proactive cull in each triplet to a date one year after culling had ceased in that triplet, and the number of historic confirmed breakdowns up to 2km outside each of the proactive and survey-only trial areas. Results of log-linear Poisson regression analyses of these data (Table 5.10) revealed reduced estimates of the impacts of proactive culling, in comparison with analyses considering confirmed breakdowns only (compare Table 5.10 with Table 5.8). The estimated detrimental effect of culling was, however, statistically significant both from the initial proactive cull and from the first follow-up cull using the location data in the RBCT database.

Table 5.9: Total numbers of herd breakdowns (including confirmed and unconfirmed breakdowns) during the period of analysis and in the historic three-year period before culling up to 2km outside proactive and survey-only trial areas. Herds were identified based on locations recorded in the VetNet database. For comparable data based on herds identified as being up to 2km outside trial areas based on locations recorded in the RBCT database, see the supplementary data published electronically with Donnelly *et al.* (2007).

Triplet	Total breakdowns (% confirmed)		Number of historic breakdowns (% confirmed)	
	Proactive	Survey-only	Proactive	Survey-only
A	35 (77%)	35 (71%)	30 (80%)	26 (73%)
B	111 (74%)	67 (75%)	24 (67%)	22 (68%)
C	70 (57%)	77 (61%)	16 (63%)	18 (78%)
D	21 (81%)	21 (86%)	7 (71%)	22 (86%)
E	49 (59%)	52 (65%)	17 (65%)	21 (81%)
F	20 (85%)	67 (64%)	3 (33%)	25 (84%)
G	49 (71%)	47 (83%)	6 (50%)	18 (83%)
H	66 (77%)	47 (62%)	20 (80%)	20 (70%)
I	33 (76%)	21 (52%)	19 (58%)	19 (79%)
J	60 (65%)	43 (58%)	30 (60%)	14 (36%)

Table 5.10: Estimated effects of proactive culling on the incidence of all (confirmed and unconfirmed) cattle TB breakdowns up to 2km outside trial areas. Analyses adjusted for triplet, baseline herds and historic TB incidence (over three years). Taken from the supplementary text published electronically with Donnelly *et al.* (2007).

	Proactive effect			Overdispersion*		
	estimate	95% CI		p-value	factor	p-value
<i>Using VetNet location data</i>						
From initial cull (cull 1)	13.5%	(-5.3%,	36.0%)	0.17	1.24	0.15
From first follow-up cull (cull 2)	11.6%	(-7.3%,	34.5%)	0.25	1.14	0.24
Between initial and follow-up	23.8%	(-11.3%,	72.7%)	0.21	0.83	0.68
<i>Using RBCT location data</i>						
From initial cull (cull 1)	29.3%	(5.2%,	59.1%)	0.015	0.73	0.81
From first follow-up cull (cull 2)	27.3%	(0.6%,	60.9%)	0.044	0.65	0.88
Between initial and follow-up	41.5%	(-9.9%,	122.4%)	0.13	0.81	0.71

* See footnote to Table 5.2.

5.36 To investigate the reduced impact of badger culling on the incidence of all breakdowns, in comparison with confirmed breakdowns only, we analysed unconfirmed breakdowns only. These estimated effects were all consistent with no effect of proactive culling on unconfirmed breakdowns; see Table 5.11. Several estimated effects were in the opposite direction to the significant effects found on confirmed breakdowns. For these reasons we conclude that there is no evidence of an impact of proactive culling on unconfirmed breakdowns up to 2km outside trial areas and focus our attention on the analyses based on confirmed breakdowns only. See paragraph 5.23 for possible reasons for this finding.

Table 5.11: Estimated effects of proactive culling on the incidence of unconfirmed cattle TB breakdowns in areas up to 2km outside trial areas. Analyses adjusted for triplet, baseline herds and historic TB incidence (over three years). Taken from the supplementary text published electronically with Donnelly *et al.* (2007).

	Proactive effect			Overdispersion*		
	estimate	95% CI		p-value	factor	p-value
<i>Using VetNet location data</i>						
From initial cull (cull 1)	-11.8%	(-31.8%,	14.1%)	0.34	1.05	0.35
From first follow-up cull (cull 2)	-7.7%	(-31.2%,	23.8%)	0.59	1.13	0.25
Between initial and follow-up	-36.5%	(-69.9%,	34.0%)	0.23	0.76	0.78
<i>Using RBCT location data</i>						
From initial cull (cull 1)	3.0%	(-31.9%,	55.8%)	0.89	1.11	0.28
From first follow-up cull (cull 2)	2.6%	(-33.3%,	57.8%)	0.91	1.02	0.40
Between initial and follow-up	-3.3%	(-59.2%,	128.9%)	0.94	0.92	0.54

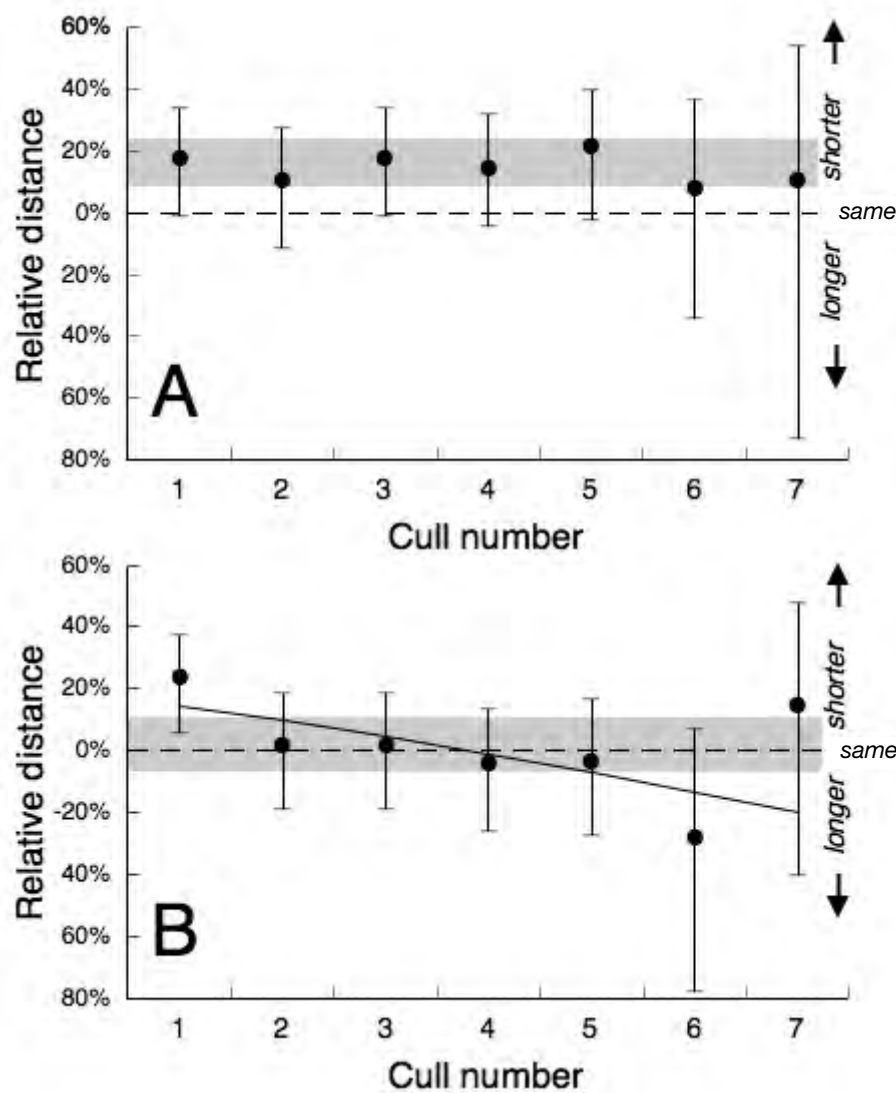
* See footnote to Table 5.2.

Effects on the spatial distribution of infections in cattle

5.37 As discussed in paragraphs 4.30 and 4.40 to 4.42, repeated proactive culling reduced the degree of clustering of infection within badger populations, and also reduced the spatial association between infections in cattle and badgers. This was probably because badgers' increased ranging behaviour allowed them to come into contact with other badgers, and with cattle herds, at greater distances from their own origins (Jenkins *et al.*, in review-b). Since expanded ranging behaviour was also observed among badgers living just outside proactive culling areas (paragraph 4.30, Woodroffe *et al.*, 2006a), similar changes in the distribution of infection may have occurred, although these could not be measured since no badgers were sampled in these neighbouring areas. Any such changes in the spatial distribution of infection in badgers might be expected to cause corresponding reductions in the clustering of infection between cattle herds, especially as our results indicate that substantial badger-to-cattle transmission was occurring just outside proactive culling areas.

5.38 Analyses revealed that this was indeed the case; while there was evidence of significant clustering of infection between cattle herds in neighbouring areas before culling occurred, this was considerably reduced after proactive culling (Figure 5.3, Jenkins *et al.*, in review-b). This contrasts with the situation inside proactive trial areas, where there was no such change in the spatial distribution of cattle TB (see paragraph 5.24).

Figure 5.3: Clustering of *M. bovis* infections in cattle. The graphs show the percent difference between TB-affected and unaffected herds in the distance to the nearest affected herd, with shorter relative distances indicating stronger clustering (A) within proactive trial areas and (B) within neighbouring areas. The solid line in B shows a significant linear trend across culls. Error bars denote 95% confidence intervals and grey shading shows the confidence interval around the estimate for all time periods combined.



Overall effects of proactive culling

5.39 The above results indicate that proactive badger culling reduced the incidence of cattle TB inside trial areas, but elevated incidence on unculled land up to 2km outside. We estimated that, in areas with a herd density of 1.25 per km² and a background incidence rate of 8 breakdowns per 100 herds per annum, proactive culling would have prevented approximately 116 confirmed breakdowns inside ten circular 100km² culling areas over a five-year period. We also estimated that proactive culling would have induced approximately 102 additional confirmed breakdowns within ten 83.5km² 'neighbouring' areas falling up to 2km outside each culling area. This gives an estimated overall benefit of 14 fewer confirmed breakdowns over five years across the ten 183.5km² combined areas (i.e. the

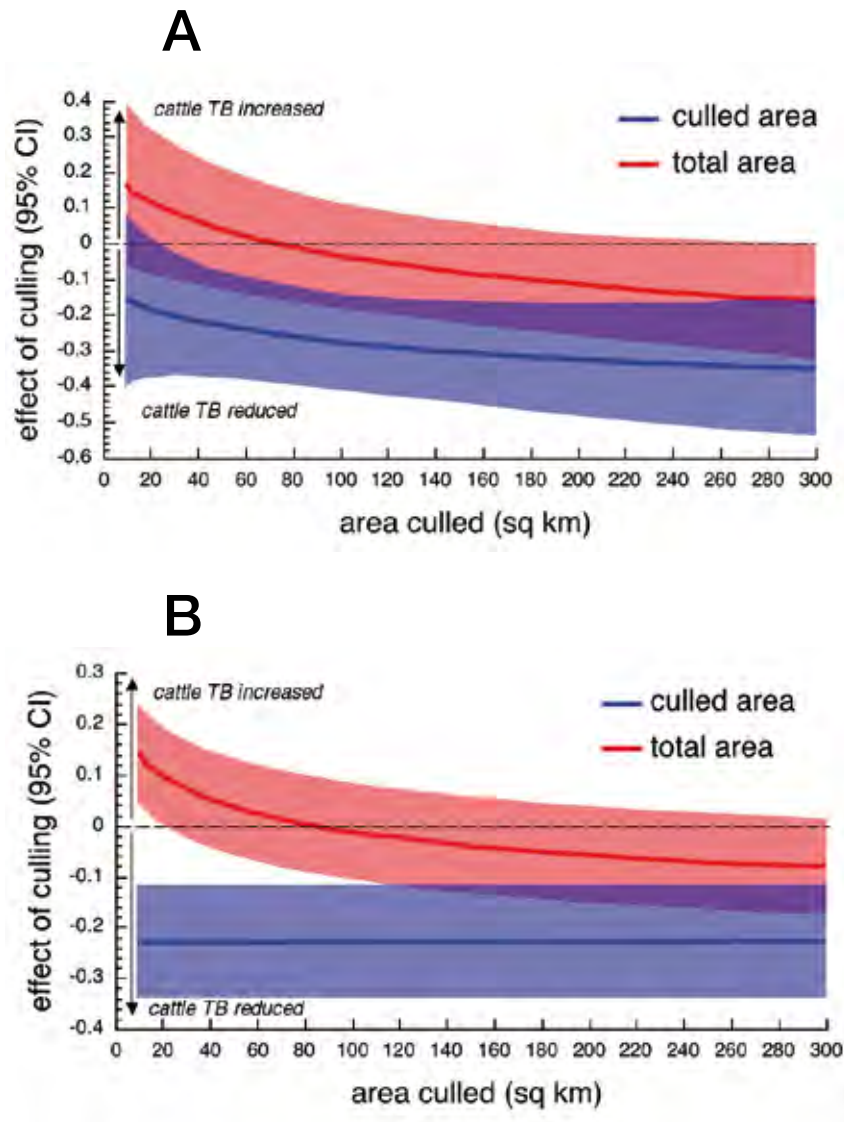
100km² culled areas and the 83.5km² neighbouring areas). Of course, if the underlying incidence rate were lower in the neighbouring area than in the culling area, then this net benefit would be greater. However, unless this underlying rate were considerably lower than that in the culling area, the 95% prediction interval for the net benefit will include zero.

5.40 Assuming the same incidence of confirmed breakdowns in culling areas as in neighbouring areas (up to 2km outside the culling area boundary) and assuming that the culling area was circular, the results obtained can be used to extrapolate to the predicted effects of culling for both smaller and larger culling areas than the 100km² trial areas studied in the RBCT. The extrapolations will depend on whether the estimated beneficial effect of proactive culling within a culling area is assumed to depend on the distance from the boundary (paragraph 5.15) or to be constant throughout the culling area. The estimated detrimental effect of culling in neighbouring areas is assumed to be constant throughout the neighbouring area.

5.41 To avoid extrapolation beyond the data available for analysis, when the beneficial effects of culling are assumed to be linearly dependent on the distance from the boundary, the effect on land more than 4km inside the trial boundary was equal to that estimated for such land in the roughly 100km² RBCT trial areas. This is despite the fact that for much larger culling areas some land will be much further than 4km from the nearest boundary. On this basis, the effect of proactive culling repeated annually for five years is estimated to be beneficial across the entire affected area (the culling area and the neighbouring area) for culling areas of 70km² or more (Figure 5.4 A). However, the 95% confidence interval for the effect across the entire affected area only excludes detrimental effects for culling areas of 265 km² or more. Furthermore, it should be noted that because estimates for different distances inside the trial area boundary are positively correlated, the confidence intervals are somewhat too narrow.

5.42 Thus, it is more conservative to assume a constant beneficial effect of proactive culling inside the culling area. On this basis, the effects of proactive culling repeated annually for five years is estimated beneficial across the entire affected area (the culling area and the neighbouring area) for culling areas of 80km² or more (Figure 5.4 B). However, the 95% confidence interval for the effect across the entire affected area only excludes detrimental effects for culling areas of 455 km² or more.

Figure 5.4: Proportional change in cattle TB incidence predicted to result from culling in circular areas of different sizes, using estimates of culling effects in culling areas and neighbouring areas. Effects are predicted both for the culled area only (in blue), and for the overall affected area (culled area plus neighbouring area up to 2km outside; in red). Shading indicates the wide 95% confidence limits around the curves. A) Assuming the estimated beneficial effect of proactive culling within a culling area depends on the distance from the boundary and B) assuming the estimated beneficial effect is constant throughout the culling area.



5.43 Under either assumption regarding the beneficial effect of proactive culling, the most important assumption underpinning these extrapolations is whether the underlying incidence of confirmed breakdowns in the neighbouring area is as high as that in the culling area. If the neighbouring area baseline incidence rate is lower, then the overall effects of culling will be more beneficial. However, it would still be the case that the reduced risks experienced by one set of herds (within culling areas) would be offset to some extent by the increased risks experienced by another (in neighbouring areas).

5.44 Based on the estimates from the models of how beneficial and detrimental effects of culling changed across successive culls, the estimated overall effect per annum appeared detrimental between the first and second culls, but beneficial after the fourth and later culls, for the range of analyses performed.

5.45 These beneficial and detrimental effects of proactive culling are readily explicable in the context of the ecological data presented in Chapter 4. Inside proactively culled areas, badger densities were substantially reduced. This would have the effect of reducing contact between cattle and badgers, leading to reduced transmission and a consequently reduced incidence of confirmed breakdowns in cattle. The reduction in cattle TB incidence inside proactive areas (approximately 33% after the fourth cull; see Figure 5.1) was more modest than the reduction in badger activity (in the region of 70% at a similar time period; see paragraphs 4.8 to 4.11). There are several possible explanations for this difference. First, badger culling would not directly influence the incidence of breakdowns caused by cattle-to-cattle transmission (Gilbert *et al.*, 2005). Indeed, such cattle-to-cattle transmission is a likely explanation for the persistent clustering of infection between cattle herds inside proactive areas (see paragraph 5.24). In addition, as the prevalence of infection in badgers rose on successive culls, the density of infected badgers was reduced to a lesser extent than was the overall density of badgers (see Table 4.9). Finally, the expanded ranging behaviour exhibited by badgers inside proactive areas would mean that each infected badger had the opportunity to come into contact with a larger number of cattle herds than would be the case in survey-only areas. It is possible that all three proposed effects contributed to the discrepancy between suppression of the badger population and reduction of TB incidence in cattle.

5.46 As described in Chapter 4, proactive culling slightly reduced the density of badgers in neighbouring uncultured areas, and expanded their ranging behaviour (Woodroffe *et al.*, 2006a). The prevalence of infection among badgers on these neighbouring lands is unknown since no badgers were sampled in these areas. However, the rise in *M. bovis* prevalence observed inside proactive areas was particularly marked for badgers captured close to culling area boundaries, and in trial areas with boundaries permeable to immigrating badgers; hence it is quite likely that prevalence also rose in neighbouring areas. The conditions occurring in these neighbouring areas – comparatively high badger densities, expanded badger ranging behaviour (hence opportunities for badgers to have contact with more cattle herds) and possibly increased prevalence – would all be expected to increase the risk of *M. bovis* transmission from badgers to cattle and hence to elevate cattle TB incidence. The loss of clustering of infection between cattle herds in neighbouring areas following proactive culling (paragraphs 5.37 to 5.38) is also consistent with this scenario. Culling is known to have dispersed clusters of infection within badger populations inside proactive areas, and to have reduced the spatial association between infections in badgers and cattle. Increased transmission by widely-ranging badgers would be expected to break up similar clusters in cattle, causing the pattern observed. The lack of a similar pattern inside proactive areas probably reflects reduced badger-to-cattle transmission of infection caused by suppression of badger population densities.

The effects of reactive culling within RBCT trial areas

5.47 It is helpful to examine the implications of the effects of proactive culling for the reactive culling strategy and then to compare those implications with the actual outcome. Ecological data show that, like badgers inhabiting uncultured lands neighbouring proactive culling areas, those inhabiting reactive areas had somewhat lower population densities and expanded ranging behaviour in comparison with badgers inhabiting survey-only areas (paragraphs 4.13 to 4.14, Woodroffe *et al.*, 2006a). Moreover, repeated reactive culling appeared to be associated with elevated *M. bovis* prevalence as in proactive areas (paragraphs 4.26 to 4.32, Woodroffe *et al.*, in review). All of this evidence suggests that farms located in the vicinity of reactive culling operations might be expected to experience elevated risks of TB infection, as was observed on farms just outside proactive culling areas.

5.48 Figure 5.4 clearly demonstrates that we predict detrimental effects from the culling of small areas. The average reactive culling operation targeted an area of 8.8km² (an estimate based on land areas targeted for culling as recorded in digitised maps; the average area over which badgers were actually removed was estimated to be 5.3km²). Thus, the results obtained for proactive culling (Figure 5.4) suggest that reactive culling should result in detrimental overall effects.

5.49 Figure 5.4 was based on the effect estimated over the course of repeated proactive culling; calculations based on the effects between the first and second proactive culls (7.2% beneficial effect inside proactive trial areas and 46.8% detrimental effect in neighbouring areas, instead of the overall estimates: 23.2% and 24.5% respectively; see Tables 5.2 and 5.8) suggest even greater detrimental effects of localised reactive culling operations at least in the short term.

Suspension of reactive culling in November 2003

5.50 Log-linear regression analyses, based on data on the incidence of herd breakdowns up to August 2003, revealed that reactive badger culling was associated with an estimated increase of 27% in the incidence of confirmed cattle herd breakdowns (95% CI: 2.4% decrease to 65% increase, Donnelly *et al.*, 2003). (This analysis was based on herds identified as being inside trial area boundaries based on individual cattle herd locations recorded in the RBCT database.) Under its agreed operating procedures the ISG was obliged to bring this information to the attention of Ministers, it being the first time that any clear indications with potential implications for policy had emerged from the trial. However, in its report (see Bourne *et al.*, 2005, Appendix I), the ISG recommended that culling operations should be continued until the start of the next closed season (1 February 2004) to allow a further analysis of data before the end of the closed season on 30 April 2004. Our stated judgement was, however, that the position was unlikely to change significantly in the interim. After receiving our report, the Minister decided, in consultation with Defra officials, to suspend reactive culling as from 4 November 2003.

Updated analyses of TB incidence

5.51 The results presented in paragraphs 5.52 to 5.58 update and extend those published previously (Donnelly *et al.*, 2003; Le Fevre *et al.*, 2005). It is now possible to investigate changes in cattle TB incidence in reactive areas following the suspension of reactive culling.

5.52 Our updated analyses of the effects of reactive culling covered four time periods:

- (i) from the completion of the initial proactive cull in each triplet until reactive culling was suspended (4 November 2003) (28.3 triplet-years);
- (ii) from the completion of the initial proactive cull until the first reactive culling operation in each triplet (11.9 triplet-years);
- (iii) from the first reactive culling operation in each triplet until 4 November 2003 (16.4 triplet-years); and
- (iv) after 4 November 2003 until the compilation of the database on 21 January 2007 (32.1 triplet-years).

5.53 The combined time period from the completion of the initial proactive cull within a triplet until the compilation of the database on 21 January 2007 includes 60.4 triplet-years. (See Table 5.12 for details.) The analyses are restricted to data entered into the dataset as of 21 January 2007. Because there is a lag between the disclosure of a breakdown, its confirmation and entry of this information into the VetNet surveillance database, very recent breakdowns are less likely to have been included in this analysis.

Table 5.12: Triplet-years by time period and triplet. (Reactive culling was suspended on 4 November 2003.)

Triplet	Initial proactive cull until the first reactive cull	First reactive culling operation until the suspension of reactive culling	After suspension of reactive culling until 21 January 2007	Initial proactive cull until 21 January 2007
A	0.46	3.31	3.21	6.98
B	0.47	4.42	3.21	8.11
C	0.58	3.44	3.21	7.23
D	0.71	0.17	3.21	4.09
E	2.09	1.36	3.21	6.66
F	2.06	1.24	3.21	6.51
G	1.79	1.19	3.21	6.20
H	2.11	0.78	3.21	6.10
I	0.62	0.45	3.21	4.29
J	1.05*	0.00	3.21	4.26

*time from initial proactive cull until the suspension of reactive culling; no reactive culling was performed in Triplet J

5.54 The results presented here are based on the simultaneous analysis of incidence data from reactive, survey-only and proactive areas. This approach makes the best use of the available data yielding the most precise estimates possible. Qualitatively similar estimates were obtained from analyses excluding data from proactive trial areas.

5.55 The data on the incidence of herd breakdowns from the initial proactive cull in each triplet until reactive culling was suspended, showed that reactive badger culling induced an estimated increase of 22% in the incidence of confirmed cattle herd breakdowns (95% CI: 2.5% to 45% increase; $p=0.025$) (Table 5.13).

5.56 As expected, the estimate of the effect of the reactive treatment since the end of the first *reactive* cull until reactive culling was suspended, 18.9%, was similar to the primary comparison (95% CI: 5.4% decrease to 49.5% increase; $p=0.14$). The 95% confidence limits for the reactive treatment effect for the period from the completion of the initial proactive cull until the end of the first reactive cull were wide, namely, from a 10.7% decrease to a 71.5% increase in herd breakdowns. The overall estimate was that the incidence of confirmed breakdowns was 23.7% higher in reactive areas than in survey-only areas, and although this estimate was non-zero, it was imprecisely estimated ($p=0.20$), and the confidence interval included the biologically plausible result of no difference between reactive and survey-only areas during this time period.

5.57 The estimate of the effect of the reactive treatment following the suspension of the cull in November 2003 was nearly zero (2.2% increase with 95% CI: 19.5 decrease to 29.8% increase; $p=0.86$), giving no evidence of either a long-term detrimental effect or a delayed beneficial effect associated with reactive culling.

5.58 Table 5.13 demonstrates that similar results were obtained for all these time periods using location data as recorded in the RBCT database.

Table 5.13: Estimated effects of reactive culling on the incidence of confirmed cattle TB breakdowns. Analyses adjust for triplet, baseline herds, and historic TB incidence (over three years).

	Reactive effect			Overdispersion*	
	estimate	95%CI	p-value	factor	p-value
<i>Using VetNet location data</i>					
From initial proactive cull until 4 Nov 03	22.0%	(2.5%, 45.3%)	0.025	0.89	0.70
From initial proactive cull until the first reactive cull	23.7%	(-10.7%, 71.5%)	0.20	1.21	0.11
From the first reactive cull until 4 Nov 03	18.9%	(-5.4%, 49.5%)	0.14	0.86	0.76
After 4 Nov 03	2.2%	(-19.5%, 29.8%)	0.86	1.54	0.001
<i>Using RBCT location data</i>					
From initial proactive cull until 4 Nov 03	25.4%	(1.8%, 54.5%)	0.033	1.16	0.16
From initial proactive cull until the first reactive cull	28.0%	(-12.3%, 86.7%)	0.20	1.43	0.008
From the first reactive cull until 4 Nov 03	19.7%	(-6.5%, 53.3%)	0.15	0.87	0.74
After 4 Nov 03	6.3%	(-15.9%, 34.4%)	0.61	1.52	0.002

*See footnote to Table 5.2.

Case-control analysis within reactive trial areas

5.59 To explore further the pattern of increased TB incidence in reactive trial areas compared with survey-only trial areas, we used a case-control study *within reactive trial areas* comparing herds with confirmed TB breakdowns (cases) with herds that were tested but revealed no evidence of infection (controls).

5.60 Each case was individually matched to a control selected randomly from those cattle herds within the same trial area that had a clear herd test within a year of the breakdown disclosure date and that had no associated land within 5km of the land associated with the case herd.

5.61 Data were analysed for three time periods:

- from the completion of the initial proactive cull until the first reactive culling operation in each triplet (11.9 triplet-years);
- from the first reactive culling operation in each triplet until 4 November 2003 (16.4 triplet-years); and

- c) after 4 November 2003 until the compilation of the database on 21 January 2007 (32.1 triplet-years).

with both the breakdown disclosure date of the case and the clear herd test of the control required to be within the time period under analysis.

5.62 The variables of key interest are the numbers of badgers culled in the vicinity (within 1, 3, or 5km) of cases and controls, and a set of indicator variables for whether or not any reactive culling had taken place in the vicinity of cases and controls. Because recent nearby reactive badger culling operations were prompted by nearby confirmed herd breakdowns, we also recorded the number of nearby confirmed breakdowns in the vicinity (again within 1, 3 or 5km) of each case and control. Each of these variables was calculated for one year prior to the date the breakdown was detected in the case herd and the herd test date of the control, and separately for the previous two years. Finally, we also recorded the number of nearby tested cattle herds not under TB-related movement restrictions (again within 1, 3 or 5km) as a measure of the herd population at risk of breakdowns.

5.63 As expected, cases were associated both with more badgers being culled nearby and with more confirmed breakdowns taking place nearby in the previous year (Table 5.14). Similar results were obtained for the previous two years. Interestingly, cases were also associated with slightly more nearby herds (Table 5.14).

Table 5.14: The average number of nearby culled badgers (in the previous year), nearby confirmed breakdowns (in the previous year) and nearby herds for cases and controls by time period: (a) from the completion of the initial proactive cull until the first reactive culling operation in each triplet; (b) from the first reactive culling operation in each triplet until the suspension of reactive culling (4 November 2003); and (c) after the suspension until the compilation of the database on 21 January 2007.

	Distance threshold	From the completion of the initial proactive cull until the first reactive culling operation in each triplet		From the first reactive culling operation in each triplet until the suspension of reactive culling		After the suspension until the compilation of the database	
		Case	Control	Case	Control	Case	Control
Nearby RBCT culled badgers*	1km	0.0	0.0	6.9	3.5	2.7	1.1
	3km	0.3	<0.1	23.6	15.3	9.8	4.8
	5km	1.0	0.3	41.2	30.8	17.2	8.8
Nearby confirmed breakdowns	1km	3.4	2.5	4.4	3.3	4.5	3.2
	3km	9.8	7.8	12.0	10.1	13.2	10.4
	5km	18.5	15.7	22.5	20.4	24.4	20.9
Nearby tested cattle herds	1km	7.9	7.8	8.3	6.6	7.0	5.6
	3km	28.2	26.6	28.5	24.7	24.9	20.7
	5km	57.4	53.9	58.1	52.4	50.5	43.6

*The very small numbers of nearby culled badgers during the period from the completion of the initial proactive cull until the first reactive culling operation in each triplet arise in situations where proactively culled badgers were within 3 or 5km of a case or control farm within a reactive area. Proactively culled badgers may similarly contribute to numbers within 3 or 5km of a case or control farm in the later time periods.

5.64 We tested the statistical significance of the effects of nearby culled badgers, and separately nearby confirmed breakdowns adjusting the latter for the number of nearby tested cattle herds not under TB-related movement restrictions, using conditional logistic regression. Each of these variables was log-transformed after the addition of 0.5 to minimise bias in the covariates (Cox, 1955). It was recognised that differences in risk could arise due to cases and controls being different herd types (i.e. beef, dairy or mixed) or having different herd sizes – because the risk of a herd having a breakdown increases with the size of the herd (Munroe *et al.* 1999, Johnston *et al.* 2005, Green and Cornell, 2005). These attributes were therefore included in all logistic regression models. Furthermore, all models reported here examining the effects of the number of nearby breakdowns adjust for the number of nearby herds with ‘nearby’ being defined identically in each analysis (within 1, 3 or 5km). An estimated odds ratio of more than one indicates that the factor is associated with an increased risk of experiencing a breakdown, and the numerically greater the odds ratio, the greater the risk.

5.65 There were strong associations between cases and greater numbers of nearby culled badgers during and after reactive culling, and as expected there were strong associations between cases and increased numbers of nearby confirmed breakdowns in all three time periods (Table 5.15).

Table 5.15: Odds ratios, and in brackets the 95% confidence intervals, for the associations of case farms with increased numbers of nearby culled badgers and increased numbers of confirmed breakdowns. Note that both variables (the number of nearby culled badgers and the number of nearby confirmed breakdowns, each in the previous year) were log-transformed for this analysis. Thus, each reported odds ratio corresponds to an increase in the covariate of one unit on the natural log scale.

	Distance threshold	From the completion of the initial proactive cull until the first reactive culling operation in each triplet	From the first reactive culling operation in each triplet until the suspension of reactive culling	After the suspension until the compilation of the database
Nearby culled badgers	1km	–	1.32 (1.10, 1.60)	1.33 (1.11, 1.61)
	3km	0.92 (0.35, 4.01)	1.27 (1.07, 1.53)	1.20 (1.06, 1.38)
	5km	1.16 (0.64, 2.41)	1.26 (1.04, 1.54)	1.21 (1.07, 1.38)
Nearby confirmed breakdowns	1km	1.67 (1.13, 2.58)	1.74 (1.18, 2.63)	2.11 (1.56, 2.92)
	3km	2.65 (1.53, 4.96)	2.84 (1.47, 6.04)	3.01 (1.98, 4.74)
	5km	2.61 (1.26, 5.94)	2.08 (1.00, 4.55)	2.88 (1.66, 5.19)

5.66 To investigate the association between TB breakdowns and increased numbers of badgers culled nearby, we examined models including both nearby culled badgers and nearby confirmed breakdowns. The associations with the number of nearby culled badgers remain for all three distance thresholds for the time periods during and after reactive culling (Table 5.16). It is reassuring that the elevated risks associated with nearby culled badgers and with nearby confirmed breakdowns are consistent over the different time periods analysed. Of course, the numbers of badgers culled nearby in the previous year were much lower following the suspension of reactive culling (Table 5.14), so the detrimental impact of reactive culling (relative to survey-only controls) would be predicted, on this basis, to be much less than in the period during reactive culling.

5.67 Similar results were obtained in the analyses based on nearby culled badgers and nearby confirmed breakdowns in the previous two years, rather than the previous year (as reported here). Furthermore, similar results were obtained when different distance thresholds were used for the two key variables (for example 1km for nearby culled badgers and 3km for nearby confirmed breakdowns) when all combinations for 1, 3 and 5km were examined.

Table 5.16: Odds ratios, and in brackets the 95% confidence intervals, for the associations of case farms with increased numbers of nearby culled badgers (BAD) and increased numbers of confirmed breakdowns (BRK). These estimates were obtained from models which estimated both effects simultaneously. Note that both variables (the number of nearby culled badgers and the number of nearby confirmed breakdowns, each in the previous year) were log-transformed for this analysis. Thus, each reported odds ratio corresponds to an increase in the covariate of one unit on the natural log scale.

Distance threshold	From the completion of the initial proactive cull until the first reactive culling operation in each triplet	From the first reactive culling operation in each triplet until the suspension of reactive culling	After the suspension until the compilation of the database
1km	–	BAD 1.22 (1.00, 1.51) BRK 1.56 (1.04, 2.40)	BAD 1.23 (1.02, 1.51) BRK 2.02 (1.49, 2.79)
3km	BAD 0.86 (0.33, 3.75) BRK 2.66 (1.53, 4.98)	BAD 1.18 (0.97, 1.45) BRK 2.43 (1.22, 5.31)	BAD 1.10 (0.95, 1.27) BRK 2.81 (1.82, 4.46)
5km	BAD 0.97 (0.53, 2.07) BRK 2.63 (1.26, 6.07)	BAD 1.21 (0.97, 1.52) BRK 1.61 (0.72, 3.73)	BAD 1.16 (1.01, 1.33) BRK 2.57 (1.46, 4.69)

5.68 The finding that badgers having been culled nearby in the previous year is a risk factor for confirmed breakdowns within reactive trial areas, even after adjustment for nearby confirmed breakdowns, provides additional evidence that reactive culling was associated with increased risks of confirmed breakdowns.

Effects on the spatial distribution of infections in cattle

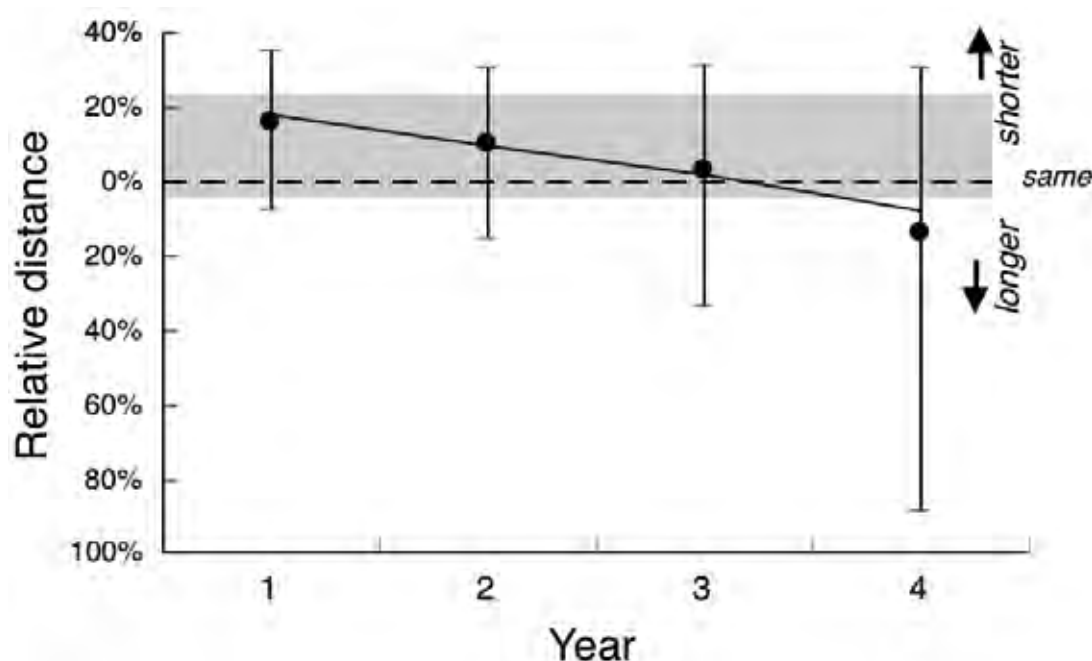
5.69 Because badgers' increased ranging behaviour in response to culling (Woodroffe *et al.*, 2006a) allowed them to come into contact with other badgers, and with cattle herds, at greater distances from their own origins, we predicted that reactive culling would reduce the degree of clustering of infection within badger populations, as it did in proactive areas (Jenkins *et al.* in review). However, we were unable to test this because reactive culling, by definition, did not sample badgers across the whole trial area (and because no reliable live testing of badger for *M. bovis* infection was possible). As the data on spatial locations of infected and uninfected badgers were limited to the badgers taken in reactive culling operations, the sample was too incomplete and biased (in terms of their proximity to infected cattle) to allow clustering of infections within badger populations to be quantified.

5.70 Nonetheless, any such changes in the spatial distribution of infection in badgers might be expected to cause corresponding reductions in the clustering of infection between cattle herds in reactive trial areas, especially as our results suggest that substantial badger-to-cattle transmission was occurring in these areas.

5.71 The data show that this was indeed the case; while there was evidence of significant clustering of infection between cattle herds in reactive trial areas before culling occurred,

this was considerably reduced after reactive culling (Figure 5.5). This pattern is very similar to the findings just outside proactive trial areas and contrasts with the situation inside proactive trial areas, where there was no such change in the spatial distribution of cattle TB (paragraphs 5.24 and 5.37 to 5.38, Figure 5.3).

Figure 5.5: Clustering of *M. bovis* infections in cattle. The graph shows the percent difference between TB-affected and unaffected herds in the distance to the nearest affected herd, with shorter relative distances indicating stronger clustering within reactive trial areas. The solid line shows a significant linear trend across culls. Error bars denote 95% confidence intervals and grey shading shows the confidence interval around the estimate for all time periods combined. Year 1 was the 12-month period prior to the first reactive culling operation in each triplet, year 2 was the following 12-month period and so on.



Consistency of results

5.72 The clear conclusion supported by all the analyses undertaken by the ISG is that there is convincing evidence that reactive culling of badgers, in the form and time span implemented in the RBCT, does not offer a beneficial effect large enough to make it useful as a practical policy option and that indeed there is substantial evidence of an adverse effect of that reactive culling strategy.

5.73 These epidemiological findings are entirely consistent with ecological findings. As badgers in reactive areas showed expanded ranging behaviour in comparison with badgers inhabiting survey-only areas (paragraphs 4.13 to 4.14, Woodroffe *et al.*, 2006a), the number of contacts of each infected badger with cattle and other badgers could be increased even though badger density was somewhat reduced. Additionally, as repeated reactive culling was associated with elevated *M. bovis* prevalence in badgers (paragraph 4.31, Woodroffe *et al.*, in review), the reduction in overall population density might not have entailed a reduction in the density of infected badgers; indeed, the latter density could conceivably have been increased by culling.

Comparison with other studies

5.74 The RBCT generated three key findings concerning the impact of badger culling on the incidence of cattle TB:

- (i) widespread (proactive) culling induced a reduction in cattle TB incidence inside culled areas;
- (ii) widespread (proactive) culling induced an increase in cattle TB incidence in neighbouring un-culled areas; and,
- (iii) localised (reactive) culling induced a general increase in cattle TB incidence when measured across whole trial areas.

5.75 In this section, we discuss whether corresponding findings have emerged from other, similar, studies conducted within the British Isles, and consider possible explanations for differences and similarities in the results from different studies.

The Thornbury study

5.76 The Thornbury study was conducted in South West England during 1975 – 1981 and involved killing badgers over an area of 104km² by repeated gassing of setts using hydrocyanic acid (Clifton-Hadley *et al.*, 1995b). The gassing area was separated from neighbouring lands by rivers and motorways. Gassing was repeated over a period of six years until badger activity reached very low levels; recolonisation was then allowed to occur. The study was not set up as an experiment: it included only one culling area and no matched control. The effects of culling were therefore assessed at a later date by comparing cattle TB incidence in the gassed area before, during, and after the gassing period, and also by comparing the trend of incidence in the gassing area with that in a nearby comparison area (Clifton-Hadley *et al.*, 1995b).

5.77 Results from Thornbury suggest that culling was very likely to be the reason for the reduced cattle TB incidence inside the gassing area. During the culling period, the average incidence of cattle TB was higher in the removal area than in a nearby comparison area (Clifton-Hadley *et al.*, 1995b); however this difference almost certainly reflected background variation in historical incidence in the two areas. Subsequently, incidence declined in the removal area but not in the comparison area (Clifton-Hadley *et al.*, 1995b). However, the magnitude of the reduction cannot be compared with that observed inside RBCT proactive areas since the two studies had such different contexts.

5.78 In the Thornbury study no attempt was made to evaluate the effect of widespread gassing on the incidence of cattle TB on neighbouring lands. However, as the gassing area was deliberately located within geographical barriers to badger movement (Clifton-Hadley *et al.*, 1995b), any such effect would be expected to be weak. The Thornbury study had no ability to investigate the effects of localised culling on the incidence of cattle TB.

5.79 These data indicate that the findings of the Thornbury study, while qualitatively consistent with RBCT results, cannot be compared quantitatively with RBCT findings. The Thornbury study does, however, provide useful information on the considerable effort needed to suppress badger densities substantially by gassing.

The East Offaly study

5.80 The East Offaly study was conducted during 1989-94 in County Offaly, Republic of Ireland (Eves, 1999). It involved culling badgers, by snaring, across a single 'removal area' of 528km², plus a 1.6km-wide 'buffer area' surrounding the removal area. The incidence of cattle TB inside the removal area (measured as the number of infected animals, rather than herds, detected each year; Table 5.17) was compared with that in a ring-shaped 'control area', 8km wide, surrounding the removal and buffer areas. Data on cattle TB in the buffer area were excluded from analyses. A limited amount of localised culling was conducted in response to breakdowns among cattle in the control area.

Table 5.17: Numbers of individual cattle showing evidence of TB exposure, and numbers of cattle tested, in the East Offaly study carried out in the Republic of Ireland. Data are presented only from years during which badger culling occurred. Data are from Eves (1999).

Year	Control (limited culling) area		Removal (widespread culling) area	
	cattle tested	cattle infected	cattle tested	cattle infected
1989	294,088	982	103,032	362
1990	286,425	904	103,332	299
1991	218,813	979	72,202	194
1992	234,888	594	65,803	89
1993	212,382	404	67,086	54
1994	210,339	443	68,527	54
All years	1,456,935	4,306	479,982	1,052
Incidence:		0.296%		0.219%
Reduction:				26%
First year excluded	1,162,847	3,324	376,950	690
Incidence:		0.286%		0.183%
Reduction:				36%

5.81 Table 5.17 presents results of the East Offaly study, derived from Eves (1999). The reduction in cattle TB incidence observed inside the removal area (26% overall, 36% excluding the first year) is comparable with that recorded inside RBCT proactive areas. Note that confidence intervals comparable to those reported for the RBCT results cannot be obtained since having only one pair of areas to compare means that overdispersion cannot be assessed. However, three factors may have acted to inflate these estimates of the beneficial effects of culling inside the removal areas. First, as RBCT results suggest that the benefits of culling are smaller close to the boundaries of culling areas than deeper inside, exclusion of results from the East Offaly 'buffer area' is likely to have led to an over-estimate of the reduction in cattle TB incidence achieved across the entire area culled (removal plus buffer area). Second, if the localised culling conducted in the 'control area' increased cattle TB incidence (as in RBCT reactive areas), comparing removal and control areas would suggest a greater beneficial effect of culling than would have been achieved had the removal area been compared with a true control in which no culling was conducted. Likewise if (as in the RBCT) widespread culling increased cattle TB incidence on farms

just outside the culled area, this would likewise inflate incidence in the ‘control area’ and make culling appear more beneficial inside the removal area.

5.82 No attempt was made to investigate whether culling caused such detrimental effects on cattle TB in the neighbouring control area; however it is possible that such effects occurred as the East Offaly culling area was not geographically isolated from neighbouring lands (Eves, 1999).

5.83 The East Offaly study had no capacity to investigate the effects of localised badger culling on cattle TB incidence.

The Four Areas Trial

5.84 The Four Areas Trial was conducted in four counties in the Republic of Ireland during 1997-2002 (Griffin *et al.*, 2005). It involved widespread culling of badgers, by repeated snaring, in four ‘removal areas’ varying in size from 188-305km². The incidence of cattle TB in these areas was compared with that in four nearby ‘reference areas’ of 199-275km². Removal areas were deliberately located where natural geographical boundaries (coastline and major rivers) would impede badger recolonisation; hence allocation of culling treatments to areas was not random (Griffin *et al.*, 2005). Where no geographical barriers occurred, removal areas were surrounded by ‘buffer areas’ up to 6km wide. Culling was conducted in buffer areas but data on cattle TB incidence from these areas were excluded from analyses (Griffin *et al.*, 2005). Localised culling was conducted in reference areas in response to breakdowns in cattle.

5.85 Primary results from the Four Areas Trial are reproduced in Table 5.18. The estimates, presented here, of the reductions in cattle TB incidence associated with widespread culling are based on direct comparisons of per-herd incidence in reference and removal areas, without adjustment for any covariates.

5.86 Although these measured benefits of culling are larger than those recorded in the RBCT, the two sets of results are not directly comparable. First, as in the East Offaly study described above, culling was conducted in ‘buffer areas’ but data on cattle TB incidence in these areas were excluded. As these buffer areas were up to 6km wide (Griffin *et al.*, 2005), the herds considered to be inside the ‘removal areas’ were in some cases very distant from the culling area boundary. In contrast, in the RBCT even a herd just inside the boundary of a proactive trial area was never more than 1km from the boundary of the area culled – and culling was found to be less beneficial for herds close to this boundary (Donnelly *et al.*, 2007). It is therefore possible that, like the East Offaly study, the Four Areas Trial over-estimated the beneficial effects of culling over the areas actually subjected to culling (removal plus buffer areas).

Table 5.18 Numbers of cattle herds experiencing confirmed TB breakdowns, and numbers of herds at risk, in the ‘Four Areas Trial’ carried out in the Republic of Ireland. Data are taken from Griffin *et al.* (2005) and are presented only from years during which badger culling occurred.

Year	Cork		Donegal		Kilkenny		Monaghan	
	reference	removal	reference	removal	reference	removal	reference	removal
1997-8	30/272	29/288	4/361	3/375	20/230	14/230	57/554	19/687
1998-9	45/271	22/285	5/349	6/375	28/222	4/230	62/565	32/701
1999-2000	33/271	11/282	5/343	3/375	25/214	6/229	42/565	24/681
2000-01	12/274	2/270	4/334	1/370	12/213	6/225	38/559	24/661
2001-02	13/269	3/259	18/320	1/365	16/206	4/214	29/545	13/644
All years	133/1357	67/1384	36/1707	14/1860	101/1085	34/1128	228/2788	112/3374
Incidence:	9.80%	4.84%	2.11%	0.75%	9.31%	3.01%	8.18%	3.32%
Reduction:		51%		64%		68%		59%
First year excluded	103/1085	38/1096	32/1346	11/1485	81/855	20/898	171/2234	93/2687
Incidence:	9.49%	3.47%	2.38%	0.74%	9.47%	2.23%	7.65%	3.46%
Reduction:		63%		69%		76%		55%

5.87 A second reason for caution in comparing the quantitative results of the Four Areas Trial with those from the RBCT is that, once again like the East Offaly study, localised culling was conducted in the ‘reference areas’. While Griffin *et al.* (2005) claim that this did not lead to increases in the local incidence of cattle TB as observed in RBCT reactive areas, this claim is difficult to check in the absence of true controls with no culling. If cattle TB incidence in reference areas was in fact elevated by localised culling, this would inflate the difference in incidence between removal and reference areas and make widespread culling appear more beneficial than it, in fact, was.

5.88 Despite these methodological concerns, it is quite possible that the widespread culling conducted in the Four Areas Trial did reduce the incidence of cattle TB to a greater extent than did the RBCT proactive treatment. As discussed in Chapter 4, there are two good ecological reasons for expecting this to be the case. First, as mentioned above, the ‘Four Areas’ were deliberately located where geographical boundaries would impede badger recolonisation of culled areas. This would allow a more efficient and sustained removal of badgers than was possible in RBCT areas, most of which lacked such barriers on their boundaries. Moreover, as the geographical barriers which did occur around some RBCT proactive areas appeared to prevent a culling-induced increase in the prevalence of *M. bovis* infection in badgers (paragraphs 4.27 to 4.28, Woodroffe *et al.*, 2006b), the lack of such an increase among badgers culled in the Four Areas Trial (paragraphs 4.37 to 4.38, Griffin *et al.*, 2003) is consistent with RBCT findings. Since most cattle herds inside RBCT areas would have been in contact with badgers experiencing an increasing prevalence of *M. bovis* infection, whereas those inside the Four Areas would have contacted badgers with a declining infection prevalence, it is perhaps unsurprising that the incidence of cattle TB appears to have fallen more markedly in the Four Areas Trial. However, as few TB-affected areas of Britain are bounded by geographical impediments to badger movement, and as creating such barriers is very difficult and expensive (see Chapter 10 for details), the

results of the RBCT are probably more representative of the effects of culling that could be expected if widespread culling were implemented as policy in Britain.

5.89 No report has been published investigating the effects of badger culling on farms just outside the Four Areas. To further inform both scientific and policy developments, we would welcome the publication of the relevant data with analyses and interpretation thereof, while predicting that detrimental effects of badger culling on nearby farms would be less evident, or even non-existent, where geographical barriers were effective at limiting badger movement across the boundaries of culled areas.

Conclusions from other studies

5.90 The RBCT is the only study of the effects of badger culling on the incidence of cattle TB which has been conducted fully according to established principles of experimental design, in that it included un-culled controls, a statistically appropriate number of replicates, and random allocation of treatments to areas. While other similar studies did not adhere to all of these scientific principles, their results appear consistent with RBCT findings, insofar as this can be judged. Beneficial effects of widespread culling have been detected inside culled areas for all four studies, and apparent differences in the magnitude of these effects are readily explicable by methodological differences between the studies and ecological differences between the study areas. Possible detrimental effects in neighbouring areas have not been investigated in studies other than the RBCT, and the capacity to detect such effects is compromised, to varying extents, by the design of the other three studies. Likewise no previous studies have been designed in ways that would allow evaluation of the landscape-level effects of localised culling, as was possible in the RBCT. However, as discussed in Chapter 4, culling-induced disruption of badger social organisation was recorded in the East Offaly area (O’Corry-Crowe *et al.*, 1996), indicating that perturbation effects similar to those recorded in and around RBCT areas could potentially occur in Ireland if studies were designed in ways that could detect effects on cattle TB.

5.91 In this context, we consider it both appropriate and constructive to consider these studies complementary, rather than to portray one as “right” and the others as “wrong”. Nevertheless, since the RBCT was conducted in the environmental conditions typical of TB-affected regions of Britain, according to protocols very similar to those used in past culling policies, we consider (for reasons described above) that the RBCT results provide the most robust evidence and the best approximation of the outcomes that could be expected if culling were to be implemented as a TB control policy in the British countryside.

Overall conclusions

5.92 Our results are highly consistent, both internally (e.g. similar patterns were detected across triplets, and between reactive and proactive culling), and in comparison with other studies. Hence, our findings provide a very reliable indication of the likely effects of badger culling on cattle TB, if conducted using similar methods in TB-affected regions of the British countryside.

5.93 Our results show that badger culling can prompt both beneficial and detrimental effects for the control of cattle TB. Both types of effect are readily explicable given the documented impacts of culling on badger ecology and behaviour, and on TB dynamics in badgers (see Chapter 4). The balance of beneficial and detrimental effects appears to vary with size of area culled, and with the number of times culls were repeated. Hence,

it is not surprising that reactive culling, which was conducted episodically in localised areas, appeared to have an overall detrimental effect. While proactive culling reduced the incidence of cattle TB in the areas actually culled, these benefits were to some extent offset by detrimental effects on neighbouring land. As a result, the overall benefits of proactive culling were moderate, and realised only after culling had been implemented repeatedly.

5.94 These detrimental effects of culling severely constrain the ability of badger culling – as conducted in the RBCT – to contribute to the control of cattle TB. Overall, reactive culling conferred no benefits. Proactive culling yielded only very moderate benefits, and those were achieved at the expense of elevated TB incidence on neighbouring lands. Given these effects, careful consideration is needed to determine whether the overall benefits of badger culling justify the costs; this is discussed further in Chapter 9. Chapter 10 discusses whether RBCT badger culling strategies could be modified to achieve more effective control of cattle TB.

6. ANALYSIS OF FARM LEVEL RISK FACTORS

Background

6.1 For cattle to become infected with *M. bovis* there have to be sources of infection and routes of transmission. It is generally believed that cattle contract infection directly from the inhalation of infected droplets from the lungs of other infected animals or through the oral ingestion of mycobacteria from farm environments. However, although the route of infection may be clear the circumstances that predispose herds to breakdowns have never been clearly understood. The ISG recognised this was an important element in understanding the epidemiology of TB in cattle, and also would be valuable to provide a basis for actions that cattle farmers themselves might take to reduce the risk of infection.

6.2 For many years MAFF had recorded information on each herd breakdown using the 'TB49' form. The purpose of this information was to document and manage the incident; it was never designed or intended to be used for epidemiological investigations. This limitation was recognised in the Krebs Report (Krebs *et al.*, 1997), in its first recommendation, that more, and transparent, data on herd breakdowns should be collected to assess the correlates of local variation in risk, taking account of the presence of badgers, severity of disease, husbandry, climate and landscape variables. Although several risk factors in relation to cattle husbandry and environmental practices had been suggested anecdotally as predisposing farms to TB breakdowns, these were not amenable to being investigated by experiments with controls, as we stated in our 4th Report (Bourne *et al.*, 2005). Consequently, because of the impracticality of conducting controlled experiments on commercial livestock farms, the need for data from a large number of representative TB breakdowns, and the low incidence of breakdowns, a particular approach to data collection and analysis – known as a case-control study – was adopted to investigate the problem. The ISG developed, with Defra, the design and implementation of several case-control studies to identify risk factors associated with TB herd breakdowns.

Development of the TB99 and CCS2005 Case-Control Studies

6.3 The initiation of the RBCT in 1998 provided an opportunity for a more in-depth collection of farm data on all herds in triplets experiencing breakdowns. In the light of this it was decided to replace the TB49 form with a new and more detailed questionnaire (called the TB99 questionnaire) which would collect information to enable a formal case-control study to be undertaken. Piloting commenced at the end of 1998 and the form was introduced for formal use in April 1999. It was designed to be used by State Veterinary Service (SVS; renamed Animal Health in April 2007) Veterinary Officers in interviews with farmers and herd managers following each TB breakdown and was intended to collect a wide range of detailed information on both the herd and the farm. The questions were designed to elicit quantifiable answers and covered an extensive number of topics including herd composition and health, type of farm enterprise, animal movements and husbandry factors. To assist with completion of the form it was accompanied by detailed definitions and instructions for completing each question.

6.4 At the request of the ISG, the TB99 questionnaire was to be completed for every breakdown that occurred within RBCT trial areas (i.e. every 'case'), with comparable data being collected on another questionnaire from three 'control' farms that had not experienced a breakdown in the 12 months prior to the date of the case breakdown. The three control farms for each case were to be selected so as to be similar to the case farm,

and such that one farm was to be contiguous with the case farm and the remaining two, randomly selected, farms non-contiguous. Data collection for the study proceeded during 1999 and 2000 using the case and control forms in RBCT areas to provide the basis for the epidemiological study. In addition, MAFF also used the TB99 case form for its own purposes on herd breakdowns outside the RBCT trial area.

6.5 It was recognised from the outset that the TB99 data collection was a substantial exercise that made major demands on the time of both farmers and SVS staff, and so needed to be kept under review. A TB99 Working Group was convened by MAFF and first met in July 1999 with a remit to review the design and progress of TB99; it was also to provide a report in 2000 describing patterns of cattle breed, type etc. associated with TB herd breakdowns in Great Britain during 1999, using this experience to redesign the questionnaire. During 2000 the Working Group gave consideration to revisions as data entry for each questionnaire typically required two SVS officers over 2 hours on each farm visit and further work on return to the SVS office. In January 2001 a revised version of TB99 was launched. The new questionnaire was similar in content to the first but was partitioned into parts to allow more clarity in its implementation. Part 1 collected the basic information required to manage the breakdown, Part 2 recorded the wide range of details on farm management including geographical and ecological characteristics required for the epidemiological risk factor analysis. (A Part 3 allowed the Veterinary Officer to record comments but these were not stored on the database.)

6.6 TB99 data collection was severely disrupted following the outbreak of foot-and-mouth Disease (FMD) in February 2001. Although RBCT areas remained largely free of FMD cases the restrictions on access to farms, and the diversion of SVS staff to other work, meant that data collection was curtailed and delayed well into 2002. By the end of 2002 it was recognised that control farm information had been lost irretrievably either because the necessary farm visits had not taken place or questionnaires had not been completed. In the light of the delays and continuing resource shortages, at the start of 2003 Defra decided no longer to pursue the collection of case forms nationally but to restrict TB99 operations to RBCT areas; this was to ensure the epidemiological information in Part 2 of the form required for the case-control analyses would be available for cases and controls within trial areas, and was in line with a recommendation the ISG had made in 2001. Defra also contracted ADAS plc (an organisation that provides consultancy and research advice on rural matters), to help collect TB99 data, mostly from control farms. However, it was still the case that by the end of 2003 case forms for 2002 and 2003 had not been completed for all the breakdown herds within the RBCT areas, and far too few controls had been collected to allow a meaningful analysis.

6.7 Originally, the ISG had expected the first 100 completed case questionnaires, with an accompanying 300 controls from across 3 triplets, to be completed within 12 months of the start of the case-control study in April 1999 so that the questionnaire could be modified in the light of data analysis and experience gained. However, the study was severely constrained by the lack of data from control farms, and following the disruption to TB99 activities between 2001 and 2003 (i.e. during and after the FMD epidemic) it was decided that resources should become more focused. The TB99 study for the calendar year 2004 was therefore restricted to the collection of 100 cases across triplets, and their associated controls, from each of three selected triplets in the RBCT. This more limited size of study was considered to still have sufficient power to detect useful differences between case and control farms. The three triplets were B (Cornwall and Devon), D (Hereford) and E

(North Wiltshire) and were chosen to be representative of the RBCT study areas. In an important departure it was also agreed that data collection was to be coordinated by a regional Veterinary Office (VO) centre with dedicated TB99 trained staff. Furthermore, in line with the recommendation made by the House of Commons Environment, Food and Rural Affairs Select Committee (EFRAC, 2003), during 2004 a small working group was charged with the development of a simpler and shorter questionnaire. This gave rise to a substantially revised questionnaire and a re-orientation of the study into what became known as the Case Control Study 2005 (Defra (2004b) CCS2005).

6.8 The CCS2005 study was launched at the end of January 2005. It had still the same objectives of investigating on-farm risk factors for TB, but was designed as solely a one-year study. Its aim was to collect information from four geographical regions where bovine TB was prevalent, along with two associated control reports for each case: one control herd from a parish of the same testing interval and one control herd matched to the case on parish testing interval, herd size class and herd type. Unlike previous investigations the case and control herds were to be recruited both inside and outside RBCT areas and included one area of new emerging TB. Targets were set of 125 cases and 250 associated controls from each of the three areas with established TB incidence, and as many cases as possible, plus two associated controls, from the emerging area. A specific Disease Report Form would be used to collect information for the purposes of disease management while the epidemiological information would be collected on a separate case control form known as the Farm Management Questionnaire (FMQ). This FMQ questionnaire was carefully designed and evaluated so that it should take no more than 1 hour for on-farm data collection, all questions would require an entered response, and data entry would be verifiable with as much information as possible being derived from existing databases. This was made possible because many questions in previous TB99 questionnaires concerning cattle movements, land type etc. (which had to be elicited directly from the farmer and/or by a VO investigation following the interview) were no longer necessary. Recent developments in establishing national farm databases meant that the Cattle Tracing System (CTS), Integrated Administration and Control System – Rural Payments Agency (IACS-RPA) and VetNet databases could be used objectively to retrieve information, which meant participants were not being asked to supply data that Defra already had. A copy of the CCS2005 Farm Management Questionnaire detailing the collection of data for analysis can be found on the Defra website (Defra (2004b) CCS2005).

Auditing and Training

6.9 As discussed in Chapter 2 the ISG had recognised from the outset the need for all aspects of the RBCT to be audited. Due to the collection of insufficient controls, and a number of interruptions, in particular the FMD epidemic, the first audit of the TB99 case-control study did not take place until 2003.

6.10 The auditor raised concerns about the complexity of the questionnaire and the time taken to complete it, the quality of responses and the lack of coordination of the project (Wahl, 2004). In particular she recommended the questionnaire should be shorter and simpler with many fewer but specifically trained interviewers undertaking the farm visits. She also criticised the coordination between data collection, management and entry, and recommended the establishment of a project coordinator along with a small management group with representation from contributing partners. This led to the revised and more focused 2004 TB99 data collection.

6.11 A follow-up audit of TB99 took place in 2004 (Wahl, 2005), the auditor being able to report that most of the recommendations from her first report had been met. Further improvements were recommended in speed of turnover of completed questionnaires, the need to further reduce the number of officers completing the questionnaire and the use of national cattle movement data as a more comprehensive alternative to movement data collected on farm. The importance of training was emphasised for the improvement of the quality of the data collection and management.

6.12 A third and final audit took place during 2005 (Wahl, 2006) when the one-year CCS2005 study was in progress. Lessons had been learnt from the previous TB99 studies and taken into consideration in the design and implementation of CCS2005. The audit assessed the whole process from design and implementation of the questionnaire to its data management. The auditor's report stated she was impressed by the professionalism and dedication throughout all stages of the study and commented on the efficiency and high data quality standards.

The Case-Control Analysis Approach

6.13 In analysing the data collected for the case control studies the established methods associated with such studies were adopted. For each case included in the study the associated control herds were required not to have been under TB-related restrictions in the 12 months prior to the case breakdown. A herd could appear only once in a study analysis, which meant in some instances that farms which had originally been recruited as controls subsequently suffered breakdowns and had to be treated as cases instead. Initially, binary logistic regression was used to examine potential risk factors individually for differences between case and control farms. Those risk factors found to be significant at $p < 0.15$ were further examined collectively using multivariate binary logistic regression to identify a small set of significant variables ($p < 0.05$). For each of these variables the odds ratio (OR) associated with the absence or presence of the explanatory variable was calculated along with its 95% confidence interval. An estimated OR of more than one indicates that factor is associated with an increased risk of experiencing a breakdown, and the greater the numerical value of the OR, the greater the risk. By contrast an OR less than one suggests that factor reduces risk and is in a sense a 'protective' factor in relation to TB breakdowns. It was recognised that differences in risk could arise due to cases and controls coming from different triplets, from different herd types (i.e. beef, dairy or mixed) and from different herd sizes (Munroe *et al.*, 1999, Johnston *et al.*, 2005, Green and Cornell 2005) and therefore these attributes were included throughout the regression modelling process as forced covariates. Tests were undertaken for interactions between variables and the final model was examined in the absence of each of the significant factors for stability.

6.14 Given the variability in the conditions under which it had been collected, the aggregate dataset resulting from the 5 years of recording information for the case-control study was analysed in the form of four separate sub-studies. The first related to the pre-FMD period, the second to the two years immediately post-FMD, the third related solely to the calendar year 2004, and finally we conducted an analysis on the reformulated CCS2005. We must however caution that although sufficient control data were collected for meaningful analyses of pre-FMD and 2004 data, the collection of control data fell short of expectations in all pre-2005 studies. Only limited checks for bias are possible with the available information; these checks revealed no evidence of bias.

Pre-FMD TB99 Study, 1998 to 2000

6.15 The outbreak of FMD occurred early in 2001. All TB herd breakdowns in triplets A (Gloucestershire/ Herefordshire), B (North Cornwall/ North Devon) and C (East Cornwall) following the initial proactive culls in these areas (see Table 2.3) until the end of 2000 were considered for inclusion in this first study of findings from the TB99. Four other triplets were in place at that time but there were too few TB99 reports for them to be included. Data were available from 151 case herds but only 117 associated control farms, the number of control farms thus clearly falling well short of the planned three controls per case. Over 170 explanatory variables from the TB99 questionnaires were considered that might explain the differences between case and control responses.

6.16 Table 6.1 summarises those factors found to be significant (full details of the findings have been published in Johnston *et al.*, 2005). From this it is evident that, taking all (confirmed and unconfirmed) cases together, not using either artificial fertiliser (Odds Ratio (OR) = 4.66) or farmyard manure (OR = 2.41) were associated with an increased risk of the farm experiencing a TB breakdown. The use of covered yard housing (OR = 4.22), other housing types (OR = 2.30) and keeping the cattle on two or more premises (OR = 1.79) also appear to increase the risk, as does bringing cattle on to the farm from markets (OR = 3.26) or from farm sales (OR = 1.93).

Table 6.1: PRE-FMD STUDY: Risk Factors found to be significantly ($p < 0.05$) associated with an increase in the odds of a herd being a TB breakdown (after adjustment made for triplet, treatment and herd size).

Risk Factor	Confirmed and unconfirmed cases		Confirmed cases only	
	Odds Ratio	95% CI	Odds Ratio	95% CI
Non-use of artificial fertiliser	4.66	(1.58, 13.76)	3.50	(1.04, 11.72)
Use of covered yard housing	4.22	(1.41, 12.65)	5.06	(1.51, 16.95)
Cattle brought on from markets	3.26	(1.71, 6.21)	3.33	(1.67, 6.62)
Non-use of farmyard manure	2.41	(1.18, 4.93)	2.86	(1.28, 6.39)
Use of 'other' housing types	2.30	(1.22, 4.33)	2.12	(1.04, 4.30)
Cattle brought on from farm sales	1.93	(1.03, 3.60)	2.41	(1.22, 4.75)
Use of 2 or more premises	1.79	(0.97, 3.32)	1.88	(0.96, 3.68)
Not 'other' soil type	–	–	3.26	(1.12, 9.45)

6.17 'Other' housing types were recorded when the herd used neither cubicle sheds, covered yards or loose boxes, or cattle were not housed at all but grazing only was practised on the farm. Movements of cattle on to the farm were associated with increased risk. Moving cattle off the farm was not considered as the TB99 questionnaire did not record this information

6.18 Of the 151 breakdown herds the number of confirmed cases was 111. Analysis of confirmed cases alone and their associated controls gave results very similar to those for all cases combined. However not having 'other' soil type i.e. the soil type on the holding being specified as loam, clay, peat, sand or chalk significantly increased the risk of a herd being associated with a breakdown (OR= 3.26).

Post-FMD TB99 Study, 2002 to 2003

6.19 Analysis of data collected during the calendar years 2002 and 2003 was severely restricted. A substantial number of cases were obtained across all triplets although, due to enrolment later in the year, three triplets had too few questionnaires completed in 2002 to be included for that year. However, a large number of triplets in both years contributed far too few control reports for any meaningful analysis to be undertaken on these data. In only two triplets did the numbers of controls even exceed the cases thus falling far short of the desired number of three controls per case. This is clear from Table 6.2 which illustrates, for each triplet and the relevant two years, the number of confirmed and unconfirmed cases for which report forms were available, along with their associated number of controls.

Table 6.2: Case and control TB99 reports received across all RBCT triplets during the post-FMD period 2002 and 2003. All cases (confirmed and unconfirmed) are included. Triplets D, I and J were only eligible for data collection near the end of 2002 and too few breakdowns occurred for inclusion.

Triplet	2002		2003	
	Cases	Controls	Cases	Controls
A Gloucester/ Hereford	54	46	53	10
B Devon/ Cornwall	61	58	46	32
C East Cornwall	75	26	57	24
D Hereford	-	-	57	42
E North Wiltshire	62	51	46*	4*
F West Cornwall	70	43	43	32
G Stafford/ Derbyshire	44	66	37	30
H Somerset/ Devon	52	45	35	18
I Gloucester	—	—	42	18
J Devon	—	—	59	68

* not included in analyses due to serious shortfall of controls

6.20 During this period farm visits were undertaken by SVS staff or by ADAS staff who had been recruited to assist with the TB99 backlog. Unfortunately farm visits and data collection for case farms and their associated controls were not always undertaken by the same personnel, so that often the case forms were completed by SVS staff and the control forms by ADAS staff, with a potential for lack of uniformity of data collection. In view of triplets A, B and C having been considered in the pre-FMD analysis it was decided to focus the analysis of the 2002 and 2003 data on the same three triplets.

6.21 Data from a total of 346 case reports and 196 associated control farms were considered in this analysis. As before, a large number of variables (over 150 in this case) was first screened for differences existing between cases and controls. From an initial list of 32 factors associated with environment, animal husbandry, biosecurity, movement, farm operations and herd health a final list of 13 factors were found to be significant ($p < 0.05$). These factors and their associated odds ratios are shown in Table 6.3.

Table 6.3: POST-FMD STUDY: Risk Factors found to be significantly ($p < 0.05$) associated with an increase in the odds of a herd being a TB breakdown (adjustment made for triplet, treatment, herd type, herd size and year.)

Risk Factor	Confirmed and unconfirmed cases	
	Odds Ratio	95% CI
Not moving on yearling stock	6.48	(2.24, 18.75)
Sandy soils	4.49	(1.71, 11.78)
Not having pasture, meadow or amenity grass	4.03	(1.48, 10.97)
Non-use of manure fertiliser	3.11	(1.57, 6.16)
Not moving off yearling stock	3.06	(1.33, 7.02)
Mixed deciduous woodland	2.99	(1.71, 5.22)
Farmer not aware of setts present on farm	2.50	(1.50, 4.16)
Not moving cattle to market	2.47	(1.33, 4.57)
No paddock grazing system	2.47	(1.53, 3.98)
Covered yard housing	2.19	(1.27, 3.77)
Treating herd for a listed disease	2.14	(1.21, 3.77)
Not having loam soils	1.77	(1.04, 3.01)
Total herd contacts	1.55	(1.12, 2.14)

6.22 This 2-year study period provided a much larger number of cases and controls than that available from the same three triplets considered in the pre-FMD study. This led to the power of the study being increased and more sensitive detection of potential risk factors, so that a larger number of significant risk factors were obtained. Prominent risk factors were not moving on yearling stock (OR = 6.48), not having pasture meadow or amenity grass (OR = 4.03), not using manure fertiliser (OR = 3.11), not moving off yearling stock (OR = 3.06) and having sandy soils (OR = 4.49) or mixed deciduous woodland (OR = 2.99). The remaining risk factors were associated with much less than a 3-fold increase in risk and included not moving cattle to market, the farmer being unaware of setts present on the farm, no paddock grazing system, use of covered yard housing and treating the herd for a listed disease. It has to be borne in mind that, while the data collected relate to the same three triplets of the RBCT, the TB99 questionnaire used in 2002 and 2003 had become more extensive and many of the questions were not the same as those in the pre-FMD TB99. In particular, information on cattle movements on and off the farm had been revised and become more specific. It is also important to note that, of the two most prominent risk factors, the observed percentages for controls and cases were not large. Approximately 11% of control farms moved on yearling stock compared with 3% of cases, and only 10% of cases had sandy soils compared with 5% of control holdings. In contrast over 18% of control holdings moved off yearling stock compared to 4% of cases.

TB99 Study 2004

6.23 Following the difficulties of data collection during 2002 and 2003, study resources were more closely focused and TB99 data collection was restricted to the collection of 100 cases across triplets B (North Cornwall/ North Devon), D (East Herefordshire) and E (North Wiltshire). A total of 98 (70 confirmed and 28 unconfirmed) cases was completed along with 144 associated controls; an improved but less than target number of control herds.

6.24 Data on cattle movements on and off the farm continued to be recorded during the farm visit, but since the information collected was in agreement with the CTS national database for cattle movements, the latter was used in analyses for all farms. The CTS had the advantage that movements were verifiable and not dependent on recall when completing the questionnaire. Moreover the CTS data could be used when the TB99 questionnaire data on animal movements were missing. In addition the VetNet and RBCT databases provided further checks on TB99 returns.

6.25 Over 150 variables arising from data collected on the farm environment, biosecurity, husbandry, herd health, movements and farm operations were first screened for differences between cases and controls, using all breakdowns as cases or confirmed breakdowns only as cases. Table 6.4 lists those factors found to be significant ($p < 0.05$) in at least one of these analyses along with the odds ratios and their 95% confidence intervals (full details of the findings have been submitted for publication in Johnston *et al.*, in review). Where a factor has been found to be significant in the analysis of confirmed and unconfirmed cases but not in the analysis based only on confirmed cases (and *vice versa*), the odds ratio that would be obtained is shown for comparative purposes.

Table 6.4: TB99 2004 STUDY: Risk Factors found to be significantly ($p < 0.05$) associated with an increase in the odds of a herd experiencing a TB breakdown (adjustment made for triplet, treatment, herd type and herd size and continuous variables not shown). Factors with large odds ratios and wide confidence intervals should be interpreted cautiously.

Risk Factor	Confirmed and unconfirmed cases		Confirmed cases only	
	Odds Ratio	95% CI	Odds Ratio	95% CI
Not having pasture, meadow or amenity grass	14.64	(2.48, 86.49)	26.00	(2.46, 275.30)
Feeding silage	5.71	(1.89, 17.27)	4.46	(1.11, 17.85)
Reported presence of badgers in housing or feed store	4.19	(1.54, 11.39)	26.49	(5.11, 137.26)
No reported evidence of wildlife not badgers or deer in housing or feed store	2.92	(1.23, 6.92)	1.75 [‡]	(0.56, 5.56) [‡]
Growing hay	2.70	(1.31, 5.60)	8.63	(2.81, 26.48)
No movements off to markets	2.61	(1.18, 5.78)	11.85	(3.81, 36.82)
Mixed, deciduous woodland	2.50	(1.19, 5.26)	2.39 [‡]	(0.95, 6.04) [‡]
Farmer not aware of setts on farm	2.22	(1.14, 4.31)	2.27 [‡]	(0.97, 5.26) [‡]
No control of wildlife species that are not badgers or deer	2.13	(1.05, 4.33)	3.39	(1.32, 8.71)
Tilled land on holding	1.86 [‡]	(0.90, 3.87) [‡]	3.72	(1.44, 9.57)
Non-use of feeding supplements	1.64 [‡]	(0.81, 3.33) [‡]	2.70	(1.08, 6.75)
‘Other’ soil types on farm	1.64 [‡]	(0.71, 3.86) [‡]	2.93	(1.01, 8.50)
Moving off adult females	1.63 [‡]	(0.69, 3.80) [‡]	4.83	(1.49, 15.60)

[‡] denotes not significant ($p > 0.05$) but included for comparative purposes

6.26 The results show that, for confirmed and unconfirmed cases together, not having pasture meadow or amenity grass (OR = 14.64), no reported evidence of wildlife other than badgers or deer in housing or feed store (OR = 2.92), no movements off to markets (OR = 2.61), farmer not being aware of setts on farm (OR = 2.22), no control of wildlife species that are not badgers or deer (OR = 2.13) and not using feeding supplements (OR = 1.64) increased the risk of a breakdown. In addition feeding silage (OR = 5.71), the reported presence of badgers in housing or feed store (OR = 4.19), growing hay (OR = 2.70) and mixed deciduous woodland (OR = 2.50) significantly increased the risk of a herd being associated with a breakdown.

6.27 When confirmed cases only are considered, additional risk factors are seen to be moving adult females off the farm (OR = 4.83), the presence of tilled land on the holding (OR = 3.72), ‘other’ soil types (OR = 2.93) and not using feeding supplements (OR = 2.70). In addition (not shown in Table 6.4) if a herd has contact with a large number of other herds under TB movement restriction the risk of being a confirmed or unconfirmed case was small. Similarly, if the number of cattle breeds on the holding or number of ‘listed’ diseases in the herd was large the risk of being a confirmed case was small.

6.28 In general, regardless of whether all breakdowns or only confirmed breakdowns are considered, there is agreement on the odds ratios for factors shown to be significant in at least one of the two analyses. The odds ratios tended to be larger in magnitude when confirmed cases alone were considered but confidence intervals were wider as the number of cases available for analysis were smaller.

6.29 Taking a conservative approach and setting aside the lack of pasture, meadow or amenity grass being a large risk factor, notable results from the analysis of confirmed and unconfirmed cases is the risk associated with feeding silage and the reported presence of badgers in housing or feed stores. The second of these is perhaps obvious as a positive risk factor, but the first is not easily explained.

CCS2005 Study

6.30 Results are shown of the analysis of the confirmed breakdowns and those controls chosen from a parish with the same testing interval. Separate analyses were undertaken for each of the animal health regions Carmarthen (61 confirmed cases and 61 controls), Stafford (90 confirmed cases and 90 controls) and Taunton (60 cases and 60 controls). Only seven confirmed cases occurred at Carlisle (an area where TB incidence was suspected to be increasing) and no meaningful analysis was possible. Table 6.5 summarises the factors found to be significant in each of the three regions.

6.31 For Carmarthen, prominent significant risk factors (odds ratio greater than 3) associated with breakdown herds were keeping one type (e.g. beef cows or replacement heifers) of cattle together (OR = 18.92), having no wildlife other than badgers and deer (OR = 17.81), increasing the number of farm premises (OR = 15.18), having forest land cover (OR = 12.81), using grass types other than cut forage, permanent pasture, sown pasture or rough grass for grazing and foraging (OR = 10.49), not feeding grains (OR = 7.17) and increasing the number of herds to which cattle are sent (OR = 6.36).

6.32 For Stafford out of sixteen factors found to be significant, large risk factors were associated with not using 'grazing only' housing (OR = 9.58), not providing feed outside the housing (OR = 7.69), the cattle having contact with other domestic animals on the farm (OR = 7.54), not using slurry as a fertiliser on grass land (OR = 7.32), not feeding straw (OR = 6.36), using feed types other than hay, straw, silage, grain or supplements (OR = 6.23), increasing the number of contacted herds (OR = 5.87), not moving animals on direct from other farms (OR = 5.47), an increase in the proportion of land with forest cover (OR = 4.66), having deep red loamy soils (OR = 3.97), not providing disinfectant for vehicles and visitors (OR = 3.94), implementing control measures for wildlife other than badgers or deer (OR = 3.46), and decreasing the typical number of cattle moved from the herd each year (OR = 3.16).

6.33 In the Taunton animal health region only eight factors were identified with farms being significantly at risk. The greatest risks were associated with an increase in farmland area (OR = 29.08), not having clay soils (OR = 18.92), providing disinfectant for vehicles and visitors (OR = 16.78), having no wild deer on the farm (OR = 15.80), not moving animals off direct to other farms (OR = 12.68), having arable land (OR = 12.43), and a source herd having experienced a confirmed breakdown in the previous two years (OR = 9.30).

6.34 The results from these geographically different regions have been based on data collected in the same way and analysed using the same methods. It is unexpected that the risk factors found to be important are different in each of the regions and that no

overarching risk factors are present. There is lack of agreement in the role of the use of disinfectant for vehicles and visitors which was found to be associated with increased risk in Taunton and decreased risk in Stafford. It is likely that the explanation for Taunton is that the use of disinfectant is practised on farms following advice received in response to disease outbreaks or TB breakdowns.

Table 6.5: CCS2005 STUDY: Risk Factors found to be significantly ($p < 0.05$) associated with an increase in the odds of a herd experiencing a TB breakdown for each of the animal health regions Carmarthen, Stafford and Taunton (adjustment made for parish testing interval, herd type and herd size). Factors with large odds ratios and wide confidence intervals should be interpreted cautiously.

Risk Factor	Carmarthen confirmed cases only		Stafford confirmed cases only		Taunton confirmed cases only	
	Odds Ratio	95% CI	Odds Ratio	95% CI	Odds Ratio	95% CI
Increase in area (ha) of farm land ($\ln \uparrow$)					29.08	(4.79, 176.48)
Not having deep clay soils					18.92	(2.51, 142.42)
Keeping one type of cattle together	18.92	(1.54, 232.48)				
No wildlife other than badgers or deer at 'other' locations on the farm	17.81	(1.94, 163.17)				
Providing disinfectant for vehicles and visitors					16.78	(3.17, 88.77)
No wild deer in 'other' locations on the farm					15.80	(1.94, 128.66)
Increase in number of premises comprising the farm ($\ln \uparrow$)	15.18	(2.14, 107.77)				
Forest land cover on the farm	12.81	(1.51, 108.46)				
No movements off direct to other farms					12.68	(2.09, 76.95)
Not having arable land					12.43	(2.35, 65.76)
Using 'other' grass types for grazing/forage	10.49	(1.76, 62.4)				
Not using 'grazing only' housing			9.58	(2.63, 34.94)		
A source herd experiencing a confirmed breakdown in the previous 2 years					9.30	(1.76, 49.21)
Not providing feed outside the housing			7.69	(2.42, 24.44)		
Contact with domestic animals on the farm			7.54	(2.42, 23.5)		
Non-use of slurry as a fertiliser on grass land			7.32	(2.13, 25.15)		

Risk Factor	Carmarthen confirmed cases only		Stafford confirmed cases only		Taunton confirmed cases only	
	Odds Ratio	95% CI	Odds Ratio	95% CI	Odds Ratio	95% CI
Not feeding grains	7.17	(1.36, 37.94)				
Not feeding straw			6.36	(1.2, 33.65)		
Increase in number of herds cattle sent to (standardised to 1 year and \ln^\dagger)	6.36	(1.33, 30.51)				
Feeding 'other' feed types			6.23	(1.85, 21.01)		
Increase in number of contacted herds (\ln^\dagger)			5.87	(1.92, 17.94)		
Not moving animals on direct from other farms			5.47	(1.76, 17.06)		
10% increase in proportion of land with forest land cover type			4.66	(1.56, 13.98)		
Deep red loamy soils on the farm			3.97	(1.28, 12.39)		
Not providing disinfectant for vehicles and visitors			3.94	(1.1, 14.07)		
Control measures for wildlife other than badgers or deer			3.46	(1.18, 10.16)		
Decrease in typical number of cattle removed from the herd in a year (\ln^\dagger)			3.16	(1.44, 6.92)		
10% decrease in proportion of land of agricultural class with natural vegetation (\ln^\dagger)	3.00	(1.4, 6.45)				
Increase in number of animals moved out of the herd (standardised to 1 year and \ln^\dagger)					2.92	(1.36, 6.26)
10% increase in proportion of days in the previous year among neighbouring herds under restriction (\ln^\dagger)	2.69	(1.49, 4.85)				
Increase in number of contacted herds experiencing a confirmed breakdown in the previous 12 months (\ln^\dagger)			2.66	(1.34, 5.29)		
Increase in number of dairy cattle typically removed from the herd (\ln^\dagger)			2.29	(1.2, 4.38)		
Increase in number of calves typically removed from the herd in a given year (\ln^\dagger)	1.92	(1.24, 2.95)				

† \ln denotes logarithmically transformed variable

Discussion and Conclusion

6.35 Case-control studies on cattle herds in Canada (Munroe *et al.*, 1999), the Republic of Ireland (Griffin *et al.*, 1996), Italy (Marangon *et al.*, 1998), Northern Ireland (Denny & Wilesmith, 1999), Michigan, USA (Kaneene *et al.*, 2002) and England (Green and Cornell, 2005; Mathews *et al.*, 2006; Ramirez-Villaescusa *et al.*, 2005) have led to widely different recommendations on practices expected to reduce TB. Marangon *et al.* (1998) compared farm data from confirmed TB breakdown herds to control herds and reported an increased risk of a breakdown to be associated with the presence of mixed enterprises and cattle purchase. Other factors such as herd size, housing system etc. did not appear to increase risk. Munroe *et al.* (1999) cited herd size and the reason a herd was investigated as risk factors associated with reactor and non-reactor Canadian cattle herds. In contrast Green and Cornell (2005) studied UK cattle herd breakdowns that occurred outside the South West of England between 1986 and 2000, and reported that the risk of a herd being a breakdown depended more extensively on year, test type, spatial location and the risk increased with number of cattle tested and test interval.

6.36 In a more recently reported case-control study, an analysis was undertaken of 229 UK cattle farms between 1995-1999 (Reilly and Courtenay, 2007) which compared control farms to TB transient and persistent case farms under TB breakdown for less than and greater than 6 months respectively. Risk factors found to be significant included purchase of cows, mixed herd types, manure storage, number of cattle purchased, silage clamp, stock density and active badger sett density. From the findings it was concluded that different factors lead to transient breakdowns compared to persistent breakdowns. Transient breakdowns are more influenced by purchase of cattle compared to other management factors. In contrast persistent breakdowns are mostly affected by management factors relating to herd enterprise, silage storage and relative density of badgers.

6.37 Table 6.6 provides a summary of the findings across the three TB99 studies. Risk factors are classified into those found to increase or decrease the risk of a (confirmed or unconfirmed) breakdown. The factors have been further classified into farm management factors e.g. cattle movements, housing, crops etc. and wildlife and landscape environmental factors. Although the TB99 questionnaire underwent revisions between 1999 and 2004 the findings indicate that cattle housing and movement on to farms were prominent risk factors pre-FMD. In contrast between 2002 and 2003 cattle movement factors that led to a decrease in risk of TB were prominent. In 2004 there was evidence of wildlife factors becoming prominent and the observation that badgers were more likely to be reported present in housing or feed stores on case farms whereas on farms with managers more aware of the presence of setts there was less risk of a breakdown. There was evidence of treating land with manure or fertilisers as being protective whereas feeding silage and growing hay were associated with increased risk of a breakdown. This was not inconsistent with Reilly and Courtenay (2007) who found manure was important but that storage (not spread) increased the risk of transient TB and concurred with their finding that the odds of persistent TB was increased 9-fold by the use of silage clamp. These findings suggest that, at least in RBCT areas, the risk factors associated with breakdowns have been undergoing change possibly as a result of the effect of badger culling in hotspots or greater concern and awareness by farmers and veterinary advisers about cattle TB following the FMD epidemic of 2001.

Table 6.6: Summary of farm management, wildlife and environmental factors found significant in TB99 studies between 1999 and 2004 (continuous covariates not shown).

	PreFMD* TB99 Study	PostFMD 2002-2003 TB99 Study	2004 TB99 Study
Factors significantly increasing the risk of a TB confirmed and unconfirmed breakdown			
Cattle and crop management	Use of covered yard housing Use of 'other' housing types Use of 2 or more premises Cattle brought on from markets Cattle brought on from farm sales	Covered yard housing Treating herd for a listed disease Total herd contacts	Feeding silage Growing hay
Wildlife			Reported presence of badgers in housing or food store
Environment		Sandy soils Mixed deciduous woodland	Mixed deciduous woodland
Factors significantly decreasing the risk of a TB confirmed and unconfirmed breakdown			
Cattle and crop management	Use of artificial fertilizer Use of farmyard manure	Moving on yearling stock Moving off yearling stock Moving cattle to market Use of manure fertilizer Paddock grazing system	Movements off to market
Wildlife		Farmer aware of setts present on farm	Reported evidence of wildlife not badgers or deer in housing or feed store Farmer aware of setts present on farm Control of wildlife other than badgers and deer
Environment		Pasture, meadow or amenity grass Loam soils	Pasture, meadow or amenity grass

*PreFMD TB99 questionnaire not as extensive as that used in PostFMD 2002 – 2003 and 2004 TB99 studies.

6.38 The findings from the three CCS2005 regions are shown in Table 6.7 where risk factors for a confirmed breakdown are summarised and classified according to the categories cattle and crop management, wildlife and environment. These indicate that there are only a few wildlife and environment factors (Table 6.7). Unlike the TB99 analyses for previous years there was no evidence of the farmer's awareness of setts on the farm or the lack of reporting of the presence of badgers in housing and feed stores being protective. Wildlife other than badgers on the farm was associated with lower risk. Consequently badgers were not identified as an important risk factor. A forest land cover environment was found to

increase risk which was not inconsistent with that previously found in the TB99 analyses where mixed deciduous woodland increased risk and pasture, meadow or amenity grass decreased the risk.

6.39 Risk factors associated with cattle and crop management factors were prevalent across the CCS2005 regions. The movement of animals on and off the farm both increased and decreased the risk of TB. In each of the three regions the movement of groups of animals off the farm was associated with increased risk whereas in Stafford region moving animals directly on to the farm and in Taunton region directly off to other farms were associated with less risk. Contact with domestic animals and other herds increased the risk as did an increase in the number of farm premises. Keeping different types of cattle and providing grazing with no housing structure decreased the risk. Grass feeding types were associated with increased risk in Carmarthen and Stafford, whereas access to feed outside the housing and feeding straw were associated with less risk in Stafford. Feeding was also found to be important in the TB99 findings where feeding silage was found to increase the risk of a breakdown.

Table 6.7: Summary of farm management, wildlife and environmental factors found significant in CCS2005 studies for each of the animal health regions Carmarthen, Stafford and Taunton (adjustment made for parish testing interval, herd type and herd size).

	Carmarthen CCS2005 Study	Stafford CCS2005 Study	Taunton CCS2005 Study
Factors significantly increasing the risk of a TB confirmed breakdown			
Cattle and crop management	Number of premises comprising the farm Using 'other' grass types for grazing/forage Number of herds cattle sent to 10% increase in proportion of days in the previous year among neighbouring herds under restriction Number of calves typically removed from the herd in a given year	Contact with domestic animals on the farm Feeding 'other' feed types Number of contacted herds Number of contacted herds experiencing a confirmed breakdown in the previous 12 months Number of dairy cattle typically removed from the herd	Area (ha) of farm land Providing disinfectant for vehicles and visitors A source herd experiencing a confirmed breakdown in the previous 2 years Number of animals moved out of the herd
Wildlife		Control measures for wildlife other than badgers or deer	
Environment	Forest land cover on the farm	10% increase in proportion of land with forest land cover type Having deep red loamy soil	

	Carmarthen CCS2005 Study	Stafford CCS2005 Study	Taunton CCS2005 Study
Factors significantly decreasing the risk of a TB confirmed breakdown			
Cattle and crop management	Keeping more than one type of cattle together Feeding grains	Providing disinfectant for vehicles and visitors Using 'grazing only' housing Providing feed outside the housing Feeding straw Using slurry as a fertilizer Moving animals on direct from other farms Typical number of cattle removed from the herd in a year	Any movements off direct to other farms Having arable land
Wildlife	Wildlife other than badgers or deer at 'other' locations on the farm		Wild deer in 'other' locations on the farm
Environment	10% increase in proportion of land of agricultural class with natural vegetation		Having deep clay soils

6.40 The results of the TB99 and CCS2005 studies suggest that individual risk factors may have changed from year to year and also been different from region to region. Across all studies there have been elements of consistency such as covered yard housing, multiple farm premises, moving stock on and off and mixed deciduous woodland all being associated with an increase in risk. In contrast, use of fertilizers (including manure), cattle movements and pasture meadow or amenity grass have generally been associated with a decrease in risk. Although a large number of risk factors have been found to be significant it must be remembered that these were the key variables to emerge from answers given to a very large number of questions posed in the questionnaire.

6.41 Unlike other analysis methods adopted in the RBCT there was no single hypothesis of interest, instead the case-control approach involved the screening of many different characteristics in the search for those transmission factors which predisposed herds to infection.

6.42 It is not possible to identify particular risk factors which can confidently be adopted across all regions with the expectation of ensuring reduced transmission of disease to and from cattle. Greater insight into the possible dynamics of infection can be seen when the risk factors are classified into management, wildlife and environment factors. Any attempt to reduce risk must realistically accept that environmental features are seldom under the farmer's control. This can be seen from Table 6.8 where the most important non-environmental factors associated with confirmed and unconfirmed breakdowns across all studies are listed. Changes of definition make direct synthesis of information from TB99 and CCS2005 difficult. One risk factor that gave contradictory results in two studies has been omitted from Table 6.8. Focussing on management factors, the results suggest that cattle movements, herd contacts, use of fertilizer, housing and feeding practices can all impact on the risk of a herd experiencing a breakdown.

Table 6.8: Edited synthesis of prominent (more than 3-fold increase) farm level management and wildlife risk factors for a confirmed and unconfirmed herd breakdown in TB99 studies and a confirmed breakdown in and CCS2005 studies (after adjustment for herd type, herd size and other variables as specified in other Tables).

Farm level management	Factor	Risk	Study
Movements	Any movements off direct to other farms	Decreased	CCS2005 (Taunton)
	Moving on yearling stock	Decreased	TB99 (2002-2003)
	Number of herds cattle sent to	Increased	CCS2005 (Carmarthen)
	Moving animals on direct from other farms	Decreased	CCS2005 (Stafford)
	Cattle brought on from markets	Increased	TB99 (PreFMD)
	Typical number of cattle removed from a herd in a year	Decreased	TB99 (2002-2003)
	Moving off yearling stock	Decreased	TB99 (2002-2003)
Feed	Using 'other' grass types for grazing/forage	Increased	CCS2005 (Carmarthen)
	Providing feed outside the housing	Decreased	CCS2005 (Stafford)
	Feeding grains	Decreased	CCS2005 (Carmarthen)
	Feeding straw	Decreased	CCS2005 (Stafford)
	Feeding 'other' feed types	Increased	CCS2005 (Stafford)
	Feeding silage	Increased	TB99 (2004)
Contacts	Keeping more than one type of cattle together	Decreased	CCS2005 (Carmarthen)
	A source herd experiencing a confirmed breakdown in the previous 2 years	Increased	CCS2005 (Taunton)
	Contact with domestic animals on the farm	Increased	CCS2005 (Stafford)
	Number of contacted herds	Increased	CCS2005 (Stafford)
Wildlife	Wildlife other than badgers or deer at 'other' locations on the farm	Decreased	CCS2005 (Carmarthen)
	Wild deer in 'other' locations on the farm	Decreased	CCS2005 (Taunton)
	Reported presence of badgers in housing or food store	Increased	TB99 (2004)
	Control measures for wildlife other than badgers or deer	Increased	CCS2005 (Stafford)
Premises	Number of premises comprising the farm	Increased	CCS2005 (Carmarthen)
	Using 'grazing only' housing	Decreased	CCS2005 (Stafford)
	Use of covered yard housing	Increased	TB99 (PreFMD)
Fertilizer	Using slurry as a fertilizer	Decreased	CCS2005 (Stafford)
	Use of artificial fertilizer	Decreased	TB99 (PreFMD)
	Use of manure fertilizer	Decreased	TB99 (2002-2003)
Other	Area (ha) of farm land	Increased	CCS2005 (Taunton)
	Having arable land	Decreased	CCS2005 (Taunton)

6.43 The ISG has always advocated caution in the interpretation of findings from the TB99 and CCS2005 studies. The findings identify associations and not causes. Nevertheless there is sufficient evidence from the findings that by applying the broad principles of biosecurity (for example, see the advice developed by the Bovine TB Husbandry Working Group in partnership with Defra, available at: <http://www.defra.gov.uk/animalh/tb/abouttb/protect.htm>) (Defra, 2007b) it would be possible to reduce the risk of cattle becoming infected by other animals, including badgers, and thus reduce the risk of infection. This means taking account of cattle movement on and off the farm, minimising contact between cattle and between cattle and badgers and taking greater care with animal housing and feeding practices. For many farms these are not readily implemented without improvements in detection of infected animals being moved off and on to the farm, and being able to keep the farm environment free from infection. The TB99 and CCS2005 analyses indicate there is no universal solution for farm management to reduce the risk of a herd becoming a breakdown.

7. CONCLUSIONS FROM RESEARCH ON THE DISEASE IN CATTLE

Introduction

7.1 The implicit assumption underlying the long established TB control procedures is that cattle-to-cattle transmission of the disease is of critical importance, which is why movement restrictions are imposed immediately reactors to the tuberculin test are found in a herd. Disease control has also been based on an assumption that testing protocols are effective at clearing herds of infection, so pre-empting the possibility of within and between-herd transmission of the disease. Because the pockets of infection that persisted in parts of the South West of England after the rest of the country was cleared of disease were attributed to re-infection by a non-cattle source (wildlife), the emphasis of disease control over the last 25 years has, until recently, focused on dealing with the wildlife reservoir and relatively little consideration has been given to potential means of improving control measures directed to cattle.

7.2 Although the tuberculin skin test has proved to be a very useful herd test, the reliance on the test, in many circumstances, to identify individual infected animals led the ISG to question the ability of the test to clear infection from herds and to prevent spread of infection within and between herds, particularly in circumstances where there may be an additional (wildlife) source of infection. The ISG encouraged Defra to put in place a research programme to address these issues. This research was designed to explore the dynamics of *M. bovis* infection in cattle, the routes of disease transmission, improvements in diagnosis and the ability of diagnostic tests to identify infected, potentially infective animals at different stages of the disease. The outputs of this programme (summarised in Appendix I), complemented by field studies and analyses of data from reactor cattle, have been informative in considering the following questions:

How do the kinetics of infection and distribution of pathology relate to the ability to transmit infection?

7.3 Natural infection of cattle with *M. bovis* presents in over 90% of cases as a disease of the lower, and/or the upper respiratory tract. In two thirds of reactor animals lesions are restricted to the lower respiratory tract (lung and associated thoracic lymph nodes), and up to a third of cases have lesions in the head lymph nodes or in the head nodes and those of the lower respiratory tract (Appendix I, Figure I.1). These observations, coupled with the patterns of pathology found in animals experimentally infected by different routes, indicate that a majority of animals are infected via the lower respiratory tract, most likely by inhalation of small aerosol droplets containing *M. bovis*. A few organisms delivered by this route are sufficient to infect and cause disease (Dean *et al.*, 2005). This implies that such infections are acquired as a consequence of close contact with other animals (cattle or wildlife). A further category of cases that have lesions confined to the head lymph nodes may result from infection via the nasal cavity by inhalation of large aerosol particles or orally by consumption of infected material. Longitudinal monitoring of experimentally infected animals has demonstrated phases of bacterial shedding during the early stages of infection (McCorry *et al.*, 2005). Results of in-contact transmission studies have indicated that transmission of infection can occur at this early stage as well as later in infection (Defra research project report SE3015 (Defra, 2004e)). Infection has been shown to result in development of overt disease in some animals but most infected animals either develop limited pathology or have no visible evidence of disease. Some of the latter animals are not diagnosed by the tuberculin skin test. They are potential disease transmitters and

therefore pose a threat to disease security of the herd. Collectively, the results of these studies demonstrate that cattle-to-cattle transmission of infection plays an important role in maintenance of infection with *M. bovis* in the cattle population and confirm the dynamic and infectious nature of the disease.

Do significant numbers of infected cattle remain undetected by the current herd testing programmes?

7.4 A number of findings from the studies of both naturally and experimentally infected animals have highlighted the limitations of the tuberculin skin test and have demonstrated a remarkably consistent inability of the test to identify a significant number of TB infected cattle. Small numbers of experimentally infected cattle failed to give a positive response to the tuberculin test (SE3015). However, the most revealing data were those obtained from a field trial of the IFN test (interferon- γ) (ISG 1578). This trial has provided insights into the dynamic nature of the disease in multiple reactor herds. The trial involved 195 herds in which three or more reactors were identified at a routine tuberculin skin test. These herds were randomly assigned to three groups: two of the groups were subjected to the routine follow-up tuberculin testing protocol, but an extra-severe interpretation of the test (i.e. removal of all animals that gave any reaction to *M. bovis* PPD in excess of that to *M. avium* PPD) was applied to one of these groups at the first 60-day follow-up test. In the third group, cattle over one year of age in the herds received an IFN test between 10 and 49 days after the disclosure test, in addition to the routine follow-up tuberculin tests. At the disclosing test, 5-6% of animals gave positive reactions at severe interpretation of the tuberculin test in all three groups and about half of these (2.4-2.9%) were found to be infected. A further 11.1% of the animals subjected to the IFN test, and meeting all quality control criteria, reacted positively and 17.9% of these were detectably infected. The IFN test identified 27% more detectably infected (visibly lesioned or culture positive) animals than were diagnosed at the disclosing tuberculin skin test. There were no significant differences between the groups in the numbers of reactors and infected animals detected at the follow-up tuberculin tests, indicating that most of these IFN-positive animals would not have been detected by these tests. This represents a considerable number of infected, undiagnosed, animals in this category of herd. Given these numbers and previous evidence that an additional small number of infected animals fail to react to either the tuberculin or IFN tests (de la Rua-Domenech *et al.*, 2006), it is likely that current testing protocols fail to remove all infected animals from a significant number of breakdown herds. This could be particularly problematic in large herds. The average numbers of animals per herd has increased over the last 30 years (see Chapter 3, paragraph 3.16) and, with decreasing farm profit margins, this trend is likely to continue. An additional consequence of the incomplete sensitivity of the tuberculin test will be a failure of routine testing to detect infection in some herds containing single infected animals. Thus, if for example the true sensitivity of the test is 75%, infection will remain undetected in one in four herds with a single infected animal. Given that only one confirmed reactor is detected at the disclosure test in about 30% of breakdown herds, this represents a large number of additional infected herds that may remain undetected.

7.5 Detection of infected animals is also influenced by the ability to confirm that animals giving a positive reaction in the tuberculin skin test are infected with *M. bovis*. Confirmation of infection relies on the detection of lesions characteristic of TB at post mortem examination and/or successful culture of *M. bovis* from tissue samples. Overall, infection is confirmed in 45-50% of the slaughtered reactor cattle, although this figure is

higher if only the reactors identified at standard interpretation of the test are considered (e.g. 66% compared to 48% – Neill *et al.*, 1994). The likelihood of culturing *M. bovis* from an infected animal is greatly increased by sampling from lesions indicative of TB detected at post mortem examination. Thus, in 2005 infection was confirmed in only 4.4% of animals in which no visible lesions were found and these animals accounted for only 5.9% of the confirmed reactor cattle. Application of a more rigorous post mortem protocol to a small sample of 55 reactor cattle has been shown to increase the rate of detection of lesions and consequently the incidence of culture positive results to 67% for all reactors and 85% for those identified at standard interpretation (McIlroy *et al.*, 1986). The approach taken in this study included subjecting the lungs of reactor cattle to ‘bacon-slicing’, which allowed detection of small lesions that otherwise would have been difficult to detect in this large organ. This finding was consistent with an earlier observation that the rate of detection of unconfirmed reactors is significantly higher in parishes with confirmed TB breakdowns than in nearby parishes with no confirmed TB (Wilesmith and Williams, 1994), suggesting that a proportion of the unconfirmed reactors are attributable to exposure to *M. bovis*. These observations imply that a significant proportion of unconfirmed reactor cattle are infected with *M. bovis*. This is to be expected given the difficulty of detecting very small lesions at post-mortem examination and the likelihood that the sensitivity of the culture method employed is less than 100%. However, the impact of the failure to confirm all infected reactors will depend on the numbers of reactors in a herd; thus, the larger the number of reactors examined the higher the likelihood that infection will be confirmed in at least one animal. Therefore, since just over 50% of herds have two or more reactors (Table 7.1), the rate of confirmation of herds is, as expected, higher than the rate of confirmation of reactors (65% versus 52% in 2005 – Table 3.1).

7.6 As discussed above, readings that define a positive response to the tuberculin test were established to give a low level of false positive results (i.e. high specificity). By definition the occurrence of false positive responses should be unrelated to the presence of infection with *M. bovis* and therefore their rate of detection would be expected to be more or less constant across areas of varying disease incidence. However, the incidence of unconfirmed breakdowns appears to be substantially higher in areas with high TB incidence than in disease-free or low disease incidence areas. For example, unconfirmed breakdowns accounted for approximately 30% of herd breakdowns in the survey-only areas of the RBCT, both in the three year period before culling and during the trial (Chapter 5); this represents about 3% of all herds tested in these trial areas. These findings suggest that a substantial proportion of the unconfirmed breakdowns in areas of high TB risk are attributable to infection with *M. bovis*. Further studies are required to obtain more detailed quantitative data on this category of herds and to investigate their potential contribution to maintenance of infection in the cattle population.

Are undetected infected animals a significant source of infection for other cattle?

7.7 The failure of current herd testing protocols to identify all infected cattle could result in persistence and transmission of infection within herds that, according to the tuberculin skin test, are TB-free. Such herds also would represent a source of infection for spread of the disease through movement of cattle to other farms. The importance of the undetected infected animals will depend on the extent to which they are able to transmit infection to other cattle. There are no quantitative data on the relative capacities of tuberculin-positive and -negative animals to transmit infection. However, follow-up data from herds participating in the IFN trial referred to above indicate that infection persisted in some of

the herds. Some 15% of the 195 herds taking part in the trial and subsequently deemed to be free of infection, suffered a further breakdown within 9 months of restrictions being lifted, and 30% suffered a breakdown within three years (A. Mitchell, VLA, *personal communication*). It might be argued that these findings are due to continued re-infection from an external source, but the incidence of recurrence, together with findings from cattle pathogenesis studies and experience from other countries, strongly suggest that at least a proportion of these breakdowns are more likely to have resulted from undiagnosed infected cattle remaining in the herds causing amplification of the disease by cattle-to-cattle transfer of infection.

7.8 A considerable proportion of herd breakdowns in GB involve multiple reactor cattle (Table 7.1). In the West region of GB (see footnote to Table 7.1), where 11.1% of herds tested in 2005 (Tables 7.1 and 7.2), representing 6.8% of all herds (Table 7.2), suffered a TB breakdown, 40% of the breakdowns (619 herds) had three or more reactors at the disclosing test. Over 28% of herd breakdowns in the North region (see footnote to table 7.1), which has a low incidence of TB (Tables 7.1 and 7.2), also involved three reactors or more at the disclosure test. The presence of multiple infected animals in these herds suggests that they include animals capable of transmitting infection. Therefore, this category of reactor herd, whose number is increasing year on year (868 in 2005), possibly as a result of an increasing weight of infection, represents a particularly important reservoir of infection. If these herds are not completely cleared by repeated use of the tuberculin skin test, which is unlikely to be achieved in all cases, the risk of within-herd and between-herd transmission of infection remains.

Table 7.1 The distribution of the numbers of reactors and infected herds taken at the disclosing test for confirmed incidents in 2005 by Defra region.

Region ¹	0	1	2	3	4	5	6	7	8	9	10	> 10	Total confirmed herd break-downs	% Herds
West	258	454	224	156	110	66	56	45	29	25	13	119	1,555	67.67
East	23	19	2	0	1	2	2	0	0	0	0	0	49	2.13
North	60	90	32	20	12	11	8	3	5	0	1	12	254	11.05
Wales	65	131	59	41	24	23	15	8	10	15	5	31	427	18.58
Scotland	7	6	0	0	0	0	0	0	0	0	0	0	13	0.57
Total Herds	413²	700	317	217	147	102	81	56	44	40	19	162	2,298	100.00
% Herds	17.97	30.46	13.79	9.44	6.40	4.44	3.52	2.44	1.91	1.74	0.83	7.05	100.00	

(Source, VLA)

¹ West region is defined as the counties of Cornwall, Devon, Somerset, Dorset, Gloucestershire, Avon, Wiltshire, Herefordshire, Worcestershire and Shropshire – counties with a higher than average TB incidence. North region is defined as the Division or County covering the following Animal Health Divisional Offices: Carlisle, Leeds, Lincoln, Newcastle, Preston, Stafford (Cheshire), Stafford (Derbyshire) and Stafford (Staffordshire).

² Confirmed incidents may be disclosed by a slaughterhouse case where no reactors are taken. Of the 413 confirmed incidents with no reactors, 349 were disclosed in this way, the remaining were disclosed by an inconclusive reactor.

Table 7.2: The number of herds by region and those undergoing surveillance tests in 2005.

Region¹	No. of herds²	No. of surveillance tests
West	22,916	13,965
East	12,703	1,851
North	24,530	6,526
Wales	14,639	6,356
Scotland	14,409	2,833
Total	89,197	31,531

(Source, VLA)

¹ See footnote 1 to table 7.1.

² The data presented for numbers of herds are for January 2007. These figures will be very close, but slightly less than those for in 2005.

Table 7.3: The numbers and percentages of cattle herds subjected to the tuberculin skin test at different testing intervals in different regions of Great Britain in 2005.

Region¹	Number of herds (%) by testing interval				
	1-year	2-year	3-year	4-year	Total
West	13,515 (59.8%)	5,705 (25.7%)	544 (2.4%)	2,817 (12.5%)	22,581
East	333 (2.7%)	243 (2.0%)	37 (0.3%)	11,692 (95.0%)	12,305
North	3,521 (14.5%)	2,036 (8.4%)	77 (0.3%)	18,583 (76.7%)	24,217
Wales	4,305 (30.0%)	3,914 (27.3%)	3 (0.02%)	6,124 (42.7%)	14,346
Scotland				14,262 (100%)	14,262
Total	21,674 (24.6%)	11,898 (13.5%)	661 (0.7%)	53,478 (61.2%)	87,711

(Source, VLA)

¹ See footnote 1 to table 7.1

How important is cattle movement in the spread of infection?

7.9 A number of studies have identified the movement of cattle between herds as a significant risk factor for the occurrence of TB herd breakdowns and for geographical spread of the disease (Christiansen *et al.*, 1992; Gilbert *et al.*, 2005; Johnson *et al.*, 2005; Carrique-Mas *et al.*, 2006). There is convincing evidence confirming the importance of cattle movements as a cause of many of the sporadic herd breakdowns in areas that do not appear to sustain endemic *M. bovis* infection (Barlow *et al.*, 1998; Goodchild and Clifton-Hadley, 2001; Gilbert *et al.*, 2005). A study of farms in low TB risk areas that were restocked following the 2001 foot and mouth disease epidemic, has clearly illustrated the risk of moving cattle from areas with persistent TB (Gopal *et al.*, 2006). Using precise molecular techniques to genotype the strains of *M. bovis* involved in the breakdowns, together with cattle tracing data, it was demonstrated that in most cases the organisms had a genotype that was characteristic of *M. bovis* strains present in the localities from which the cattle had been purchased. By analysing the outcome of the first tuberculin test after restocking

of virtually all farms depopulated as a result of foot and mouth disease virus (FMDV), Carrique-Mas *et al.* (2006) found that the numbers of animals bought from farms that had a high rate of testing (which is associated with a recent history of *M. bovis* infection in the local parish), and purchase of animals from herds that had been positive to the tuberculin test in the previous five years, were the most important risk factors.

7.10 The attribution of TB risk to cattle movement or wildlife in areas of high cattle TB incidence is more difficult to quantify. The local persistence and spread of the disease in cattle in such areas has typically been ascribed to wildlife and the existence of local wildlife reservoirs of infection. However, analyses of the GB cattle tracing data have highlighted the extent of local cattle movements that take place as a result of normal farm trading practice (Gilbert *et al.*, 2005; Mitchell *et al.*, 2005). During the period 2001-2003, several hundred thousand cattle movements were recorded each year from herds in the West of England and Wales, and 43% of movements occurred over a distance of less than 20 km (Mitchell *et al.*, 2005). Analyses of cattle herds in the RBCCT revealed that the mean number of cattle moved into herds during 2005 ranged from 7 to 19 animals for the different triplets (ISG 1686). These data, considered together with the limitations in the tuberculin test (discussed above), suggest that movement of cattle is likely to be responsible for a proportion of the herd breakdowns in areas where *M. bovis* also persists in wildlife. Pre-movement testing would be expected to decrease this risk but there may be circumstances where strategic use of the IFN test in pre-movement testing should be considered to provide a higher degree of assurance that animals being moved are free of TB (see paragraphs 7.11 to 7.15).

Is there scope for improving current testing procedures?

7.11 There is little doubt that some infected cattle remain undetected by current testing protocols and that such animals have the potential to transmit infection to other cattle in these herds. Residual undetected infection is likely to lead to repeat breakdowns in some affected herds and, perhaps more importantly, result in spread of infection to other herds through animal movements.

7.12 As discussed above, trials using the IFN test have been particularly informative in revealing the extent to which infected animals remain undetected. The specificity of the current version of the IFN test, although usually greater than 96% (Wood *et al.*, 1992; Neill *et al.*, 1994; Monaghan *et al.*, 1997; SB4008, Defra 2006a; SB4021, Defra 2006a), is not sufficiently high to allow its use as a primary diagnostic for routine herd testing. However, because the test has relatively high sensitivity and it detects a slightly different cohort of *M. bovis*-infected animals than the tuberculin skin test (Neill *et al.*, 1994; Vordermeier *et al.*, 2006), its use in conjunction with the skin test can substantially enhance the capacity to detect infected animals. As with the tuberculin skin test, the lack of availability of sufficiently large numbers of in-contact test-negative animals for post-mortem examination, does not allow calculation of the absolute sensitivity of the IFN test, when used under the conditions that prevail in the UK and Ireland. However, comparisons of the tuberculin skin test and IFN test in cattle removed from breakdown herds have demonstrated that combined use of the two tests can result in relative sensitivity levels in excess of 90%, compared with 65-80% obtained by use of the tuberculin skin test alone (Wood *et al.*, 1991; Whipple *et al.*, 1995; Collins, 2002). Combined use of the two tests would have particular application for clearing infections from large multiple reactor herds.

7.13 Previous studies carried out in other countries indicated that tuberculin skin testing of cattle within one month prior to applying the IFN test resulted in boosting of the IFN response and, in some cases, enhanced sensitivity (Rothel *et al.*, 1992; Ryan *et al.*, 2000;

Whipple *et al.*, 2001). However, analyses of responses to the test in the UK and Ireland did not confirm these findings, but importantly demonstrated that skin testing of infected animals has no adverse affect on subsequent responses to the IFN test, even when applied as soon as three days later (Gormley *et al.*, 2004; Coad *et al.*, 2007). Therefore, there are no constraints to using the IFN test as a rapid follow-up test in herds where infection has been detected by the tuberculin skin test. This would be feasible in multiple reactor herds in which diagnosis of TB can be made with some certainty based on the number of reactors and/or the presence of lesions typical of TB at post-mortem examination of the reactors.

7.14 Research into the development of an improved version of the IFN test, based on the use of defined *M. bovis* proteins rather than PPD, has particularly focused on identifying proteins that are present in *M. bovis* but absent from other mycobacterial species to which cattle are exposed. The primary aim of this work is to improve the specificity of the test with no loss (and possibly improvement) of sensitivity. Small scale trials with an IFN test using two proteins (ESAT-6 and CFP-10) present in *M. bovis* but absent from *M. avium* have yielded levels of sensitivity approaching those obtained with the standard IFN test, with some improvement in specificity (Vordermeier *et al.*, 2001; Buddle *et al.*, 2003; Cockle *et al.*, 2006). Identification of further diagnostic proteins has been aided by the recent completion of the genome sequences of *M. bovis* and *M. avium* (Garnier *et al.*, 2003; Li *et al.*, 2006); by comparing these sequences, it has been possible to identify a further series of genes encoding proteins that are specific for *M. bovis*. Screening of the responses of infected cattle to these proteins in an IFN test has identified several additional promising diagnostic proteins. Preliminary experiments using four of these proteins together with ESAT-6 and CFP-10 in an IFN test, demonstrated further increased sensitivity of the test above that achieved using the latter two proteins on their own (Cockle *et al.*, 2006). This approach, therefore, offers considerable potential for developing an improved diagnostic test. Field trials will be required to obtain more detailed information on both sensitivity and specificity of any new tests, in a range of epidemiological situations. The use of defined proteins should improve the reproducibility of the test and, if a sufficient improvement in specificity can be achieved, with acceptable sensitivity, it would enable the test to be used as a primary diagnostic tool, providing the option of replacing the tuberculin skin test.

7.15 Current testing protocols involve a prolonged period of herd restriction following detection of a confirmed reactor animal, despite the fact that no further reactors are detected by the follow-up tests in many of the breakdown herds. This prompts the question: would it be possible to accelerate the follow-up testing protocol without compromising the ability to clear infection from the herds? The requirement for a 60-day interval between follow-up tests (which is currently specified by EU regulations) appears to be based on allowing sufficient time to detect animals that were incubating infection at the time of the disclosure test and on a belief that previous tuberculin testing of animals interferes with the response to a subsequent test conducted within a short time period. In addition, confirmation of some breakdowns requires a prolonged period to obtain the results from bacteriological cultures of samples from the slaughtered reactors. However, data suggesting that sequential testing of animals within a period of less than 60 days may interfere with responses to the second test, derive mainly from old studies carried out with previous versions of the tuberculin skin test (Kerr *et al.*, 1946) or with animals challenged with killed *M. bovis* rather than live infectious organisms (Radunz and Lepper, 1985). While there is evidence that re-testing of naturally infected animals at an interval of seven days results in a reduced response to the second test (Doherty *et al.*, 1995), recent Defra-funded research (Thom *et al.*, 2006) has demonstrated that, in animals experimentally infected with a dose of *M. bovis* that resulted in disease similar to that observed in the field, repeated testing at three week intervals has no adverse effect

on tuberculin skin test responses. The same study showed that infected animals develop a strong positive response to the tuberculin skin test three weeks after infection. These findings suggest that the application of shorter interval follow-up testing would not compromise the ability to detect any infected animals remaining following the disclosure test.

How reliable is surveillance?

7.16 The incidence of herd breakdowns remains low in the North and East regions, which contain about 60% of cattle herds in England and are subject to herd testing at 3 or 4 year intervals (A. Mitchell, VLA, *personal communication*). Although less than 10% of the confirmed breakdowns (161 herds in 2005) occur in these areas, the ISG has expressed concern that the long time intervals between herd tests and the parish-based annual pattern of testing could allow the establishment of undetected foci of infection, which might lead to the establishment of infection in local wildlife.

7.17 Slaughterhouse surveillance provides an additional means of detecting infection throughout the country. Over 4 million cattle are slaughtered each year, out of a total population of over 8 million animals. Data on the numbers of infected animals detected in routinely slaughtered cattle and in tested populations in 2005, are summarised in Table 7.4. Testing of about 4.8 million cattle identified 9,727 confirmed reactor cattle, whereas only 516 infected animals were revealed by inspection of approximately 4.3 million carcasses. Nevertheless, the latter animals led to identification of 14% of the breakdown incidents recorded in that year. In addition to animals that acquired infection following the most recent herd test, this figure will include animals not detected by routine herd testing, although the proportion of cases in this latter category is difficult to determine. Pathogenesis studies have demonstrated that visible lesions can develop as early as 14 days following infection with *M. bovis* (Cassidy *et al.*, 1998) and therefore a substantial proportion of the animals infected after the most recent herd test should be detectable at post-mortem examination.

Table 7.4: Comparison of numbers of confirmed infected animals detected by herd testing and slaughterhouse surveillance.

Testing interval	Incidents disclosed by herd testing		Incidents disclosed after examination of animal(s) at routine slaughter		
	Total number of animals tested (thousands)*	Total confirmed reactors identified	Total number of animals slaughtered (thousands)**	Number of confirmed infected animals	Number of new herd breakdown incidents triggered
1 year	3,275	8,180	1,304	335	213
2 years	788	1,165	604	80	59
3 years	31	18	10	4	3
4 years	725	364	2,428	97	60
Total	4,820	9,727	4,346	516	335

(Source, VLA)

* For tests in which *all* eligible animals in the herd were tested (i.e. excluding tests of inconclusive reactors or cattle sold to other herds by breakdown farms, etc).

** Estimations based on the assumptions that (a) the total number of cattle slaughtered in UK was 5,236,000 in 2006 (Defra 2007c), (b) 83% of them were slaughtered in GB (Defra and National Statistics), and (c) slaughtered cattle were distributed amongst testing intervals similarly to the total numbers of cattle (which were 2,522, 1,169, 20 and 4,696 thousand; total = 8,407 thousand).

Data derived from Defra (2007), Defra and National Statistics (2007c) and VLA (2006) SB4500.

7.18 Although animals subjected to annual or 2-yearly testing are over-represented within the tested population, the proportion of confirmed reactors detected in animals subject to these testing intervals was still much higher than in the equivalent categories of slaughterhouse animals. For example, the detection rate for confirmed reactors in animals subjected to annual testing was 0.25%, whereas slaughterhouse inspection only detected infection in an estimated 0.026% of animals derived from annually tested areas. The animals passing through slaughterhouses will contain a disproportionate number of animals between 18 and 36 months of age, reared specifically for beef production, compared to the population undergoing herd testing. However, analysis of the age at which animals are detected as *M. bovis*-positive shows that, except possibly for a lower rate in the very young animals, the rate of infection is not age-dependent. The large discrepancy in numbers of infected animals detected in the two populations indicates that inspection in slaughterhouses is less efficient at detecting *M. bovis*-infected animals than the procedures applied to reactor cattle. This is consistent with studies in Australia and New Zealand (Whipple *et al.*, 1996; Buddle *et al.*, 1994), which concluded that abattoir inspection is not a sufficiently sensitive means of sentinel surveillance for bovine TB in countries with endemic infection. In addition, about 6% of confirmed reactor cattle in GB show no grossly visible lesions at post-mortem examination. Given the high throughput of animals in slaughterhouses and the fact that many confirmed reactor cattle have only one or two small grossly visible lesions, or none, it is perhaps unrealistic to expect slaughterhouse inspection to provide anything other than cursory surveillance. This is not to underestimate its important role in protecting public health, but its role in surveillance is secondary to herd testing, allowing detection of some additional infected herds in the intervals between herd tests.

Some assessments via mathematical modelling

7.19 Mathematical models, that is systems of equations to represent the progress of a disease, have a long history of effective use in infectious disease epidemiology (Anderson and May, 1992). ISG work of this kind (Cox *et al.*, 2005) has concentrated on a simple model highly idealized but intended to capture key features of the epidemic. The objective is to obtain conclusions that, while expressed quantitatively, give some qualitative insight. Such models aim, in particular, to give guidance over the answers to questions such as “what if...”, where no directly relevant data are available. Modern computers also allow the development of relatively complicated and more realistic models (Smith, 2001) but these typically require giving numerical values to aspects of the epidemic process about which very little is known. The ISG chose to use a relatively simple model rather than a more complicated and potentially more realistic model because the objectives were to reach rather broad conclusions, and because the more realistic models require the specification of many essential unknown features. The simple model developed by ISG has suggested the following points.

7.20 The model was used to predict the course of the incidence of cattle TB as a consequence of reduced tuberculin skin testing of cattle during the 2001 FMD epidemic. Calculations made at the end of the FMD epidemic predicted an approximate doubling in the rate of detection of herd breakdowns on resumption of testing with the increase dying away after one to two years. This is what happened, showing any concern about the increase to be unwarranted.

7.21 The incidence of new herd breakdowns in the high incidence part of Great Britain over the period from 1986 to 2000 follows a remarkably smooth pattern corresponding to an effective exponential rate constant of about 0.15 per year. This is effectively equivalent to

a compound annual interest rate of 15%. This equates to a doubling time of about 4.5 years. In the rest of Great Britain the rate was appreciably lower. The rate can be regarded as the difference of two quantities, the cross-infection rate, the average number of new infected herds induced during one year of life of any undetected infection in a particular herd, and the removal rate, where removal is either by routine slaughter or following detection in a skin test.

7.22 One of the consequences of the model analysis is that the net reproduction rate of the epidemic can be estimated. If this rate is greater than one, the epidemic is likely to grow, whereas if it is less than one an initially local outbreak will become extinct without additional intervention. The estimated value for bovine TB is about 1.1 (Cox *et al.*, 2005), as contrasted with about 5 at some points for FMD during the nationwide epidemic in 2001. The implication of the small value for TB is that relatively small changes in the defining parameters should reverse the increasing trend.

7.23 One way of assessing the effect of possible changes is by considering the changes that might be necessary to change the rate of 0.15, for example into minus 0.15. Such a change would mean that in the first place the herd breakdowns would decrease in a curve mirroring the increase over recent years, although the longer term effect would probably be greater.

7.24 The effect of changes cannot be assessed directly from available data but simple mathematical models, combined with the large amount of data now assembled, do allow some very tentative predictions. The infection rate concerns all sources of infection for cattle, local infection for example across farm boundaries, infection from animals bought, in particular but not only, from high incidence areas, and infection from wildlife, especially badgers. All these are important but their relative importance, and that of cattle-to-badger transmission, cannot be estimated directly. In the following calculations we assume all three sources to be roughly equally important.

7.25 Calculations reported in the modelling paper (Cox *et al.*, 2005) suggest that the rate constant of 0.15 per year is the difference between 1.45 per year, the infection of new herds component, and 1.30 per year, the removal of infection from herds component.

7.26 Consider first the possibility of increasing the removal rate. This could be by either or both of decreasing the routine testing interval from say one year to six months in high incidence areas and to one year in all other areas and by improved test sensitivity (see paragraphs 7.11 to 7.15). For the present calculation, the testing interval has, however, been regarded as remaining unchanged. As discussed in paragraphs 7.11 to 7.15, there is scope for increasing the sensitivity of cattle testing protocols. An improvement of sensitivity from an assumed initial value of 0.66 to 0.80 would change the removal rate to 1.53 and hence the rate constant to minus 0.08 per year. It is thus reasonable to predict that such an improvement in sensitivity if applied systematically would probably at least stop the increase in the epidemic and probably induce a decrease in herd breakdowns, but the uncertainties of the calculation are such that the magnitude of the decrease is hard to judge.

7.27 Consider now the incidence rate. The RBCT has shown a roughly 25% reduction in herd breakdowns following proactive culling of badgers (see Chapter 5, paragraphs 5.9 to 5.11) and if applied nationwide would change to 1.09. The rate constant of about minus 0.2 would produce not only a quite quick drop in incidence but a continuing downwards

trend. This does, however, ignore boundary effects, which were found to be considerable. The powerful arguments against this as a practical strategy are set out elsewhere in the report (Chapter 10). A reactive strategy in the form used historically and in the trial is not a serious possibility for disease control and careful consideration of alternatives, discussed in Chapter 10, shows no alternative reactive strategy likely to be an improvement on it.

7.28 This leaves for consideration the reduction of incidence by movement controls and the effectiveness of these involves again issues of test sensitivity. Assuming the present level of test sensitivity is 0.66, pre-movement testing would reduce the rate of infection of new herds to 1.13 per year, whereas the figure corresponding with an increase of test sensitivity to 0.8 is 1.06 per year. These correspond to rate constants of respectively minus 0.17 and minus 0.24 per year assuming in the latter case that the enhanced testing is applied only to pre-movement testing.

7.29 These conclusions are subject to substantial uncertainty and should be taken as broad guidance only. They suggest that enhanced testing sensitivity, especially if applied to pre-movement control, would have an appreciable effect on the epidemic. Although pre-movement control at present levels of test sensitivity also is predicted to have a clear effect, possibly being equivalent to reversing the trend, nevertheless this would be appreciably less than the effect at the higher sensitivity level.

7.30 In these assessments and in interpreting the RBCT results on the effect of culling on herd breakdown rates the following distinction is important. In the RBCT the impact on the trial area of importing cattle from well outside the trial area remained unaffected. On the other hand, were a national policy available that would affect also the importation of *M. bovis* from outside into a herd, the consequences would be appreciably greater than in the trial. The assessments made above of the possible effect of enhanced testing assume nationwide implementation.

7.31 These calculations concern areas of relatively high incidence. In preventing the spread to areas of currently very low prevalence different quantitative arguments apply although the roles of test sensitivity and pre-movement testing remain pivotal.

8. VACCINES

Vaccination

8.1 In its report in 1997 (Krebs *et al.*, 1997), the Krebs Committee recommended that a research programme aimed at developing a vaccine against tuberculosis for use in cattle should be implemented, although the option of developing a vaccine for use in wildlife (badgers) should also be retained. Defra adopted this recommendation and established a programme on vaccination. In 2003, the ISG was asked to form a sub-committee to review vaccination against bovine TB, specifically to advise Defra Ministers on the feasibility for pursuing a TB vaccination strategy for either cattle or badgers. This sub-committee, which included experts on animal and human TB, as well as on vaccine regulatory approval, consulted widely with the various stakeholder groups. The results of their deliberations – Development of vaccines for Bovine Tuberculosis (Bourne *et al.*, 2003) – were published in July 2003. The report discussed the requirements for effective vaccination of the two host species, how vaccines might eventually be applied and the nature of the research that would be required to develop and test new vaccines. The following is a brief summary of the main conclusions of this report.

(a) *Utilising vaccination*

- (i) While recognising that the use of vaccination was not a realistic option in the short-term, the report concluded that the possibility of utilising vaccination as a control tool in the longer term should continue to be investigated.

(b) *A vaccine for cattle*

- (i) That vaccination of cattle could contribute to control of the disease but use of a vaccine would require either the development of a new diagnostic test that was not compromised by vaccination or adoption of a radically different control strategy that was less reliant on herd testing;
- (ii) That the currently available candidate vaccine – the attenuated Bacille Calmette Guerin (BCG) strain of *M. bovis* – did not provide a sufficiently high level of protection for use as a vaccine in cattle in Great Britain; and,
- (iii) That future research should focus on identification of improved vaccines and a companion diagnostic test.

(c) *A vaccine for badgers*

- (i) That use of a vaccine that reduced the severity of pathology and bacterial shedding might reduce transmission of infection and the risk of infection for cattle, thus providing another possible control option;
- (ii) That the outcome of such vaccine development was uncertain and could only be considered a medium- to long-term option;
- (iii) That there were insufficient data on the efficacy of BCG in badgers to assess whether or not it represented a viable vaccine candidate;
- (iv) That, in any event, a vaccine for badgers would need to be delivered by the oral route, in the form of a bait, in order to be practical and economically viable.

Development of a baiting system would need to address the risk of accidentally exposing cattle to the vaccine, generating spurious ‘breakdowns’;

- (v) That, even if efficacy could be demonstrated under experimental conditions, the impact of vaccination on risk of infection to cattle could not be predicted and therefore could only be determined by field testing on a large scale; and,
- (vi) That future research should focus on determining the efficacy of BCG in badgers under experimental conditions, developing an oral delivery system for BCG (or other vaccine candidates) and putting in place reagents and methodologies for vaccine field testing.

8.2 Broadly speaking, these are the areas being pursued by the current research programme supported by Defra, which is overseen by a Vaccine Programme Advisory Group (VPAG) made up of scientific experts, policy makers and representatives of the Animal Health Industry.

Implications of the RBCT findings for vaccination of badgers

8.3 The above report pre-dated the analyses of results from the RBCT. Hence, while it acknowledged the possibility that culling-induced changes in badger behaviour might influence transmission rates, and hence the relative merits of culling and vaccination for TB control, the existence of such effects was not then certain. As discussed in Chapters 4 and 5, it is now known that such ‘perturbation’ effects can increase *M. bovis* transmission both among badgers and from badgers to cattle, undermining beneficial effects of badger culling on the incidence of cattle herd breakdowns. Since vaccination could be applied to populations of badgers not subjected to culling, it presumably would not result in such adverse effects. Hence, if vaccination could reduce *M. bovis* transmission among badgers, and from badgers to cattle, this might have an overall beneficial effect on cattle herd breakdowns greater than that achieved by culling. However, as discussed above, there is still considerable uncertainty as to whether such a reduction in infectivity in target badger populations is achievable with the currently available vaccine candidate.

8.4 Given the potential value of vaccines to future TB control, whether targeted at badgers or cattle, we fully support the vaccine research programme currently pursued by Defra and VPAG. We do, however, caution that the many obstacles to establishing the control value of a wildlife vaccine, which we highlighted in our Fourth Report (Bourne *et al.* 2005), still remain. We also caution that, although the development of a cattle vaccine (and an appropriate diagnostic test required for use of such a vaccine in the field) may be technically achievable, it is critical that Defra identify a policy framework in which a cattle vaccine could be used. It is also important to recognise that progress on development of improved vaccines relies on scientific breakthroughs in this field and is therefore uncertain in outcome and timing.

9. ECONOMIC ASPECTS OF TB CONTROL

Disease control as an economic issue

9.1 In discussing the effects of badger control on herd breakdowns, some attention has been directed towards the concept of 'efficiency'. This related to a conventional idea of operational efficiency, specifically the proportion of the resident badger population that was captured in the culling operations. If badger culling were to form part of a TB control programme, however, there is a further aspect of efficiency that must be considered, and that is the *economic* efficiency of the operation.

9.2 The simplest definition of whether an action is efficient relates to whether the benefits it creates outweigh the costs – in short, whether it is worth doing. Obviously, except in cases where there is no choice, it makes no sense to undertake actions that are not worthwhile, regardless of how intrinsically desirable the outcomes are. Thus, it would be irrational to undertake any disease control policy where the benefits gained were not expected to exceed the costs involved. This highlights the necessity of identifying and measuring the benefits and costs associated with disease management, and Defra have declared this to be a principle which guides their policy decision making (Defra, 2004a). The formal approach to evaluating strategies is cost-benefit analysis (CBA), a technique whose logic and procedures are well established in economic analysis.

9.3 The threshold criterion for a policy to be economically efficient is that its total benefits exceed the total costs – i.e. the benefit:cost ratio (BCR) should exceed one. Although useful as a minimum indicator of acceptability, however, it is not sufficient to base decisions on the BCR, especially where there is a choice of strategies or, as is almost always the case, where disease control resources are limited and there are competing claims on those resources. The appropriate criterion for cost-benefit analysis is that the net present value (NPV) of the proposed programme is positive, and disease control options should be chosen that show the highest NPV. The NPV calculation accounts for the time period over which the programme is to operate and sets the pattern of benefits (which may be delayed and irregular over time) against the pattern of implementation costs (which also may be irregular but tend to be incurred most in the early years), all brought to a common base using an appropriate discount factor or interest rate.

9.4 However, it is not the mathematical complexity of the final cost and benefit comparison that requires specialist attention, but rather the task of defining and measuring appropriately the stream of costs incurred and the stream of benefits expected to follow. Those costs and benefits may be manifested not only in monetary terms, or by those financially involved; they may also arise more indirectly as a gain or a loss felt by others who have an interest in the outcome. Generally speaking, too, the benefits of any action are not distributed equally amongst affected groups, and similarly the costs as well; furthermore, it is typical that the gainers (those who experience a benefit) are often a different group of people from the losers (those who carry a cost). Consequently, a disease control programme may appear to be 'worthwhile' from the standpoint of livestock farmers or those who supply disease control services (veterinary practices, pharmaceutical companies) but 'not worthwhile' for arable farmers, the Government (taxpayers) or wildlife interest groups. This complexity makes it essential that, in order to ensure a balanced overall evaluation, cost-benefit analyses are conducted in a wide-ranging and detailed framework. This will first identify all the groups and variables affected and then measure those (positive or negative) effects using the best information and methodology available.

9.5 The conventional economic analysis of livestock disease (see McInerney, 1996) evaluates the economic effects that a disease would impose (the ‘disease losses’) against the costs incurred in treating or preventing it (the ‘disease expenditures’). The benefits of control are thus measured by the disease losses that are thereby reduced or avoided. A CBA can be conducted from the narrow standpoint of just the monetary costs and benefits to livestock producers or, more appropriately, for the economy as a whole by including the impacts on all groups whose interests are affected. The potential economic impacts of a livestock disease are highly diverse, and in physical terms can include animal mortality, reduced productivity, output loss or wastage, and reduced product quality; in a wider setting livestock disease can result in adverse animal welfare, negative effects on trade and, in some cases, health effects on humans as well. This indicates how wide the assessment of disease control benefits must be in order to ensure a valid economic appraisal. The costs of disease control action, similarly, are extremely diverse and include the resource costs of surveillance as well as those of prevention, intervention and treatment. Generally speaking they are incurred primarily by farmers and/or by government bodies, but sometimes (as in the case of badger culling) a loss in value is experienced by members of the public as well. In particular instances there may be substantial cost effects on those within the wider food supply chain (as there was with Bovine Spongiform Encephalopathy control) or even (as with foot-and-mouth disease measures) those outside it.

The economic evaluation of TB control

9.6 In the case of cattle TB the benefits of disease reduction are not measured in the usual manner defined above relating to the effects of the disease on production. No information is obtainable on the losses in terms of mortality, reduced cattle productivity, etc that clinical tuberculosis would cause because they are almost never manifested. For over 50 years, at the first sign of infection (a reactor identified in a herd test or detection at a slaughterhouse) a set of standard control actions is set in train, involving the slaughter of reactors, movement restrictions, laboratory examination, tracing of dangerous contacts, further tests, etc. Instead of disease losses, therefore, the economic cost that TB imposes is the cost of all these measures. Added to this are the continuing expenditures on the cattle TB surveillance programme in which herds are regularly tested for evidence of infection. In this sense the economic cost of cattle TB is a voluntary cost associated with the standard methods of reacting to or looking for breakdowns, rather than the cost the disease itself would impose on livestock production. Nor is it clear that the inherent benefits of dealing with the threat of TB in this way exceed the costs incurred – but this question is not posed because the routine test and slaughter policy is now treated as the baseline situation.

9.7 The direct benefits of any action to lower the incidence of cattle TB are therefore measured in physical terms as the number of breakdowns thereby avoided, and in economic terms as the saving in financial and resource costs that would have been associated with those breakdowns. These costs are not insignificant, either to the farmer or, under present arrangements, to the Government (taxpayers). They have been estimated to amount on average to almost £27,000 for every confirmed breakdown, divided roughly in the proportion 70:30 between taxpayers and farmers (Defra, 2005b). That total cost is made up from the value of reactors and dangerous contact animals slaughtered, the resources used in herd testing following a breakdown, and the impact of restrictions imposed on the farm business until the herd is declared to be free of infection. Although this overall figure is useful for aggregate computation purposes it has to be borne in mind that it is the average of a very wide range of per herd breakdown costs, differing between dairy, beef and pedigree

herds and depending on such factors as herd size and duration of the breakdown. A study conducted by Reading University (Defra, 2004f; Bennett and Cooke, 2006) which focused on just the farm level costs and using data collected from a survey of breakdown farms, refrained from quoting a mean cost per breakdown on the grounds that it would not be particularly meaningful as the variability was so great. It also found that up to one-fifth of all farmers suffered no net cost, or even gained financially, because the compensation they received from the government exceeded the value of the reactors slaughtered (the rates of compensation paid have now been revised). In all such instances the cost to the government of compensation is not a true measure of economic cost, since a proportion of it is simply a monetary transfer from taxpayers to farmers not balanced by an equivalent loss.

9.8 The benefits to be gained from any particular approach to TB control are clearly dependent on the effectiveness of the actions taken to reduce the incidence of herd breakdowns – and that has long been a matter of considerable uncertainty, regardless of whether the action taken was the standard test and removal programme, badger culling, restrictions on cattle movement or other biosecurity measures. The cost of such actions, however, is reasonably easy to estimate by accounting for and valuing the resources that are utilised in the process. Thus, the costing of TB control is relatively straightforward, whereas the cost-benefit appraisal is far more elusive. In the case of badger culling, for example, which has long been presumed to be a worthwhile strategy, the costs of implementing the approach are considerable. An approach based on cage trapping as employed in the RBCT was estimated to cost about £3,800 per km² annually if implemented in a five-year programme (Defra, 2005b). The alternative culling methods of snaring or gassing at setts, while less capital and labour intensive, were still estimated to cost in the region of £2,400 per km² each year of a sustained programme if undertaken by skilled and specialist field staff like those of Defra's Wildlife Unit. Even if farmers undertook the culling operations themselves the predicted annual cost is estimated to be around £1,000 per km² (higher if contractors are employed), although this is a somewhat speculative accounting estimate and takes incomplete account of the true opportunity cost of the farmer's time.

9.9 These overall average figures are useful to provide an indication of the orders of magnitude implicit in an economic assessment of TB control policy, but they are not particularly refined. As emphasised earlier, for a full economic analysis it is essential to explore in more detail the expected technical outcomes of the actions taken and the range of economic effects, both positive and negative, that might be involved. For example, there are likely to be wider scale and longer term cumulative benefits of a successful control strategy that are not captured in a simple calculation based on the estimated number of breakdowns directly prevented. A sufficiently large reduction in overall herd incidence in a region could lead to future breakdowns involving fewer reactors, becoming of shorter duration, or ultimately allowing a lengthening of test intervals – all of which enhance the benefits gained. Furthermore, it is important to recognise that not all breakdowns have the same economic implications. A breakdown occurring in a previously 'clean' area could become the source of a series of further breakdowns due to onward transmission (via cattle or wildlife) and so preventing it represents a potentially far higher benefit than an 'average' breakdown in an already hotspot area. A declining incidence undoubtedly will bring benefits in terms of less stress and personal disappointment for the farm families involved, and in principle represents also a lowering of risks to human health – and these are all genuine economic benefits even though they may not appear directly as financial quantities.

9.10 Similarly, as well as the ongoing expenditures on measures to deal with the incidence of cattle TB there is a range of ‘overhead’ costs associated with improving their success. For example, the costs of scientific research into the epidemiology and pathology of the disease, into new means of control (such as vaccines) and the many other elements (including the RBCT itself) involved in the search for better information to guide decisions on TB control have ultimately to be set against the benefits gained. Even in the case of individual control actions, such as implementing a badger-focussed control policy, a range of accessory costs that go well beyond the direct resource costs of culling have to be considered. In particular, there may be a need for security and police involvement to deal with the potential conflict with protestors (as was encountered in the RBCT) and the ecological consequences of widespread badger removal may be considered to be strongly negative. Added to this, although badgers have no explicit ‘price’ because they are not traded items, there is nevertheless a clear economic value attached to them as elements of the wildlife diversity that society values. An attempt at discerning such a value has been undertaken at Reading University in an innovative research project that was proposed by the ISG and funded by Defra (Defra, 2004g).

9.11 Recognition of these many wider aspects emphasises the need to consider the full spectrum of costs and benefits that should be included if the economic evaluation of TB control policies is to be appropriately balanced and informative. One important distinction that has relevance in an economic evaluation is that between, on the one hand, a continuing strategy of suppressing the incidence of the disease and containing the spread of infection, and on the other hand an all-out programme targeted at complete eradication of TB from the national herd. In line with its original aspiration of progressive reduction in herd incidence the current TB control policy is essentially operating as the first of these. An economic evaluation of current policy measures, therefore, would involve calculating the NPV of the ongoing sequence of estimated annual control expenditures and the predicted disease reduction benefits over a designated planning horizon (the national animal health and welfare strategy (Defra, 2004a) is framed in terms of a ten-year period). The cost and benefit comparisons of badger culling later in this chapter are presented in this ‘limited term’ context. By contrast, an eradication objective involves a much longer planning horizon and needs to be viewed in the conventional context of investment appraisal. This immediately introduces the difficulties associated with decisions about the long term future – particularly the increasing uncertainties about predicting resource requirements and outcomes many years ahead, and the impact of the discounting process on the value attached to benefits distant in time. The apparent paradox is that the costs incurred in disease eradication over, say, 25 years may well exceed the benefits gained over that period and so the programme cannot be justified economically; yet once eradication is achieved, the economic benefits continue in perpetuity and come at no (or minimal) cost. However, frustrating though this may appear, it does not provide a reason for ignoring the logic of cost-benefit analysis in the allocation of limited public expenditures when there are numerous competing uses for those funds, both within livestock disease management and elsewhere in the economy.

Cost-benefit analyses of badger culling

9.12 Although the national TB control programme has been in operation for over 50 years there has been no general economic evaluation of its merits. The issue that has received some focus is that of badger culling, and there have been a few studies that have attempted to assess the extent to which it was worthwhile. The first of these is presented in the Dunnet report (Dunnet *et al.*, 1986, pages 23-25) and was a CBA of the gassing operations

over the period 1975-82, assessing the monetary gains and losses (i.e. excluding social, environmental and other 'intangible' values) to the overall economy. Its conclusions were quite emphatic in showing that the culling policy yielded a negative NPV, the estimated costs over the period amounting to almost £10 million for a total benefit of less than £2 million. Furthermore, the report concluded that "it appears technically impossible for the control strategy ever to achieve a sufficient reduction in breakdowns to generate a level of benefit even approaching the operational costs", and it was partly on these grounds that the much more limited culling approach of the interim strategy was recommended.

9.13 A more recent CBA study was that conducted by Defra (Defra, 2005b) as background for the national consultation document on badger culling issued in 2005 (Defra, 2005a). This was a carefully considered evaluation of four different approaches to badger culling – trapping, gassing or snaring undertaken by Defra staff, and licensing farmers to cull – compared to no intervention in badger management. Their procedure was built on a detailed compilation of the estimated costs of implementing each approach. However, the benefit calculations were constrained by the fact that there was no scientific information on which to predict the number of herd breakdowns that would be prevented by each method (this was undertaken before the RBCCT results had been published). Consequently, the analysis calculated instead the number of herd breakdowns that each method would need to prevent per year if the culling operation was to break even in economic terms and cover its implementation costs. Starting from a baseline figure of 9 confirmed breakdowns per 100km² per year (considered typical for a hotspot area) those estimates ranged from an 89% reduction in annual incidents for the most costly method (cage trapping) to a 30% reduction if culling were undertaken by farmers. The culling strategies were assumed to be implemented for a five-year period, with benefits in terms of reduced breakdowns being manifested over 10 years. Making reasonable assumptions about the proportion of herd breakdowns attributable to badgers and the efficacy of badger removal, the study then estimated the number of breakdowns each method might achieve and calculated a NPV for each strategy over the 10-year period. All three of the Defra-implemented culling strategies showed a negative NPV, indicating that they could not be justified economically. By contrast the option of licensing farmers to cull did yield a positive NPV, but the bulk of the economic gains accrued to taxpayers (because of the much lower level of expenditures falling on the government); from the standpoint of farmers, however, the culling strategy was not worthwhile as the costs to them exceeded their benefits.

9.14 Another example where the economic merits of badger culling were investigated within a CBA framework is the study by Smith *et al.*, (2007). The approach they took was to simulate the effects of culling in a 400km² area using a detailed computer model. They made plausible assumptions about badger density, the prevalence of *M. bovis* infection in the badger population, the transmission rate of infection to cattle and an efficiency of 80% in removing badgers. They then simulated the effects on herd breakdowns over 30 years of both reactive and proactive culling; the strategies they considered involved either cage trapping or gassing of setts, conducted on different scales and for different time periods. Using estimates of the costs of each method and the benefit of preventing a breakdown they then derived a stream of costs and benefits over time that were encapsulated in an overall NPV calculation for each strategy. However, even in the context of what they called "an ideal simulated world with full land access and efficient control" their results failed to show a positive NPV for either reactive or proactive culling.

9.15 It is difficult to conclude from the studies summarised above anything other than that the economic justification for badger culling as a means of controlling TB in cattle is lacking. All three CBA studies based their estimates of the benefits from culling on assumptions about the contribution of badgers to cattle infection, and predictions of how many breakdowns would be prevented (or had been prevented, in the case of the Dunnet study) by removing badgers. This was entirely reasonable at the time when it was assumed there was a relatively straightforward relationship between local badger density and the transmission of infection to cattle. It was not until the RBCT findings became available that there was quantitative evidence, not only of the direct reduction in breakdowns that badger culling could achieve, but also of the associated effects of increased breakdowns on neighbouring lands. These have been reported in detail in Chapter 5 and show the extent to which social perturbation of badgers due to culling tends to neutralise many of the beneficial effects gained. Consequently, including these latter effects in the CBAs would inevitably make the NPV outcomes even more negative and emphasise further the economic deficiencies of badger culling.

Economic evaluation in the RBCT

9.16 In our first report (Bourne *et al.*, 1998) it was anticipated that we would undertake cost-benefit analyses of badger culling options that emerged from the trial as potential candidate policies. In the event, however, the results from the trial show that the potential for culling to lower the incidence of herd breakdowns appears to be so poor that the inherent economic weakness of culling strategies can be seen from simple cost and benefit accounting without recourse to the complexity of a formal CBA.

9.17 As reported in Chapter 5, the results from the reactive treatment show that this approach to badger culling produced no reduction in herd breakdowns but rather a 23% rise within the overall triplet area where it was implemented, compared to the comparable no-cull areas. Thus there are only negative benefits which, added to the cost of culling, demonstrates a totally adverse economic outcome and makes it pointless to undertake any CBA of the potential for reactive culling to serve as a TB control strategy.

9.18 The situation seems somewhat better based on findings from the proactive treatment. Here culling demonstrated a 23.2% reduction in confirmed breakdowns in the culled area over the period of the trial, indicating that some economic benefit was generated. However, percentage reductions are not directly useful for incorporation in an economic assessment; it is the absolute number of breakdowns avoided which measures the benefits, and which then have to be set against the culling costs. We can estimate this number using the average number of herds and the underlying incidence rate of breakdowns in the 'typical' proactively culled area in the RBCT. These calculations (see paragraph 5.39) indicate that, in numerical terms, a 23.2% reduction represents an average of 11.6 fewer confirmed breakdowns than would have been expected over a five-year period in a 100km² hotspot area like the proactive treatment areas. In a simple (undiscounted) calculation, at £27,000 per breakdown saved this amounts to an estimated total benefit of £313,200 that could be gained in a 100km² area subjected to proactive culling for five years. Assuming (based on RBCT experience) that direct access was obtained to 75% of the total land area and that cage trapping was the culling method employed, this benefit would be achieved at a cost of about £1.425 million (i.e. £3,800 for each km², repeated for five years) to undertake the culling. Clearly there is no net economic gain, and in economic terms the operation would be nowhere near worthwhile. The implied BCR on these figures is merely 0.22 or, put another way, it would cost almost £123,000 for every confirmed herd breakdown that was prevented.

9.19 The actual outcome of a proactive culling strategy is considerably worse than this, however, because those figures have not taken into account the adverse edge effects that occur. Here the trial results show that herd breakdowns rose by 24.5% in the 2km zone surrounding the culled area; assuming the same baseline herd incidence as in the culled area, this would amount on average to an estimated 10.2 additional breakdowns per 100km² proactively culled over a five year period. Taken together for the whole area affected by culling (culled land plus 2km surrounding zone), therefore, this indicates a net overall impact of just 1.4 fewer confirmed breakdowns (i.e. 11.6 minus 10.2) for the average 100km² proactively culled area. This represents a benefit of only £37,800 – a derisory return for the £1.425 million in costs. Put another way, if a proactive culling strategy along the lines of the RBCT were to be adopted it would cost over £1 million for every £27,000 saved in breakdowns, clearly economically indefensible.

9.20 Simple though they are, these figures demonstrate clearly why there was no point in undertaking a detailed CBA of the trial operations as potential policy options; it was abundantly clear that, whatever the NPV would turn out to be arithmetically it was going to be strongly negative, and offered no prospect of culling being shown as economically worth considering. This is also an obvious instance where the question: “for whom would it be worthwhile?” is appropriate. Despite being economically unsatisfactory overall, proactive culling would be clearly worthwhile for the cattle farmers inside the 100km² culled area who gain the benefits of reduced TB and yet (if culling is conducted as in the RBCT) pay none of the culling costs. However, their gain results in a direct cost to the farmers in the 2km surrounding zone who suffer the consequent increase in breakdowns, and it is not clear that taxpayers would gain any benefit for the costs they fund. There may be some beneficiaries of the culling policy other than cattle farmers in the culled areas, though it is difficult to imagine their gains would be sufficient to change the overall cost: benefit balance. Furthermore, the calculations do not take into account the economic value associated with the badgers that are killed. The RBCT data suggest (Table 2.4) that almost 900 badgers were killed in the average 100km² area proactively culled over five years; based on the valuation study referred to earlier (Defra, 2004g) this would represent an additional £25,000 loss felt by members of the wider public that should be included in the costs of the culling programme.

9.21 These estimates have followed the simplest computational route of assuming constant annual values, multiplying them up to estimate the implied total costs over a specific period of years, and then comparing with the implied sum of benefits over that same period. Even if discounting had been employed to bring the financial values arising at different points in time to a common base, the orders of magnitude are such that it would not change the substantial excess of costs over benefits. Nor is this relative imbalance likely to change materially if the parameters relating to culling costs, the benefits from avoiding a breakdown or the changes in herd incidence were to be altered within plausible limits. The core technical data – the recorded impacts of badger culling on herd breakdowns as revealed in the trial – demonstrate such a small beneficial effect on the incidence of TB that it seems unlikely it would be worthwhile under any economic conditions. There are indications from the concluding analyses of the RBCT that the beneficial impacts in the culled areas might increase for a number of years after initial proactive culling, while the deleterious edge effects might decline. It is not known for how long these trends might be significant because insufficient time has passed for the data to reveal a predicted path of such growth and decay in the effects of culling over time. It is in circumstances like this (where predicted effects vary through time) that it is necessary in principle to adopt

the conventional time-adjusted procedures of CBA, with the differential positive and negative effects over the years being brought to a comparable baseline by discounting before combination into a NPV calculation. Again, however, in the present case this is essentially just a theoretical point. The orders of magnitude of the respective beneficial and deleterious trends in breakdowns prevented or caused are such that, while the net reduction in breakdowns overall might ultimately be somewhat greater than the simple estimates presented above, the difference would need to be immense to alter the overall economic outcome.

Using RBCT data to evaluate alternative culling methods

9.22 It is recognised that cage trapping is probably the most costly method of culling badgers. However, for the purposes of formally assessing economic efficiency it is the only method for which adequate data are available; while there are estimates (Defra, 2005b) for the costs of other methods – snaring, gassing, farmer/contractor culling – there is no comparable science-based information on their expected effect on herd breakdowns, either on land where culling takes place or on surrounding areas. It is a matter of judgement, therefore, (see Chapter 10) as to whether any of these methods might be substantially more effective than were the culling operations in the RBCT.

9.23 However, it is possible to estimate the effect these other methods would need to achieve if they are simply to cover their costs. Conducted on a scale of 100km², for example, and with access to 75% of the land area, snaring or gassing programmes would involve an estimated cost in the region of £180,000 per year. To justify this expenditure these methods would need to achieve something like a *net* reduction of 6.6 confirmed breakdowns per year across the culled and surrounding areas combined. This is almost 24 times greater than was achieved by cage trapping in the RBCT. In the absence of scientific information on the impacts of these culling methods it is a matter of judgement as to whether this is feasible in practice, but it seems highly improbable.

9.24 Using the (admittedly approximate) Defra estimates of the costs if farmers were to undertake the operations (the so-called ‘licensing’ option), the equivalent calculation implies a need to reduce breakdowns by a net 2.8 confirmed breakdowns per year in a culling programme spread across a 100km² area (approximately 25,000 acres). While at first sight this may appear a reasonable target, it is still 10 times better than the estimated breakdown reduction achieved in the RBCT. Added to this, the logistic difficulties of co-ordinating a farmer-managed badger cull across 100km² with sufficient continuity and spatial coherence so as to approximate the effectiveness of RBCT operations seem likely to be severe. This in turn suggests that the beneficial effects may be lower and the adverse edge effects due to badger perturbation perhaps higher than the figures assumed here. Hence, even the cheapest methods of culling appear to have little likelihood of being economically justifiable.

9.25 The above simple computations on the economic implications of different badger culling methods are summarised in Table 9.1. In the absence of more specific information the economic benefits of each method have been assumed to be the same as in the RBCT and hence appear identical; the primary difference between methods, therefore, emerges in terms of their overall costs. As stated at the outset, the BCR is not a dependable criterion for choice between alternatives, but its magnitude does give a ready indication of how close to acceptability each might be. Given that the minimum requirement is that the BCR

should exceed one, the figures shown highlight how far from economic acceptability the culling approaches are.

Table 9.1: Estimated costs and benefits (undiscounted) for a culling programme carried out over a 100km² area for five years.

Culling method	Annual cost of culling per km ² #	Total culling cost (75km ² for 5 years) ^a	Value of changes in breakdown numbers over a 5-year culling programme§			Benefit–cost ratio
			Direct benefit from culling (100km ² area)⌘	Negative benefit from culling (‘edge’ effect)+	Net culling benefit (total area affected)	
Cage trapping	£3,800	£1,425,000	£313,200	–£275,400	£37,800	0.027
Gassing	£2,390	£896,250	£313,200	–£275,400	£37,800	0.042
Snaring	£2,460	£922,500	£313,200	–£275,400	£37,800	0.041
Farmer licensing	£1,000	£350,000	£313,200	–£275,400	£37,800	0.108

Derived from Defra, 2005b

^a Assumes 75% access to overall land area

§ Benefit of one breakdown prevented valued at £27,000. Assumes beneficial and adverse effects of culling as found in the RBCT

⌘ 23.2% reduction in breakdowns equivalent to 11.6 fewer breakdowns over five years

+ 24.5% increase in breakdowns equivalent to 10.2 extra breakdowns over five years

9.26 Making favourable (but realistic) adjustments to the parameters of cost, benefit and herd incidence, as discussed in the previous paragraph could ease the conditions for economic acceptability of these different culling methods. Nevertheless, there is no avoiding the implications of the scientific findings of the RBCT, that the beneficial effects of culling badgers from one area of land has adverse effects on herd breakdowns in adjacent areas, and these seriously undermine the economic merits of the whole strategy. Even if the cheapest possible methods of culling are adopted these negative side effects still dominate the overall outcomes. The burden of this whole discussion, therefore, is that without even attempting a detailed CBA the clear indications are that badger culling, by whatever method adopted, is simply not a cost effective means to control cattle TB.

Confirmed and unconfirmed breakdowns

9.27 From an economic standpoint it is immaterial in the first instance whether a breakdown is confirmed or not because it still imposes the same sort of costs on the cattle economy and hence would yield the same sort of benefits if it were prevented. Reactors are slaughtered, movement restrictions imposed, laboratory culture and additional testing takes place, and so all of the costs associated with the disclosure of a breakdown are incurred. The only difference is that, if breakdowns are unconfirmed, they are generally of shorter duration and result in the slaughter of fewer cattle than a confirmed breakdown, and so the overall magnitude of cost they impose is less.

9.28 It seems well worthwhile examining whether, by applying more time, care and resources to the laboratory culture processes, the rate of confirmation could be increased and more true cases correctly identified. Given the risk of disease spread within and between herds if infection is missed, and the consequent high economic costs that this implies, it may be the case that a greater investment in investigation resources, or even taking a more 'hard line' attitude in dealing with unconfirmed cases (especially targeted towards high risk herd situations) could offer substantial economic returns.

10. POLICY OPTIONS FOR TB CONTROL

Options involving badger management

10.1 Having reviewed the impacts of badger culling on TB incidence in cattle, along with the ecological mechanisms underlying these effects, we here evaluate various forms of badger management as potential strategies for the control of cattle TB. As well as discussing the RBCT treatments themselves, we consider a variety of other culling approaches, some of which have been proposed as future policy options by interested groups. We also discuss non-lethal measures that might be taken to reduce contact between badgers and cattle.

RBCT culling treatments

10.2 The RBCT was designed as a trial, under field conditions, of two culling options which could potentially be employed as elements of a future TB control strategy. Here, we briefly discuss the utility of these two options in the light of RBCT findings. We later discuss whether modifications of these approaches would usefully contribute to TB control.

(a) Reactive culling

10.3 Reactive (localised) culling was designed to target badger social groups which could have caused specific TB breakdowns in cattle. Since it entailed removal of only moderate numbers of badgers, it was expected to be both cheaper and more publicly acceptable than more widespread culling.

10.4 Reactive culling was associated with increased cattle TB incidence in the RBCT (Chapter 5). This is consistent with the failure of previous localised culling strategies (particularly the ‘interim strategy’) to control cattle TB (details in Chapter 1). Plausible and consistent ecological explanations for this detrimental effect are available (Chapter 4). It is therefore highly unlikely that reactive culling – as practised in the RBCT – could contribute, other than negatively, to future TB control strategies.

(b) Proactive culling

10.5 Proactive (widespread) culling was associated with reduced TB incidence inside culled areas, but increased incidence on neighbouring land (Chapter 5). Similar beneficial effects of widespread culling were documented inside the Thornbury area, and in Ireland’s East Offaly and Four Areas Trials. None of these earlier studies investigated the effect of culling on TB incidence in neighbouring areas; however detrimental effects may have been weak in Thornbury and the Four Areas Trial because culling area boundaries were largely impermeable to badgers. As was the case for reactive culling, a plausible and consistent ecological explanation is available for the simultaneous beneficial and detrimental effects of RBCT proactive culling on cattle TB (see Chapter 4).

10.6 The magnitude of these beneficial and detrimental effects changed on successive proactive culls, so that the overall effect was initially detrimental, but became moderately beneficial after 3-4 culls (Chapter 5). The overall benefits were sufficiently small, however, that the economic costs greatly outweighed the benefits (Chapter 9).

10.7 Given the very high cost of proactive culling as conducted in the RBCT, and the much more modest benefits (including detrimental effects for large numbers of farmers), this approach appears unlikely to contribute effectively to the future control of cattle TB.

Could RBCT culling approaches be usefully adapted?

10.8 The RBCT tested the two approaches to culling which appeared most promising at the time of its instigation. However, it is important to be aware that the impacts of culling observed in the RBCT are likely to be specific to the circumstances under which the study was conducted, and the methods used. Were culling to be conducted on different spatial scales, using different trapping methods, or under different landscape conditions, its effects on cattle TB would be quantitatively (and perhaps also qualitatively) different from those recorded in the RBCT. Fortunately, the RBCT and associated research have provided valuable insights into the ecology and epidemiology of *M. bovis* in British agricultural landscapes, and how badger culling affects TB dynamics. It is therefore possible to use RBCT and other findings to make plausible extrapolations about the likely outcomes of several modifications of RBCT culling approaches.

10.9 Various modifications of RBCT culling procedures could be considered which might be expected to influence the costs and benefits of culling. Here, we use RBCT and other data to project the likely consequences of such alternative approaches.

(a) *Approaches based on proactive culling*

(i) *Improving culling efficiency*

10.10 All RBCT culling was conducted using cage traps. Other methods, such as gassing and snaring, have the potential to kill a higher proportion of the badger population than was achievable by cage trapping (although at the potential cost of greater real or perceived impacts on badger welfare), and might therefore be expected to influence culling outcomes.

10.11 In considering the impact of culling efficiency, it is important to appreciate that the badger population present in an area subjected to repeated culling will be composed of three types of animals: those that evaded capture on the most recent cull, those born in the area since the most recent cull, and those that have immigrated into the area since the most recent cull. Improved culling efficiency would reduce the numbers evading capture, and could therefore be expected to have an indirect effect on the numbers born. However, it would not reduce the number of immigrants, and might even increase immigration rates. Since both ecological and genetic evidence indicate substantial immigration of badgers into RBCT proactive areas (Chapter 4), improvements in culling efficiency might not generate proportional reductions in badger density.

10.12 Even if improved culling efficiency were to cause reductions in badger density substantially greater than those achieved in the RBCT, mathematical models predict that this might generate only small improvements in cattle TB incidence (Smith *et al.*, 2001; Cox *et al.*, 2005).

10.13 Improved culling efficiency would not be expected to lessen the detrimental effects of culling observed on farms located just outside culling area boundaries. In the RBCT, such detrimental effects were associated with disruption of badger social and territorial organisation caused by culling on nearby land. Since similar (or, possibly, greater) disruption would be caused by more efficient culling methods, similar detrimental effects are to be expected.

10.14 We therefore conclude that improvements in culling efficiency – if implemented in isolation from other changes – are unlikely to generate benefits substantially greater than those recorded in the RBCT. We also note that these alternative culling methods, which are widely perceived to be less humane than cage trapping, have been shown to be less publicly acceptable than those used in the RBCT (Defra, 2006b).

(ii) Proactive culling using different configurations of operations

10.15 It has been suggested informally that detrimental effects on land neighbouring proactive culling areas might be neutralised by culling boundary areas first, and moving in towards the core. However, we see no good reason why this ‘outside-in’ approach would be expected to reduce these detrimental effects. This approach would resemble the ‘sector-based’ operations conducted on a small number of proactive culls (Chapter 4). ‘Sector-based’ culling prompted increases in *M. bovis* prevalence in badgers more marked than those observed on proactive culls conducted as single operations (Chapter 4), and a similar effect would be expected for any form of proactive culling not conducted in a simultaneous fashion across all areas. Hence, the ‘outside-in’ approach could prompt particularly marked increases in *M. bovis* prevalence in badgers, further undermining any beneficial effects of reduced badger density for cattle TB. Moreover, the ‘outside-in’ approach would be expected to result in detrimental edge effects comparable with those recorded on land neighbouring proactive trial areas.

(iii) Proactive culling over larger areas

10.16 Proactive culling, as conducted in the RBCT, had a limited capacity to control cattle TB (Chapter 5). This was partly because some of the beneficial effects observed inside culling areas were offset by detrimental effects outside. However, the relative importance of these beneficial and detrimental effects would be expected to vary with the size of the culling area, since larger areas have lower perimeter:area ratios. This means that, were culling to be conducted over spatial scales larger than those used in the RBCT (100km²), the overall benefits could be expected to be relatively greater – although in absolute terms the numbers of breakdowns both induced and prevented would be increased.

10.17 While culling badgers over larger areas could in principle generate greater overall benefits than those recorded in the RBCT (Chapter 5), two important issues need to be taken into account. First, a careful analysis would need to be undertaken to determine whether the benefits (in terms of disease control) of very large scale culling would make this approach economically worthwhile. Analyses presented in Chapter 9 indicate that, even in the absence of any detrimental edge effect, the costs of badger culling (as conducted in the RBCT) greatly exceeded the economic benefits per unit area. Alternative capture methods such as gassing and snaring are estimated to be less costly than cage trapping (Defra, 2005b), but these lower costs are insufficient to make culling worthwhile unless such methods also prevent substantially larger numbers of breakdowns (which appears unlikely, see above and Chapter 9). Hence, although culling over larger areas would dilute the detrimental ‘edge effect’, it would be unlikely to generate net benefits in economic terms.

10.18 A second concern associated with culling badgers over very large areas relates to the environmental sustainability of this approach. Removing badgers from the agricultural ecosystem has environmental impacts (Chapter 4) which would need to be taken into

account, alongside the need to comply with international treaties on wildlife conservation (Council of Europe, 1979) and the need to conduct management in ways acceptable to the general public (Defra, 2005a). Large scale removal is known to be less acceptable to the general public than more constrained approaches (Defra, 2006b).

(iv) Proactive culling in areas with boundaries impermeable to badgers

10.19 The detrimental effects observed on farms neighbouring proactive culling areas have been attributed to culling-induced disruption of nearby badger populations (Chapter 4, Chapter 5). Likewise, the culling-associated increase in badger *M. bovis* prevalence, which may have undermined the beneficial effects of culling inside proactive areas, appears to be caused in part by immigration of badgers from neighbouring areas (see Chapter 4). Since these effects are likely to be greatly reduced where the boundaries of trial areas are relatively impermeable to badgers, culling might be more effective in areas bounded by coastline, major rivers, motorways and large conurbations. The greater reductions in cattle TB incidence reported from Ireland's Four Areas Trial may in part reflect the deliberate siting of culling areas in locations with badger-impermeable boundaries.

10.20 While culling within existing geographical boundaries is appealing in principle, in practice there are currently few such barriers in TB-affected areas. The coastline of the southwest peninsula, the M4 and M5 motorways, and rivers such as the Severn and the Wye, provide potential barriers but are too sparse to indicate clearly-defined culling areas. It is worth noting that in the RBCT, the TB-affected region with the clearest geographical boundaries – the Penwith peninsula in West Cornwall – also experienced the lowest level of landholder consent and the highest level of interference with trapping of any RBCT area (Chapter 4). Overall, while culling within existing natural or man-made barriers may have relevance to a small number of isolated areas, it offers little promise for TB control in the key 'hotspot' areas.

10.21 In principle, it would be possible to construct badger-proof boundaries around areas to be culled. However, it is difficult to exclude badgers by fencing: their ability to both dig and climb means that specially designed fences are needed (Harris *et al.*, 1994; Poole *et al.*, 2002). These fences are expensive to construct and maintain (the latter being particularly important for electrified fences, Poole *et al.*, 2002), and the costs are likely to be very large in comparison with the benefits. Moreover, fencing on all but the smallest scales would be influenced by the need to keep roads open; electrified grids prevent entry of wildlife into the Channel Tunnel, but installing and maintaining such barriers across the many roads that traverse TB hotspots would be highly problematic. Hence, culling within artificially-constructed boundaries is likely to contribute to TB control only on a very local scale.

(v) Proactive culling in areas adjoining land with low or zero TB risk

10.22 In principle, the detrimental effect of badger culling could be eliminated if neighbouring areas had either no badgers, or no cattle. Badgers are widely distributed in and around TB-affected areas of Britain, so the former would be difficult to achieve. While cattle might in theory be removed from adjoining land through appropriate incentives, this is unlikely to be practicable and it is highly unlikely that the costs of such measures would approach the benefits.

10.23 A less draconian approach would be to locate culling areas so that they adjoin areas of low underlying cattle TB risk. As discussed in Chapter 5, a proportional increase in

cattle TB incidence in such areas would equate to a smaller absolute number of breakdowns induced than was observed immediately outside RBCT areas. This approach might reduce – though not eliminate – the detrimental edge effect. However, it is likely that this approach would also prevent fewer breakdowns than did proactive culling as conducted in the RBCT. This is because TB ‘hotspots’ do not have sharply defined boundaries. Positioning culling areas so that they adjoined land of low cattle TB risk would therefore be likely to involve culling some areas of moderate (rather than high) TB risk, with a proportional reduction in risk therefore representing fewer breakdowns prevented. It is also worth noting that such an approach would entail a risk of spreading infection across the landscape. This approach is unlikely, therefore, to achieve greater overall benefits than did the RBCT.

(vi) Prevent recolonisation by destroying setts

10.24 It has been suggested that badger recolonisation of culled areas might be prevented by destroying setts once culling is complete (e.g. British Veterinary Association, 2005). While such measures might impede or divert immigration in the short term, it is very unlikely that they would greatly reduce recolonisation rates. Badgers regularly dig new setts (e.g. da Silva, Woodroffe and Macdonald, 1993) and would be expected to do so rapidly at sites with appropriate habitat and geological conditions (often but not invariably the sites of old setts), as long as foraging habitat remained available. Given the difficulty of accessing setts with the heavy machinery needed to destroy them, the costs of this approach are likely to be high, while the potential benefits appear small.

(b) Approaches based on reactive culling

(i) Improving culling efficiency

10.25 All RBCT culling was conducted using cage traps. As discussed above for proactive culling, it is possible that other measures such as snaring or gassing could remove a larger proportion of the original badgers, with a theoretical capacity to reduce TB risks to the targeted herd(s). However, since reactive culling successfully removed badgers spatially associated with herd breakdowns, markedly reducing badger density (Chapter 4), yet did not reduce local TB risks for cattle (Chapter 5), any such beneficial effects are expected to be small.

10.26 Recolonisation of small, localised culling areas is expected to be rapid (Chapter 4); this may help to explain the lack of beneficial effects for herds targeted by reactive culling. Whatever the efficiency of the original cull, detrimental ‘edge effects’ are to be expected, of magnitude comparable with those recorded in the reactive strategy (Chapter 5). This suggests that improvements in capture efficiency – if conducted in isolation – are very unlikely to generate overall beneficial effects from localised culling.

(ii) Reactive culling over larger areas

10.27 Available evidence strongly suggests that the reason for the failure of reactive culling to control cattle TB was that culled areas were so small that detrimental effects on nearby uncultured farms outweighed any possible benefits in culled areas (Chapter 5). This indicates that reactive culling conducted over larger areas might be more beneficial. Such hypothetical culling areas would be similar to the proactive areas discussed above; hence refer to the preceding paragraphs (10.17 – 10.18) for a detailed discussion of the likely consequences of reactive culling over larger areas. However, since the costs of proactive

culling appear to substantially outweigh the benefits, even when conducted on very large scales, such a reactive approach is unlikely to generate overall benefits for the control of cattle TB.

(iii) Repeated reactive culling

10.28 In the RBCT, each reactive cull was a one-off event; recolonisation of culled areas is likely to have been rapid. It is conceivable that greater protection of cattle herds might be achieved by repeating reactive culls, as was conducted for proactive culling. However, available data provide no evidence to suggest that this approach would be effective. A reduction in detrimental effects was observed following the suspension of reactive culling (Chapter 5), probably because re-establishment of a stable badger spatial organisation slowed disease spread. By contrast, repeated culling would sustain perturbation, and such culling was associated with elevated *M. bovis* prevalence in badgers in both proactive and reactive areas (Chapter 4). Hence, repeated reactive culling appears likely to increase, rather than decrease, the detrimental effect associated with localised culling.

(iv) Reactive culling conducted more rapidly after detection of infection in cattle

10.29 There is an inevitable time lag between the time of infection of herds and the detection of disease by herd testing, and a further time lag between confirmation of infection in cattle and culling of badgers. These time lags were considered potential weaknesses of the reactive strategy, since they allowed opportunities for badgers associated with particular breakdowns to infect additional cattle. Delays were an inevitable component of the reactive strategy since:

- (i) reactive culling was conducted in response to confirmed breakdowns, and several weeks may elapse between the detection and confirmation of a breakdown;
- (ii) reactive operations were often postponed until herds contiguous with the original breakdown herd had been tested, to ensure inclusion of all land associated with a breakdown cluster;
- (iii) additional surveying was often needed to prepare for culling;
- (iv) reactive and proactive operations were conducted by the same teams, necessitating that the two strategies follow complementary timetables; and
- (v) no culling could be conducted during the closed season.

10.30 Modification of culling practices (e.g. abandonment of the closed season, involvement of more staff, culling in response to unconfirmed breakdowns) could potentially allow culling teams to respond to herd breakdowns more rapidly than was possible in the RBCT.

10.31 The mechanism whereby such ‘rapid response’ reactive culling might be expected to generate beneficial effects for cattle would be by removing infected badgers before infection could spread to additional cattle. Such rapid removal would not, however, address the detrimental ‘edge effect’ which was the main weakness of reactive culling. Indeed, if ‘rapid response’ reactive culling was conducted without waiting for contiguous testing to identify other affected herds in the area, it could lead to smaller culling areas,

with consequently greater edge effects. Such an approach therefore appears to offer little promise of an effective control strategy for cattle TB.

10.32 Based on an assessment of modified forms of reactive culling we recommend that none is suitable as a base for TB control.

Culling badgers under licence

10.33 A consultation document issued in 2005 (Defra, 2005a) suggested that the costs (to Defra) of culling badgers would be greatly reduced if operations were conducted under licence by farmers (or their appointees), rather than by Defra staff. If such licensed culling could generate benefits (in terms of disease control) comparable with those achieved in the RBCT, it might in principle provide an economically viable policy for TB control (although calculations presented in Chapter 9 suggest that this is unlikely). The outcome of such licensed culling would depend upon the methods used, and the geographic area covered.

10.34 If licences were granted to individual farmers to cull badgers on their own land, culling would be localised – somewhat akin to the interim strategy, in which culling operations were restricted to the farms on which recent breakdowns had occurred (Chapter 1). RBCT data strongly suggest that any such localised culling would be likely to elevate, rather than reduce, the overall incidence of cattle TB.

10.35 The detrimental effects of localised culling could in principle be reduced (in relative though not absolute terms) if landholders across a sufficiently large area conducted culls in a coordinated manner. However, we consider it unlikely that such coordinated culling would achieve benefits comparable with those experienced in the RBCT proactive culling treatment. There are several reasons for this view:

- (i) Acquiring permission to cull on scales comparable to those used in the RBCT is a logistically demanding exercise. In seeking landholder consent to participate in the RBCT, Defra contacted about 180 landholders, on average, in each 100km² trial area. Even with the resources available to a large Government department, Defra was unable to contact landholders for 13% of land inside proactive areas. Were culling to be conducted by farmers, informal coordination would be likely to generate culling areas which are less compact than those in the RBCT, possibly leading to greater internal and external ‘edge effects’;
- (ii) Culling would be likely to cover a smaller proportion of the land area than occurred in the RBCT. Defra staff were given consent to cull badgers on 70% of land inside proactive trial areas. However, capture efficiency was extended by trapping along the boundaries of inaccessible land and this procedure appears to have contributed to the overall beneficial effect of proactive culling (Chapter 5). This practice requires skill and experience that would not be immediately available to farmers conducting their own culls (it may also carry a welfare cost for badgers as it captured actively lactating females but failed to catch their cubs (Chapter 4));
- (iii) It is almost certain that, for logistical reasons, culls would not be conducted simultaneously across areas, yet RBCT data suggest that simultaneous culling is vital. Most RBCT proactive culls were conducted in single operations across entire areas; this entailed deployment of over 500 traps, on average, on each

initial cull. It is extremely unlikely that farmers (or contractors) could coordinate simultaneous operations on this scale, whatever the culling method used. This is cause for concern, because on the few occasions when RBCT proactive culls were conducted sequentially in smaller sectors, the culling-induced increase in *M. bovis* prevalence in badgers was significantly greater (Chapter 4). Hence, sector-based culling conducted by farmers (or their contractors) would be expected to generate increases in *M. bovis* prevalence in badgers greater than those observed in the RBCT. This means that culling-induced increases in *M. bovis* infection in badgers could undermine beneficial effects for cattle to a greater extent than occurred in the RBCT; and,

- (iv) A further demanding requirement would be the need to repeat culls regularly. RBCT findings show that badger culling reduced cattle TB only when it was repeated regularly: proactive culling had overall detrimental effects between the first and second culls, and became beneficial only after the third or fourth cull (Chapter 5). Hence, any farmer-led operations would have to coordinate culling over large areas not once, but repeatedly over several years. This could inhibit or erode compliance, potentially causing detrimental effects. Eventual cessation of culling would be expected to prompt a return to original conditions of cattle TB risk.

10.36 Given these difficulties, we consider it likely that licensing farmers (or their appointees) to cull badgers would not only fail to achieve a beneficial effect, but would entail a substantial risk of increasing the incidence of cattle TB and spreading the disease in space, whether licences were issued to individual farmers or to groups. This would have economic implications for Government, and could also have legal consequences (UK Parliament, 1992).

Other approaches to badger culling

10.37 The discussions above concern comparatively minor adjustments to the culling practices conducted in the RBCT. Here, we consider other potential approaches to badger culling which might influence cattle TB risks through very different mechanisms.

(i) Culling in response to detection of infection in road-killed badgers

10.38 Most previous culling strategies have been conducted in response to confirmed breakdowns in cattle herds. An alternative approach would be to cull in response to detection of infection in badgers. One way of doing this would be to use road-killed badgers as a sentinel of local infection. However, as described in Chapter 4, detection of infection in road-killed badgers was a very poor indicator of local TB risk to cattle. Hence, localised culling in response to confirmation of infection in road-killed badgers would seem likely to generate the detrimental effects of reactive culling, without the putative benefits.

(ii) Selective culling of infected badgers

10.39 Many diseases (including TB) have been successfully controlled in livestock by selective slaughter of infected animals. It is appealing, therefore, to extend this logic to badgers. Such a ‘test-and-slaughter’ approach to badger culling has been considered repeatedly in the past, but has been constrained by the lack of a reliable live test. In particular, the ‘Live Test Trial’, conducted in the early 1990s, tried to reduce *M. bovis* transmission

by using an ELISA blood test to identify and cull groups of badgers showing evidence of infection. However, the test's low sensitivity severely constrained abilities to identify and remove infected social groups (Woodroffe *et al.*, 1999). This trial was abandoned, and its effects on cattle TB are therefore unknown; however as data suggest that this approach was unlikely to achieve substantial reductions in either badger density or the prevalence of infection in badgers (Woodroffe *et al.*, 1999), beneficial effects for cattle appear unlikely.

10.40 More recently, molecular methods have been used to detect mycobacteria in the environment (Courtenay *et al.*, 2006), raising the possibility that such methods could be used to target culling at infected social groups. However, these tests have limitations (de la Rua-Domenech *et al.*, 2006), positive sample rates are extremely high and specificity – as well as relevance to transmission – are unknown.

10.41 Since *M. bovis* infections are clustered within badger populations on a scale of 1-2km (Chapter 4), any approach entailing selective removal of infected badgers (or badger social groups) is likely to involve localised culling. Such removals would involve a substantial proportion of the badger population in TB-affected areas: on RBCT initial proactive culls, 12.0% of adult badgers, and 33.5% of social groups, showed evidence of *M. bovis* infection at post mortem examination (Chapter 4), and weaknesses in diagnostic methodologies suggest that this was an under-estimate of the true prevalence (Chapter 4). Even if all infected animals within a social group could be correctly identified and removed, such localised culling would be likely to disrupt social organisation, encourage immigration, and increase mixing within the badger population. This would encourage transmission unless conducted simultaneously across extremely large spatial scales. The finding that infected badgers appear to range more widely and disperse further than uninfected animals (Garnett *et al.*, 2005; Pope *et al.*, 2007) makes such an outcome particularly likely. Imperfect detection of infection in badgers, and imperfect badger removal, elevate the chances that selective removal would lead to increased contact rates and increased transmission.

10.42 These scientific data suggest that a test-and-slaughter approach is very unlikely to reliably reduce the prevalence of *M. bovis* infection in badgers, and could increase overall infection rates. Such an approach is therefore unlikely to reduce TB risks for cattle. It would also be extremely costly.

(iii) *Culling at 'hospital setts'*

10.43 It has been proposed that infection might be controlled by repeated culling of badgers at a number of 'hospital setts'. This suggestion stems from the speculation that *M. bovis* infected badgers may be "expelled from their own setts due to disease...[making them]...more likely to colonise setts vacated by other badgers as they are too weak to dig their own.." (British Veterinary Association, 2005). However, as the majority of infected badgers show very mild pathology (see Chapter 4), it is extremely unlikely that any but a very small proportion are too weak to dig setts; moreover setts persist for many generations and few badgers inhabit setts they initiated themselves. While infected badgers may be statistically more likely to disperse long distances than are uninfected animals (Pope *et al.*, 2007), repeated culling at vacated setts would be a highly imprecise method of removing infected badgers. Moreover, such an approach would be expected to generate detrimental effects for cattle TB risks on neighbouring lands. This highly speculative approach therefore appears to have little or nothing to contribute to future TB control strategies.

(iv) *Badger culling combined with vaccination*

10.44 Combinations of badger culling and vaccination have been considered for future use, although the lack of a vaccine with proven efficacy under field conditions currently limits discussion to theoretical considerations (Smith *et al.*, 2001). In principle, such combinations might lower transmission rates between infectious and susceptible hosts by simultaneously reducing both overall host density (through culling) and the density of susceptible hosts (through vaccination). However, the RBCT finding that contact rates between badgers apparently increase, rather than decline, in response to culling suggests that, were a vaccine available for badgers, its effectiveness at the population level would be undermined, rather than reinforced, by combining it with culling. General models of wildlife disease likewise predict that culling and vaccination are more likely to achieve control when deployed separately rather than in combination (Barlow, 1996). In addition, given the recognised requirement for a practical vaccine for badgers to be delivered orally via baits (Chapter 8), the incorporation of culling into a badger vaccination programme would substantially increase the costs and would be difficult to apply across large areas of the country.

Conclusions regarding badger culling

10.45 None of the badger culling options discussed here shows promise of contributing to the control of cattle TB in a manner which is economically viable. Of the culling approaches that were formally tested in the RBCT, reactive culling generated overall detrimental effects, while proactive culling achieved very modest overall benefits only after the investment of sustained culling effort, by professional staff, over several years, and at the cost of elevated incidence on neighbouring farms. The reasons for the limited capacity of badger culling – as conducted in the RBCT – to substantially reduce overall TB incidence in cattle stem from the behavioural and ecological responses of badgers to culling, leading to strongly nonlinear relationships between badger density and *M. bovis* transmission.

10.46 Insights derived from the RBCT, and from other research, indicate that these limitations on the beneficial effects of RBCT culling are likely to influence other approaches to culling that might be considered for deployment in Britain. None of the measures discussed here, whether deployed in isolation or in combination, is considered likely to generate outcomes markedly more beneficial than those achieved in the RBCT; several approaches are likely to have detrimental outcomes.

10.47 We are unable to conceive of a system of culling, other than the systematic elimination, or virtual elimination, of badgers over very extensive areas, that would avoid the serious adverse consequences of perturbation. Given the logistical, economic, legal, environmental and welfare concerns associated with the methods that would need to be employed to attempt eradication on such scales, in addition to the likelihood of significant public opposition to such widespread culling (Defra, 2006b) elimination of badgers across large areas does not represent a feasible control option.

10.48 On the basis of our careful review of all currently available evidence, we conclude that badger culling is unlikely to contribute positively to the control of cattle TB in Britain.

Separating cattle and badgers

10.49 In principle, disease transmission between cattle and badgers could be reduced without badger culling, if the two host species could be physically separated. Unfortunately, lack of information concerning the precise mechanism of transmission of infection from badgers to cattle (and *vice versa*) makes it difficult to make confident predictions about effective approaches. For example, it is not known whether transmission requires direct contact between badgers and cattle, or whether infection can occur through contamination of the cattle's environment; direct respiratory transmission is the most likely, but it is possible that both transmission mechanisms contribute to the maintenance of infection. Further, if infection can occur through environmental routes, it is unclear to what extent badger faeces, urine, saliva or pus are the principle source(s) of infection. This lack of information is problematic because avoiding cattle contact with each of these excreta or secretions would entail different management approaches.

10.50 Infection could occur while cattle are grazing, or while they are housed; since badgers regularly forage on cattle pasture (Kruuk *et al.*, 1979), and frequently enter farm buildings (Garnett *et al.*, 2002), both environments offer opportunities for direct and indirect contact between cattle and badgers. While one of the analyses of risk factors presented in Chapter 6 showed strong associations between cattle TB and farmer reports of badgers in farm buildings, it is not known whether this represents opportunities for badger-to-cattle transmission of infection or simply increased awareness of badgers' presence by farmers who have recently experienced breakdowns.

10.51 Badgers enter farm buildings primarily to forage on livestock feed (e.g. cattle cake, maize silage) which are either stored there or being fed to livestock (Garnett *et al.*, 2002). Storage of such feed in badger-proof containers would presumably help to deter badgers and limit opportunities for both direct and indirect contact with cattle. While badgers are strong, reasonably agile, animals able to gain access to many different sorts of containers, lockers have been devised to exclude far more formidable animals (e.g. grizzly bears, *Ursus arctos*), so developing badger-proof containers would certainly be possible. While the benefits of such an approach are unknown, the costs might not be substantial; hence improved feed storage could be worth exploring as a simple approach to reducing contact between cattle and badgers.

10.52 Badgers are also able to access cattle feed while it is in troughs being fed to cattle; video surveillance inside farm buildings revealed that badgers and cattle sometimes fed as little as 2 metres apart, and surveys have shown that feed in troughs can be contaminated with badger excreta (Garnett *et al.*, 2002). While Defra has, in the past, advised farmers to construct troughs ≥ 80 cm in height to exclude badgers, experiments showed that badgers can climb substantially higher than this level (Garnett *et al.*, 2003). While no simple trough seemed high enough to exclude badgers yet low enough to be accessible to calves (Garnett *et al.*, 2003), it would probably be possible to devise a trough that could be used by cattle but not badgers. Once again, the capacity of such a device to reduce TB risks to cattle is not guaranteed but, given the technologically advanced systems used to feed cattle on some farms, this possibility could be worth exploring.

10.53 Badgers could also, in principle, be excluded from the vicinity of farm buildings by electric fencing. However, the fencing needed to exclude badgers – which can both climb and dig – is substantial and consequently costly (Poole *et al.*, 2002). Once again, benefits are unknown and the costs might be difficult to justify.

10.54 Separating cattle and badgers on pasture land is more problematic than excluding badgers from farm buildings. Cattle pasture is prime foraging habitat for badgers (Kruuk *et al.*, 1979; da Silva, *et al.*, 1993) and, while badgers and cattle are rarely in close proximity to one another on pasture land (Benham, 1985), there are multiple opportunities for indirect contact. As mentioned above, badger-proof fencing is expensive to both build and maintain (Poole *et al.*, 2002) but on a limited scale might be appropriate for some farms. Efforts would be needed to ensure that no badgers were (or remained) inside the fence; the possibility of culling badgers inside fenced areas was discussed in paragraph 10.21.

10.55 In the past, Defra has advised farmers to fence cattle away from badger setts and latrines, which are associated with relatively high densities of badger excreta and might therefore be high risk sites for cattle to become infected. Unfortunately, badger latrines are not fixed in space. Indeed, badgers prefer to place latrines close to fences (Delahay *et al.*, 2007), so it is quite conceivable that fencing around a latrine could simply cause the badgers to shift the latrine to both sides of the fence. Physically removing latrines does not prevent badgers from continuing to defecate at the same sites (King, 1997).

10.56 This information indicates that it is not currently possible to make quantified, informed recommendations about measures to prevent direct or indirect contact between cattle and badgers that will reduce risks of TB transmission. However, some research is in progress on this issue, and should be continued, as it is important to generate more specific advice. In the meantime, several reasonable suggestions can be made; these mostly involve discouraging badgers from entering farm buildings. See also the advice developed by the Bovine TB Husbandry Working Group (<http://www.defra.gov.uk/animalh/tb/abouttb/protect.htm>; Defra, 2007b). Although the potential benefits of these measures are currently unknown, in many cases the costs may be comparatively small and therefore the approaches arguably worth adopting, especially as some (e.g. discouraging badgers from taking stored feed) have other benefits including reduced wastage and exclusion of other pests such as rats.

Options based on cattle controls

10.57 We have concluded that to be successful future control strategies for cattle TB, in the absence of effective vaccines to control the disease in wildlife, will require heightened measures directly targeting cattle.

10.58 Cattle herd TB breakdowns affect only a small percentage of herds nationally (2.6% of herds disclosed new TB breakdowns in 2005, source VLA, and see Chapter 7, Table 7.1) and even in high disease risk areas, although there are foci where a large proportion of herds are affected, overall the large majority of herds remain free of the disease. Nonetheless the year-on-year rise in incidence, local spread of the disease in high risk areas and the increasingly wide geographical spread of the disease to distant parts of the country associated with the movement of infected cattle (Gopal *et al.*, 2006; Carrique-Mas *et al.*, 2006) all suggest that cattle TB is largely out of control in some areas, causing serious disruption to farming activities at considerable economic cost and distress to farmers. The national disease control and surveillance strategies that have been in place since the 1970s are clearly inadequate and although persistent infection within the badger population will result in a residual level of infection in cattle, it is essential that more effective cattle based control measures be adopted.

10.59 The following recommendations for future improved control of the disease are informed by past successes and failures with the measures applied, by improved understanding of disease epidemiology and pathogenesis and by technological advances in disease diagnosis.

10.60 Mathematical models have indicated that the basic reproduction number for between-herd infection in cattle in Great Britain is about 1.1 (Cox *et al.*, 2005 and Chapter 7). This means that, for each new TB herd breakdown identified, on average a further 1.1 new herd breakdowns arise. Notwithstanding the contribution that badgers make to cattle TB, the value of 1.1 suggests that relatively modest changes aimed at more effective detection of infected cattle and prevention of their movement between herds would force the critical value below 1, leading to a reverse in the upward trend in incidence. The major epidemiological factor influencing this, in addition to transmission from wildlife, is the presence of undiagnosed cattle that can act as a source for amplifying infection within herds and for exacerbating spread of infection by movement of infected cattle between herds. Therefore, improved diagnosis and more rigorous cattle movement controls should be key to the success of any future control policy.

10.61 In considering what measures might be taken, it is important to distinguish between those parts of the country with a relatively high risk of disease, where infection is established and where there is a wildlife reservoir of infection, and the remainder of the country (low risk areas) where sporadic infection occurs, largely as a consequence of spillover from the high risk areas by the movement of infected cattle. High risk areas are experiencing a year-on-year increase in incidence and local foci (or hotspots) that historically have had a particularly high disease incidence are expanding. This in turn has increased the risk of disease spread by cattle into low risk areas. Therefore, a primary objective of future control strategies must be to prevent further disease spread into these areas. This necessitates a clear distinction between surveillance to detect early spread of infection and control functions aimed at eliminating the infection in new areas.

10.62 Given the demonstrated limitations of the tuberculin skin test, future control policies will require strategic use of the IFN test. Although there is clear evidence that use of the IFN test can enhance detection of infected cattle, field data on how the test might be most appropriately applied in various control strategies in Great Britain are unfortunately still lacking. Therefore, the IFN test should be used in a carefully planned way that will provide essential new scientific data, allowing adaptive management of the disease by further refinement of control strategies where appropriate.

10.63 We are aware that Defra have recently tightened TB control measures in cattle. The following recommendations are intended to reinforce these recent changes. They are not intended to be prescriptive, but rather to highlight major considerations for a more successful future cattle TB control programme.

Control of Cattle Movement

10.64 The movement of TB-infected cattle, as part of normal animal trading practices, poses the greatest threat to the disease security of uninfected farms and particularly so in the case of farms in low disease risk areas. Given the high proportion of animal movements that occur at a local level, they are also likely to make a significant contribution to the local spread of infection in high risk areas. Although the introduction of pre-movement testing is an important step to address this problem, its success is dependent on the reliability of the

test used; this leads us to conclude that it is only likely to be partially effective. Therefore, the ISG recommends that introduction of more thorough movement controls should be considered which could be expected to have a more substantial and immediate impact on disease spread:

- (i) Cattle movement could be controlled by zoning the country into relatively low disease risk and high disease risk areas, and by prohibiting animal movement from high to low risk areas. While this would provide protection to low risk areas, it would not have an impact on breakdowns caused by animal movements within high risk areas and indeed (in the absence of rigorous pre-movement testing) might increase local spread of disease as a result of increased local trading of cattle;
- (ii) A more flexible, and possibly more effective, movement control option would be to categorise farms as either low or high disease risk status and to then control cattle movement between the two categories of holding. Freedom from disease for three to four years, based on previous annual testing history, would be the main criterion for classifying farms as low disease risk. Movement of animals from high risk to low risk farms would not be sanctioned. This would have the advantage of protecting low risk farms within high risk areas but also allow high risk farms to upgrade their status following a successful history of TB control;
- (iii) To reinforce cattle movement controls, more rigorous pre-movement testing protocols, involving combined use of the tuberculin and IFN tests, could be used. Such testing could be applied to all animals moving from high risk areas and any other areas with a recent history of cattle TB. Animals that gave a positive result in one or both tests would not be permitted to move. This option would also yield valuable new data on use of the IFN test in the field; and,
- (iv) It would be desirable, in some situations, for purchased animals to be isolated for a period of 3-4 weeks and retested (post-movement testing) by combined use of the tuberculin and IFN test prior to introduction into the herd.

Disease Control in Low Risk Areas

(a) Preventing introduction of infection

10.65 Since many of the breakdowns that occur in low risk areas are believed to originate from movement of infected animals from high risk areas, emphasis should be placed on prevention of such movements utilising one or more of the options outlined above.

(b) Dealing with herd breakdowns

10.66 Elimination of infection from all breakdown herds, to prevent establishment of persistent foci of infection, should be a policy priority in low disease risk areas, requiring a more thorough approach than at present. Breakdown herds with one or two reactors at the disclosing tuberculin test, and no previous breakdown history, should be subjected to one follow-up IFN test, repeated, dependent upon its outcome.

10.67 Additional measures could be prescribed for dealing with multiple reactor herds in low risk areas, dependent on the number of reactors at the disclosing and first short interval tests, the severity of disease detected at post-mortem examination and the herd size. These could involve further application of the IFN test in parallel with the tuberculin test, or slaughter of the whole herd or cohorts of animals in affected herds. It would be advisable to be rigorous in these situations and whole herd slaughter should be a more readily exercised option for heavily infected herds.

(c) Surveillance

10.68 The adequacy of disease surveillance in low risk areas, which is currently based on 3- or 4-yearly testing and follow-up testing of herds with which breakdown herds have traded animals, complemented by slaughterhouse inspection of carcasses, must be questioned (Mitchell *et al.*, 2005). Given the high throughput of animals in slaughterhouses, the scope for improving detection of infected animals by more detailed carcass inspection is likely to be limited. In the absence of any new movement controls, more frequent, possibly annual, skin testing of all farms should be considered. Even with the imposition of movement controls as suggested above, modification of testing intervals to a maximum of two or three years, focused on individual farms rather than parishes, but with possible clusters of herds, should be considered.

Disease Control in High Risk Areas

10.69 It is important to acknowledge the persistent nature of infection in many farms in high risk areas and to recognise that elimination of infection from some of these areas is unrealistic in anything other than the very long term. This problem is a consequence both of a failure of testing to remove all infected cattle on some farms and, in some cases, re-introduction of infection from wildlife. Control measures adopted must be effective in driving down the incidence but be proportionate so as to allow farms, even though not confirmed clear of infection, to continue trading.

10.70 A proportionate, pragmatic, approach to improved disease control in these areas, involving application of different measures dependent on the status of the breakdown farm, would therefore be applied. A key element of this approach would be to apply more rigorous testing but to reduce the durations of herd restriction. The overall objective, over a period of time, would be to reduce the level of infection by minimising between-herd spread and reducing the reservoir of infection within herds.

(a) Preventing spread between herds

10.71 This would be achieved by applying movement restrictions and more rigorous pre-movement testing as discussed in paragraph 10.64.

(b) Dealing with herd breakdowns

10.72 The objective for herds with one or two reactors at the disclosing tuberculin skin test, which have no recent history of infection, would be to identify and remove all infected animals and strive for low disease risk status. IFN would be used as a complementary test for one or two short interval tests and herd restrictions would be maintained until the herd has had one further short interval test.

10.73 Multiple reactor herds (with three or more reactors at the disclosing test), which constitute about 40% of breakdowns in these areas, can be expected to have more established but variable infection. The control objective for these herds would be to reduce the weight of infection to an acceptable level in the first instance by removing as many infected animals as possible, but limiting the period of restriction imposed on the herds. This could be achieved by parallel use of the IFN test at the first short interval test. Movement restrictions would be lifted after a further short interval test, except in cases where more than one reactor was detected by this test.

10.74 Previous testing history will reveal a hard core, possibly 5% or more, of these multiple reactor breakdown herds in high risk areas, which have been difficult to clear of infection. These herds pose a substantial disease risk and should be considered for whole herd slaughter or slaughter of cohorts with a history of infection.

10.75 As at present, animals moved from herds within 60 days of the annual herd test would not be subjected to a pre-movement test. After this period animals would only be permitted to move to slaughter or, following pre-movement testing by the combined use of the tuberculin and IFN test, to farms of similar disease status.

(c) Surveillance

10.76 Annual testing should be applied to all cattle herds in high risk areas.

Re-stocking and biosecurity

10.77 It is essential that farms subjected to whole herd slaughter or those cleared of infection receive appropriate veterinary advice on sound, bio-secure restocking policies and in particular how to avoid purchasing infected cattle.

Refinement of diagnostic tests and testing procedures

(a) The tuberculin test

10.78 Simple statistical quality control methods should be introduced to summarise the testing outcomes in different areas and attempt to improve test performance. The time interval between tests should also be reviewed. The imposition of movement restrictions on breakdown herds has a significant economic impact on many affected farms. Even if no further reactors are found following the disclosing test, affected farms are unable to trade animals for at least 120 days (i.e. following two clear 60-day tests). The demonstration by Defra-supported research that infected animals give a positive response to the tuberculin skin test three weeks after experimental infection and that repeat testing at three week intervals has no adverse effects on the test response (Thom *et al.*, 2006) indicate that there is scope for shortening these testing intervals. In light of these findings, and in view of the potential risk of further transmission of infection by any remaining infected animals during the 60 day interval, serious consideration should be given to applying more rapid follow-up testing (e.g. 3-4 weeks) to breakdown herds. This timing would also be suitable for carrying out simultaneous IFN and tuberculin testing during a single farm visit. In order to support this approach, methods of achieving more rapid confirmation of infection in reactor cattle, such as the combined use of culture and PCR assays in laboratory diagnosis, need to be explored.

(b) Further development of the IFN test

10.79 The strategic use of the IFN test will be a crucial element of future disease control strategies. Field data on the most appropriate use of the IFN test to support a range of policy options are limited. To date, only the version of the IFN test that utilises PPD antigen preparations has been used in disease control programmes. Research on alternative use of defined *M. bovis* proteins in the test has yielded promising results (see Appendix I) and, if further developed, could result in a test with improved sensitivity and specificity. The ISG strongly recommends continued research support both for development and for field testing of improved versions of the IFN test. An eventual aim of this research should be to improve the specificity of the test to a level that would permit it to be used strategically as a primary diagnostic tool in place of the tuberculin test. The latter would require investment in infrastructure to automate the test and in systems to ensure rapid transport of samples to one or more centralised laboratories. However, use of such a test would greatly improve standardisation and quality control of testing procedures and would allow routine testing to be conducted by a single farm visit, rather than the two visits currently required for tuberculin skin testing.

(c) Application of M. bovis genotyping

10.80 Molecular analyses of *M. bovis* have led to the development of methods for identifying genotypically distinct strains of the organism (Hewinson *et al.*, 2006). Studies of field isolates using these typing methods have demonstrated that different strains of *M. bovis* have different geographical distributions within Great Britain (Smith *et al.*, 2003). Application of these typing methods in conjunction with tracing of cattle movements can thus be expected to provide valuable information on disease spread. We recommend that Defra continue to give high priority to this research and would encourage integration of the use of these methodologies into disease control strategies.

(d) Unconfirmed reactors

10.81 Some 45-50% of reactors and about 35% of breakdown herds are subsequently unconfirmed, but these still have economic consequences. Efforts should be made to determine the cause of these breakdowns and in particular what proportion have epidemiological impact.

Use of field data to inform control policy

10.82 Large amounts of statistical data relating to cattle TB are now available via databases, which include herd testing results, *M. bovis* genotypes and cattle movement records. These data provide a valuable resource for identifying changes in disease trends and for exploring improvements in disease control methods.

Analyses and presentation of cattle testing data

10.83 In conjunction with National Statistics, Defra publishes a monthly report entitled The Incidence of TB in Cattle – Great Britain, which presents numbers of cattle herds and individual cattle tested and numbers of reactor cattle and breakdown herds, recorded over the preceding months of the current year and over previous years. The report provides useful information on long-term disease trends. However, for some time the ISG has expressed reservations about the statistical presentation, particularly with respect to its

ability to identify short-term changes in patterns of disease. These concerns arise from the sensitivity of the published data to changes in testing regime frequencies of farms or parishes, between one-, two-, three- or four-year testing. Such changes, which are quite frequent, can easily generate apparent short-term increases and decreases, which are all too easy to misinterpret. Further, the data as currently published give no information about regional trends and differences (see Appendix Q).

10.84 We recommend that Defra:

- (i) Revise the current presentation of the national statistics so as to give an accurate indication of trends in TB incidence that are independent of changes in testing regime;
- (ii) Publish a version of the statistics that allows some regional comparisons; and,
- (iii) Set up a procedure to provide at a relatively local level, information about the potential development of the disease in current low risk areas.

Effective use of data to address policy needs

10.85 The ISG considers that Defra has not devoted sufficient effort to analysis of cattle testing and movement data, and that this in turn, coupled with a reluctance within Defra to consider any radical changes in control policies, has impaired the development of new policies. The ISG considers that ongoing interrogation of these data is essential to allow early identification of changes in disease patterns (e.g. emergence of new foci of infection in low risk areas), to explore new means of improving control measures and to monitor the effect of policy changes.

10.86 We strongly recommend that a group of external scientists with appropriate expertise is put in place to advise Defra on data collection and analysis, and to consider the systematic use of such data for local, regional and national monitoring of disease and for assessing the impact of changes of Government policy.

Formulation and implementation of disease control policy

10.87 We wish to commend Defra for supporting the science programme recommended to it by the ISG. Defra is fortunate to have scientific expertise available at the Veterinary Laboratories Agency (VLA) and the Central Science Laboratory (CSL), and research programmes which are of high international standing. However, we have concerns, previously expressed, concerning the capacity of Defra policy groups to translate scientific findings into policy. This we consider stems, in part, from Defra's own organisational structures which we believe enforce a separation of policy development and the scientific evidence on which policy should be based.

10.88 We strongly recommend that urgent consideration be given to ensuring that scientific expertise, particularly that available at VLA and CSL, is used more effectively to develop and implement TB control strategies and further that economic analysis, in its widest sense, be applied to evaluate the merits and distributional impacts of these strategies. It is our further considered view that effective TB control will only be achieved by assembling a small but focused, dedicated informed team made up of scientific and other experts, veterinarians with field expertise and Government policy makers, who will establish a clearly defined disease control strategy, with a sufficiently long time frame, which they can review at regular intervals and communicate with stakeholder groups.

EU legislation

10.89 The above comments, observations and recommendations are notwithstanding issues, particularly with respect to EU legislation, that will need to be addressed. We recognise that a number of these policy recommendations, although necessary to help control the disease, may be incompatible with EU law on cattle TB as it currently stands. In the short term, this could make related measures difficult to implement in legal terms. However, the EU rules in this area have been adapted over time as knowledge of the disease has improved, and we believe that the time is right for them to be revisited again in light of the comprehensive evidence base which the United Kingdom has now put in place. Scientific understanding must inform the regulatory framework; the reverse cannot be true.

Vaccines

10.90 Vaccination of either cattle or badgers can be considered only as a long term option for the control of cattle TB.

Need for 'ownership' of the disease

10.91 Many of our recommendations are consistent with the need for farmers to take 'ownership' of the TB disease problem in their cattle herds, rather than leaving it largely to Government to resolve.

Overall conclusion

10.92 Our overall conclusion is that after careful consideration of all the RBCT and other data presented in this report, including an economic assessment, that badger culling cannot meaningfully contribute to the control of cattle TB in Britain.

10.93 We further conclude from the scientific evidence available, that the rigorous application of heightened control measures directly targeting cattle will reverse the year-on-year increase in the incidence of cattle TB and halt the geographical spread of the disease.

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MEMBERSHIP OF THE INDEPENDENT SCIENTIFIC GROUP ON CATTLE TB

Professor John Bourne CBE, MRCVS (Chairman)

Former Professor of Veterinary Medicine at the University of Bristol (1980 – 1988). Former Director of the Institute for Animal Health and Professor of Animal Health at the University of Reading (1988 – 1997). Professor of Animal Health at Bristol since 1988. Foreign member, Polish Academy of Sciences. Honorary Research Fellow, The Edward Jenner Institute for Vaccine Research.

Professor Christl Donnelly (Deputy Chairman)

Professor of Statistical Epidemiology, Department of Infectious Disease Epidemiology, Faculty of Medicine, Imperial College London. A specialist in infectious disease modelling and statistical analysis.

Sir David Cox Hon. FBA, FRS

Honorary Fellow of Nuffield College, University of Oxford since 1994. A statistician with considerable experience in developing and applying statistical methods of analysis and design.

Professor George Gettinby FRSE

Professor in the Department of Statistics and Modelling Science at the University of Strathclyde. An applied statistician and modeller and a specialist in experimental design for the evaluation of veterinary products.

Professor John McInerney OBE, FRSA, FRASE

Lately the Glanely Professor of Agricultural Policy and Director of the Agricultural Economics Unit at the University of Exeter. An agricultural economist with specialist interest in the economic analysis of livestock disease.

Professor Ivan Morrison FRSE

Professor of Immunology, Centre for Veterinary Tropical Medicine, University of Edinburgh. A veterinarian and specialist in bovine immunology and disease pathogenesis with practical experience of field experiments.

Professor Rosie Woodroffe

Professor of Conservation Biology, Department of Wildlife, Fish and Conservation Biology, University of California, Davis, USA. A specialist in wildlife disease and badger ecology and behaviour.



(Left to right): George Gettinby, Mike Summerskill (Secretary), Christl Donnelly, John McInerney, John Bourne, Ivan Morrison, Rosie Woodroffe, David Cox.

TERMS OF REFERENCE OF THE INDEPENDENT SCIENTIFIC GROUP ON CATTLE TB

The Terms of Reference of Independent Scientific Group on Cattle TB (ISG) are:

“To advise Ministers on implementation of the Krebs Report on bovine TB in cattle and badgers by:

- overseeing the design and analysis of the randomised trial to test the effectiveness of badger culling as a means of controlling bovine TB;
- regularly monitoring the progress of, and outputs from, the trial and assessing any important differences in results between the treatments;
- monitoring data on the *Mycobacterium bovis* situation in areas and species outside the trial;
- reporting to Ministers on progress; and
- advising, as requested, on related issues.”

REGISTER OF MEMBERS' INTERESTS

Professor John Bourne CBE, MRCVS (Chairman)

Honorary Professorship of Animal Health from the University of Bristol (1988 – present).

Honorary Research Fellow of The Edward Jenner Institute for Vaccine Research (2002 – present).

Consultant to MLC on pig disease research from (2001 – present).

Professor Christl Donnelly (Deputy Chairman)

Current main employment is as Professor of Statistical Epidemiology in the Department of Infectious Disease Epidemiology, Faculty of Medicine, Imperial College London.

Principal investigator of a Defra-funded research grant for epidemiological / statistical research assistants analysing data on bovine TB in cattle and badgers, in association with the ISG.

Principal investigator of a Defra-funded research grant for ongoing analyses of TB incidence in cattle herds in and near the Randomised Badger Culling Trial (RBCT) areas.

Sir David Cox Hon. FBA, FRS

None relevant.

Professor George Gettinby FRSE

Research contracts held in the area of sea lice epidemiology on salmon farms funded by Defra, and endophthalmitis in cataract patients, funded by the European Society of Cataract and Refractive Surgeons.

Past member of the Defra Veterinary Fellowship Review Panel and the UK Veterinary Products Committee.

Scientific advice given to Waltham Centre for Pet Nutrition, Novartis, Intervet, Orion, Triveritas, Organon Medical and David Begg & Associates.

Professor John McInerney OBE, FRSA, FRASE

Member of the Farm Animal Welfare Council and service on the Economics Advisory Panel of the South West of England Regional Development Agency.

Emeritus Professor, University of Exeter.

Visiting Professor, Royal Agricultural College.

Land owner within the buffer zone of one of the trial areas (Cadbury) of the Devon (J) triplet.

Professor Ivan Morrison FRSE

Visiting Professorship held at Bristol University.

Horserace Betting Levy Veterinary Advisory Committee (1997 – present).

Wellcome Trust Veterinary Medicine Interest Group (1998 – present).

The Moredun Research Institute, External Strategy Group (2001 – present).

Professor Rosie Woodroffe

Professor of Conservation Biology at the University of California, Davis, USA.

Past grant support from Defra (“Ecological correlates of TB incidence in cattle”).

Member of the World Conservation Union’s Canid and Veterinary Specialist Groups, and a member of the Society for Conservation Biology.

SUMMARY DATA ON TRIPLETS RECRUITED TO THE RBCT

Triplet	Gloucestershire / Herefordshire		
Trial area	Blaisdon A1	Dymock A2	Broadway A3
Treatment	Reactive	Survey-only	Proactive
Treatment area km ²	112.5	113.2	103.8
Accessible land area km ²	78.1	87.9	82.2
Accessible land area as a percentage of treatment area	69%	78%	79%
Culling period start #	July 2000		January 2000
Culling period end #	May 2003	Not applicable	October 2005
Number of culls #	10		5
Badgers culled	117	0	362
Number of badgers culled found to be infected with TB	31	Not applicable	82

Triplet	Cornwall/Devon		
Trial area	Hartland B1	Putford B2	Bude B3
Treatment	Reactive	Proactive	Survey-only
Treatment area km ²	96.8	101.8	96.7
Accessible land area km ²	73.6	88.2	65.8
Accessible land area as a percentage of treatment area	76%	87%	68%
Culling period start #	May 1999	December 1998	
Culling period end #	July 2003	October 2005	Not applicable
Number of culls #	9	7	
Badgers culled	301	787	0
Number of badgers culled found to be infected with TB	28	76	Not applicable

See footnotes at end

Triplet	East Cornwall		
Trial area	Otterham C1	Launceston C2	Lanreath C3
Treatment	Reactive	Survey-only	Proactive
Treatment area km ²	120.6	130.3	121.2
Accessible land area km ²	87.2	101.8	98.2
Accessible land area as a percentage of treatment area	72%	78%	81%
Culling period start #	May 2000		October 1999
Culling period end #	May 2003	Not applicable	September 2005
Number of culls #	19		6
Badgers culled	394	0	964
Number of badgers culled found to be infected with TB	56	Not applicable	90

Triplet	Hereford		
Trial area	Pudleston D1	Withington D2	Bosbury D3
Treatment	Reactive	Survey-only	Proactive
Treatment area km ²	115.2	108.8	104.1
Accessible land area km ²	94.9	71.6	75.9
Accessible land area as a percentage of treatment area	82%	66%	73%
Culling period start #	August 2003		December 2002
Culling period end #	September 2003	Not applicable	May 2005
Number of culls #	4		4
Badgers culled	122	0	1052 ^^
Number of badgers culled found to be infected with TB	31	Not applicable	298

^^ includes one badger found dead in a trap
See footnotes at end

Triplet	North Wiltshire		
Trial area	Cold Ashton E1	Charlcott E2	Poulshott E3
Treatment	Reactive	Survey-only	Proactive
Treatment area km ²	108.6	110.8	118.8
Accessible land area km ²	69.2	71.8	77.9
Accessible land area as a percentage of treatment area	64%	65%	66%
Culling period start #	June 2002		May 2000
Culling period end #	October 2003	Not applicable	September 2005
Number of culls #	10		6 **
Badgers culled	188	0	1,459
Number of badgers culled found to be infected with TB	23	Not applicable	140

** includes two operations conducted in one culling year

Triplet	West Cornwall		
Trial area	Madron F1	Godolphin F2	Stithians F3
Treatment	Proactive	Survey-only	Reactive
Treatment area km ²	110.8	118.9	113.9
Accessible land area km ₂	55.8	66.9	57.2
Accessible land area as a percentage of treatment area	50%	56%	50%
Culling period start #	July 2000		July 2002
Culling period end #	June 2005	Not applicable	September 2003
Number of culls #	5		10
Badgers culled	1,177	0	435
Number of badgers culled found to be infected with TB	66	Not applicable	52

See footnotes at end

Triplet	Derbyshire/Staffordshire		
Trial area	Nettly Knowe G1	Lady Edge G2	Cubley Brook G3
Treatment	Reactive	Proactive	Survey-only
Treatment area km ²	115.7	114.0	115.6
Accessible land area km ²	96.0	74.0	77.3
Accessible land area as a percentage of treatment area	83%	65%	67%
Culling period start #	August 2002	November 2000	
Culling period end #	October 2003	June 2005	Not applicable
Number of culls #	7	5	
Badgers culled	256	995	0
Number of badgers culled found to be infected with TB	31	82	Not applicable

Triplet	Devon/Somerset		
Trial area	Brendon Hills H1	Tarr Steps H2	Huntsham H3
Treatment	Reactive	Proactive	Survey-only
Treatment area km ²	123.6	116.0	114.3
Accessible land area km ²	89.2	77.5	70.6
Accessible land area as a percentage of treatment area	72%	67%	62%
Culling period start #	January 2003	December 2000	
Culling period end #	October 2003	August 2005	Not applicable
Number of culls #	4	5	
Badgers culled	159	590 ^^	0
Number of badgers culled found to be infected with TB	29	70	Not applicable

^^ includes one badger found dead in a trap
See footnotes at end

Triplet	Gloucestershire		
Trial area	Alderton I1	Wetmoor I2	Apperley Grove I3
Treatment	Reactive	Proactive	Survey-only
Treatment area km ²	137.6	131.4	124.4
Accessible land area km ²	78.1	84.0	80.5
Accessible land area as a percentage of treatment area	57%	64%	65%
Culling period start #	May 2003	September 2002	
Culling period end #	September 2003	July 2005	Not applicable
Number of culls #	3	4	
Badgers culled	94	659	0
Number of badgers culled found to be infected with TB	30	167	Not applicable

Triplet	Devon		
Trial area	Luffincott J1	Cadbury J2	Northlew J3
Treatment	Proactive	Reactive	Survey-only
Treatment area km ²	110.5	103.9	103.8
Accessible land area km ²	83.0	80.8	61.5
Accessible land area as a percentage of treatment area	75%	78%	59%
Culling period start #	October 2002	No cull ~	
Culling period end #	May 2005	No cull ~	Not applicable
Number of culls #	4	0	
Badgers culled	846	0	0
Number of badgers culled found to be infected with TB	135	Not applicable	Not applicable

~ Eligible for reactive culling in 2003 but no culls had been performed when the reactive treatment was suspended in November 2003

Some of the treatment area will automatically be unsuitable for trial operations (including, for example, settlements, airfields, roads, river, lakes, quarries etc.)

No culling was performed in the period 1 February 2001 to 31 January 2002 due to the FMD epidemic. All culling was suspended from 1 February to 30 April each year to avoid killing females with dependent cubs confined to the sett.

AUDITS OF RBCT, TB99 AND CCS2005 STUDIES

REPORT	AUDITOR	REPORT DATE	REF. NO.*	SUMMARY OF ACTION TAKEN
Humaneness of dispatch procedures (1st audit)	James Kirkwood	October 2000	PB 5325	The Department accepted and acted on all but one recommendation, namely that relating to the firearm to be used, given the Government's acceptance of the Cullen Report, 1996.
Statistical design of trial (1st audit)	Denis Mollison	November 2000	PB 5385	The recommendations were accepted and acted on by the ISG.
Effectiveness of surveying and of social group delineation (1st audit)	Cresswell Associates	February 2001	PB 5497	The Department accepted and implemented the recommendations, with the exception of one relating to a more complex sett classification, which was not adopted.
Humaneness of dispatch procedures (2nd audit)	Roger Ewbank	June 2003	PB 8253	The Department accepted in full and acted on four of the five recommendations. A recommendation relating to the firearm to be used was not taken up, given the Government's acceptance of the Cullen Report, 1996.
Effectiveness of trapping procedures	Cresswell Associates	August 2003	Internet only	The report was published without Department comment. The auditor re-assessed the effectiveness of badger trapping and re-iterated a number of earlier recommendations in the February 2001 audit (PB5497) in relation to improving aspects of the trapping SOPs and said more comprehensive recording of outlying setts would be helpful.
Repeat audit of the Surveying SOP	Cresswell Associates	September 2003	Internet only	The report was published without Department comment. The auditor reported that, generally, the accuracy of surveying had improved since the first audit (February 2001, PB5497), although some errors remain. The auditor recommended that a simple model be constructed to apply a variable "correction factor" to baseline survey results.

REPORT	AUDITOR	REPORT DATE	REF. NO.*	SUMMARY OF ACTION TAKEN
Post mortem examination procedures used in the RBCT	Graham Hall	May 2004	PB 9702	The Department accepted and implemented the recommendations, although a small recommended change to a SOP was deemed unnecessary.
Statistical design of the trial (2nd audit)	Denis Mollison	May 2004	Internet only	The report was published without Department comment. The auditor agreed with the ISG's March/April 2004 interim analyses and their subsequent conclusions, supported the continuation of the RBCT, but opposed the release of the interim results. The auditor agreed that the reactive element of the RBCT was abandoned prematurely.
TB99 Epidemiological Questionnaire Process (1st audit)	Martine Wahl	July 2004	PB 9839	The Department accepted and acted on the recommendations.
Humaneness of dispatch procedures (3rd audit)	Roger Ewbank	July 2004	PB 9957	The Department accepted and acted on the recommendations.
Bacteriological culture procedures	Mike Corbel	September 2004	PB 10204	The Department accepted and acted on the recommendations.
Humaneness of dispatch procedures (4th audit)	James Anderson	October 2005	PB 11329	The Department accepted three recommendations but did not accept a recommendation to modify the SOP to reflect more strongly that accuracy is more important than speed in shooting a badger.
Statistical aspects of the RBCT: Report for 2004/5 (3rd audit)	Denis Mollison	December 2005	Internet only	The report was published without Department comment. The auditor confirmed the correctness of the ISG's analyses and supported their interpretation of data.

REPORT	AUDITOR	REPORT DATE	REF. NO.*	SUMMARY OF ACTION TAKEN
TB99 Epidemiological Questionnaire Process (2nd audit)	Martine Wahl	July 2005	Internet only	The report was published without Department comment. The auditor reported on the implementation of activities following the first audit (PB9839), confirming that most of the recommendations had been implemented, thus forming a good basis for the quality of data to be collected in the new CCS 2005.
Humaneness of despatch procedures (5th audit)	James Anderson	May 2006	PB 11908	The Department accepted the two recommendations made, both of which related to any future scientific work and cage trapping.
Audit of the CCS 2005 study	Martine Wahl	June 2006	Internet only	The report was published without Department comment. The auditor reported that the target number of completed forms had been met on time and made two recommendations: that Defra capitalises on the expertise acquired in the study; and that prioritisation should be given to analysis of the CCS 2005 data.
An audit of the RBCT administrative data	Martine Wahl	November 2006	Internet only	The Department looked closely at how it may best implement the auditor's recommendations, recognising that these were made with the intention of benefiting the future use of data generated by the RBCT, and the interpretation of results from their analysis. A number of recommendations had been implemented by the time the report was published.
Statistical design of the trial (4th audit)	Denis Mollison	June 2007	Internet only	The report was published without Department comment. The auditor confirmed the correctness of the ISG's analyses and supported their interpretation of data.

* Full report obtainable from Defra Publications, Admail 6000, London, SW1A 2XX or can be found on the Defra Internet site (<http://www.defra.gov.uk/animalh/tb/culling/p5aud.htm>).

STANDARD OPERATING PROCEDURES

NO.	TITLE	LATEST VERSION	DATE
1	Administration	4	May 2005
2	Selection of Triplets	1	Jun 2000
3	Delineation of Trial Areas	1	Feb 1999
4	Visiting land owners and occupiers	1	Sep 1999
5	Surveying	3	Apr 2004
6	Cage trapping of badgers	3	Apr 2004
7	Randomised Treatment allocation	1	Feb 2000
8	Delineation of badger social group territories	2	May 2003
9	Humane dispatch of badgers	4	Jul 2004
10	Heart blood sampling of badger carcasses	3	Jun 2004
11	Badger post mortem procedures – RBCT	4	May 2004
11a	Badger post mortem procedures – RTA Survey	1	Nov 2000
12	Mycobacteria cultural isolation from badger tissue	2	Aug 2002
13	Spoligotyping of badger tissue	1	Apr 1999
14	TB99 – selection of control herds	2	May 1999
15	Notification of confirmed TB breakdowns in cattle	1	Nov 2000
16	Release of Trial-related data	1	Apr 2003
17	Development, ratification & maintenance of SOPs	2	Mar 2002
18	Badger carcass submission	2	Sep 2004
19	Biosecurity	3	Nov 2002
20	Reactive strategy	2	Apr 2003
–	Bait marking procedures	2	Jan 2005
–	Firearms and Ammunition Manual	5	Oct 2002
–	Quality Assurance Manual	1	May 2004

OCCUPIER CONSENT TO THE RBCT 2002-2007

Summary

To examine trends in consent to the RBCT among occupiers in the treatment areas of the 30 trial areas, levels of consent were extracted from trial database snapshots dating back to March 2003 and from GIS database snapshots from Nov 2002. Five trial database snapshots were included in this investigation: Mar 2003, Mar 2004, Mar 2005, Mar 2006 and Jan 2007. Three GIS database snapshots were available: Nov 2002, May 2005 and Jan 2007. From the trial database snapshots, the proportions of occupiers refusing the trial, agreeing to survey only or agreeing to both cull and survey were examined by Triplet and Treatment. Changes of consent for individual occupiers in annual periods (Mar-Mar except the Mar 2006-Jan 2007 period) were also examined. The GIS database was used to calculate and compare the area of land included in each access class between Triplets, Treatments and over time.

Levels of consent based on numbers of occupiers or land area were found to vary between Triplets and Treatments. There is evidence of a general decline in consent over time within the trial although the changes are relatively small. There was a 2.6% drop in the numbers of occupiers granting full access between Mar 2003 and Jan 2007. In terms of the area of land for which full access was granted, there was a drop of 1.4% across all trial areas between Nov 2002 and Jan 2007.

Part 1 – Analysis of Occupier records from successive snapshots of the Trial Database (Mar 2003 – Jan 2007)

All occupiers listed as being completely or partially inside the Treatment area were included. Associations were tested using χ^2 tests. Within-Triplet and within-Treatment associations between agreement and snapshot date were done using Mantel-Haensel χ^2 tests with Triplet or Treatment as the strata.

Consent to the Trial

In the Jan 2007 snapshot, 69.8% of occupiers agreed to culling, 17.7% agreed to survey only and 12.5% refused access. These proportions varied by Triplet ($\chi^2 p < 0.01$; Fig 1a) ranging between 54.3% (Triplet F) and 80.4% (Triplet D) culling access. Agreement also varied by Treatment ($\chi^2 p < 0.01$; Fig 1b) although by a smaller amount (Proportion of occupier granting access to cull: Proactive 70.4%, Reactive 71.6% and Survey Only 67.5%). Similar patterns were observed in all of the database snapshots.

Changes to consent

Between Mar 2003 and Jan 2007 the number of occupiers agreeing to full access, survey-only access or refusing access changed with the proportion granting access declining (Mar 2003: 72.4% of occupiers Cull access, Jan 2007: 69.8% of occupiers Cull access; $\chi^2 p < 0.01$; Fig 2). Although similar downward trends in the numbers of occupiers granting access were observed within each Triplet, none of these were significant (Range $\chi^2 p = 0.09$ (C) to 0.97 (G); Fig 3). The downward trend over time was significant for the Proactive ($\chi^2 p = 0.001$) and Reactive ($\chi^2 p = 0.03$) treatments but not for the Survey Only treatment ($\chi^2 p = 0.21$; Fig 4).

Occupier changes in consent

To examine occupier-level changes to consent, the 4-year period was split into four annual periods. A negative change in consent is a change from cull to either survey only or refuse or a change from survey to refuse. A positive change in consent is a change from refuse to either survey only or cull or a change from survey only to cull.

Between Mar 2003 and Jan 2007, 350 changes to consent (either positive or negative) were recorded, representing 5.2% of the occupiers that could have changed consent (Table 1). In any given one-year period, changes in consent were recorded at a lower rate. The rate of changes to consent decreased with successive years, regardless of treatment. Negative changes in consent occurred at a higher rate than positive changes (4.1% and 1.1%, respectively, for all occupiers) and this pattern was also observed within each treatment (Table 2). The proportion of occupiers changing consent was higher in the Proactive treatment (7.8%) than in the Reactive (4.5%) or Survey Only (3.5%) treatments.

Breakdowns and changes in consent

1170 occupiers listed as being cattle owners had breakdowns between 1 Mar 2003 and 1 Jan 2007. Of these, 68 changed consent: 14 increased consent, 54 decreased consent. The proportions of herds changing consent (in either direction) did not differ between herds experiencing a breakdown and those not experiencing a breakdown (Fisher's exact $p = 0.98$). Changes to consent were not correlated with whether the herd has breakdown in the same annual period (2003-2004: $p = 0.50$; 2004-2005: $p = 0.87$; 2005-2006: $p = 0.93$; 2006-2007: $p = 1.00$) or the previous annual period (2004-2005: $p = 0.11$; 2005-2006: $p = 0.49$; 2006-2007: $p = 0.66$).

Part 2 – Analysis of land parcels from three snapshots of the Trial GIS database (Nov 2002–Jan 2007)

All land parcels wholly or partially located inside the treatment boundaries of the trial were included in these analyses. The data layers were processed such that new land parcels were created corresponding to areas within the treatment areas where no occupier parcel existed ('Unsigned' land). Processing did not account for landscape features such as water bodies, roads and urban developments therefore any of these features, if present within the treatment area will be included as unsigned land. Associations were tested using χ^2 tests. Tests were carried out assuming each km² within a trial area was an observation.

Land area access

Across the entire trial, 66.5% (2289 km²) of the treatment area was available for culling as of Jan 2007. This compares to 386 km² (11.2%) for which survey-only access was obtained, 333 km² (9.7%) for which access was refused and 432 km² (12.6%) that remained unsigned. The proportion of land to which access was granted varied by Triplet ($\chi^2 p < 0.01$; range in proportion available for culling: 47.3% (Triplet F) to 77.2% (Triplet D); Fig 5A). Access also varied between Treatments ($\chi^2 p < 0.01$; Proportion available for culling: Proactive, 68.4% (788 km²), Reactive, 68.0% (783 km²), Survey Only 63.2% (719 km²); Fig 5B).

Changes to access

The accessibility of land across the entire trial varied between the snapshots ($\chi^2 p < 0.001$; Fig 6) with the proportion of land to which access for culling had been granted falling from 67.9% (2322 km²) in Nov 2002 to 66.5% (2289 km²) in Jan 2007. The area of unsigned land decreased by 74 km² over this period similarly, the area of land for which survey only access had been granted decreased (24 km²) but the area of land for which access was refused increased by 152 km². The increased proportion of no-access area in Jan 2007 compared to Nov 2002 was observed within Triplets but was only found to be significant in Triplet C ($\chi^2 p = 0.022$; range among other Triplets $\chi^2 p$: 0.10 (Triplet F) to 0.95 (Triplet D); Fig 7). Levels of access varied by time within the Proactive and Reactive treatments ($\chi^2 p < 0.01$) but did not change within the Survey Only treatment ($\chi^2 p = 0.10$). The proportion of land for which access was refused increased in both Proactive (from 5.8% to 11.3%) and Reactive (from 3.9% to 8.2%) treatments (Fig 8).

Initial Consent

The consent status of occupiers and/or land at the outset of the RBCT is no longer available and was inferred from the available data (see Supplementary Information, Donnelly *et al.*, 2007). The estimates of consent obtained from this process are presented in the following figures. However, in assessing the trends in consent over time, the inferred initial consent was not considered. It should be noted that inferred changes to consent affected few occupiers (86 of 6984 occupiers across all RBCT areas) and little land (28 km² out of 3417km² in total).

Table G.1: Numbers of occupiers showing positive†, negative‡ or any change in consent between successive database snapshots by treatment and in total.

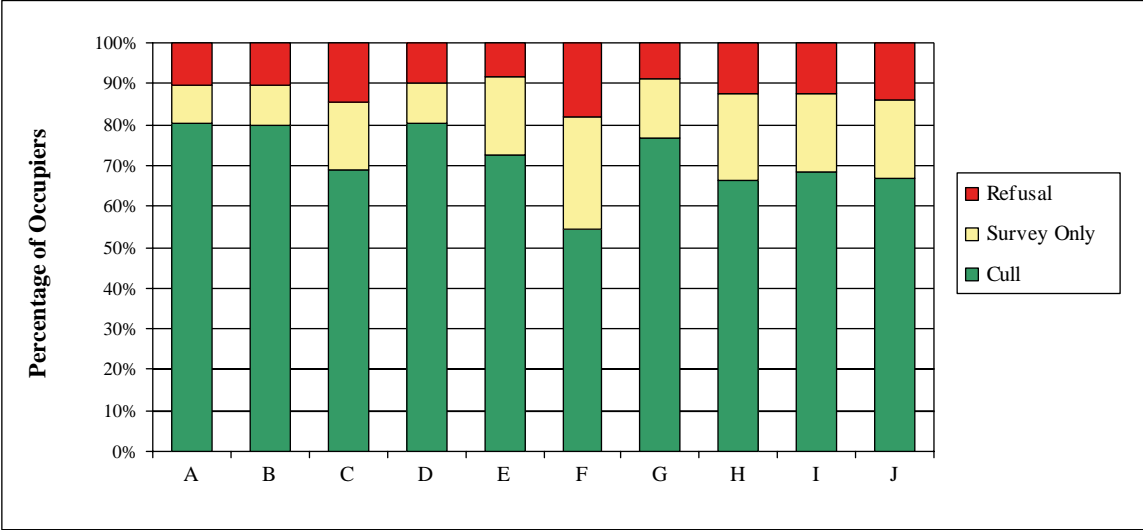
	Period	Proactive	Reactive	Survey Only	Total
Number of occupiers	2003-2004	2099	2287	2393	6779
	2004-2005	2145	2318	2415	6878
	2005-2006	2177	2344	2431	6952
	2006-2007	2202	2347	2437	6986
	2003-2007	2091	2284	2389	6764
Occupiers with a positive change	2003-2004	26 (1.2%)	19 (0.8%)	5 (0.2%)	50 (0.7%)
	2004-2005	18 (0.8%)	5 (0.2%)	0 (0%)	23 (0.3%)
	2005-2006	12 (0.6%)	4 (0.2%)	0 (0%)	16 (0.2%)
	2006-2007	2 (0.1%)	1 (0%)	1 (0%)	4 (0.1%)
	2003-2007	43 (2.1%)	24 (1.1%)	6 (0.3%)	73 (1.1%)
Occupiers with a negative change	2003-2004	56 (2.7%)	34 (1.5%)	26 (1.1%)	116 (1.7%)
	2004-2005	38 (1.8%)	26 (1.1%)	27 (1.1%)	91 (1.3%)
	2005-2006	41 (1.9%)	13 (0.6%)	21 (0.9%)	75 (1.1%)
	2006-2007	0 (0%)	8 (0.3%)	3 (0.1%)	11 (0.2%)
	2003-2007	121 (5.8%)	79 (3.5%)	77 (3.2%)	277 (4.1%)
Occupiers with any change	2003-2004	82 (3.9%)	53 (2.3%)	31 (1.3%)	166 (2.4%)
	2004-2005	56 (2.6%)	31 (1.3%)	27 (1.1%)	114 (1.7%)
	2005-2006	53 (2.4%)	17 (0.7%)	21 (0.9%)	91 (1.3%)
	2006-2007	2 (0.1%)	9 (0.4%)	4 (0.2%)	15 (0.2%)
	2003-2007	164 (7.8%)	103 (4.5%)	83 (3.5%)	350 (5.2%)

† a positive change is a change in consent from 'refusal' to either 'survey' or 'cull' or a change from 'survey' to 'cull'

‡ a negative change is a change from 'cull' to either 'survey' or 'refusal' or a change from 'survey' to 'refusal'

Figure G.1: Proportion of occupiers agreeing to various degrees of access by A) Triplet and B) Treatment as recorded in the Jan 2007 snapshot of the trial database.

A)



B)

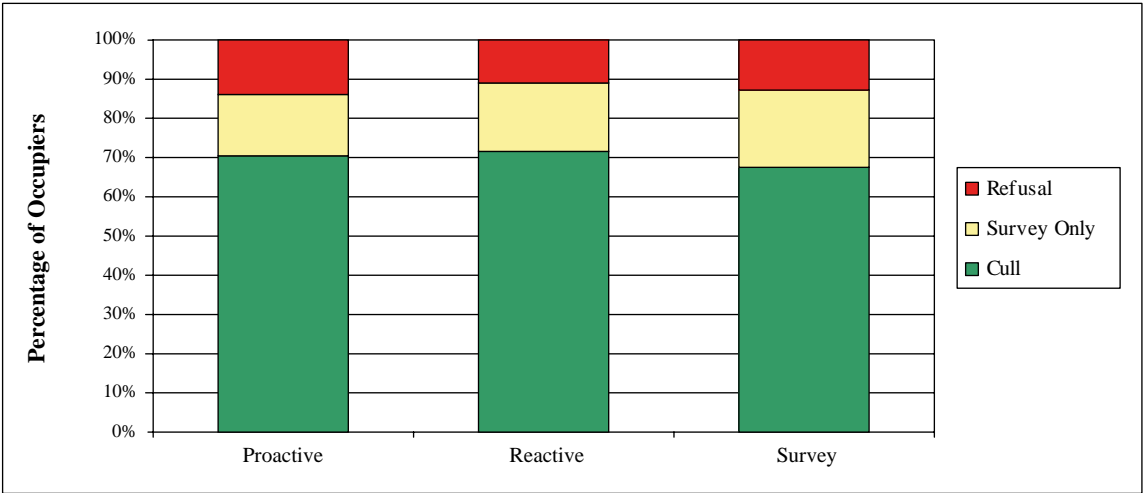


Figure G.2: Overall consent to the Trial for all occupiers listed in the database downloads from Mar 2003 – Jan 2007. The inferred initial consent status is shown for comparison.

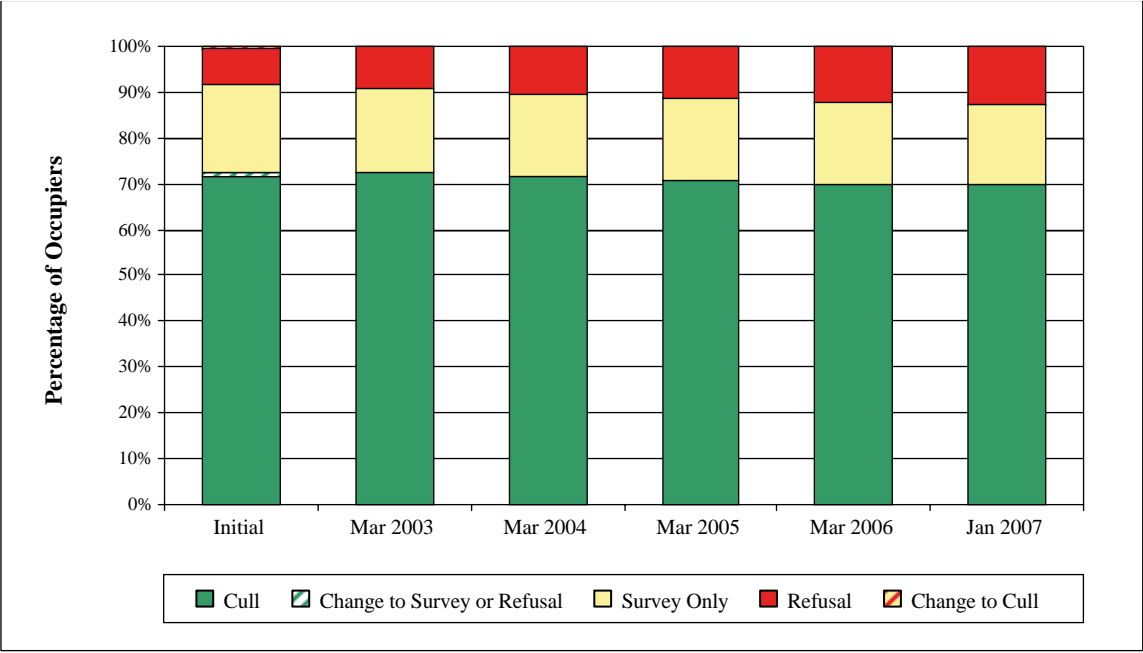
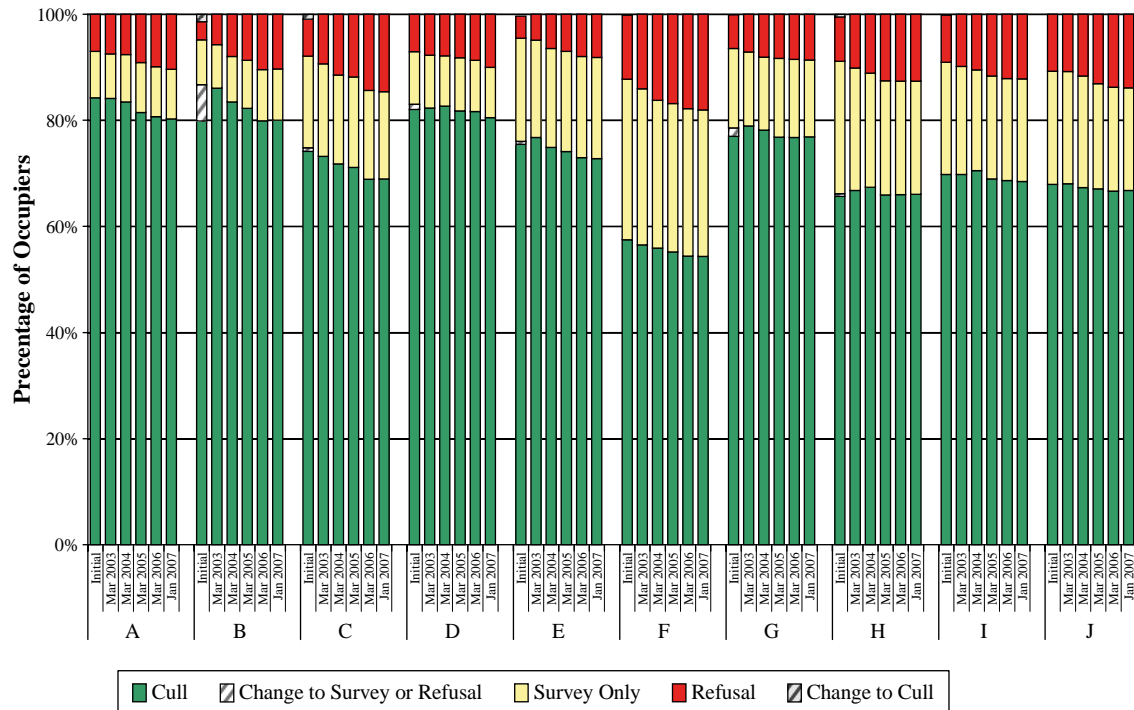


Figure G.3: Consent to the Trial by Triplet for all three treatments (A) and for the proactive treatment only (B) for all occupiers listed in the database downloads from Mar 2003 – Jan 2007. The inferred initial consent is included for comparison.

A)



B)

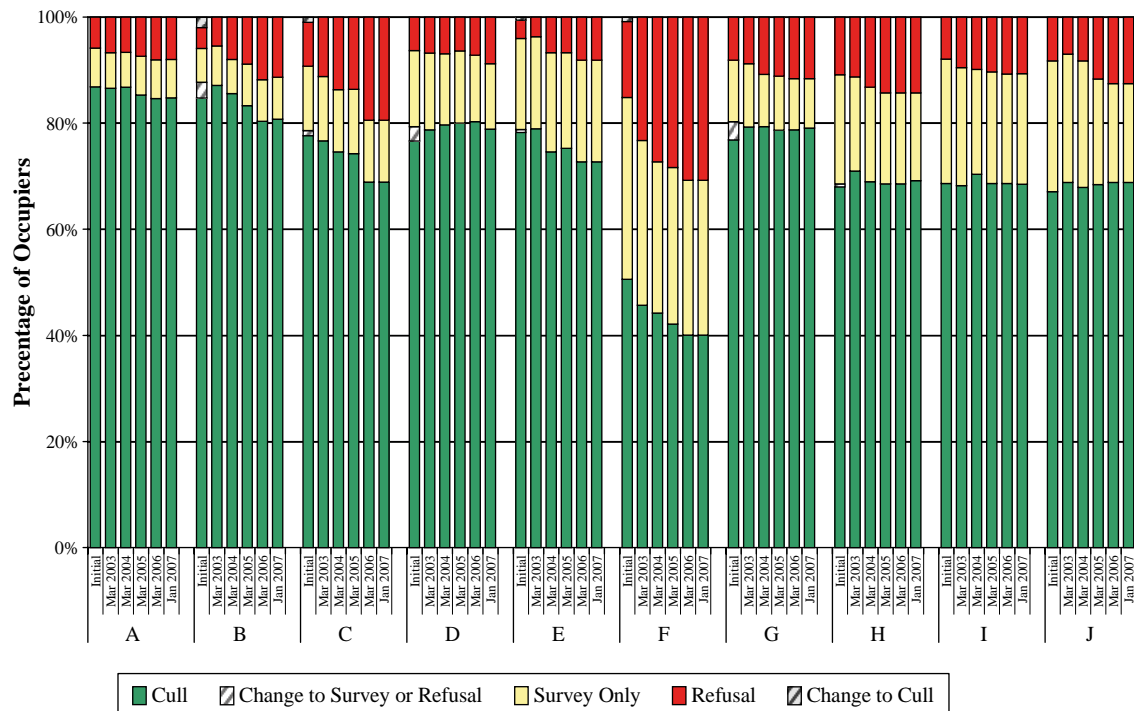


Figure G.4: Consent to the Trial by Treatment for all occupiers listed in the database downloads from Mar 2003 – Jan 2007. Inferred initial consent is shown for comparison.

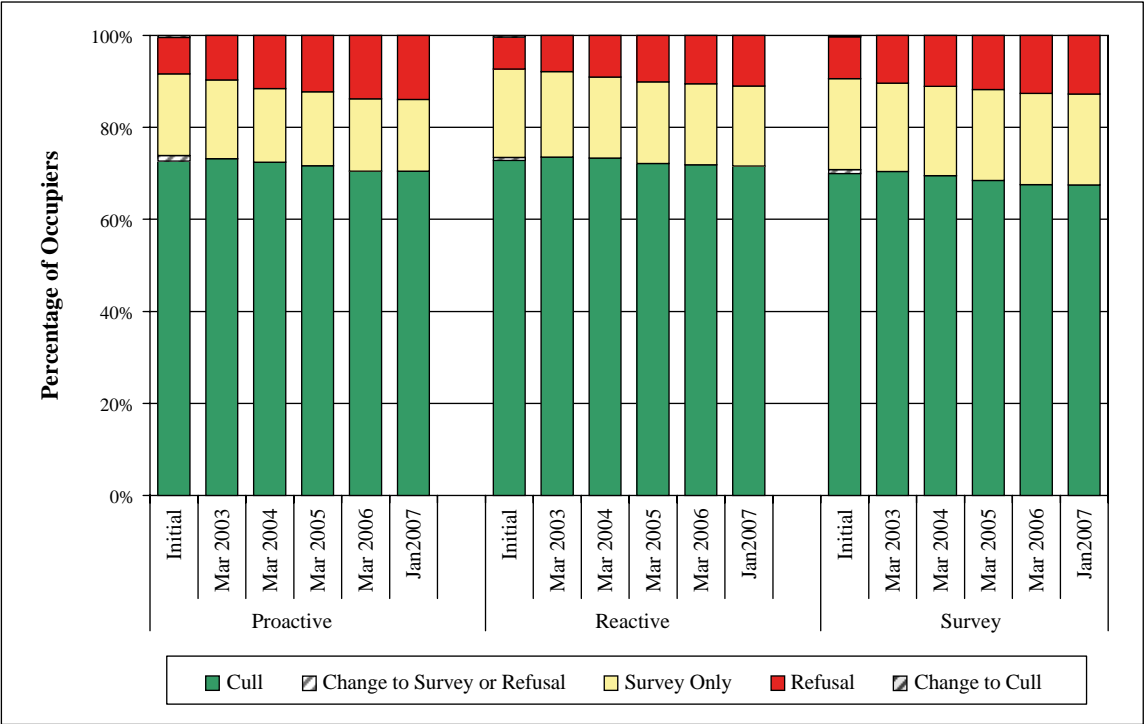
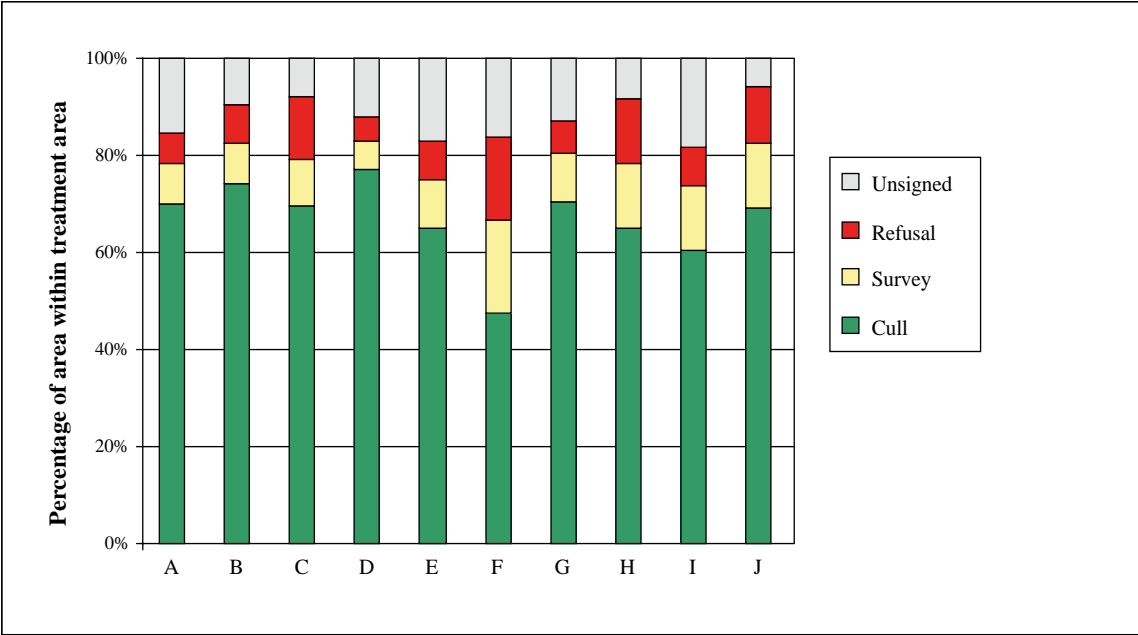


Figure G.5: Proportion of land within each Triplet (A) and Treatment (B) by level of access from the Jan 2007 GIS data.

A)



B)

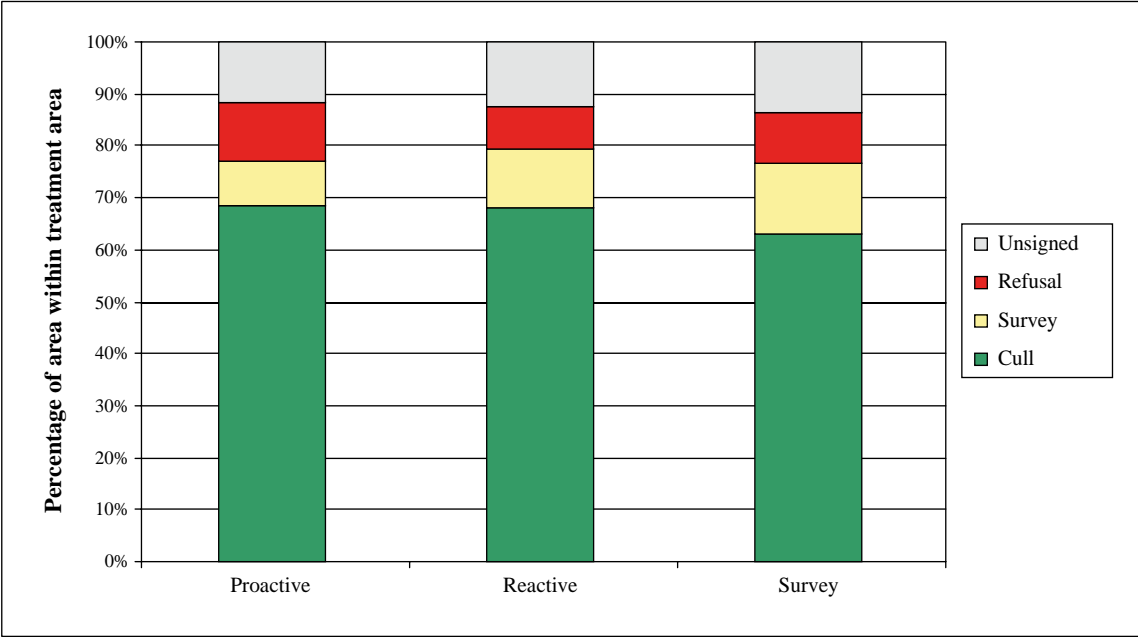


Figure G.6: Proportion of land across the trial by level access Nov 2002 – Jan 2007.
Inferred initial consent is shown for comparison.

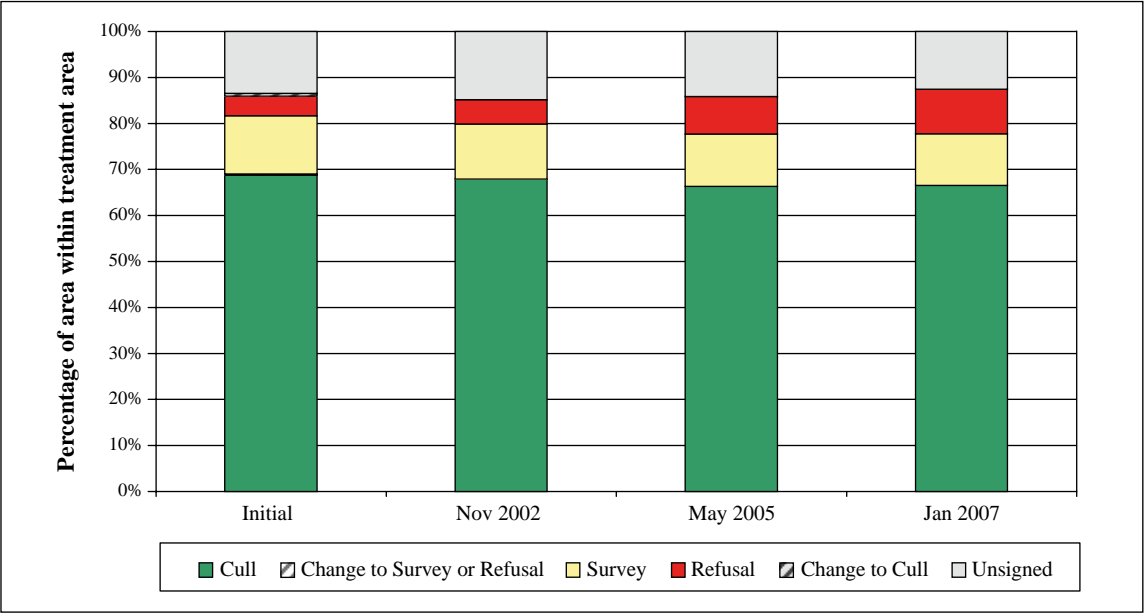
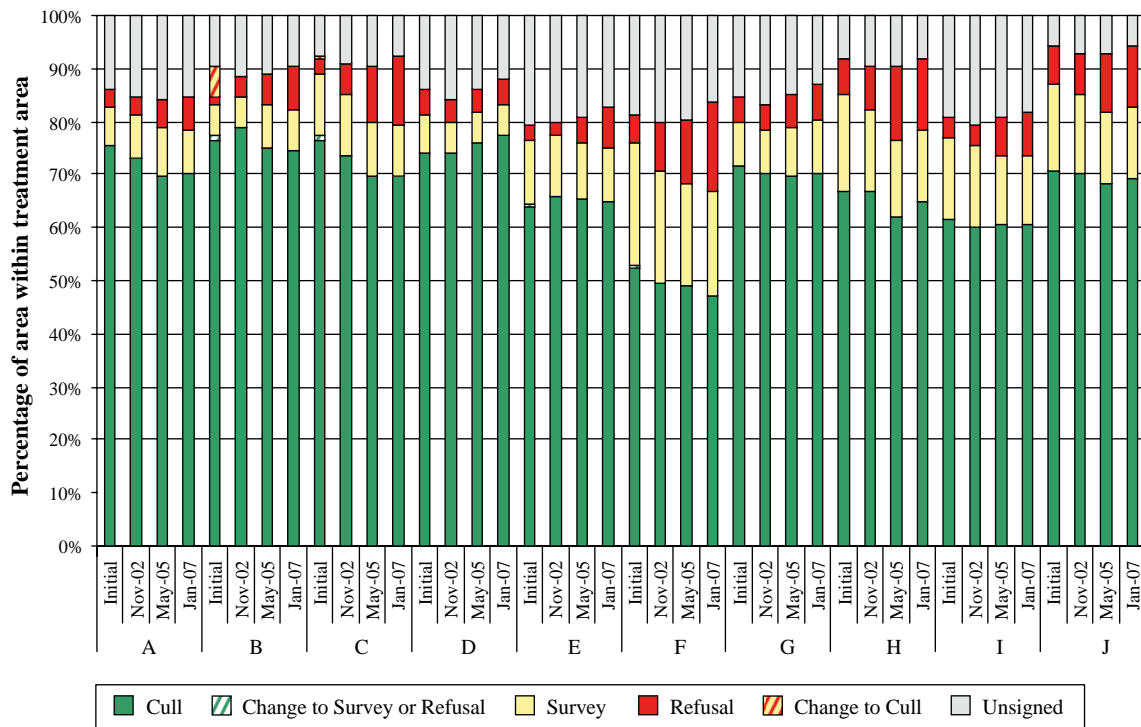


Figure G.7: Change in proportion land in each access class between Nov 2002 and Jan 2007 by Triplet:
A) for all treatment areas and B) for the proactive area only.

A)



B)

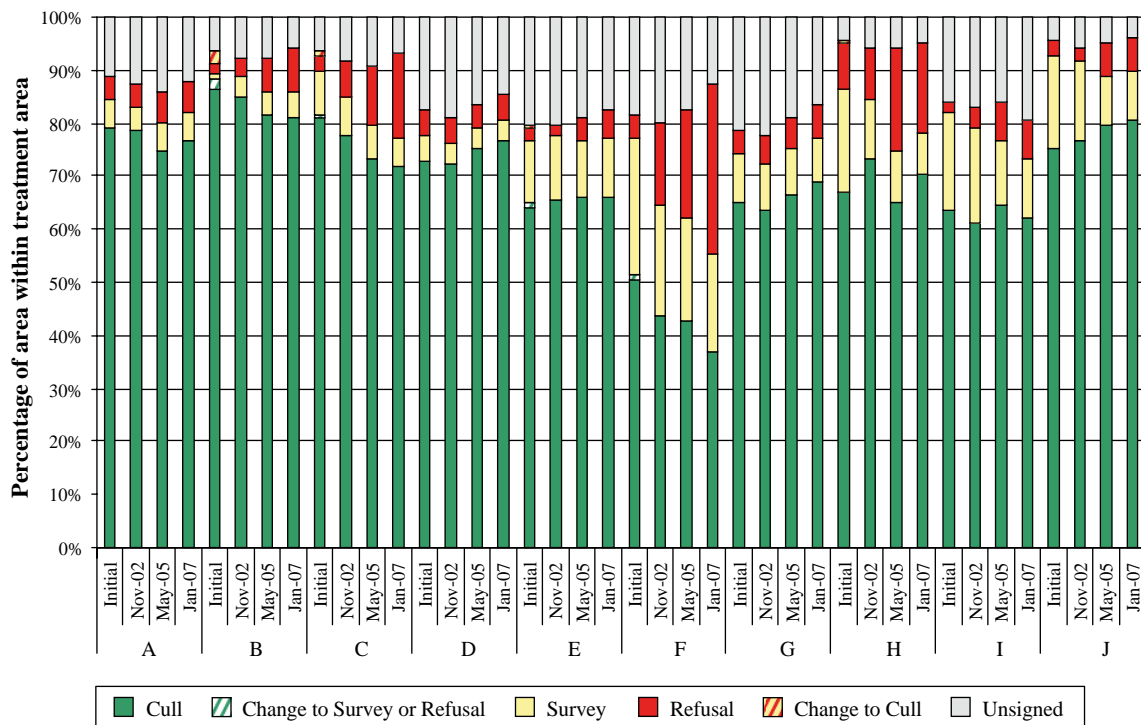
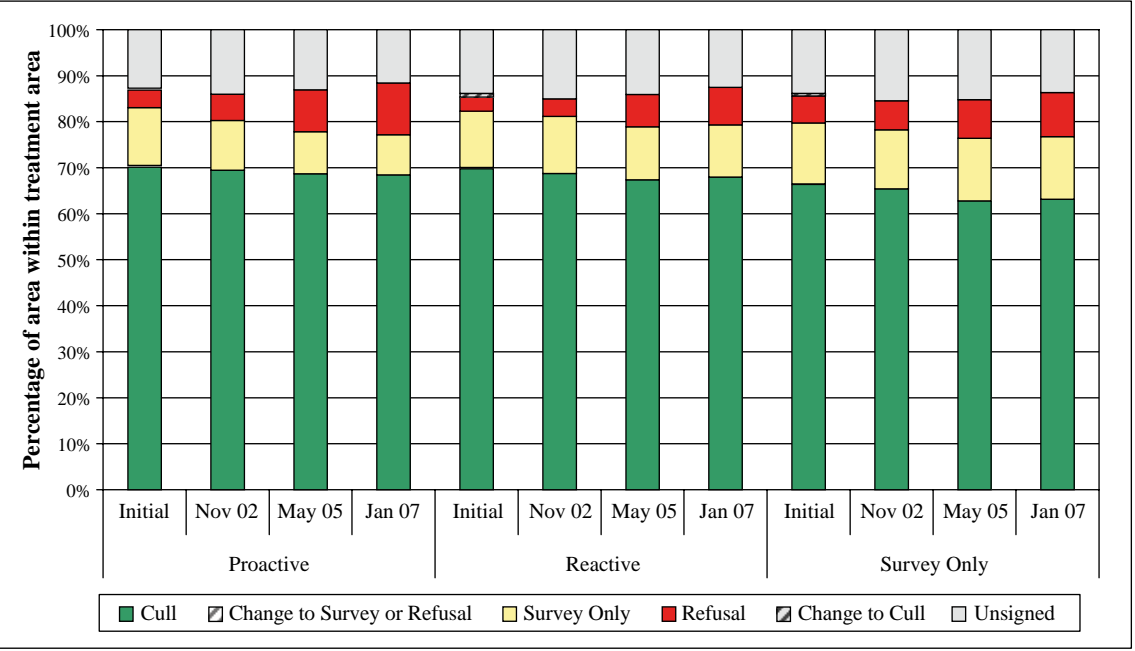


Figure G.8: Proportion of land area by access level within each Treatment for Nov 2002 – Jan 2007.
 Inferred initial consent is shown for comparison.



STATISTICAL MATTERS IN RELATION TO THE RBCT AND ASSOCIATED WORK

General

The design and analysis of the RBCT and of associated studies has involved extensive statistical analysis. The amount of data accumulated is very great but even so many of the conclusions require quite delicate and careful analysis and interpretation. As with other aspects of ISG work, the statistical aspects have been audited. Details are reported in peer-reviewed papers in the scientific literature (see Appendix J) and are largely omitted from the present report. This Appendix outlines a few more issues under the following headings:

- a. Design of RBCT
- b. Primary analysis of RBCT
- c. Interim analysis of RBCT
- d. More detailed analyses
- e. Case-control studies
- f. Further issues

Design of RBCT

The design of the RBCT followed closely general principles well established in numerous fields, the use of triplets achieving comparisons that were between geographically fairly closely related areas and the replication enhancing precision. Randomisation, rigorously enforced except in Triplet I due to security concerns, was judged essential to avoid bias and, in particular, accusations of prejudiced allocation.

The size of the trial, i.e. the 10 triplets studied for five years, was settled by the power calculation summarised in Chapter 2 (paragraphs 2.14 to 2.16). That is, it established that with reasonably high probability the trial would detect an important true difference between, say, proactive and survey-only area breakdown rates as statistically significant. After discussion, it was, however, decided to use a different but for immediate design purposes absolutely equivalent formulation. This was based on the notion that if a true effect were present it would be necessary to estimate its magnitude with reasonable precision, so as, in particular, to provide a reasonably secure base for a cost-benefit analysis. The formulation adopted was that the 95% confidence limits on the estimated percentage benefit, if any, should be approximately the estimate plus and minus 10%. This was in fact very close to the precision eventually achieved. This formulation in terms of estimating the magnitude of the effect, as contrasted with testing significance, is both more realistic and also has some technical advantages in that it avoids any need to adjust the final analysis for any intermediate analyses made (Anscombe, 1952; Barndorff-Nielsen and Cox, 1984).

Primary analysis of RBCT

The primary analysis of the RBCT takes a trial area, the unit of randomisation, as the unit of study and the overall breakdown rate as the outcome variable. Note that we are concerned with breakdowns in herds previously unrestricted, that is with the spread of the disease. For

that reason we did not consider the number of animals detected as *M. bovis* positive, only with whether or not a herd had a breakdown. The method of analysis had in effect been specified at the design stage but was set out in more explicit written form in January 2002. The very simplest idea is that within any circle breakdowns occur totally randomly in time, that is in what is called a Poisson process, and that the ratio of rates in, say, proactive and survey-only areas is the same in all triplets. It was recognised that this was likely to be too simple and that there would be additional sources of variability, so-called overdispersion. In line with standard practice attempts would be made to explain any overdispersion by taking account of base-line variables, that is variables referring to what happened before the instant of randomisation and therefore incapable of being influenced by the treatment allocation. This was the route taken and the overdispersion was largely removed in this way, for example by taking account of the three-year breakdown rate before randomisation and the number of herds at baseline. Any overdispersion remaining led to an inflation, always quite modest, in the length of the confidence interval. A further issue concerned possible interactions, that is that the effect of culling might vary between triplets in a way that could be explained by measured features. In fact, despite extensive search, very few such interactions were uncovered.

Interim analysis of RBCT

The interim analyses were essentially primary analyses conducted at regular intervals as data emerged from the RBCT. The results remained exclusively confidential to the two ISG members responsible for the analyses and the statistical auditor; other ISG members, including the Chairman, were to be informed only when statistically significant effects were detected.

More detailed analyses

The analyses summarised in the previous paragraph all treated a trial area as yielding one outcome, the total number of breakdowns over the trial period. In fact a very large amount of additional data was available concerning the position and timing of detected breakdowns and the concerned with badger ecology, including the position of capture and disease status of culled badgers. Analysis of this has called for a variety of statistical techniques.

Case-control studies

To investigate farm management aspects a randomised study was clearly impossible. Two routes might have been taken. One would have been a cohort (or prospective) study in which data are collected at the start of the study on a large number of farms and the farms followed to see which experienced a breakdown. The second route was a case-control (retrospective) study in which data are collected on all breakdown farms and compared with data on a sample of non-breakdown farms aiming to find by looking backwards which features are likely to have influenced the occurrence of breakdowns. Because the breakdown rate is relatively low the second method was adopted and details of these studies are set out in Chapter 6.

Methods of analysis have followed those used in other epidemiological investigations. The main special feature has been the very large number of potential risk factors recorded, only a relatively small number of which are likely to play a major role. A systematic method for finding the more important risk factors has been used which also ensures that in the rather complex series of steps involved it is unlikely that an important risk factor is overlooked.

Further issues

Most of the analyses involved use of relatively standard procedures available in the computer packages SAS or minor modifications thereof. This does not mean that the analyses and their interpretation were simple, in particular especial care was needed to ensure that the primary conclusions did not depend on unwarranted assumptions about the complex data involved. There were issues, however, that called for somewhat non-standard procedures. Some of these are as follows.

The combination of measures of lesion severity and occurrence into a single severity index called for a new theoretical development in order to handle the mixture of data types (numerical severity of individual lesions and position). The comparison of spolotype distributions in cattle and badgers needed an appropriate measure of concordance and methods for assessing its precision. For the primary method of analysis for the RBCT, log Poisson regression, the conclusions are conventionally presented in a form that does not lend itself to vivid presentation and direct understanding. Instead a graphical method of presentation was developed and used.

A special theoretical analysis (ISG 1684, and reproduced in Appendix Q) was made of the impact of variable testing regimes (one-, two-, four- year testing) on prevalence and incidence and on the implications for the interpretation of routine national data on the outcomes of herd testing.

The modelling work reported by Cox *et al.* (2005) was new. The model made many simplifying assumptions but allowed assessment of a number of aspects not accessible to direct study. These included the consequences of imperfect sensitivity of the standard skin test and the impact of less than full culling efficiency on herd breakdown rates.

CATTLE PATHOGENESIS RESEARCH STEERING GROUP – SUMMARY OF MAJOR SCIENTIFIC FINDINGS

Steering Group membership:

J. Bourne	Chairman
I. Morrison	ISG
M. Vordermeier	Veterinary Laboratories Agency, Weybridge, Surrey
G. Hewinson	Veterinary Laboratories Agency, Weybridge, Surrey
A. Mitchell	Veterinary Laboratories Agency, Weybridge, Surrey
R. Clifton – Hadley	Veterinary Laboratories Agency, Weybridge, Surrey
T. Goodchild	Veterinary Laboratories Agency, Weybridge, Surrey
S. Downs	Veterinary Laboratories Agency, Weybridge, Surrey
P. Durr	Veterinary Laboratories Agency, Weybridge, Surrey
J. McNair	AFBI, Bacteriology Department, Veterinary Sciences Division, Stormont
R. Skuce	AFBI, Bacteriology Department, Veterinary Sciences Division, Stormont
J. Pollock (deceased)	AFBI, Bacteriology Department, Veterinary Sciences Division, Stormont
C. Howard	Institute for Animal Health, Compton, Berks.
B. Villa-Real	Institute for Animal Health, Compton, Berks.

Introduction

1. The cattle pathogenesis research programme was designed to explore the dynamics of TB in cattle, routes of disease transmission, the refinement and development of diagnostic tests and their relative performance, including specificity and sensitivity, and their ability to identify infected, and potential disease transmitting animals at different stages of the disease. Of particular value was the opportunity to complement laboratory based studies with field studies.

The Cattle Disease – experimental findings

2. Natural infection of cattle with *M. bovis* presents, in over 90% of cases, as a disease of the lower and/or the upper respiratory tract. In two thirds of reactor animals lesions are restricted to the lower respiratory tract (lung and associated thoracic lymph nodes), and up to a third of cases have lesions in the head lymph nodes or in the head nodes and those of the lower respiratory tract.

3. Experimental models have replicated the patterns of pathology observed in the natural disease in cattle and demonstrated the high susceptibility of the bovine lower respiratory tract to *M. bovis* infection. As few as five bacteria, forming one infectious particle, can cause progressive infection and pathology, consistent with that associated

with the natural disease (Dean *et al.*, 2005). Intranasal infection with high numbers of pathogens, resulted in pathology in head lymph nodes, with a high proportion (up to 40%) having lung and thoracic lymph node involvement, also consistent with natural infections. Nasal shedding of *M. bovis* was shown to occur sporadically after experimental infection, although two phases of more frequent shedding were apparent in most animals. The first occurred in the early stages of infection at 20-30 days post inoculation and the second at 80-90 days post infection (McCorry *et al.*, 2005). Higher infectious doses resulted in increased bouts of more persistent shedding. The validity of the intranasal infectious model, with respect to shedding, has been questioned because animals were infected with doses of *M. bovis* (10^4 - 10^6 CFU) that might be higher than those normally giving rise to natural infections. In a recent related study of natural infection involving 200 skin test-positive, reactor animals and 200 in-contact animals (ISG 1669), and in a separate longitudinal study of reactor animals (Vordermeier, unpublished data), no bacilli could be detected in nasal mucus samples. However, since the time of infection of these natural cases could not be determined, the possibility that nasal transmission of infection occurs during the early stages of infection cannot be excluded.

4. Field investigations in several countries have shown that 9-20% of naturally infected cattle shed viable *M. bovis* bacilli in their nasal secretions (Rempt, 1954; De Kantor *et al.*, 1978; Krishnaswamy *et al.*, 1984) and, in a study in Northern Ireland, *M. bovis* was recovered from the nose and tonsil of over 50% of skin test positive cattle (Cassidy *et al.*, 1999a). The possibility of nasal transmission of infection particularly in the early stages of infection cannot be excluded and it has been suggested that all cattle infected with *M. bovis* have the potential to shed bacilli at some stage during the infection (Neill *et al.*, 1992).

5. An important question is at what stage of infection can the disease be diagnosed and how does this relate to the kinetics of bacterial shedding? By subjecting experimentally infected cattle to diagnostic tests at varying intervals after infection, Thom *et al.*, (2006) showed that infected animals gave positive responses to both the tuberculin skin test and the IFN test three weeks after infection. In a series of studies reported by Neill and co-workers, involving animals experimentally infected by low-dose intranasal challenge, uninfected animals held in contact with infected animals (sharing accommodation and feed) and naturally infected field cases, shedding of bacilli was detected in animals in one study before the development of skin test responses (Neill *et al.*, 1992) and in another before responses to either the skin test or IFN test developed (Cassidy *et al.*, 1999b); shedding was also, in some cases, detected in the absence of any detectable cellular or humoral immune responses or disease-related pathology (Neill *et al.*, 1988).

6. Studies of the pathogenesis of experimental infections in cattle (SE 3015) have demonstrated variation in responsiveness to the tuberculin test. In a typical experimentally infected group of 18 animals, 17/18 developed visible pathological lesions and were culture positive, of which 15 gave positive responses to both the tuberculin skin test and the IFN test and 2 were negative to the skin test, but were positive to the IFN test. The remaining animal showed no evidence of tissue pathology, was skin test-negative, but was culture-positive and gave a positive IFN test response. These studies suggest that a proportion of infected animals, all potential disease transmitters, evade diagnosis by the skin tuberculin test but can be detected by the IFN test. Not all infected cattle however are diagnosed by the IFN test. Comparative studies of the skin test and IFN test in naturally infected cattle have shown that the two tests identify slightly different cohorts of infected animals, some animals being skin test-positive and IFN test-negative and others *vice versa* (Neill *et al.*,

1994 and Vordermeier *et al.*, 2006). This evidence supports the complementary use of the two tests, in parallel, to improve test sensitivity. It also needs to be highlighted that a proportion of animals will also test negative to both tests.

7. Further insights into the pathogenesis of the disease have been gained from transmission experiments (SE 3015; ISG 1662), in which donor calves experimentally infected by the intranasal route (10^6 CFU) were housed in-contact with 36 disease-free calves for a period of 7 to 11 weeks, following which the in-contact animals were housed separately for a further period of 18 or 26 weeks prior to slaughter. To meet health and safety requirements these experiments were conducted in contained, environmentally controlled housing, which provided liberal air space and 15-16 air changes per hour. There was evidence of infection in 22% (8/36) of the in-contact animals. A single animal (3%) developed visible lesions; this animal was also culture positive for *M. bovis*, and positive to both the skin test and the IFN test. There was evidence of infection in a further 19.4% (7/36) of the in-contact animals, which were culture-negative and showed no visible lesions. 5.5% (2/36), including the visibly lesioned animal were consistently IFN-positive and were also skin test positive, while the remaining 17% (6/36) exhibited a transient response to the IFN test but were skin test-negative. A further ongoing in-contact transmission study involves housing of disease-free animals with naturally infected skin test reactor cattle, in accommodation likened to on-farm conditions. Judged by detection of responses to the IFN- γ test, using defined *M. bovis* proteins (ESAT-6 and CFP-10) as antigen, as well as the standard PPD antigens, preliminary findings show that about half of the sentinel group of animals have become infected with *M. bovis* after a 7-month in-contact period.

8. These experimental studies summarised above have confirmed that *M. bovis* is readily transmitted between cattle and causes pathology of variable severity focused mainly in the respiratory tract. The predominance of lesions in the lower respiratory tract of naturally infected animals, taken together with experimental observations, suggests that infection is likely to have occurred by inhalation of small aerosol particles directly into the lung (Table I.1). This could arise through coughing and would imply that animals (whether wildlife or cattle) need to be in close proximity for transmission to occur. Those cases where the pathology is predominantly associated with the head lymph nodes may become infected by inhalation of larger particles or ingestion of contaminated material from the environment. In addition, eructation/cudding of swallowed organisms from a lung primary focus can also not be excluded to account for this disease presentation. Experimental data on the kinetics of infection indicate that transmission of infection can occur at any stage of the disease process, but that there are phases of more frequent shedding of *M. bovis* during the early stages of infection, which are likely to be associated with an increased risk of transmission.

9. The demonstration of cattle-to-cattle transmission, and its extent, confirms the dynamic infectious and contagious nature of the disease and demonstrates that there is ample opportunity for within-herd amplification of infection. This has been shown to result in development of overt disease in some animals but a larger number become infected with little or no pathology, but may still present a potential source of infection to others.

Table I.1: Lesion distribution: Comparison between natural and experimental infections (examples from literature and recent studies)

Reference	Lesions in Lung/ Pulmonary LN only	Head LN and Lung/ pulmonary LN
Natural infection		
Plum (1939)*	70+%	19%
Sutherland (1953)*	63%	Not recorded
Taylor (1953)*	66%	Not recorded
Corner, 1994	56%	32%
Neill <i>et al.</i> , 1994	57%	28%
Whipple <i>et al.</i> , 1996	66%	27%
SE3013 (Peter Durr, Sara Downs), reactor animals, Final report to Defra 2006	55.5% with lung/pulmonary LN lesions (thoracic), 37% had thoracic lesions only	41% had head LN lesions (34% had head and/or thoracic lesions)
Defra, 1/1/1999 – 7/4/2004**	60%	31.1%
Experimental infection		
i.t. experimental infection (VLA, SE3024)	Up to 100%	Occasionally
i.n. experimental infection (VSD/VLA/IAH, SE3013)	0%	100%

* as quoted by Francis, 1958, table 3, p. 22.

** unpublished data from 11,000 reactors, slaughterhouse cases, IRs and contacts recorded on TB99 questionnaires

10. Of particular significance is the observation that the tuberculin skin test fails to identify a significant proportion (6/8 animals in the studies described above) of infected cattle, but that many of these can be diagnosed by the IFN test, and that use of both tests identifies more infected animals than either test on its own.

Exposure, infection, disease, latency

11. Observations on the disease caused by infection with *M. bovis* in cattle suggest that the pathogenesis of the disease follows closely that caused by *M. tuberculosis* in humans (Pollock and Neill, 2002). Animals in a herd with tuberculosis will be exposed to *M. bovis* in a similar way to that of human contacts exposed to *M. tuberculosis* from TB patients. In the case of humans, 10-30% of those exposed will become infected, as defined by the development of a specific cellular immune response detected by a skin test and/or an IFN test. About 5% of this group of infected humans develop disease within one year of infection (primary tuberculosis), whilst 95% of infected individuals, although tuberculin skin test and IFN test positive, do not present with clinical or radiological signs of disease, but become latently infected. To what extent the *M. tuberculosis* organisms in latently infected people persist in a latent non-replicative state, and/or their numbers are controlled by immune responses, remains unresolved. However, the end result is the same, namely that infection can persist for many years. This is a very important epidemiological group, since 5-10% of latently infected humans will develop clinical tuberculosis during their

lifetime following reactivation of infection (reactivation tuberculosis) and they represent an important reservoir of infection for transmission to susceptible humans. Hence this category of infection plays a key role in maintaining infection in the human population. Exposure of latently infected humans to further challenge with *M. tuberculosis* may lead to subsequent development of disease. However, there is relatively little information available concerning responses of infected cattle to re-exposure to *M. bovis*, in particular whether susceptibility is reduced or enhanced due to immunological priming as a result of previous exposure to the organism. Nevertheless, recent data generated in project SE3024 with animals treated with anti-TB drugs (Rhodes *et al.*, 2007) suggest that a primary infection provides some degree of protection (but not total protection) against exogenous re-infection rather than resulting in increased susceptibility. This is in line with observations in other animal models of tuberculosis.

12. The different disease states in humans, which are defined largely on the basis of observations on live people, are not directly comparable with the categories of disease defined by postmortem findings in cattle. Nevertheless, the concept of ‘infected’, ‘latent’ and ‘diseased’ states appear to apply equally to bovine tuberculosis, although the frequency of latency is likely to be lower than in humans. Earlier researchers including Francis (1950) pointed out that, in contrast to human TB with its vast proportion of latently infected individuals, bovine TB in cattle presents itself as a (sometimes very slow advancing but often not) progressive disease. This view is supported by experimental studies of cattle challenged with very low doses (1-100 CFU) of *M. bovis* where the majority of animals demonstrating detectable immune responses developed visible pathology at post-mortem examination (Dean *et al.*, 2005). However, even in these studies, a proportion of animals developed detectable immune responses (IFN and skin test responses) but remained culture-negative and had no visible pathology, thus satisfying the most widely used definition for latency. The pattern of pathology observed in association with natural *M. bovis* infection in the cattle population is undoubtedly strongly influenced by the fact that a large proportion of infected cattle are continuously being removed by herd testing and therefore most animals are in the relatively early stages of infection. Therefore, the patterns of disease are not directly comparable to those observed in humans and the relative proportions of cattle that develop different disease states are difficult to define. Nevertheless, the experimental findings suggest that in a significant proportion of cattle infected with *M. bovis*, infection results in a state comparable to the latent state defined for humans. This would explain, at least partially, why a large proportion of the skin test reactors (or IFN responders) from herds with culture-confirmed bovine TB, are culture-negative and have no gross visible lesions. Many of these animals are likely to be carrying infection that is not detectable by the culture methods employed and that has the potential to re-emerge at a later date. They should therefore be considered as potential disease transmitters that pose a threat to the disease security of the herd.

Field Studies

13. The laboratory-based research was complemented by three field-based studies in order to provide a range of further information on the pathogenesis and diagnosis of the disease in cattle.

14. The first of these studies (summarised in ISG 1669, Pathogenesis and Diagnosis of Tuberculosis in Cattle Complementary Field Studies and reports of project SE 3013) was designed to provide a range of immunological, pathological and metabolic data, and particularly information on the relative performance of the tuberculin skin test and the

IFN test. The study was conducted on two groups of animals, 200 reactor animals and 200 skin test-negative animals. The first group was randomly selected from herds representing TB endemic regions of GB, but purposely biased to ensure that single reactor herds were under-represented. The skin test-positive animals were selected from groups of cattle containing reactors in herds with a history of persistent recurring, confirmed, bovine TB. The skin test-positive reactor animals were held for only the normal, short time period after the disclosing herd skin test before they were slaughtered, whereas the skin test-negative animals were held in isolation for a period of 60 days, during which time they were monitored for immune responses to *M. bovis*.

15. Both sets of animals were subjected to a range of immunological, bacteriological and metabolic investigations, and an enhanced post mortem examination.

16. The study showed that 20% of the in-contact animals that were skin test-negative at the disclosing skin test, were positive to the IFN test.

17. Detailed post mortem examination revealed macroscopically visible lesions characteristic of TB in 14% (28/200) of the skin test-negative in-contact animals. 23/200 were subsequently found to be positive by culture and/or histology. A further seven animals without gross macroscopic lesions typical of TB were culture and/or histology-positive.

18. A detailed quality controlled immunological study was carried out on 20 of these skin test-negative animals that were subsequently shown to be infected with *M. bovis*. Sixteen of these animals gave positive responses in blood based tests – 14/20 by the IFN test alone and a further 2/20 by a serological test only. It is also important to note that only 3/20 of these animals gave a positive skin test response when the skin test was repeated 60 days after the first (negative) skin test. Hence, most of these animals would not have been detected at the first follow-up short interval skin test. It was also demonstrated that the IFN-positive animals were many times more likely to be *M. bovis* culture-positive compared to the IFN-negative animals (Odds Ratios of between 11 and 76, depending on the diagnostic antigens used in the IFN test) (Coad *et al.*, submitted).

19. The second study involved analyses of data from *ad hoc* field use of IFN on breakdown herds by the State Veterinary Service (now renamed Animal Health) (ISG 1578). The test was used in selected herds for a number of different reasons: to enhance test sensitivity; to assist in confirming results obtained with the skin test; to support decisions on slaughter of whole herds or cohort groups; to reduce the risk of new hot spots developing in areas relatively free from the disease. Although use of the IFN test in these herds was not designed, or intended to be, a scientific exercise, the analyses of the results yielded some valuable data.

20. From 53 herds, IFN testing of 9,206 skin test-negative animals revealed 1,281 (13.9%) animals that gave a positive IFN response and 250 (19.5%) of these had visible lesions typical of TB and/or were culture-positive for *M. bovis*. Comparison of this figure with the level of detection of positive animals from infected herds indicates that, in addition to the animals with confirmed infection detected by the IFN test, a substantial proportion of the IFN-positive, skin test-negative animals that were culture-negative and had no visible lesions are likely to have been infected. These animals represent a considerable reservoir of infection.

21. These figures can be further broken down in respect to herd classification: Over 80% of the IFN results were obtained from 36 herds, in which the test was used to enhance diagnostic sensitivity and where the skin test often failed to detect animals subsequently shown to be infected. Of 7,549 animals tested in this category, 13.1% (992) were IFN test-positive and 11.7% (116) of these were shown to be infected at slaughter. This represents a considerable number of infected animals in these herds, particularly in view of the fact that three quarters of them were annually tested. In eight herds where the IFN test was used to inform the decision on whole herd slaughter, an even higher proportion of infected animals failed to be diagnosed by the skin test; 23% (224) of the 974 skin test-negative animals were IFN-positive, and 56% of these (125) were shown to be infected. Of the 384 animals tested in two infected herds in 'clean areas', 6.8% (26) were IFN-positive and 23% (6) of these were confirmed as infected.

22. The third field study was conducted as a trial (National Gamma Interferon Pilot Trial – reported in ISG 1578 and report to project SB4008) (Defra 2006a) to determine whether a single use of the IFN test in infected herds containing multiple reactors could shorten the period of herd restriction.

23. Because the number of herds recruited into the trial fell short of the target figure, it failed to meet its primary objective. Although ideally it was considered that IFN testing should be applied to herds in control groups in which IFN-positive animals would not be removed, this raised legal concerns and was not pursued. There was a desire to maximize the acceptability of the trial to farmers and optimise its scientific value. However, legal and ethical considerations, and misunderstanding of the value of the IFN test by farmers or their representatives unfortunately had the effect of reducing the amount of data generated and limiting the scientific rigour of the study. Nonetheless the trial provided valuable insights into the epidemiology of the disease in cattle.

24. The trial compared three treatment groups made up of multiple reactor herds. Each herd had three or more skin test reactors under severe interpretation at the disclosing test, at least one of which had visible lesions at postmortem examination. The three groups of 59 (SQ), 78 (IFN) and 58 (XS) herds, each herd containing on average about 170 animals, received one of three treatments. Group SQ received statutory skin testing and culling of skin test-positive animals; the IFN group was treated as for SQ but with an additional IFN test applied 8-49 days after the disclosure test to animals over 12 months of age and any IFN-positive animals also removed; the XS group was treated as for SQ but with any animals giving a skin test response to *M. bovis* PPD in excess of that to *M. avium* PPD at the first short interval test additionally removed.

25. Of 7,346 skin test-negative animals subjected to the IFN test, meeting all quality control criteria for the test, 11.1% (861 animals) were positive to the test. Of these, 17.9% were confirmed as infected based on detection of visible lesions typical of TB and/or a positive culture for *M. bovis*. An average of 2.5 confirmed infected animals per herd were detected by the IFN test combined with the subsequent first short interval test in herds subjected to treatment IFN, significantly more than were detected by the first short interval test in treatments SQ (1.2) or XS (0.8), whether or not animals giving an inconclusive response at standard interpretation were removed and included in the analyses. The IFN test identified 27% more confirmed infected animals than were diagnosed at the disclosing tuberculin skin test (Vordermeier *et al.*, 2006). Given the numbers of IFN-positive animals detected and the estimated specificity of the test as applied in the trial (~97% – see report

on specificity trial below), it is likely that the vast majority of the IFN-positive animals in which infection was not confirmed had undetectable infection with *M. bovis*. Parallel use of a serological test on these herds would be expected to reveal even more infected animals, not diagnosed by the tuberculin test or the IFN test, although the proportion of antibody test-positives only animals is not accurately known.

26. Subsequent testing histories of the trial herds have been examined to January 2007 (14 months after completion of the trial). In the three treatment groups, 24/78 (30.8%) IFN herds, 19/59 (25.4%) SQ herds and 15/58 (25.9%) XS herds have experienced further confirmed breakdowns since coming off movement restrictions imposed after the original breakdowns were detected, i.e. those leading to recruitment into the trial. In 17/78 (21.8%) IFN herds, 7/59 (11.9%) SQ herds and 5/58 (8.6%) XS herds, these subsequent breakdowns were detected within 9 months of movement restrictions being lifted. Previous infection is a powerful predictor of future herd breakdowns and it is likely that undisclosed infection from the original breakdowns accounted for a proportion of these subsequent breakdowns.

27. These studies on naturally infected herds complement experimental studies and together show a remarkably consistent inability of the tuberculin skin test to identify a significant number of infected and diseased animals, especially in breakdown herds containing multiple reactors. In these field studies, overall an additional 11-13% of the animals subjected to the IFN test (a proportion that rose to 23% in herds with heavy disease burden that were considered for whole herd removal), gave a positive response; the results of skin testing in control infected herds indicated that most of these animals would have been missed by the short interval tuberculin skin test. The presence of infection was confirmed in a proportion of the IFN-positive animals and significantly this proportion increased as the number of IFN-positive animals diagnosed in the herd increased. It is likely that the presence of a large number of IFN-positive animals in a herd is associated with highly active infection, which would in turn be associated with a disproportionately large proportion of infected animals. The higher proportion of lesioned animals could be a consequence of some of the animals escaping detection at the disclosing skin test. These animals in turn constitute a source of further transmission in these herds.

28. An IFN specificity trial, involving 23 herds in six low-prevalence counties (in which all IFN test-positive animals were assumed to be uninfected, although they were not slaughtered to confirm negative status) has recently been conducted by Defra (http://www.defra.gov.uk/animalh/tb/pdf/gifn_specificityreport.pdf; and ISG 1573). In line with previously published data, a level of specificity of approximately 97% was obtained employing the cut-off readings used in the National Gamma Interferon Pilot Trial (Defra, 2006a). Since use of the IFN test in multiple reactor herds revealed that 11% of animals tested gave a positive response, this would indicate that a large majority of these positive results are attributable to infection with *M. bovis* and not due to false-positive results.

29. Available data from use of the IFN test under field conditions indicate that it does not yet have sufficiently high specificity to consider using it as a primary surveillance tool to replace the tuberculin skin test. However, the results of field trials point to the benefits of using the IFN test in some herds where the presence of infection has been identified using the tuberculin skin test as a herd disclosing test. The ability to identify additional infected animals missed by the skin test must be balanced against the disadvantage of also removing some uninfected animals. These studies therefore highlight, in some circumstances, the value of the complementary use of the IFN test alongside the tuberculin test, where relative

sensitivity values ranging from 88% to 97% have been recorded by combined use of the tests (reviewed in Vordermeier *et al.*, 2006).

Overcoming the problem of non-specific responses in diagnostic tests

30. Cattle are known to be exposed to and infected with a number of other mycobacterial species which can induce immune responses that cross-react with *M. bovis* and thus can complicate the interpretation of the tuberculin test, which is the reason why the comparative skin test using bovine and avian PPD is used. Experimental studies with *M. avium* (1.6×10^6 CFU, subcutaneous route) in cattle have demonstrated that such responses interfere with detection of a positive response to *M. bovis* in the skin test, particularly at standard interpretation, but also in some animals at severe interpretation. Infection of cattle with *M. avium* was also shown to interfere with the response to the IFN test; 50% of calves experimentally infected (intranasal route, 10^4 CFU) with *M. bovis* and *M. avium* failed to give a positive IFN test reading (Hope *et al.*, 2005). However, use of a version of the IFN test that utilised two defined *M. bovis* proteins (ESAT-6 and CFP-10) instead of PPD improved sensitivity, detecting most but not all of the dually infected animals (Hope *et al.*, 2005).

31. These findings illustrate the potential that exists for improving both specificity and sensitivity of the IFN test by using defined antigens (although at present these reagents are generally less sensitive in animals infected with *M. bovis* only) and highlight the need to identify additional antigens which can be added to the test to increase overall signal strength and sensitivity.

Cattle movement and geographical spread of the cattle disease

32. The spread of disease within infected areas, and from infected areas of the country to non-infected areas, is a well recognized epidemiological feature of cattle TB. Gilbert *et al.*, 2005 (funded in SE 3034, Defra) have suggested that cattle movement between herds, specifically movement of cattle from areas with a high level of infection, is a major predictor of bovine TB in areas with a low incidence of disease. In trial-related studies, the high risk of herd breakdowns has been associated with cattle movement (Johnston *et al.*, 2005) and Carrique-Mas *et al.*, (2006) have demonstrated a very high risk of herd breakdowns following cattle purchase, particularly from herds with a previous history of TB. Christiansen *et al.*, (1992) reported that, in Ireland, herds that had a TB breakdown and purchased cattle following lifting of movement restrictions were twice as likely to breakdown at the 6-month follow-up test than herds that did not purchase animals.

33. It has been suggested by other authors that the majority of incidents of bovine TB in areas without a wildlife reservoir of *M. bovis* infection result from movements of infected cattle into TB-free herds (Barlow *et al.*, 1998; Goodchild and Clifton-Hadley, 2001 and Gilbert *et al.*, 2004; cited by Gopal *et al.*, 2006). The latter authors have provided more substantial and precise evidence of geographic spread of the disease by infected cattle, using cattle tracing data in conjunction with molecular genotyping techniques to identify the strain type and origin of the *M. bovis* isolate involved in the breakdown. Thirty-one herd breakdowns were investigated in the North East of England, a relatively TB-free part of Great Britain, between January 2002 and June 2004. The affected herds were all in 4-yearly tested parishes at the time of the breakdowns. Nine of the breakdown herds depopulated as a result of the foot and mouth disease (FMD) epidemic and restocked involved relatively large numbers of animals. The remaining herds involved smaller numbers of animals.

34. In 30 of the breakdowns, the purchase of one or more animals, mainly from endemic TB areas in Wales and the West of England, was considered the most likely source of infection, and in 17 of these herds the genotype of the *M. bovis* isolates closely matched that of *M. bovis* strains prevalent in the regions from which the animals were purchased. In the remaining herd, the source of infection could not be identified, although the molecular type was typical of that found in a geographically distant part of the country. A feature of five of these herd breakdowns was evidence of in-herd amplification and spread of the disease. Eleven breakdowns were associated with the movement of infected animals when they were one year old or less and in five of these cases the animals were 20 weeks or less; a clear example of the risks of infection at any age.

35. Carrique-Mas *et al.*, (2006) analysed the outcome of the first tuberculin test after FMD for virtually all herds that were depopulated and restocked. In herds from areas of Britain with high disease incidence (South West of England) a number of risk factors were identified but the three biggest were the number of animals bought from farms that had a high rate of testing, purchase of animals from herds that had been positive to the tuberculin test in the previous five years and herd size. For herds in areas with low incidence of TB (in the North of England) only purchasing from herds with a high rate of testing (herds in the South West of England) was a significant risk.

INDEPENDENT SCIENTIFIC GROUP ON CATTLE TB PUBLISHED SCIENTIFIC PAPERS

The strength of science is based on the long-established principle that findings are subjected to critical and independent peer review by qualified scientists, with findings judged to be sound then given prominence by publication in respected journals. It is only in this manner that the validity of claims of 'new knowledge' can become accepted in the wider community, and the ISG has worked hard to ensure that, whenever possible, our work appeared in peer-reviewed published manuscripts. Most importantly this process ensures that the Government can genuinely claim to be basing future bovine TB policy decisions on sound science.

This appendix summarises the ISG's published scientific papers and other important published material. At the time this report was printed, several ISG manuscripts were undergoing peer review. The ISG web page listing publications <http://www.defra.gov.uk/animalh/tb/isg/isgpublications.htm> will continue to be updated with details of ISG papers as they become available.

Impacts of widespread badger culling on cattle tuberculosis: concluding analyses from a large-scale field trial

Christl A. Donnelly, Gao Wei, W. Thomas Johnston, D. R. Cox, Rosie Woodroffe, F. John Bourne, C. L. Cheeseman, Richard S. Clifton-Hadley, George Gettinby, Peter Gilks, Helen E. Jenkins, Andrea M. Le Fevre, John P. McInerney and W. Ivan Morrison. *International Journal of Infectious Diseases*, Published online 2007 (print publication to follow).

<http://www.sciencedirect.com/science/journal/12019712>

<http://dx.doi.org/10.1016/j.ijid.2007.04.001>

This paper updates published analyses (Donnelly *et al.* *Nature* 2006) of the impact of proactive (repeated widespread) badger culling in the Randomised Badger Culling Trial on TB incidence in cattle herds. Overall, cattle TB incidence was 23.2% lower inside culled areas, but 24.5% higher on land ≤ 2 km outside, relative to matched uncultured areas. Inside the culling area boundary the beneficial effect of culling tended to increase with distance from the boundary and to increase on successive annual culls. In adjoining areas, the detrimental effect tended to diminish on successive annual culls. On the basis of these trends, the estimated net effect per annum for culling areas similar to those in the trial was detrimental between the first and second culls, but beneficial after the fourth and later culls, for the range of analyses performed. The paper concludes that careful consideration is needed to determine in what settings systematic repeated culling might be reliably predicted to be beneficial and in these cases whether the benefits of such culling warrant the costs involved.

Culling and cattle controls influence tuberculosis risk for badgers

Rosie Woodroffe, Christl A. Donnelly, Helen E. Jenkins, W. Thomas Johnston, David R. Cox, F. John Bourne, Chris L. Cheeseman, Richard J. Delahay, Richard S. Clifton-Hadley, George Gettinby, Peter Gilks, R. Glyn Hewinson, John P. McInerney and W. Ivan Morrison. *Proceedings of the National Academy of Sciences, USA*, 103, 14713-14717, 2006.

<http://www.pnas.org/cgi/doi/10.1073/pnas.0606251103>

This paper shows that repeated badger culling in the same area is associated with increasing prevalence of *M. bovis* infection in badgers, especially where landscape features allow badgers from neighbouring land to recolonise culled areas. It suggests that this impact on prevalence in badgers might reduce the beneficial effects of culling on cattle TB incidence, and could contribute to the detrimental effects that have been observed. Additionally, the paper shows that suspension of cattle TB controls during a nationwide epidemic of foot and mouth disease, which substantially delayed removal of TB-affected cattle, was associated with a widespread increase in the prevalence of *M. bovis* infection in badgers. This pattern suggests that infection may be transmitted from cattle to badgers, as well as vice versa. It was clear that disease control measures aimed at either host species may have unintended consequences for transmission, both within and between species. The findings highlight the need for policymakers to consider multiple transmission routes when managing multihost pathogens.

Effects of culling on badger *Meles meles* spatial organization: implications for the control of bovine tuberculosis

Rosie Woodroffe, Christl A. Donnelly, D. R. Cox, F. John Bourne, C. L. Cheeseman, R. J. Delahay, George Gettinby, John P. McInerney and W. Ivan Morrison. *Journal of Applied Ecology*, 43, 1-10, 2006.

<http://dx.doi.org/10.1111/j.1365-2664.2005.01144.x>

Having found that TB incidence in cattle was no lower in RBCT areas subject to localised badger culling than in nearby areas where no experimental culls occurred, the paper evaluates one hypothesis that was advanced to explain this pattern, namely that localised culling disrupted badgers' territorial behaviour, potentially increasing the rate of contact between cattle and infected badgers. This paper reports on a study in which badger home ranges were mapped by feeding colour-marked baits at badger setts and measuring the area in which colour-marked faeces were observed. Badger home ranges were mapped in 13 study areas subjected to different levels of culling. Badger home ranges were consistently larger in culling areas. Moreover, in areas not subjected to culling, home range sizes increased with proximity to the culling area boundary. Patterns of overlap between home ranges were also influenced by culling. The study demonstrates that culling badgers profoundly alters their spatial organisation as well as their population density: that these changes have the potential to influence contact rates between cattle and badgers, both where culls occur and on adjoining land, and that the results may help to explain why localised badger culling appears to have failed to control cattle TB. The paper concludes that the results should be taken into account in determining what role, if any, badger culling should play in future control strategies.

Positive and negative effects of widespread badger culling on cattle tuberculosis

Christl A. Donnelly, Rosie Woodroffe, D. R. Cox, F. John Bourne, C. L. Cheeseman, Richard S. Clifton-Hadley, Gao Wei, George Gettinby, Peter Gilks, Helen Jenkins, W. Thomas Johnston, Andrea M. Le Fevre, John P. McInerney and W. Ivan Morrison. *Nature*, 439, 843 – 846, 2006.

<http://dx.doi.org/10.1038/nature04454>

This paper presents the first findings from the proactive element of the RBCT. It shows that on the basis of the analyses conducted at that time, the incidence of herd breakdowns

was 19% lower in proactive trial areas than in survey-only areas. Analyses also reveal a 29% increase in cattle TB incidence on land neighbouring proactive areas, relative to land in survey-only areas. This result was consistent across all ten proactive culling areas. The estimated effect when measured after the first follow up cull rather than the initial cull was a 23% reduction in the incidence of herd breakdowns in culled areas and a 22% increase on neighbouring land. Analyses revealed no significant change in the effect of culling on breakdown incidence over time.

The paper concludes that these findings have important implications for the development of sustainable bovine TB control policies, and will present challenges for the development of such policies. Also, the overall reduction in cattle TB is expected to be greatest for very large culling areas with consequently lower perimeter to area ratios, although in absolute terms the costs, as well as the benefits, will be greatest for large areas. The paper further concludes that detailed consideration is needed to determine whether culling on any particular scale would be economically and environmentally sustainable.

Simple model for tuberculosis in cattle and badgers

D. R. Cox, Christl A. Donnelly, F. John Bourne, George Gettinby, John P. McInerney, W. Ivan Morrison, and Rosie Woodroffe. *Proceedings of the National Academy of Sciences, USA*, 102, 17588-17593, 2005.

<http://www.pnas.org/cgi/doi/10.1073/pnas.0509003102>

As an aid to the study of bovine TB, this paper develops a simple model of an epidemic involving two species, cattle and badgers, where each species may infect the other. In the paper the proportion of animals affected is assumed relatively small so that the usual non-linear aspects of epidemic theory are avoided. The model is used to study the long-run and transient effect on cattle of culling badgers and the effect of a period without routine testing of cattle for TB, such as occurred during the 2001 epidemic of foot-and-mouth disease in Great Britain. Finally, by examining the changes in cattle TB over the last 15 years, and with some other working assumptions, it is estimated that the net reproduction number of the epidemic is approximately 1.1 (conditions for epidemic growth are that this number exceeds 1.0).

The paper shows that although the net reproduction number is clearly above 1.0, it is sufficiently close to 1.0 that relatively modest improvements either in TB test performance or TB testing frequency would be sufficient to bring an epidemic under control, but under the highly idealised assumptions made in the model. The paper goes on to discuss the implications for disease control.

Spatial association of *Mycobacterium bovis* infection in cattle and badgers *Meles meles*

R. Woodroffe, C. A. Donnelly, W. T. Johnston, F. J. Bourne, C. L. Cheeseman, R. S. Clifton-Hadley, D. R. Cox, G. Gettinby, R. G. Hewinson, A. M. Le Fevre, J. P. McInerney and W. I. Morrison. *Journal of Applied Ecology*, 42, 852-862, 2005.

<http://dx.doi.org/10.1111/j.1365-2664.2005.01081.x>

Using data from the RBCT, this paper investigates local geographical associations between *Mycobacterium bovis* infection in badgers and cattle. Infections were locally clustered

within both badger and cattle populations and the paper shows, for the first time, that *M. bovis* infections in badgers and cattle are spatially associated at a scale of 1–2 km. Badgers and cattle infected with the same strain type of *M. bovis* are particularly closely correlated and the paper says these observational data support the hypothesis that transmission occurs between the two host species; however, it concludes that they cannot be used to evaluate the relative importance of badger-to-cattle and cattle-to-badger transmission. The paper suggests that the close associations between *M. bovis* infections in cattle and badgers show that localised badger culling could reasonably be expected to reduce the risks of cattle TB infection; however, during the RBCT no such beneficial effects over the time-scale on which they were tested were found, demonstrating the difficulty of predicting the outcome of management interventions, and reinforcing the need for well-designed empirical assessments of future bovine TB control strategies.

Herd-level risk factors associated with tuberculosis breakdowns among cattle herds in England before the 2001 foot-and-mouth disease epidemic

W. T. Johnston, G. Gettinby, D. R. Cox, C. A. Donnelly, J. Bourne, R. Clifton-Hadley, A. M. Le Fevre, J. P. McInerney, A. Mitchell, W. I. Morrison and R. Woodroffe. *Biology Letters*, 1, 53-56, 2005.

<http://dx.doi.org/10.1098/rsbl.2004.0249>

This paper contains the first case-control results from the TB99 epidemiological survey, a case-control study of the factors associated with the risk of a bovine tuberculosis (TB) breakdown in cattle herds. The study was undertaken within the RBCT and TB breakdowns occurring prior to the 2001 foot-and-mouth disease epidemic in three RBCT triplets were eligible to be cases; controls were selected from the same RBCT area. Data from 151 case farms and 117 control farms were analysed and the results suggest that the strongest factors associated with an increased TB risk were movement of cattle onto the farm from markets or farm sales, operating a farm over multiple premises and the use of either covered yard or 'other' housing types. Spreading artificial fertilisers or farmyard manure on grazing land were both associated with decreased risk.

Welfare of badgers (*Meles meles*) subjected to culling: Patterns of trap-related injury

R. Woodroffe, F. J. Bourne, D. R. Cox, C. A. Donnelly, G. Gettinby, J. P. McInerney and W. I. Morrison. *Animal Welfare*, 14, 11-17, 2005

This, the first of two badger welfare papers, assesses the risk of badgers confined to cage traps prior to despatch becoming injured as a result of rubbing or biting on the cage. In the RBCT, 88% of badgers received no detectable injuries as a result of being confined in a trap. Of those that were injured, 72% received only minor skin abrasions. A minority (1.8% of the total) acquired damage to the teeth or jaws that may have caused serious pain. Although trap rounds were commenced in the early morning, badgers were no more likely to sustain injuries when they remained in traps until later in the day. Coating of cage traps, intended to give the wire mesh a smoother surface, was associated with a reduction in the incidence of minor skin abrasions, although it may have slightly increased the frequency of less common but more serious abrasions. Modification of the door design reduced tooth damage.

Welfare of badgers (*Meles meles*) subjected to culling: Development and evaluation of a closed season

R. Woodroffe, F. J. Bourne, C. L. Cheeseman, D. R. Cox, C. A. Donnelly, G. Gettinby, J. P. McInerney and W. I. Morrison. *Animal Welfare*, 14, 19-25, 2005.

This second badger welfare paper assesses the killing of breeding females, which risks leaving their unweaned cubs to starve in the den. To avoid the possibility of this risk, a three-month closed season was adopted in the RBCT, running from 1st February to 30th April, based on the best available estimates of the timing of birth and weaning in British badgers. During May 1999-2003, when a total of 4705 adult badgers were culled, field teams failed to capture 12 unweaned litters when their mothers were despatched. In 31 other cases, lactating females were culled but litters of almost-weaned cubs were also caught and despatched at the same dens, usually within a day of capture of the mother. The number of unweaned cubs missed by culling teams – estimated at approximately 9 per year on average – was dramatically lower than that projected by a badger welfare lobby group. Data suggests that the closed season is effective in reducing the suffering of unweaned cubs in badger populations subject to culling, and we recommended that this measure be maintained should badger culling form a component of any future TB control policy.

Bovine Tuberculosis – Towards a Science Based Control Strategy

F. J. Bourne, C. A. Donnelly, D. R. Cox, G. Gettinby, J. P. McInerney, W. I. Morrison and R. Woodroffe. *Science in Parliament*, 62 (2), 25-28, 2005.

Potential use of vaccination in cattle and badgers to control bovine tuberculosis.

Control of Infectious Animal Diseases by Vaccination

W. I. Morrison, F. J. Bourne, D. R. Cox, C. A. Donnelly, G. Gettinby, J. P. McInerney and R. Woodroffe. Eds. A. Schudel and M. Lombard. Series: Development of Biologicals, 119. Karger, Basel, 351-359, 2004.

The paper considers vaccination either of cattle or wildlife as a possible bovine TB control measure and discusses the potential merits, problems and obstacles that need to be overcome before vaccination can be considered a practical option. It says, theoretically, vaccination could be directed either to cattle to protect against transmission from wildlife and amongst cattle, or to wildlife to render them less infectious to cattle, but the challenges are different, depending on whether the vaccine is intended for use in cattle or wildlife. It considers that the latter would be viable only if wildlife represents a dominant source of infection, whereas vaccination of cattle might be expected to provide protection irrespective of the source of infection. The paper says the likelihood of success and the timescale for developing an improved vaccine against *M. bovis* are difficult to predict, however, recent advances have opened new approaches to vaccine development.

Impact of localized badger culling on tuberculosis incidence in British cattle

Christl A. Donnelly, Rosie Woodroffe, D. R. Cox, John Bourne, George Gettinby, Andrea M. Le Fevre, John P. McInerney and W. Ivan Morrison. *Nature*, 426, 834-837, 2003.

<http://dx.doi.org/10.1038/nature02192>

This paper presents the first results from the reactive element of the Randomised Badger Culling Trial. Analyses reveal that the reactive treatment had been associated with a 27%

increase in the incidence of cattle herd breakdowns. This was highly consistent, with more breakdowns than expected in all nine of the areas that had been reactively culled. The paper suggests that this provides evidence for a link between badgers and TB in cattle, but points to transmission dynamics that must be highly complex. It concludes that localised badger culling, as conducted in the RBCT, not only fails to control but also seems to increase TB incidence in cattle and similar past policies may have been of no benefit to the control of TB in British cattle.

Towards a sustainable policy to control TB in cattle.

Conservation and Conflict: Mammals and Farming in Britain

R. Woodroffe, F. J. Bourne, C. A. Donnelly, D. R. Cox, G. Gettinby, J. P. McInerney and W. I. Morrison. Linnean Society. Eds. F. Tattersal and W. Manley. 142-151, 2003.

This paper describes the history of bovine TB control in Britain, and outlines the ISG's programme of work to develop science-based policy options for future TB control.

Towards a Sustainable Policy to Control Cattle TB in Britain.

F. J. Bourne. *Science in Parliament*, 58 (3), 4-5, 2001.

Bovine Tuberculosis: towards a future control strategy

J. Bourne, C. A. Donnelly, D. R. Cox, G. Gettinby, J. P. McInerney, W. I. Morrison and R. Woodroffe. *Veterinary Record*, 146, 207-210, 2000.

This, the first of two articles published in the *Veterinary Record*, discusses the ISG's approach to ensure that future strategies for the control of bovine TB in cattle are scientifically based.

Pathogenesis and diagnosis of infections with *Mycobacterium bovis* in cattle

W. I. Morrison, F. J. Bourne, D. R. Cox, C. A. Donnelly, G. Gettinby, J. P. McInerney and R. Woodroffe. *Veterinary Record* 146, 236-242, 2000.

This second article considered the extent to which efforts to control bovine TB in cattle may be constrained by limitations in current testing procedures.

Other publications

To cull or not to cull

F. J. Bourne, C. A. Donnelly, D. R. Cox, G. Gettinby, J. P. McInerney, W. I. Morrison and R. Woodroffe. *Science and Public Affairs*, March 2007.

This article sets out a brief history of TB control measures, describes the RBCT, discussed the effects of culling on bovine TB, explains the RBCT results available at the time of publication and considers the way forward.

Patterns of trap-related injury recorded in the Randomised Badger Culling Trial – an update.

R. Woodroffe, C. A. Donnelly, Gao Wei, F. J. Bourne, C. L. Cheeseman, D. R. Cox, G. Gettinby, J. P. McInerney and W. I. Morrison. 2007.

<http://www.defra.gov.uk/animalh/tb/isg/pdf/trapinjuries.pdf>

Updates the analyses in Woodroffe *et al.*, *Animal Welfare*, 14, 11 – 17, 2005 to the end of the 2005 culling year, when RBCT culling was completed.

Evaluating the closed season adopted in the Randomised Badger Culling Trial – an update.

R. Woodroffe, C.A. Donnelly, Gao Wei, F.J. Bourne, C.L. Cheeseman, D.R. Cox, G. Gettinby, J.P. McInerney and W.I. Morrison. 2007.

<http://www.defra.gov.uk/animalh/tb/isg/pdf/closedseason.pdf>

Updates the analyses in Woodroffe *et al.*, *Animal Welfare*, 14, 19 – 25, 2005, to the end of the 2005 culling year, when RBCT culling was completed.

Report of the work of the Group and its published findings in 2005

F. J. Bourne, C. A. Donnelly, D. R. Cox, G. Gettinby, J. P. McInerney, W. I. Morrison and R. Woodroffe. 2006, Defra (London).

<http://www.defra.gov.uk/animalh/tb/isg/5th-isgreport.pdf>

Fifth Report of the Independent Scientific Group on Cattle TB.

The impact of localised badger culling versus no culling on TB incidence in British cattle: a randomised trial

Andrea M. Le Fevre, Christl A. Donnelly, D. R. Cox, John Bourne, Richard S. Clifton-Hadley, George Gettinby, W. Thomas Johnston, John P. McInerney, W. Ivan Morrison and Rosie Woodroffe.

<http://www.defra.gov.uk/animalh/tb/isg/pdf/lefevre1005.pdf>

This paper reports on an extended analysis of the reactive element of the RBCT, and updates the initial publication (Donnelly *et al.*, *Nature*, 2003). This analysis uses additional incidence data, up to 22 August 2004, up to which there had been 358 confirmed TB cattle breakdowns in the control areas and 356 in the areas receiving localised reactive culling. After adjustment for covariates, localised reactive badger culling was associated with an estimated 25% increase in the number of cattle herds disclosing TB. This paper presents many previously unpublished extensions to these comparisons. It concludes that reactive culling as performed in the Randomised Badger Culling Trial cannot contribute constructively to the control of bovine TB in Britain.

An epidemiological investigation into Bovine Tuberculosis – Towards a science-based control strategy

F. J. Bourne, C. A. Donnelly, D. R. Cox, G. Gettinby, J. P. McInerney, W. I. Morrison and R. Woodroffe. 2005, PB10138, Defra (London).

<http://www.defra.gov.uk/animalh/tb/isg/4th-isgreport.pdf>

Fourth Report of the Independent Scientific Group on Cattle TB.

Development of vaccines for Bovine Tuberculosis

F. J. Bourne, C L Cheeseman, M. J. Colston, C. A. Donnelly, S. M. Eades, P. Fine, B. Grenfell, R. G. Hewinson, S. Houghton, W. I. Morrison, J. Pollock, A. G. Simmons, R.

Woodroffe and D. B. Young. 2003, PB9102, Defra (London).

<http://www.defra.gov.uk/animalh/tb/pdf/vsssc.pdf>

Report of the Independent Scientific Group on Cattle TB Vaccine Scoping Sub-Committee.

Changes in badger setts over the first three years of the randomised badger culling trial

A. M. Le Fevre, W. T. Johnston, J. Bourne, C. A. Donnelly, D. R. Cox, G. Gettinby, J. P. McInerney, W. I. Morrison and R. Woodroffe. Society for Veterinary Epidemiology and Preventive Medicine, 2003, Warwick

<http://www.svepm.org.uk/posters/2003/LeFevre.pdf>

This reports on surveys of badger setts that were carried out before culling in all RBCT areas and also in the third year after culling in the nine trial areas available at the time of writing. Fewer setts were identified in the follow up surveys, particularly in the proactive areas. In addition, fewer setts persisted between the initial survey and the three-year survey, and more setts disappeared, indicating that culling had a significant effect on badger sett distributions.

Preliminary assessment of enrolment questionnaires from the randomised badger culling field trial proactive areas

W. T. Johnston, A. M. Le Fevre, C. A. Donnelly, J. Bourne, D. R. Cox, G. Gettinby, J. P. McInerney, W. I. Morrison, R. Woodroffe and A. R. Sayers. Society for Veterinary Epidemiology and Preventative Medicine, 2003, Warwick

<http://www.svepm.org.uk/posters/2003/Johnson.pdf>

This reports on the return rate and data provided in response to questionnaires posted to occupiers of seven of the proactive areas at the time of recruitment to the RBCT. The overall return rate was poor and smaller farms were under-represented. It is suggested that extensive analysis may not be possible, and that perhaps future analyses should focus on larger farms.

An epidemiological investigation into bovine tuberculosis – Towards a Sustainable Policy to Control TB in Cattle

F. J. Bourne, C. A. Donnelly, D. R. Cox, G. Gettinby, J. P. McInerney, W. I. Morrison and R. Woodroffe. 2001, PB5801, Defra (London).

<http://www.defra.gov.uk/animalh/tb/isg/report/isg3.pdf>

Third Report of the Independent Scientific Group on Cattle TB.

An epidemiological investigation into bovine tuberculosis – Towards a Sustainable Policy to Control TB in Cattle

F. J. Bourne, C. A. Donnelly, D. R. Cox, G. Gettinby, J. P. McInerney, W. I. Morrison and R. Woodroffe. 2000, PB4870, MAFF (London).

<http://www.defra.gov.uk/animalh/tb/isg/report/contents.htm>

Second Report of the Independent Scientific Group on Cattle TB.

Towards a sustainable policy to control TB in cattle in Great Britain

This paper, for the Proceedings of the 3rd International Conference on *M. bovis*, Cambridge, 2000, explains the ISG's approach to ensure that future strategies for the control of bovine TB in cattle are scientifically based.

Towards a sustainable policy to control TB in cattle – A scientific initiative

F. J. Bourne, C. A. Donnelly, D. R. Cox, G. Gettinby, J. P. McInerney, W. I. Morrison and R. Woodroffe. 1998, PB3881, MAFF (London).

<http://www.defra.gov.uk/animalh/tb/isg/isgprep1.htm>

First Report of the Independent Scientific Group on Cattle TB.

AVAILABILITY OF PAPERS, DATABASES AND BIOLOGICAL SAMPLES

1. A document containing the texts of minutes of all ISG meetings will be published by Defra and its availability will be advertised on Defra's Bovine TB website.
2. A list will be published, on Defra's Bovine TB website, of all papers prepared for ISG meetings. Individual papers can be made available to the public on request. A fee may be payable to Defra for this service to cover the cost of retrieval, photocopying and postage. Papers that contain scientific manuscripts that are in press, or have yet to be submitted for publication, will not be released until the papers are published in the scientific press.
3. A list of Group letters to Ministers and Senior Officials is given in Appendix L which also shows which letters have been published and where. Letters, not already published, may be made available. A fee may be payable to Defra for this service to cover the cost of retrieval, photocopying and postage.
4. ISG scientific publications, that had been published at the time of the preparation of this report, are listed in Appendix J. An updated list will be published on Defra's Bovine TB website. Copies of a limited number of these publications are available from Defra's Bovine TB website. Copies of all the ISG's scientific publications can be obtained from the Journals in which these were published or by application to the National or Regional libraries that deal with requests for such scientific information.
5. Defra Food and Farming Group Information Section will keep a "Compendium of ISG Scientific Publications", to include published supplementary data. Individual papers, of material published more than 6 months previously, can be made available to the public on request. A fee may be payable to Defra for this service to cover the cost of retrieval, photocopying and postage.
6. RBCT databases will be preserved and be made available for future use by researchers. Defra's policy will be to encourage access to the data to maximise their use in further study of TB epidemiology. The databases will be held and managed by Centre for Epidemiology and Risk Analysis (CERA) at the Veterinary Laboratories Agency, Weybridge. A list of databases will be published on the Defra Bovine TB website and those with an interest can receive a full Data Inventory. A fee may be payable for provision of this service.
7. An inventory of RBCT biological samples available for distribution to bona-fide researchers will be advertised by Defra on its Bovine TB website. The Veterinary Laboratories Agency, Weybridge will be responsible for the storage and release of samples. A fee may be payable for provision of this service.
8. The Defra Bovine TB website is at: <http://www.defra.gov.uk/animalh/tb>.
9. For an undetermined period after the conclusion of the ISG's work, their website <http://www.defra.gov.uk/animalh/tb/isg/index.htm> will be maintained by Defra.
10. For those who do not have access to the Internet, enquiries should be directed to the Defra Helpline, telephone 08459 33 55 77.

ISG CORRESPONDENCE WITH MAFF/DEFRA MINISTERS AND SENIOR OFFICIALS

Date	To	Subject
17 July 1998 ¹	Secretary of State	First Report of the ISG
25 February 1999	Minister of State (Commons)	Note of meeting held to discuss progress of the trial
5 July 1999	MAFF/SVS Wildlife Unit	Badger Trials
17 September 1999	Secretary of State	RBCT
26 October 1999	Minister of State (Lords)	Follow up to meeting held on 20 October 1999
17 December 1999 ²	Secretary of State	Second Report of the ISG
2 February 2000	Secretary of State	Follow up to meeting held on 22 January 2000 to discuss the ISG's Second Report
3 August 2000 ³	Head, TB & Zoonoses Division	ISG response to the Report of the Independent Husbandry Panel
12 February 2001	Permanent Secretary	Meeting with Permanent Secretary
18 July 2001 ³	Secretary of State	Third Report of the ISG
18 March 2002	Parliamentary Under Secretary (Commons)	Impact of Foot and Mouth Disease on the ISG's work programme
20 March 2002	Chief Veterinary Officer (CVO)	Note of meeting with CVO held on 7 March 2002
28 March 2002	Chief Veterinary Officer	Action list from meeting held on 7 March 2002
22 May 2002	Parliamentary Under Secretary (Commons)	Welfare aspects of the RBCT
18 June 2002	Head, TB & Zoonoses Division	Resumption of TB testing in trial areas
25 July 2002	Chief Veterinary Officer	TB99 epidemiological questionnaire
13 August 2002 ⁴	Head, TB & Zoonoses Division	Proposed pilot field trial γ -IFN
3 October 2002	Parliamentary Under Secretary of State (Commons)	Interim measures to control cattle TB
7 November 2002 ⁴	Parliamentary Under Secretary (Commons)	Diagnostic test: γ -IFN field trial
22 November 2002	Parliamentary Under Secretary (Commons)	Proposed pilot of γ -IFN test
24 March 2003	Chief Scientific Adviser	Note of meeting
11 April 2003	Parliamentary Under Secretary (Commons)	Note of meeting held on 9 April 2003
9 May 2003	Chief Veterinary Officer	Sampling procedures for TB
9 May 2003 ⁴	Parliamentary Under Secretary (Commons)	Update on progress of the trial and related work

Date	To	Subject
15 July 2003	Parliamentary Under Secretary (Commons)	Review of RBCT
29 October 2003 ⁴	Secretary of State	ISG advice on the Reactive treatment
4 November 2003	National Trial Manager	Reactive treatment findings
10 November 2003 ⁴	Chief Veterinary Officer	Reply to invitation to comment on bovine TB in the Furness Peninsula
13 January 2004	Chief Veterinary Officer	Analysis of Reactive trial data
16 March 2004	Independent Scientific Review Group	Response to the Report of the Independent Scientific Review of the RBCT and Associated Epidemiological Research
21 August 2004	Director, TSE & Zoonoses	Note of meeting on Reactive strategy
3 June 2004	Chief Veterinary Officer	Analysis of Reactive data
1 September 2004	Parliamentary Under Secretary (Commons)	TB control strategy
7 December 2004	Head, Animal Disease Control Division	Note of meeting held on 30 December 2004 on future of RBCT
7 December 2004 ⁵	Head, Veterinary Exotic Diseases and Zoonoses Division	Note of meeting held on 30 December 2004 on future of RBCT
23 December 2004	Secretary of State	Fourth Report of the ISG
23 February 2005	Parliamentary Under Secretary (Commons)	ISG comments and advice on RoI Four Area Badger Study
23 February 2005	Head, TB Division	Diagnosis and the tuberculin test
19 May 2005	Chief Veterinary Officer	Minutes of meeting held on 5 May 2005
5 September 2005 ⁵	Parliamentary Under Secretary (Commons)	Premature release of trial data
29 September 2005 ⁵	Parliamentary Under Secretary (Commons)	Interim analysis of RBCT Proactive data
29 September 2005 ⁵	Chief Scientific Adviser	Interim analysis of RBCT Proactive data
7 October 2005 ⁵	Parliamentary Under Secretary (Commons)	Summary interim report of RBCT Proactive data
21 October 2005 ⁵	Chief Scientific Adviser	Statistical analyses of RBCT data
29 November 2005 ⁵	Parliamentary Under Secretary (Commons)	Analysis of Proactive data
11 January 2006	Parliamentary Under Secretary (Commons)	Consultation on controlling the spread of bovine tuberculosis in cattle in high incidence area in England: badger culling
1 February 2006	Parliamentary Under Secretary (Commons)	Updated analysis of Proactive data

Date	To	Subject
24 February 2006	Parliamentary Under Secretary (Commons)	Consultation on controlling the spread of bovine tuberculosis in cattle in high incidence area in England: badger culling
14 March 2006	Parliamentary Under Secretary (Commons)	RBCT: badger culling and data release
21 March 2006	Parliamentary Under Secretary (Commons)	Updated analysis of Proactive data
31 March 2006	Chief Scientific Adviser	RBCT: data release
3 July 2006	Parliamentary Under Secretary (Commons)	Temporal patterns of <i>M. bovis</i> infection in badgers
29 January 2007	Minister of State (Commons)	Effects of culling on badger abundance
1 May 2007	Minister of State (Commons)	Concluding analyses of Proactive culling data from the RBCT
23 May 2007	Minister of State (Commons)	Final Report of the ISG

¹ Available within the First Report and at: <http://www.defra.gov.uk/animalh/tb/isg/isgprep1.htm>

² Available within the Second Report and at: <http://www.defra.gov.uk/animalh/tb/isg/report/contents.htm>

³ Available within the Third Report and at: <http://www.defra.gov.uk/animalh/tb/isg/report/isg3.pdf>

⁴ Available at Appendix I of the ISG's Fourth Report and at: <http://www.defra.gov.uk/animalh/tb/isg/4th-isgreport.pdf>

⁵ Available at: <http://www.defra.gov.uk/animalh/tb/isg/index.htm>

OPEN MEETINGS

19 November 2003

The ISG met at One Great George Street in London. The meeting was the first that the Group had conducted in public and they were pleased to welcome around 70 delegates.

The audience observed the Group discuss presentations on 'Strain Typing of *M. bovis* in Great Britain', 'Bovine TB Pathogenesis', and 'Diagnosis of Infection with *M. bovis*'.

Apart from observing the Group deliberate, the audience participated in a Question and Answer session during which were discussed issues such as the cessation of reactive culling, vaccines to control bovine tuberculosis, and pre- and post-movement cattle testing. Informal discussions also took place over lunch and provided attendees with the opportunity to ask further questions.

The Chairman thanked those present for attending the meeting and hoped it had demonstrated the broad-spectrum scientific approach taken by the ISG to advise on the control of bovine tuberculosis.

The attendees were asked for feedback on the meeting; 97% found the meeting informative and 91% indicated that they would like to attend future meetings.

17 November 2004

The ISG held their second public open meeting at One Great George Street, London. The Group was pleased to welcome representatives from 19, mainly farming, organisations together with 39 individuals.

The audience heard Professor Christl Donnelly give a talk entitled 'Presentation of analysis of the Randomised Badger Culling Trial data', Professor Ivan Morrison spoke on 'Pathogenesis of TB in cattle' and Professor George Gettinby gave a presentation entitled 'TB99 Farm Survey'.

The audience participated in a Question and Answer session during which a range of issues was discussed, such as badger culling in the Reactive element of the Trial, biosecurity measures, genetic susceptibility to TB and the specificity of the gamma interferon test. Informal discussions also took place over lunch and provided delegates with the opportunity to ask further questions.

In closing the meeting the Chairman said that he hoped it had demonstrated the broad-spectrum scientific approach taken by the ISG to advise on the control of bovine tuberculosis.

Subsequent feedback from delegates was generally positive.

25 January 2006

The ISG's third open meeting was also held at One Great George Street, London, and was attended by over 80 delegates, some attending as individuals, others representing a broad range of interested organisations.

Delegates heard presentations from several ISG members. Professor John Bourne provided a general overview of the work of the ISG and the developing science base, Dr Rosie Woodroffe spoke on how culling affects badger ecology, Professor Christl Donnelly provided an update on the latest data emerging from the RBCT, Professor Gettinby offered some analyses of the TB99 data and Professor John McInerney spoke about the economic aspects of TB control.

The presentations ensured a lively and stimulating question and answer session which enabled a number of wide ranging matters to be discussed, including the need for badger culling to control TB in cattle, possible trends in cattle TB herd incidence, the geographical and topographical differences between RBCT treatment areas, the efficiency of culling in the RBCT, the relevance of cattle movements and other studies and trials both in the UK and elsewhere.

Feedback showed that all delegates who responded found the event informative. Some delegates recommended a longer question and answer session for any subsequent open meeting, and 90% of those who completed a feedback form said they would attend another ISG open meeting.

DISCUSSION WITH INTERESTED PARTIES AND PARTICIPATION IN MEETINGS AND CONFERENCES (NOVEMBER 2004 – JUNE 2007)

1. Environment, Food and Rural Affairs Committee evidence session, 7 February 2006.
2. Selected individual members of Parliament and Parliamentary Groups by request.
3. Organisations met:
 - British Cattle Veterinary Association
 - Defra's Science Advisory Council TB sub-group
 - England Implementation Group
 - Farmers' Union of Wales
 - Gwent Badger Group
 - National Trust
 - TB Advisory Group
 - The Wildlife Trusts
 - Wales TB Action Group
 - Welsh Assembly Government
4. Public meetings and conferences attended
 - British Cattle Veterinary Association
 - First Annual bTB Conference
 - Meetings of the TB Forum
 - Moredun Research Institute
 - NFU Cymru Annual Conference
 - Scottish Centre for Animal Welfare Sciences
 - The Royal Bath and West of England Society
 - Zoological Society, London
5. Individuals by request.

FINANCIAL STATEMENT

The total expenditure for each financial year is set out below. The expenditure includes ISG members' fees, travelling expenses and subsistence and catering and room hire for meetings:

1997/1998	£0
1998/1999	£81,246
1999/2000	£76,837
2000/2001	£78,000
2001/2002	£76,100
2002/2003	£89,886
2003/2004	£135,181
2004/2005	£162,592
2005/2006	£110,320
2006/2007	£118,301
2007/2008	£35,000 (provisional)

Fees that members are entitled to claim are set out below. The fees have been increased on two occasions. Increases were in line with Cabinet Office guidance.

		On appointment	1 April 2004 (+2.8%)	1 June 2006 (+5.3% to 5.9%)
Chairman	Daily rate	£185.00	£190.20	£200.00
	Hourly rate	£25.70	£26.45	£28.00
All other members	Daily rate	£153.00	£157.30	£166.00
	Hourly rate	£21.25	£21.85	£23.00

Appendix P

SUMMARY OF MAFF/DEFRA FUNDED BOVINE TB RESEARCH PROJECTS

Number	Title	Years	Contractor	Cost (£)
CB0115	Field trial to assess the safety and efficacy of BCG vaccine administered parenterally	2006 – 2010	Veterinary Laboratories Agency	5,458,613
CB0116	Efficacy testing of BCG in badgers	2006 – 2010	Veterinary Laboratories Agency	1,468,873
SE3001	A spatial analysis using GIS of risk factors associated with TB incidents in cattle herds in England and Wales	1999 – 2003	Veterinary Laboratories Agency	188,373
SE3002	Ecological correlates of tuberculosis Incidence in cattle	1999 – 2003	University of Warwick	436,784
SE3003	Multivariate analysis of risk factors affecting incidence of TB infection in cattle	1999 – 2000	Royal Veterinary College	37,563
SE3004	Multivariate analysis of risk factors affecting tuberculosis incidence in cattle herds – phase 1	1999 – 2004	Veterinary Laboratories Agency	273,209
SE3005	Improved diagnostics for cattle	1999 – 2002	Veterinary Laboratories Agency	511,347
SE3006	Quantification of the risk of transmission of bovine TB from badgers to cattle within localised areas	1999 – 2002	Veterinary Laboratories Agency	167,504
SE3007	Integrated modelling of <i>M. bovis</i> transmission in badgers and cattle	1999 – 2003	Central Science Laboratory	902,769
SE3008	Detection and enumeration of <i>Mycobacterium bovis</i> from clinical and environmental samples	1999 – 2004	Veterinary Laboratories Agency	548,808
SE3009	The risk to cattle from <i>Mycobacterium bovis</i> infection in wildlife species other than badgers	1999 – 2004	University of Oxford	1,214,788
SE3010	The risk to cattle from wildlife species other than badgers in areas of high herd breakdown risk	2000 – 2004	Central Science Laboratory	762,623
SE3011	Understanding the route of TB transmission from badgers to cattle	1999 – 2001	University of Bristol	266,942

Number	Title	Years	Contractor	Cost (£)
SE3012	The potential of ticks as vectors of <i>Mycobacterium bovis</i>	2000	University of Oxford	49,942
SE3013	Pathogenesis and diagnosis of tuberculosis in cattle – complementary field studies	2000 – 2005	Veterinary Laboratories Agency	2,850,729
SE3015	<i>Mycobacterium bovis</i> pathogenesis	2000 – 2004	Institute for Animal Health	2,440,159
SE3017	Development and evaluation of strain typing methods for <i>Mycobacterium bovis</i>	1999 – 2005	Veterinary Laboratories Agency	1,275,223
SE3018	Cost-effectiveness of using the gamma interferon test in herds with multiple tuberculin reactors	2000 – 2001	Veterinary Laboratories Agency	124,682
SE3020	An integrated approach to the application of <i>M. bovis</i> genotyping for the control of bovine tuberculosis in GB	2001 – 2004	Veterinary Laboratories Agency	927,801
SE3022	Survival of <i>Mycobacterium bovis</i> in laboratory made silage	2001 – 2002	Veterinary Laboratories Agency	4,408
SE3023	Exploratory study to model the distribution and spread of bovine tuberculosis using multi-temporal satellite imagery	2001	Environmental Research Group Oxford	42,450
SE3024	Low dose TB infection in cattle: disease dynamics and diagnostic strategies	2002 – 2006	Queens University Belfast / Veterinary Laboratories Agency	2,560,207
SE3026	Bovine TB transmission in restocked herds: risk factors and dynamics	2002 – 2006	University of Warwick	1,114,496
SE3027	Pathogenesis and immunology of <i>Mycobacterium bovis</i> infection in cattle	2002 – 2005	Institute for Animal Health	1,506,135
SE3028	The development of improved tests for the diagnosis of <i>Mycobacterium bovis</i> infection in cattle	2002 – 2005	Veterinary Laboratories Agency	428,428
SE3029	An investigation of potential badger/cattle interactions and how cattle husbandry methods may limit these	2003 – 2005	Central Science Laboratory	556,851
SE3030	Application of postgenomics to reveal the basis of virulence, pathogenesis and transmissibility of <i>M. bovis</i>	2001 – 2006	Veterinary Laboratories Agency	3,318,624

Number	Title	Years	Contractor	Cost (£)
SE3031	Mapping badger sett density in England and Wales	2002	Veterinary Laboratories Agency	35,000
SE3032	The long term intensive ecological and epidemiological investigation of a badger population naturally infected with <i>Mycobacterium bovis</i>	2003 – 2007	Central Science Laboratory	1,761,990
SE3033	Housing of naturally infected cattle (field reactors) at VLA for immunological and bacteriological analysis	2004 – 2007	Veterinary Laboratories Agency	775,076
SE3034	Exploratory investigation of cattle movement records in Britain to enhance animal disease surveillance and control strategies	2003 – 2004	University of Oxford	84,780
SE3035	Estimating badger density in RBCT Proactive and Control Areas	2005 – 2006	Central Science Laboratory	153,346
SE3036	A quantitative risk assessment on the rôle of wild deer in the perpetuation of TB in cattle	2002 – 2005	Central Science Laboratory	146,656
SE3037	A quantitative risk assessment of the rôle of wild deer in the perpetuation of TB in cattle	2002 – 2005	Risk Solutions	49,718
SE3039	Identification of changes in individual and global farmer behaviour relating to the movement and management of cattle in the UK with particular reference to the introduction of bTB control measures	2007 – 2009	University of Liverpool	289,530
SE3040	A preliminary analysis of existing data to provide evidence of a genetic basis for resistance of cattle to infection with <i>M. bovis</i> and for reactivity to currently used immunological diagnostic tests	2008 – 2009	Roslin Institute	144,211
SE3103	An assessment of the validity of the current necropsy protocol to detect tuberculosis lesions in the badger	1998 – 1999	Veterinary Laboratories Agency	39,002
SE3104	Modelling badger populations, epidemiology of TB, risk of spread to cattle and consequences of.	1998 – 1999	Central Science Laboratory	132,532

Number	Title	Years	Contractor	Cost (£)
SE3106	An ecological and epidemiological study of a badger population naturally infected with <i>M.bovis</i>	1998 – 1999	Central Science Laboratory	278,408
SE3107	Develop innovative methods to estimate badger population density	1999 – 2005	Central Science Laboratory	1,150,521
SE3108	An integrated study of perturbation, population estimation, modelling and risk	1999 – 2004	Central Science Laboratory	1,376,056
SE3109	Novel methods of estimating badger numbers in the wider countryside	1999 – 2003	University of Bristol	308,982
SE3110	A molecular genetic analysis of badger social structure and bovine tuberculosis	2000 – 2006	Central Science Laboratory	1,094,055
SE3112	Assessment of the economic impacts of TB and alternative control policies	2001 – 2004	University of Reading	156,959
SE3113	Using herd depopulation for effectively controlling bovine tuberculosis	2001 – 2002	Veterinary Laboratories Agency	26,758
SE3116	The economic value of changes in badger populations	2003 – 2004	University of Reading	75,330
SE3117	Cost-Benefit analysis of badger control	2004 – 2007	Central Science Laboratory	443,714
SE3118	Review and economic analysis of the use of PCR assays for <i>M tuberculosis</i> complex detection and incorporation into routine bovine TB testing	2005	Veterinary Laboratories Agency	46,506
SE3119	An experiment to assess the cost-effectiveness of farm husbandry manipulations to reduce risks associated with farmyard contact between badgers and cattle	2005 – 2009	Central Science Laboratory	1,114,730
SE3120	Investigate the longer-term effects on farm businesses of a bTB breakdown	2007 – 2008	University of Exeter	138,971
SE3201	The effect on viability of <i>mycobacterium bovis</i> of freezing samples prior to cultural testing	1998 – 2005	Veterinary Laboratories Agency	30,872
SE3202	The development of animal models to test candidate vaccines for <i>M. bovis</i> infection in badgers	1998 – 1999	Veterinary Laboratories Agency	202,445

Number	Title	Years	Contractor	Cost (£)
SE3203	Blood tests to distinguish vaccinated from TB-infected cattle; IFN assay to improve diagnosis in reactors	1998 – 1999	Veterinary Laboratories Agency	374,924
SE3205	Development of vaccine candidates for protection of badgers against infection with <i>Mycobacterium bovis</i>	1998 – 1999	Veterinary Laboratories Agency	248,573
SE3206	Genome sequence analysis of <i>Mycobacterium bovis</i>	1999 – 2005	Veterinary Laboratories Agency	1,156,293
SE3207	Antigen presenting cells and T cell responses to <i>Mycobacterium bovis</i>	1999 – 2002	Institute for Animal Health	1,200,000
SE3208	Generation of vaccine candidates against <i>Mycobacterium bovis</i>	1999 – 2005	Veterinary Laboratories Agency	1,566,005
SE3209	Testing of vaccine candidates for bovine tuberculosis using a low dose aerosol challenge guinea pig model	1999 – 2004	Veterinary Laboratories Agency	1,068,045
SE3210	Development of badger vaccines	1999 – 2002	Veterinary Laboratories Agency	370,274
SE3211	Development of a turf model to assess the biological control of <i>Mycobacterium bovis</i> using mycobacteriophages	1999 – 2000	Centre for Applied Microbiology and Research	80,000
SE3212	Testing TB vaccines in cattle	1999 – 2005	Veterinary Laboratories Agency	1,609,963
SE3213	Development of badger immunological reagents	1999 – 2002	Veterinary Laboratories Agency	432,642
SE3215	Development of immunological assays for the detection of <i>Mycobacterium bovis</i> infection in badgers	2002 – 2005	Veterinary Laboratories Agency	525,041
SE3216	Development and testing of vaccines against badger tuberculosis	2002 – 2005	Veterinary Laboratories Agency	477,994
SE3217	Kinetics of skin test response in bovine tuberculosis	2004 – 2005	Institute for Animal Health	252,100
SE3220	Molecular and epidemiological characterisation of the PPD diagnostic reagent	2005 – 2007	Veterinary Laboratories Agency	274,970

Number	Title	Years	Contractor	Cost (£)
SE3221	Volatile organic compound analysis for the rapid diagnosis of disease: TB in badgers and cattle as proof of principle	2006 – 2008	Veterinary Laboratories Agency	457,390
SE3222	Development of improved diagnostic tests for the detection of bovine tuberculosis	2005 – 2008	Veterinary Laboratories Agency	1,907,392
SE3223	Development of an oral BCG vaccine bait formulation for badger	2006 – 2008	Veterinary Laboratories Agency	1,886,300
SE3224	Continuation of the development for vaccines against bovine TB in cattle	2005 – 2008	Veterinary Laboratories Agency	5,622,823
SE3225	In-depth histopathology characterisation of lymph node granulomas in natural and experimental bovine tuberculosis	2005 – 2006	Veterinary Laboratories Agency	46,590
SE3226	Development of tools to study immunopathology in badger tuberculosis	2005 – 2006	Veterinary Laboratories Agency	44,036
SE3227	Evaluation of the protection efficacy of vaccines against bovine TB in a natural transmission setting	2005 – 2011	Veterinary Laboratories Agency	6,781,127
SE3228	A safety study on BCG vaccine in wild badgers – preparatory work	2005	Veterinary Laboratories Agency	478,375
SE3229	Enhanced modelling and prediction of the spread of bovine tuberculosis in mainland Britain: impacts of cattle movements, climate and spoligotype	2005 – 2007	Veterinary Laboratories Agency	588,361
SE3230	The problem TB herd-characterisation, prediction and resolution	2007 – 2009	Veterinary Laboratories Agency	411,556
SE3231	Validation and epidemiological application of molecular methods for monitoring <i>M. bovis</i> survival and dissemination in the environment	2007 – 2010	Veterinary Laboratories Agency / University of Warwick	1,309,583
ZF0531	The ecological consequences of removing badgers from an ecosystem	1999 – 2007	Central Science Laboratory	1,846,627
TOTAL				70,511,463

Further information on these projects can be obtained from:
http://www.defra.gov.uk/research/project_data/Default.asp

NOTES ON NATIONAL TB STATISTICS

Note on the monthly TB statistics

1 Introduction

The monthly statistics emphasize the number of confirmed (or unconfirmed) positive cases as a percentage of the number of tests on unrestricted herds. This gives a guide to broad trends so long as the pattern of testing as between one-, two- etc year testing is reasonably constant. Note, however, that if there were a change to frequent testing in low-risk areas the number of new cases would not increase much whereas the percentage would drop. Correspondingly if the testing were more concentrated largely in high risk areas the percentage would increase.

There are two further difficulties with the present arrangements. The absence of regional breakdowns may disguise important regional trends. Further the commentary often encourages interpretation by comparing the latest results with those for the previous year, which is not a secure comparison. In particular the interpretation of the 2005-2006 results may be better focused on explanation of the high values of early 2005 rather than on the return to earlier levels in 2006.

These points raise issues for discussion and decision about precisely what data should be collected and how it is best presented. There are also broader issues about rational allocation of resources as between the differing testing periods.

Testing serves two different roles. One is to aid control of within- and between-herd infection by removing *M bovis* positive animals as quickly as possible. The other is that of monitoring the disease to detect changes in its pattern. The discussion here concentrates on the latter role. Also for the most part the role of test sensitivity is ignored; low sensitivity is broadly equivalent to an increase in the effective testing interval.

The points summarized below are based on the theoretical analysis in the attached paper. The points are intended as a basis for discussion rather than as definitive conclusions. The concentration is on interpreting the most recent data. Reconstruction of the history after say two years is slightly different as more data is by then available and so updating of the earlier analysis possible.

2 Objectives

There are two related but different features of the epidemic that may be monitored. One is incidence. How many new herd breakdowns were there in, say, the last year? (Note this is the actual number of cases not the number detected.) If expressed as a percentage the denominator is the number of herds not under restriction. This quantity does not depend directly on the testing regimes in operation.

The second is prevalence. At any instant of time how many unrestricted herds are there with as yet undetected *M bovis* positive animals? Again this could be expressed as a percentage of the total number of herds not currently under restriction. The prevalence cannot be observed directly but can be inferred from test results. The prevalence is affected by changes in testing regime. More frequent testing would reduce prevalence by eliminating *M bovis* positive animals more quickly. Seasonal variation in testing numbers

might affect prevalence; following months of relatively little testing prevalence would, other things being equal, be relatively high.

Prevalence is important for considerations of control. It is a measure of the force driving infection between animals within a herd, between adjacent herds and, to the extent that movement controls may not be totally effective, between distant herds.

3 Incidence

A broad summary of the theoretical analysis is that the total number of new breakdowns recorded in a particular month is an estimate of the incidence in the previous year in the herds due to be tested in that particular month including those not tested in the current year. This is irrespective of testing pattern subject to some assumptions set out in detail separately. This is essentially because herds on say two-year testing which had a breakdown in the year preceding the one under study are roughly balanced by herds on two-year testing not tested in the current year. This should not, however, be expressed as a percentage of herds currently tested but as a percentage of the herds that were on one-year testing plus twice the number that were on two-year testing and so on.

4 Prevalence

To define average prevalence over a period a herd positive for six months out of the current annual interval counts as one-half and so on. Such possibilities are not directly observed. A calculation shows that the contribution to prevalence is best found as

$$x_1/2 + 5x_2/4 + 3x_3/2 + 2x_4,$$

where x_1 is the number of positive herds in the data that are on one-year testing, x_2 the number recorded in the data that are on two-year testing and so on.

5 Implications for data recording

These considerations suggest that for immediate purposes it is necessary to record only the outcome of the test on the herd (negative, positive, etc), the date and the date of the previous negative test or release from restriction. There are also some implications for the assignment of herds to the various testing intervals.

DRC

On testing for unwanted events

February 7, 2007

SUMMARY

A theoretical study is made of the inspection of a population of individuals for the occurrence of an adverse state, for example infection or not directly observable failure. The testing interval is in general different for different individuals. The definition of incidence and prevalence is considered. Estimation of these is analysed both for the interpretation of historical data and for the monitoring of current state, with an emphasis on the difficulties induced by the differing testing intervals. Implications are drawn for the planning of data collection and for the design of testing regimes.

1 Definitions

Consider a population of individuals (for example herds) each of which may be in one of two states, satisfactory (*M bovis* free), 0, or unsatisfactory (*M bovis* positive), 1. Each individual is tested from time to time according to a not directly informative programme, that is one that does not draw on unobserved information suggesting occurrence or non-occurrence. Initially we assume the test error-free. When a positive result is found the individual is removed (restricted). New individuals may enter the system, for example

when an individual is removed from restriction. We consider the estimation of prevalence and incidence from such data. The individuals are not assumed statistically identical and different individuals may have different testing regimes. The individuals are assumed independent. In particular cross-infection is not explicitly considered. That is, this analysis is about testing for monitoring and surveillance not as a control procedure for reducing cross-infection.

2 A preliminary

Consider an individual that is in state zero at time zero and when first tested at time b is found to be positive. What is the probability that it was positive at time a , where $a < b$? We assume that transition occurs in a Poisson process of rate ρ , not in general the same for all individuals. Then the required probability is

$$(1 - e^{-\rho a}) / (1 - e^{-\rho b}) \quad (1)$$

and if ρb is small this is approximately

$$a/b, \quad (2)$$

corresponding to a uniform distribution of the transition point over the test period. Note that if $b = 2a$ the probability that the transition is in the first part of the interval is $1/(1 + e^{-\rho a})$ and that the denominator is 2 minus the probability of a transition in the time a .

Equation (2) holds under much more general conditions provided that the event in question is rare on each test occasion.

In the following discussion we use (2) throughout, so that for many purposes a numerical value of ρ is not required. A more refined analysis is possi-

ble but involves either estimating the value of ρ relevant for each individual or a sensitivity analysis.

3 Incidence in an interval

Consider first the estimation of the number of transitions to state 1 occurring in a specified time-interval (t_0, t_1) . Call a test interval active if it ends with state 1, inactive otherwise. Consider an active interval (a_j, b_j) . Define its weight for the time interval in question by

$$w_j = w_j(t_0, t_1) = \begin{cases} 1 & \text{if } t_0 < a_j < b_j < t_1 \\ (b_j - t_0)/(b_j - a_j) & \text{if } a_j < t_0 < b_j < t_1 \\ (t_1 - a_j)/(b_j - a_j) & \text{if } t_0 < a_j < t_1 < b_j \\ (t_1 - t_0)/(b_j - a_j) & \text{if } a_j < t_0 < t_1 < b_j. \end{cases} \quad (3)$$

Then the estimated incidence in the interval (t_0, t_1) is

$$\tilde{N}(t_0, t_1) = \sum_{j \in \mathcal{A}} w_j, \quad (4)$$

where \mathcal{A} is the set of active intervals intersecting (t_0, t_1) .

Note that (4) requires that observations are available sufficiently before t_0 and sufficiently after t_1 to ensure that all intervals in \mathcal{A} are fully observed. If, for example, some intervals starting at a_k , where $t_0 < a_k < t_1$ are observed until at least t_1 but are incomplete the relevant weight is $1 - \exp\{-\rho(t_1 - a_k)\}$ which for small ρ may be approximated by

$$\rho(t_1 - a_k), \quad (5)$$

thus requiring an estimate of ρ appropriate for the individual in question.

If $\tilde{N}(t_0, t_1)$ is regarded as an estimate of the number of events actually occurring in the interval in question it has variance

$$\sum_{j \in \mathcal{A}} w_j(1 - w_j). \quad (6)$$

If, however, that number is for analytical purposes regarded as having a Poisson distribution around, for example, a mean specified by a model, this new variance reflects a measurement error leading to an overdispersion defined by a variance ratio of approximately

$$1 + \Sigma w_j(1 - w_j)/\Sigma w_j. \quad (7)$$

Some covariance would be induced between estimates referring to nearby time intervals.

4 Prevalence at a point

Now consider prevalence, the number of individuals present with as yet undetected positivity. This, unlike incidence, depends on testing intervals; if all individuals were tested virtually continuously prevalence would be very small, individuals being removed as soon as they become positive. Note also that if testing intensity varies periodically, for example seasonally, so too will prevalence, being high towards the end of a period of little testing. In some contexts prevalence represents a force of infectivity. In another context being positive might indicate a need for preventive maintenance with an implied risk of catastrophic failure. We do not examine the possible effects on the full system of the implied periodicity.

The argument is much as before. Let \mathcal{B} be the set of intervals active at time t , that is the next test is positive. Let (a_j, b_j) be such an interval. Define a weight $z_j(t)$ by

$$z_j = z_j(t) = (t - a_j)/(b_j - a_j) \quad (8)$$

and then the estimated prevalence is

$$\tilde{P}(t) = \Sigma_{j \in \mathcal{B}} z_j(t) \quad (9)$$

with variance

$$\Sigma z_j(1 - z_j) \quad (10)$$

interpreted as before as referring to a finite population total not to a notional model value. Again if a testing interval starting at a_k is incomplete the relevant weight is $\rho(t - a_k)$.

Prevalence could be expressed as a proportion or rate by dividing by the number of individuals in the system at time t . An average prevalence for an interval (t_0, t_1) can be obtained after integration with respect to t , that is from

$$\int_{t_0}^{t_1} \bar{P}(t) dt. \quad (11)$$

Four types of active interval (a_j, b_j) contribute to (11), namely intervals, called respectively Types 1 to 4, that are:

- wholly within (t_0, t_1)
- starting before t_0 and ending before t_1
- starting after t_0 and ending after t_1
- starting before t_0 and ending after t_1

5 Current monitoring

The previous discussion has essentially been concerned the analysis of historical data rather than with current monitoring. We suppose that individuals are tested at time intervals of m or $2m, \dots$. Thus m might be one year. The tests within a period m take place over an appreciable time and we suppose each period m divided into l subintervals. For example with m one year,

one might take $l = 12, 6, 4$ corresponding to looking at the data monthly, two-monthly or quarterly. Each individual is thus assigned to a substratum for testing. The data available from each subinterval refer directly only to the substratum in question. To infer anything about the whole population from a subinterval test it is necessary to suppose either that the substrata are effectively random, which may be implausible, or to involve correction factors derived from historical data. We do not consider the latter possibility.

Suppose that in a particular subinterval of testing there are r_c tests corresponding to testing period cm , x_c of which are positive. Thus in this substratum there are r_1 individuals assigned to testing interval m , all observed and x_1 are positive. There are r_2 individuals assigned to testing interval $2m$ and in the second phase of their testing and therefore observed; let there be r_{21}^* individuals assigned to interval two, in their first phase and therefore not observed. Similarly let r_3, r_{32}^*, r_{31}^* be the numbers on $3m$ testing, observed, not observed and in their second phase and not observed and in their first phase, and so on.

We consider as before two questions. How many new positive events occurred in the substratum in the previous period m ? What was the contribution of the substratum in the last m to prevalence of undetected positivity? Note that other time periods could be considered but in the case of annual testing data averaging over a year is desirable to bypass periodicities. Further, as we move between different substrata the integrated incidence or prevalence refers to different annual periods. This difficulty does not arise with historical reconstruction, but it is not clear how to avoid it with virtually continuous monitoring. This consideration suggests that initial estimates should be updated after an appropriate period.

In the substratum in question there were x_1 new positive transitions in the

testing interval m . There were x_2 positive individuals with testing interval $2m$ and, by (2), an estimated $x_2/2$ of these were in the time period of interest. Further in an estimated $(x_2/2) \times (r_{21}^*/r_2)$ individuals there will be a transition in the unobserved part of the $2m$ period subcohort. Therefore the estimated incidence in the period in question is

$$x_1 + x_2(1 + r_{21}^*/r_2)/2 + x_3(1 + r_{31}^*/r_3 + r_{32}^*/r_3)/3 + \dots \quad (12)$$

If the testing is divided equally between phases, each ratio involving an r^* is one and the estimated incidence is

$$\Sigma x_s, \quad (13)$$

the observed total number of positives. This seems the most meaningful interpretation of (13) as referring to a preassigned single time m period even though the data refer to different testing intervals. The interpretation of the ratio of this to the number of tests is fragile if the testing regime changes.

Different subcohorts may be of very different sizes and if it is required to summarize (13) as a rate the appropriate denominator is

$$r_1 + 2r_2 + \dots \quad (14)$$

or in the fuller version (12)

$$r_1 + r_2 + r_{21}^* + \dots \quad (15)$$

If these values are aggregated then (13) and (14) should be added up separately.

The discussion assumes throughout that the rates of occurrence are sufficiently small to allow throughout (2) rather than (1). If the rate is high in subsections of each subcohort events are likely to take place early in the

relevant exposure period, in extreme cases leading to the Horvitz-Thompson estimate for probability proportional to size sampling.

The implication of this discussion is that the total number of new positive cases found in a period has, under certain assumptions, a reasonable interpretation for the population but that that number expressed as a proportion of the total number of tests performed does not in general have a stable interpretation so that changes in the ratio are easily misinterpreted.

In considering prevalence the most relevant definition is probably to consider the total expected contribution of time in state 1 in the testing interval m immediately preceding the point of analysis. This is

$$\Sigma \frac{2c-1}{2c} x_c \quad (16)$$

arising from the individuals actually tested. In addition there is a contribution for $c \geq 2$ from subcohorts not tested in the period in question making a total contribution of

$$\Sigma_c \left\{ \frac{2c-1}{2c} + \Sigma_{s=1}^{c-1} \frac{2s-1}{2c} \frac{r_{cs}^*}{r_c} \right\} x_c. \quad (17)$$

Under the simplifying assumptions made previously about the r^* this leads to

$$x_1/2 + 5x_2/4 + 3x_3/2 + 2x_4 + \dots \quad (18)$$

This is an estimate of the total contribution to integrated prevalence over the previous period m derived from this subcohort.

6 Distribution of testing effort

Suppose that the population is divided into groups within each of which the rate ρ is effectively constant. Let the s th such group be of size r_s , have

associated rate ρ_s and be tested every t_s units of time. The simplest special case has $t_1 = 1, t_2 = 2$. If ρ_s is the occurrence rate of transitions to state 1, then the long run proportion of time that such an individual is an as-yet-unobserved positive is

$$(e^{-\rho_s t_s} - 1 + \rho_s t_s) / \rho_s, \quad (19)$$

which is approximately

$$\rho_s t_s^2 / 2. \quad (20)$$

The implied rate of testing is r_s / t_s .

Suppose the objective of testing is to minimize (19).

If a cost per unit time is put on each period of exposure and the cost per test is known then an economic optimum can be found. A different possibility is to choose the t_s to minimize the total time spent in state 1 subject to a constraint on the total testing effort. For this we consider the Lagrangian

$$\Sigma_s r_s \rho_s t_s^2 / 2 - \lambda \Sigma_s r_s / t_s, \quad (21)$$

where λ is a Lagrange multiplier. On differentiating with respect of t_s we have that for the optimum

$$t_s = \text{const} \times \rho_s^{-1/3}. \quad (22)$$

The implication is that in this formulation testing interval should vary only slowly with rate and should be independent of stratum size.

This suggests, although this needs numerical confirmation, that in a fairly broad range of conditions a uniform testing interval across all individuals may not be far from optimal. This is all for one specific objective of testing.

7 Imperfect testing

So far it has been assumed that there are no test errors. Suppose now that the test has high specificity but rather lower sensitivity, p . There are two possibilities. The first is that p is large enough to ensure that virtually all positive individuals are detected before being removed from the system for some other reason. Then the total incidence over a long enough period is unaffected, whereas additional errors are introduced into temporal comparisons essentially because of an additional measurement error. If on the other hand, there is some probability \tilde{q} that an individual escapes detection then incidence is lowered by a factor $(1 - \tilde{q})^{-1}$. The effect on prevalence and integrated prevalence is more substantial. A delay of one testing interval to detection adds an additional unit to current prevalence.

8 Estimation of rate ρ

Some but not all of the above results require estimation of the transition rate ρ . There are broadly two ways of approaching this. One is to group the individuals into strata and to assume that all individuals in the same stratum have the same value of ρ . The other is to set up a model in which ρ for an individual depends on explanatory features of the individual probably via a log linear representation.

In the former case there are contributions to the log likelihood from an inactive interval (a, b) of $-\rho(b - a)$ and from an active interval fully observed of $\log(1 - e^{-\rho(b-a)})$. Partially observed intervals are handled similarly. Maximum likelihood estimation of ρ is straightforward.

9 Implications for data recording

Except perhaps for some special purposes it suffices to know for each test the date of the test, the outcome of the test and the date of the last previous test, or release from restriction. It would be helpful to know for individuals not tested, their testing frequency and the date of last test. In addition general information may be required in each specific context.

DRC

GLOSSARY OF TERMS

Adjuvant: a substance to boost (immune) response.

Aerosol: a fine spray of liquid.

Animal Health: the former State Veterinary Service.

Antibody: a protein that reacts with a foreign substance, as part of an immune response.

Antigen: usually a protein, capable of provoking an immune reaction.

Bacterium: a single celled organism; many types are present in the environment and most are essential to support other forms of life; some species can cause disease, in which circumstances these are commonly called “germs”.

Badger population density: the number of badgers per unit area, normally per square kilometre.

Badger removal: the culling (killing) of badgers in a specific countryside area.

Bait marking: a method of mapping badger home ranges by feeding them coloured plastic beads and then locating dung containing those beads.

BCG: Bacille Calmette Guerin, a modified strain of *M. bovis* used for human vaccination to protect against *M. tuberculosis*.

BCR: benefit: cost ratio, the simple ratio of the total benefits gained to the total costs incurred in a project.

Biomarker: a chemical which when studied can define a biological feature.

Blood test: the analysis of blood for any of a range of parameters.

Bovine tuberculosis (bTB): a disease caused by the mycobacterium *M. bovis*.

Breakdown: or bTB incident, when one or more cattle in a herd shows evidence of exposure to *M. bovis* the infectious agent of bovine TB (i.e. reacts to the tuberculin skin test).

BRO: Badger Removal Operation, the culling (killing) of badgers in a specific countryside area.

Brock test: an ELISA test to detect *M. bovis* in blood.

Buffer zone: an area (with zero treatment) separating different treatment areas or triplets.

Carrier: a TB infected individual or animal showing no sign of disease.

Case control study: an observational study in which diseased animals or herds are compared with non-diseased animals or herds for exposure to a hypothesised cause.

Cattle herd: a group of cattle that live a collective life together.

CBA: cost-benefit analysis, a series of techniques for evaluating the economic merits of a course of action.

Cell: basic structure unit of living organisms.

CFU: colony forming unit – a measure of viable bacterial numbers.

Clean ring strategy: the GB badger control policy of MAFF in 1982-6.

Clinical: applying to observation and treatment of, in the present context, animals.

Confidence Interval: a numerical interval in which a population attribute or a treatment effect is estimated to lie within a specified probability.

Confirmed breakdown: when cattle are proven (e.g. by post mortem examination) to have TB.

Covariate: a supplementary variable used to explain a statistical relation.

Culture: the generation of living tissue cells.

Defra: Department for Environment, Food and Rural Affairs.

Diagnosis: identification of an illness or disease by clinical signs or response to a surveillance or laboratory test(s).

DNA: strands of genetic material.

Ecological correlates: factors that affect an eco-system.

ELISA test: a rapid (colour based) biochemical test to detect antibodies or antigens.

Endemic disease: a disease present in an animal population on a continuous basis.

Epidemiological study: investigation of the factors that determine the occurrence of disease.

Epidemiology: The study of the distribution and dynamics of disease in a population.

FMD: Foot and Mouth Disease: a highly infectious viral disease affecting cloven-hoofed animals.

Gamma interferon: a product generated by white blood cells during an immune reaction. (See IFN-g).

Genotype: a DNA fingerprint.

GIS: geographical information system; a computer technique for analysing data plotted on maps.

Herd breakdown: when cattle are found to be infected with bovine TB (i.e. when one or more “reactors” are found in a herd).

IFN-g assay: a specific blood test for gamma interferon.

Immunological reagents: the chemicals used in a laboratory study of immunity.

Incidence: the rate of new infections in a population.

Interim strategy: the GB badger control policy of MAFF in 1986 – 1997 (see *Krebs et al.*, p143).

Krebs: The Independent Scientific Review Group, chaired by Professor John R. Krebs FRS, that reported on bovine tuberculosis in cattle (often referred to as ‘Krebs’, and their report as the ‘Krebs report’), 1997.

Lesion: an injury or wound, or discontinuity (i.e. a pathological change) of tissue caused by disease, such as TB.

Live test: another name for the Brock test.

Logistic regression: a statistical technique for analysing how a binary outcome, such as infection status (infected or not infected), depends on one or more explanatory features.

Log-linear regression: a statistical technique for analysing how counts of occurrences of events such as herd breakdowns depend on one or more explanatory features (also known as Poisson regression).

Longitudinal study: a study that follows individuals or groups over a period of time.

MAFF: Ministry of Agriculture, Fisheries and Food. Ceased to exist in 2001 when Defra was established.

***M. bovis*:** the bacterium *Mycobacterium bovis*.

***Meles meles*:** genus and species names of the European badger.

Molecular typing: structural investigation of, e.g., *M. bovis* strains.

Multivariate analysis: study of simultaneous variation of a number of factors.

Mycobacterium: a family of related bacteria.

Naturally infected: occurring ‘in the field’, not in the laboratory.

Necropsy: post mortem examination.

NPV: net present value, the difference between the total benefits of a project and its total costs, each expressed as a present value by discounting at an appropriate rate.

NVL: no visible lesion or lesions (following post mortem examination).

Odds ratio: a measure used to compare the risks of adverse events.

Overdispersion: greater variation in the data than is expected under the assumptions of a model.

p-value: the outcome of a statistical significance test, small values indicating that the conclusion drawn is unlikely to have arisen by the play of chance.

Parish: the smallest administrative area of local government in England and Wales.

Parish Testing Interval: PTI or testing interval, the interval between routine TB tests for herds in a particular area (parish), set at 12, 24, 36 or 48 months.

Pathogenesis: the process of disease development.

PCR: Polymerase Chain Reaction, a DNA amplification process.

Perturbation: the disruption of the social organisation or structure of badger populations such as that which is caused where trapping/culling has taken place.

Poisson regression: a statistical technique for analysing how counts of occurrences of events such as herd breakdowns depend on one or more explanatory features (also known as log-linear regression).

Power (statistical): the measure of the ability of a study to detect important effects.

PPD: purified protein derivative, extract of *Mycobacterium bovis*; tuberculin.

Prevalence: the proportion of a population infected.

RBCT: Randomised Badger Culling Trial, a large field trial designed to test the impact of two badger culling strategies on TB incidence in cattle.

Reactor: an animal which gives a positive result (i.e. reacts) to the tuberculin skin test.

Sensitivity (of a diagnostic test): % of truly infected animals correctly identified.

Serology: the science of serum.

SICCT: single intradermal comparative cervical tuberculin test (i.e. the tuberculin skin test): the primary screening test for TB in cattle in Great Britain.

Sett: a burrow system that badgers use for shelter and breeding.

Social group: a group of badgers that live together and occupy one or more setts within a well-defined territory from which badgers from other social groups would be excluded.

SOP: Standard Operating Procedure, a set of instructions for carrying out work related to the RBCT.

Specificity (of a diagnostic test): % of truly uninfected animals correctly identified.

Spatial analysis: analysis of one or more attributes by geographical location.

Spoligotyping: a technique to define molecular structure of, e.g., *M. bovis*.

Statistical significance test: a check that conclusions are unlikely to have arisen by the play of chance.

Strain: isolate of a bacterial species which is differentiated from other isolates of the same species by particular characteristics.

Strain typing: to differentiate organisms within a species.

SVS: State Veterinary Service – an Agency of Defra. Renamed *Animal Health*, 1 April 2007.

T-cell: a white blood cell involved in immune responses.

TB: tuberculosis.

TB incident: when cattle are found to be infected with bovine TB (i.e. when one or more “reactors” are found in a herd).

Testing interval: see Parish Testing Interval.

Transmission: the passing of disease from animal to animal or to humans.

Treatment: the relevant action carried out within one of the three trial areas that comprise a triplet, i.e. proactive culling, reactive culling or survey only.

Trial: often used as shorthand to refer to the Randomised Badger Culling Trial (RBCT).

Triplet: a group of three trial areas, each area subject to a different treatment.

Tuberculin: a protein extract used to diagnose TB in a skin test.

Tuberculin skin test: the SICCT test which is used throughout the world to screen cattle, other animals and people for TB, and is the internationally accepted standard for detection of infection with *Mycobacterium bovis* (*M. bovis*).

Vaccine: that used to prevent disease by stimulation of an immune response to the causative agent.

VetNet: the State Veterinary Service* Animal Health IT data storage system. (*The State Veterinary Service was renamed *Animal Health* on 1 April 2007).

VL: visible lesion(s).

Zoonosis: disease communicable between animals and humans.