Title	The impact of badger removal on the control of tuberculosis in cattle herds in Ireland. A report prepared for the Minister of Agriculture and Food, December 2004
Publication date	2004-12
Publication information	"The Impact of Badger Removal on the Control of Tuberculosis in Cattle Herds in Ireland. A Report Prepared for the Minister of Agriculture and Food, December 2004." University College Dublin. Centre for Veterinary Epidemiology and Risk Analysis, December 2004.
Series	Other reports
Publisher	University College Dublin. Centre for Veterinary Epidemiology and Risk Analysis
Item record/more information	http://hdl.handle.net/10197/8907

The impact of badger removal on the control of tuberculosis in cattle herds in Ireland

A report prepared for the Minister of Agriculture & Food

December, 2004

Centre for Veterinary Epidemiology and Risk Analysis
Faculty of Veterinary Medicine
University College Dublin

Foreword

Report to Mary Coughlan T.D., Minister for Agriculture and Food.

On behalf of the Centre for Veterinary Epidemiology and Risk Analysis, I am pleased to present to you a report on 'the Four Area Project', which was conducted to critically assess the impact of badger removal on the control of tuberculosis in cattle herds in Ireland.

The four area project, which was conducted in four counties of Ireland during 1997 to 2002, has been a team effort from a wide range of organisations and individuals, including:

- Michael Sheridan (Department of Agriculture and Food), central support
- John D. Collins (CVERA and University College Dublin, now retired), academic leadership
- John Griffin (DAF), project design and coordination
- Tracy Clegg (CVERA), statistical input and report development
- David Williams and Gabrielle Kelly (UCD Department of Statistics and Actuarial Science), statistical input
- Ian O'Boyle (DAF), project management in the field
- Staff of CVERA (particularly Bob Hammond, Guy McGrath, Kieran Towey, Isabella Higgins, Dan Collins and Jackie Smith), GIS support and data input
- Staff in DAF's Veterinary Laboratory Service in particular the regional laboratories in Cork, Kilkenny and Dublin; the tuberculosis section in the Central Veterinary Research Laboratory in Abbotstown and the Irish Equine Centre in Co. Kildare, laboratory support.
- Paddy Sleeman (University College Cork) and Chris Smal, ecological assistance
- Staff of the District Veterinary Offices of Cork (particularly Finbarr O'Shea), Donegal (particularly Des Lavin), Kilkenny (particularly Murt Duggan) and Monaghan (particularly Jim Murphy), field support

Aspects of this report have and are currently being submitted for publication in international scientific journals. A further report on the ecology of badgers, based on the present study, is in preparation.

Professor Simon More
Director, Centre for Veterinary Epidemiology and Risk Analysis
Department of Large Animal Clinical Studies
Faculty of Veterinary Medicine
University College Dublin
Belfield
Dublin 4

22 December, 2004.

EXECUTIVE SUMMARY

Background

There has been a national bovine tuberculosis eradication programme in Ireland since 1954. During the initial stages of this programme, progress was rapid and led to a considerable reduction in the prevalence of the disease by the mid 1960s. From the mid 1960s to the late 1980s, national attention focused on issues relating to biosecurity, while tuberculin testing standards were subject to intense scrutiny. In 1988, a major initiative was undertaken with the launch of a new executive agency, ERAD, to oversee the management of the national bovine tuberculosis eradication programme, the progress of which had declined for reasons that were unexplained. Over the following four years, the ERAD programme involved exhaustive testing together with an extensive range of new and improved support measures. These included the refinement of the programme management system, pre-movement tuberculin testing; improved control of dealers; a reactor collection service; improved *post-mortem* procedures during factory surveillance; depopulation of problem herds; extended restriction periods; implementation of a farmer awareness campaign, covering a range of issues including disease-proof fencing and cleansing and disinfection; improved control of slurry/factory waste; and the establishment of a specialised epidemiological research and tuberculosis investigation unit together with supporting laboratory services. During this period, research was initiated on the possible role of tuberculous badgers in bovine tuberculosis, along with licensed badger control services.

Despite these intensive measures which had effectively eliminated cattle-to-cattle transmission of the bovine tubercle bacillus, *Mycobacterium bovis*, in other countries, little substantive progress was observed. However, the initiation of a comprehensive research programme led to a much clearer understanding of the disease dynamics and the relative contribution of the various control measures, and led to a major epidemiological input into policy formulation at national level. During the period since the end of the ERAD era, Ireland has continued to implement a comprehensive disease control programme making steady but not significant progress.

Meanwhile, a number of other countries, notably New Zealand, Great Britain, Northern Ireland, and more recently the state of Michigan in the USA, have faced similar concerns regarding the progress of their eradication programme. In each case, the persistence of an *M. bovis* infected wildlife reservoir has been considered a constraint in the control of tuberculosis in cattle. More specifically, there has been building evidence of the role of infected badgers (*Meles meles*, a species with legal protection in Ireland since 1976) as a reservoir for bovine tuberculosis in Ireland and Britain. There was recognition that badgers were highly susceptible to *M. bovis* infection and that tuberculosis was endemic within the badger population in Ireland. However, this information on its own is not sufficient to prove that *M. bovis* is being transmitted from badgers to cattle since it is possible to have coincident disease (with identical strains) in local badgers and cattle but without badgers being the source of infection. This could occur, for example, if cattle were to infect badgers, and not *vice-versa*.

Given this background, a field trial offers the best opportunity to critically determine whether badgers are a source of *M. bovis* for Irish cattle. Conceptually, relevant field trials would involve the ongoing comparison of tuberculosis in cattle populations in two matched areas, one grazing an area where there has been minimal badger disturbance, and another area where badgers have been removed. To ensure a fair comparison, these matched areas and cattle populations should be as similar as possible, apart from the presence or absence of badgers. The East Offaly project in Ireland was the first study of this type, comprising a 738 km² 'project' area (where badger removal was conducted under licence) in county Offaly and a surrounding 1,455 km² 'control' area (where badger disturbance was minimal). Results from this work provided the first robust Irish evidence of a link between tuberculous badgers and tuberculosis in cattle, with badger removal resulting in a statistically significant decrease in the risk of disclosure of a tuberculin reactor in a herd. The current study (known as the four area project, with field work undertaken during 1997 to 2002) seeks to build on the East Offaly project, and to determine the effect of badger removal on both the probability of, and the time to, a herd breakdown due to bovine tuberculosis at a number of sites representing a wider range of farming environments in Ireland.

The four area project

a. The study areas

The study was conducted between 1 September 1997 and 31 August 2002 in matched removal and reference 'study areas' in four different geographical regions in Ireland, namely, counties Cork, Donegal, Kilkenny and Monaghan. During the selection of the removal areas, a range of criteria were used, including apparent disease prevalence, the presence, if possible, of natural geographical boundaries, and areas considered representative of the diverse Irish landscape. Where natural boundary barriers were absent, 'buffer areas' were created, up to 6 km in width, at the periphery of each selected removal area. Likewise, the matching criteria for the reference areas used in the study included county, livestock density, herd size, farm-enterprise type, disease prevalence and selected geographic features. The latter criteria, including land use and soil type, are known to influence badger numbers. In addition, but only when natural barriers were absent, each reference area was separated from both the removal and (where present) adjoining buffer areas by a distance of at least 3 km.

The total size of the removal and reference areas (excluding the buffer areas) was 1961 km², which is approximately 3.9% of the agricultural land area of the Republic of Ireland.

b. The badger population

Badger population and habitat

On all participating farms, a comprehensive survey of badger habitat and activity was conducted of all land parcels within each removal, buffer and reference areas. During the initial survey, over 5,000 setts were identified, with a further 400 being found later in the study period.

Badger removal policy

In the removal and buffer areas, a proactive programme of badger removal was carried out under licence on 2 to 3 occasions each year. In each of the reference areas, badger removal was entirely reactive and was only conducted following severe outbreaks of tuberculosis (involving four or more standard reactors) in cattle herds.

Level of farmer co-operation

There was a high level of farmer cooperation in all areas throughout the full study period.

Participation was entirely voluntary; refusal to provide permission to survey arose on a single holding, while failure to capture badgers following the sett survey occurred at only 13 setts in 3 counties.

Badger removals

In the removal and buffer areas 2,360 badgers were removed. In the reference areas, a total of 258 badgers were removed over the course of the study.

The tuberculosis status of captured badgers

In the removal and buffer areas, following proactive removal, 19.5% of badgers examined at *post-mortem* were found to be tuberculous. The corresponding figure for badgers removed reactively in the reference areas following serious herd breakdowns was 26.1%.

c. The cattle population

Methods of analysis

Two different measures were used to assess the distribution of tuberculosis amongst cattle. The first was the 'confirmed restriction risk' (CRR) defined as the number of newly confirmed herd restrictions (restricted herds that recorded at least one animal with a lesion) per 100 herds *per annum,* and the second was the number of standard tuberculin reactors per 1,000 animals tested (SPT). Two types of multivariable analysis were used to test for differences between the reference and removal areas after accounting for other possible confounders, such as herd size, including logistic regression (providing a critical assessment of the probability of a confirmed herd restriction due to tuberculosis, after accounting for key confounders) and survival analysis (providing a critical assessment of the time to a confirmed herd restriction due to tuberculosis, after accounting for key confounders).

A comparison of the matched removal and reference areas

There was evidence in support of the trial being a valid comparison of similar removal and reference areas, apart from badger removal. During the 5 years prior to the study (the pre-study period), there was no significant difference between the removal and reference area, in terms of the hazard of a confirmed herd restriction, in counties Kilkenny and Monaghan. Although there was a significant difference in this measure between the matched areas in counties Cork and Donegal, the direction of this difference is such that it will have been even more difficult to detect an impact from badger removal. In anticipation of these study results, concern had been raised about the potential effect of reactive culling within each of the reference areas, and the possibility that this might affect the validity of these study findings. However, these concerns are unfounded; for example, there is no significant change in the hazard of a confirmed herd restriction in any of the reference areas between the pre-study and study periods.

The impact of badger removal on tuberculosis in cattle herds

A total of 193 (11.7% of all) and 393 (26.7% of all) herds in the removal and reference areas, respectively, were the subject of a confirmed restriction on at least one occasion during the study period. The CRR was lower in the removal area compared to the reference area in every year of the study and, in agreement with results from the east Offaly project, the effect of treatment also appeared to increase over time. During the study period, there was a significant difference between the removal and reference areas in all four counties in both the probability of, and the time to, a confirmed herd restriction due to tuberculosis. To illustrate, in the final year of the study the odds of a herd restriction in the removal as compared to the reference areas was 0.25 (95% C.I.

0.07-0.88) in Cork (that is, a confirmed herd restriction during the final year of the study was on average four times more likely in the reference than the removal area in Cork), 0.04 (0.00-0.27; on average, 25 times more likely) in Donegal, 0.26 (0.08-0.79; on average, 3.8 times more likely) in Kilkenny and 0.43 (0.22-0.84; on average, 2.3 times more likely) in Monaghan. Further, during the final year of the study the hazard ratios (comparing removal over reference) ranged from 0.4 to 0.04. That is, in comparison to the reference area and during this period, there was a 60-96% decrease in the rate at which herds in the removal areas were becoming the subject of a confirmed restriction.

Discussion and conclusions

It is critical that this study is considered within a clearly-defined context. The Irish bovine tuberculosis eradication programme is comprehensive, incorporating each of the accepted elements of disease control, including mandatory annual tuberculin testing of all animals in the national herd and early, ongoing removal of infected animals. It has long been suspected that another source of the bovine tubercle bacillus is involved, given the lack of national progress towards eradication despite these efforts. These suspicions have now been confirmed, with the results from the four area (and earlier East Offaly) study clearly highlighting wildlife (and specifically transmission of infection from badgers to cattle) as a key constraint to disease eradication in Ireland. These findings are of national importance and provide compelling evidence of the linkage between proactive badger removal and tuberculosis in Irish cattle. Note that this linkage (and the consequent impact of proactive badger removal) would not have been as evident if the national control programme were less effective. To illustrate, if cattle-to-cattle transmission were still common, differences in disease incidence between the removal and reference areas would not have been as marked. As a direct consequence of these findings, cattle-to-cattle transmission has become relatively less important in the epidemiology of bovine tuberculosis in Ireland. In the future, it is critical that Ireland initiate medium and long-term measures to minimise transmission from badgers, whilst maintaining existing measures (with additional enhancements, as appropriate) to control cattle-to-cattle transmission. Ongoing cooperation between government and industry will also be critical. The relative importance of cattle-to-cattle and wildlife-to-cattle transmission will depend on a range of circumstances, including the standard of animal husbandry, aspects of national disease control and badger ecology. Therefore, the results should be extrapolated to other regions with care.

In order to eradicate tuberculosis from the Irish cattle population, Ireland will need to sustainably control tuberculosis in badgers, with which cattle may come in contact. This presents significant challenges for scientists and policy-makers, including the international legal protection, and national status, afforded to badgers; the potential for increases in badger numbers, as a consequence of agricultural intensification and increase in productive pastures; the close physical proximity of badgers and cattle, given the preference of badgers in Ireland to locate setts in hedgerows; and the high prevalence of infection among Irish badgers. Ireland is currently implementing a comprehensive strategy to address these challenges. In the short-term, the Department of Agriculture and Food is implementing a national programme for wildlife control when and where wildlife are implicated in on-farm breakdowns of bovine tuberculosis. In the longer-term, Ireland is committed to the development of an effective badger vaccine and the implementation of a strategic programme of badger vaccination, with the aim to reduce disease transmission between infected badgers and susceptible cattle. Results from early experimental studies have been promising.

CONTENTS

1 Background

There has been a national bovine tuberculosis eradication programme in Ireland since 1954. During the initial stages of this programme, progress was rapid, leading to a considerable reduction in the prevalence of the disease by the mid 1960s. At this point, however, progress stalled. From the mid 1960s to the late 1980s, national attention focused on issues relating to quality control and biosecurity, and tuberculin testing standards were subject to intense scrutiny. During this period, pre-movement tuberculin testing was made mandatory, animal identification and the ability to trace animals was improved, strategic disease control measures were introduced in areas of high prevalence, and data analysis was substantially enhanced following the advent of computerisation. In 1988, a major initiative was undertaken with the launch of a new executive agency, ERAD, to oversee the management of the eradication programme. Over the following four years, the ERAD programme involved exhaustive testing (44 million tests on the 7 million cattle in the national herd over 4 years) together with an extensive range of new and improved support measures. These measures included the refinement of the programme management system, a reactor collection service and improved compensation/hardship grants; random sample testing of herds by government veterinarians; the establishment of a specialised epidemiological research and tuberculosis investigation unit; extended laboratory services; continuation of a pre-movement test; improved control of dealers; depopulation of problem herds; improved cattle tags and checking of cattle at factories and marts; extended restriction periods; the establishment of local ERAD committees and a tuberculosis farm advisory service; the development and implementation of a farmer awareness campaign, covering a range of issues including disease-proof fencing and cleansing and disinfection; improved *post-mortem* procedures during factory surveillance; establishment of badger research and control services; improved control of slurry/factory waste; control of calf movements; attention to the cleaning of trucks of the reactor collection service; and improved District Veterinary Office (DVO) procedures (Downey, 1990, 1992). However, despite these intensive measures, and a substantial investment of financial and human resources, little substantive progress was observed. Part of the ERAD legacy, however, was the initiation of a comprehensive research programme coupled with an (major) epidemiological input into policy formulation. This approach led to a much clearer understanding of the disease dynamics and the relative contribution of the various control measures.

Two factors have been instrumental in highlighting the potential role of wildlife as a constraint to eradication of bovine tuberculosis in Ireland. Firstly and as illustrated previously, there was limited observable progress towards disease eradication despite the implementation of intensive measures that have effectively eliminated cattle-to-cattle transmission in other countries (Collins, 2001). Secondly, there was increasing evidence in support of wildlife as a reservoir of bovine tuberculosis. In general terms, a number of other countries, notably New Zealand, Great Britain, Northern Ireland, and more recently the state of Michigan in the USA, have faced similar concerns regarding programme progress. In each case, the persistence of an *M. bovis* infected wildlife reservoir has been considered a constraint in the control of tuberculosis in cattle. More specifically, there has been building evidence of the role of infected badgers (*Meles meles*, a species with legal protection in Ireland since 1976) as a reservoir for bovine tuberculosis in Ireland and Britain. This evidence included isolation of *Mycobacterium bovis* in badgers in Switzerland, the UK and Ireland (Noonan et al., 1975; Bouvier et al., 1962 cited by Cheeseman et al., 1989; Krebs, 1997); recognition that badgers were highly susceptible to *M. bovis* infection (Gormley and Costello, 2003), and that tuberculosis was endemic within the badger population in Ireland (O'Boyle et al., 2003); increasing recognition of the possible role of wildlife as reservoirs for *M. bovis* in the UK (Krebs,

1997) and New Zealand (Cook, 1975; Julian, 1981; Coleman, 1988; Hickling et al., 1991) and the identification of the same strains of *M. bovis* in local cattle and badger populations (Costello et al., 1999). However, this information on its own is not sufficient to prove disease causation. In particular, there was little direct evidence in support of a temporal relationship (providing evidence for transmission of *M. bovis* from badgers to cattle). To illustrate, it is possible to have coincident disease (with identical strains) in local badgers and cattle but without badgers being the source of infection. This could occur, for example, if cattle were to infect badgers, and not *vice-versa*.

Given this context, a field trial offers the best opportunity to critically assess the impact of badger removal on the control of tuberculosis in cattle herds in Ireland. The East Offaly project in Ireland was the first study of this type, comprising a 738 km^2 'project' area (where badgers were removed under license) in county Offaly and a surrounding 1,455 km^2 'control' area (Ó'Máirtín et al., 1998a; Ó'Máirtín et al., 1998b; Eves, 1999). Smaller trials have been conducted in Great Britain at Thornbury (104 km^2, in Avon), at Steeple Leaze (12 km^2, in Dorset) and at Hartland (about 62 km^2 in North Devon) (Hansard (House of Commons Daily Debates), 2004). Results from the East Offaly project provided robust evidence of the link between tuberculous badgers and tuberculosis in cattle, with badger removal resulting in a statistically significant decrease in the risk of disclosure of a tuberculin reactor in a herd. To illustrate, in the final year of the study, the odds of such a disclosure was 14 times greater in the control area (where badgers were not proactively removed) than the project area (Ó'Máirtín et al., 1998b).

The current study seeks to build on the East Offaly project, and to determine the effect of badger removal at a number of sites representing a wider range of farming environments. Further, the study seeks to address concerns with that project, relating to the design of the project ('removal') and control ('reference') areas, which resulted in ongoing migration of badgers from the control into the project area throughout the study period (Eves, 1999). Additionally, the East Offaly project represented only one type of farming environment in Ireland. Therefore, the objective of the current study is to assess the impact of badger removal on the control of tuberculosis in cattle herds in a wider range of environments in Ireland.

2 Study Areas

2.1 Methods

2.1.1 Overview

In 1996, and following negotiations with farming organisations on new arrangements for the disease eradication schemes, Duchas (the Irish agency responsible for heritage and wildlife) agreed to issue licences for the large-scale removal of badgers for scientific purposes in four areas of Ireland. This study was designed to objectively assess the impact of badger removal on tuberculosis control in Irish cattle herds. The study was conducted between 1 September 1997 and 31 August 2002 (the 'study period') in matched removal and reference 'study areas' in four different geographical regions in Ireland, namely, counties Cork, Donegal, Kilkenny and Monaghan (Figure 1). In each removal and adjoining buffer areas, initially, as many badgers as possible were removed; then badger numbers were kept as low as was feasible throughout the period of the study. In the reference area, badgers were removed during the study period only on and around those farms where severe outbreaks of tuberculosis were recorded. Comparison is made between the removal and reference areas over five years of the study period. Comparison is also made with the 5-year 'pre-study period' (1 September 1992 to 31 August 1997).

2.1.2 Selection of the study areas

2.1.2.1 Removal areas

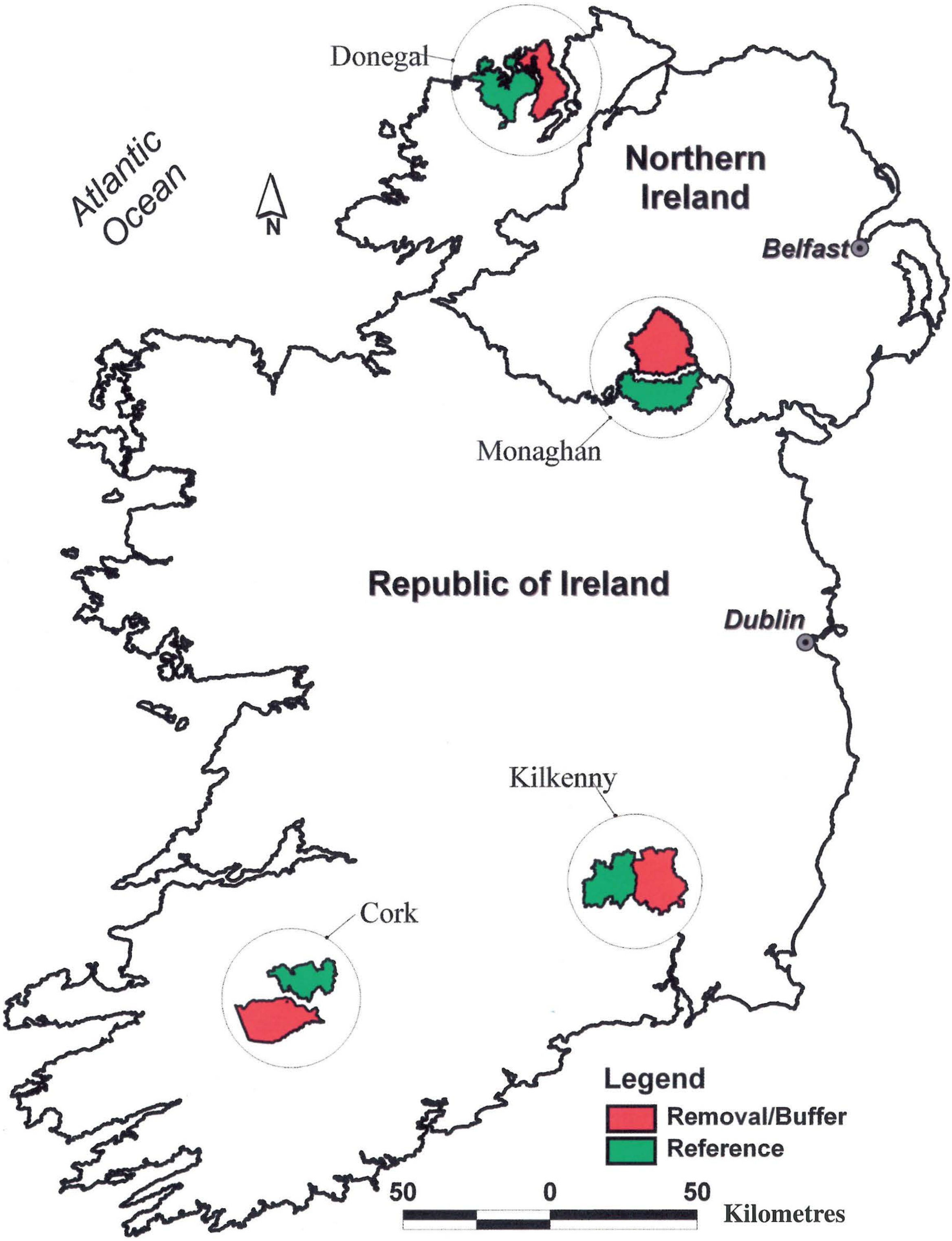
Purposive sampling was used to select the removal areas. Key selection criteria included apparent disease prevalence (that is, 'problem areas' with historic or recent evidence of higher-than-average apparent disease prevalence), the presence, if possible, of natural geographical boundaries (such as rivers, mountain ranges and sea inlets), and areas considered representative of the diverse Irish landscape. Where natural barriers were absent, 'buffer areas' were created, up to 6 km in width, at the boundary of each selected removal area.

2.1.2.2 Reference areas

Purposive sampling methods were used to match each removal area with a defined reference area within the same county. The matching criteria, based on factors known to influence badger density and herd prevalence of tuberculosis, including county, livestock density, herd size, farm-enterprise type, disease prevalence (based on the number of tuberculin reactors per thousand animal tests, APT) during the 9 years prior to study start, and selected geographic features. The latter criteria, including land use and soil type, are known to influence badger numbers (Hammond et al., 2001). In addition, but only when natural barriers were absent, each reference area was separated from both the removal and (where present) adjoining buffer areas by a distance of at least 3 km, to minimise any effect of badger migration on tuberculosis levels in cattle in these areas.

The matched removal and reference areas in each county were supervised by that county's District Veterinary Office (DVO), and managed by a single appropriately-trained team throughout the study period.

Figure 1 The location of the paired removal and reference areas in Ireland.



2.2 Results

2.2.1 Description of the study areas

The total size of the removal and reference areas (excluding the buffer areas) was 1961 km^2 (Table 1), which is approximately 3.9% of the agricultural land area of the Republic of Ireland. The size of each individual removal area, buffer area and reference area is shown in Table 1.

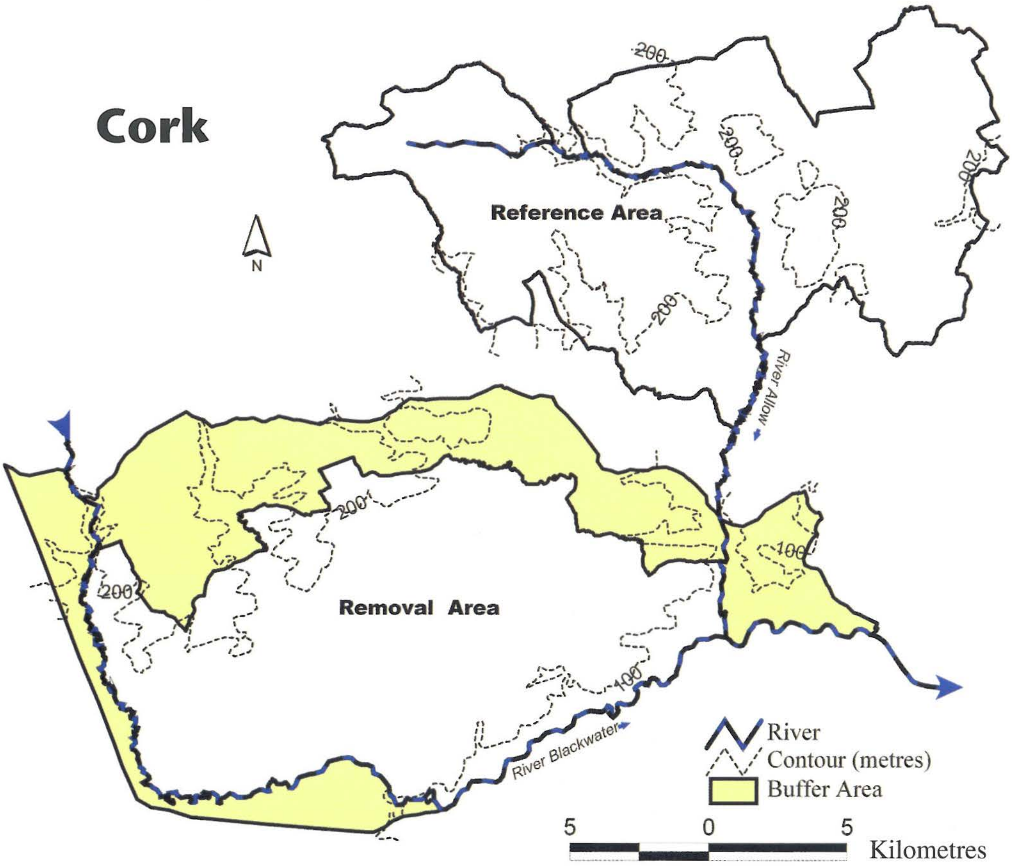
Table 1 The area (km^2) of the removal, buffer and reference areas in counties Cork, Donegal, Kilkenny and Monaghan.

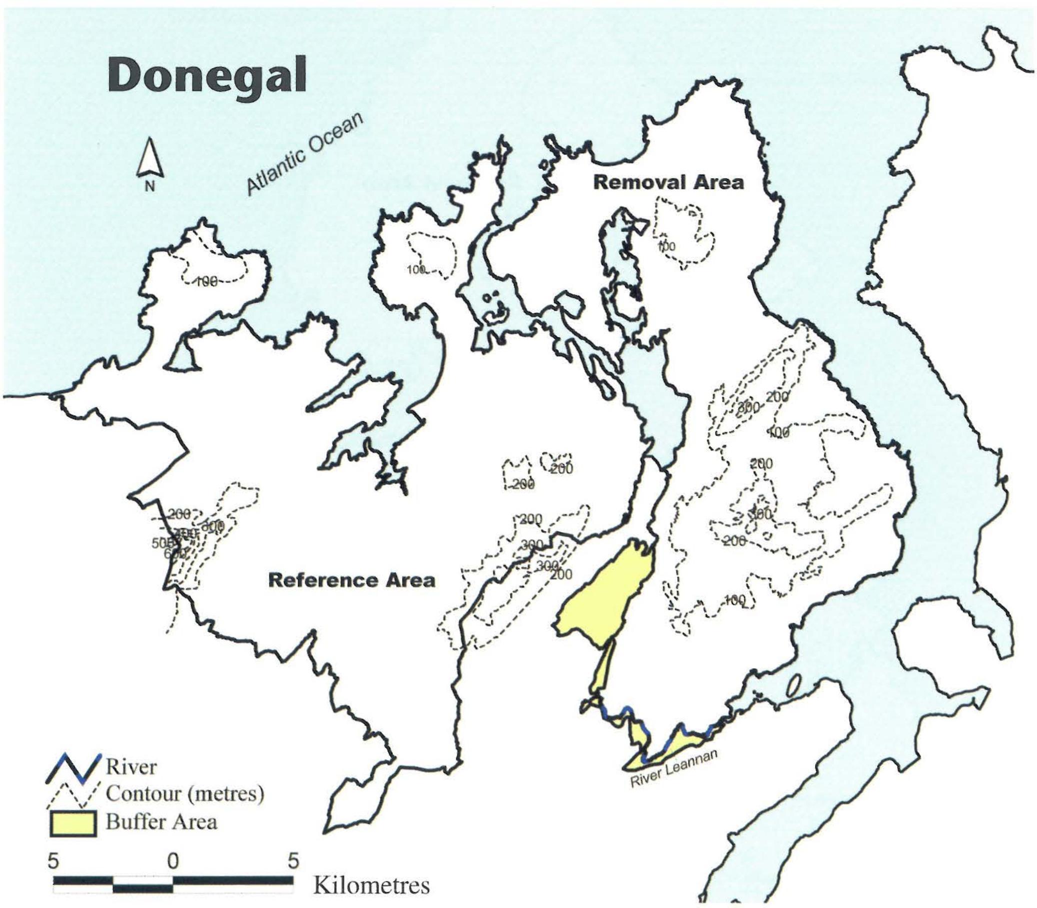
County	Removal	Buffer	Reference
Cork	188	119	199
Donegal	215	11	275
Kilkenny	252	61	253
Monaghan	305	63	274

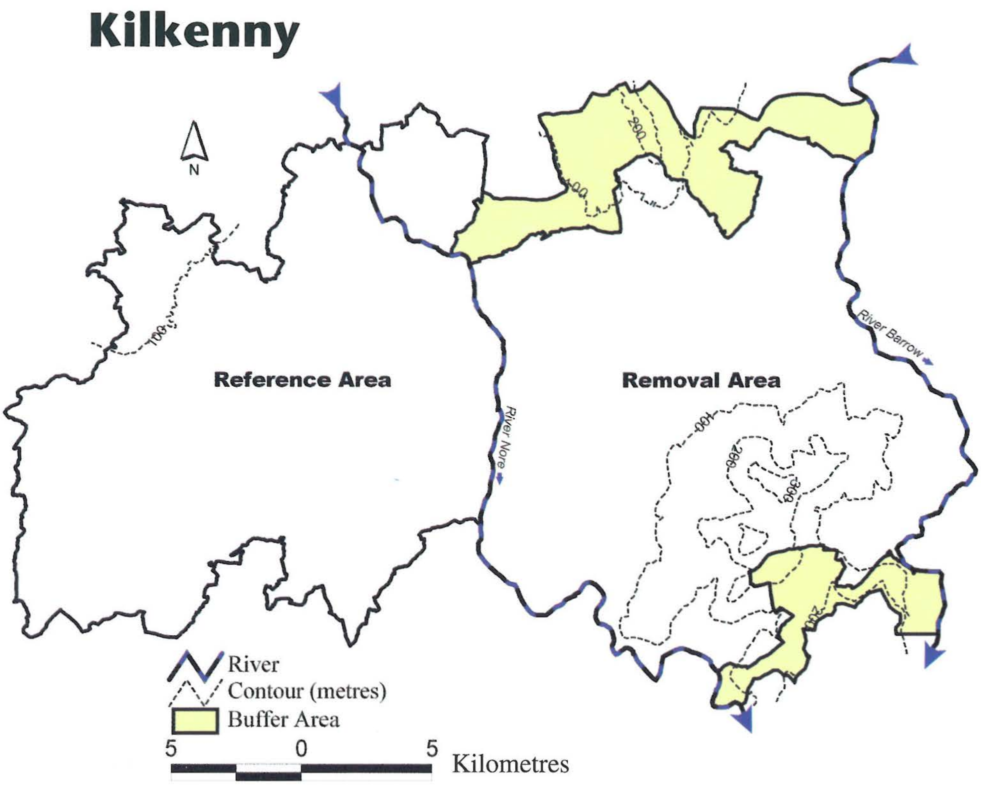
The study areas (removal and reference) in Cork (with a total area of 387 km^2) lie in a major dairying area of Ireland, with a high proportion (89%) of pasture land and high grazing density (1.7 livestock unit (LU) per hectare (ha)). The removal area was bounded to the south and east by the rivers Blackwater[1] and Allow, to the north and west by a total of 119 km^2 of buffer areas (Figure 2). In the study areas of Donegal (covering a total of 490 km^2), the key landscape features are mountains, moors, heathland, bog and sea inlets, and with only 37% pasture land. In this region, stock grazing density is low (1.0 LU/ha), cattle farming is predominantly suckler production, and herd sizes are small. The Donegal removal area was bounded by the sea and small (11 km^2) buffer areas to the south. The Kilkenny study areas (covering 505 km^2) are generally flat, and characterised in the main by rich pasture land divided by extensive hedgerow. In this area, cattle enterprises are mainly suckler and beef production, with the average herd size and grazing density (1.9 LU/ha) being larger than all other study areas. The Kilkenny removal area was bordered on the east by the river Barrow, the west and south by the river Nore, and by buffer areas (61 km^2 in total) to the north and southeast. The largest study area was in county Monaghan, covering 579 km^2. In this county, the landscape is dominated by rolling hills and pasture land, and intensive suckler production with high grazing densities of approximately 1.8 LU/ha. The Monaghan removal area was separated from Northern Ireland by the river Blackwater[1] to the northeast and by a series of mountains including Slieve Beagh (380m) to the north west. There was a 63 km^2 buffer area to the south. Throughout the study period, there was no official removal of badgers in Northern Ireland.

[1] The rivers Blackwater in counties Cork and Monaghan are separate Irish rivers.

Figure 2 **The removal, buffer and reference areas within counties Cork, Donegal, Kilkenny and Monaghan.**






Kilkenny
N
Reference Area
Removal Area
River Nore
River Barrow
100
200
300
River
Contour (metres)
Buffer Area
5
0
5
Kilometres


Monaghan
River Blackwater
Northern Ireland
Northern Ireland
N
Removal Area
300
200
100
Reference Area
River
Contour (metres)
Buffer Area
5
0
5
Kilometres

2.2.2 Comparison of the study areas

The matching attributes for the removal and reference areas in each county are presented in Table 2. In the removal areas, the apparent prevalence of bovine tuberculosis, measured as the average number of tuberculin reactors per thousand animal tests (APT) during the 9 years prior to study start, ranged from 4.2 to 5.7. In contrast, the average national APT during that period was 3.3. With the exception of Monaghan, the removal area APT was higher than that in the corresponding reference area.

Table 2 Attributes of the matched removal and reference areas in counties Cork, Donegal, Kilkenny and Monaghan.

County, attribute	Removal area	Reference area
Cork		
APT (1987-1995)	4.9	4.0
Cattle population	32,252	27,533
Average herd size[1]	56	58
% dairy herds	44.6	35.1
% grassland	89.5	83.8
Grazing density (LUs[2]/100 ha)	167.5	159.6
Donegal		
APT (1987-1995)	5.7	4.3
Cattle population	16,819	10,660
Average herd size[1]	21	15
% dairy herds	5.1	4.2
% grassland	37.1	19.8
Grazing density (LUs[2]/100 ha)	106.0	120.3
Kilkenny		
APT (1987-1995)	4.2	3.7
Cattle population	31,508	41,951
Average herd size[1]	71	93
% dairy herds	14.9	6.4
% grassland	70.8	70.9
Grazing density (LUs[2]/100 ha)	189.1	193.2
Monaghan		
APT (1987-1995)	5.4	6.5
Cattle population	36,465	41,218
Average herd size[1]	31	37
% dairy herds	17.9	24.8
% grassland	73.2	94.9
Grazing density (LUs[2]/100 ha)	180.3	176.2

[1] Average number of cattle in each herd

[2] Livestock units per 100 hectares.

3 The badger population

3.1 Methods

3.1.1 Sett surveys

Farmer participation in the survey was voluntary. On all participating farms, a comprehensive survey of badger habitat and activity was conducted on all land parcels within each removal, buffer and reference areas. Pre-trial surveying began in November 1996 and was completed in all removal areas by 1997, and in all reference areas by the end of 1999. The purpose of the survey was to locate and describe all setts. This was undertaken by a team of approximately 30 surveyors; all fields and hedgerows were examined for badger setts. Further, selected parts of the areas were re-surveyed during the study by a badger ecologist. The locations of setts were recorded and computerised using a custom-designed geographical information system. Each sett was defined as either a main sett or a non-main sett on the basis of size and level of activity (Thornton, 1988). The activity status of a sett was based on the initial survey of the sett.

3.1.2 Badger removal

3.1.2.1 Overview

Details of the badger-removal procedure, including the equipment required, are given in the Badger Manual prepared by the Department of Agriculture, Food and Forestry (DAFF, 1996). Briefly, restraints were laid on badger tracks in a loop secured by an angle iron and wooden support stakes and were normally left in position for 11 nights (representing a single badger removal operation). Some restraints were left in place for a second 11-night period depending on the level of badger activity. Each consecutive 11-night period is considered a 'removal operation'. The restraints used in Ireland consist of a multi-strand steel wire which was 143cm long with a stop at 28cm. Restraints were inspected each morning by a trained operative and captured badgers were killed, using a 0.22 calibre rifle (Eves, 1993). All operatives involved in this work were trained in the safe and humane use of firearms specifically in relation to badgers, and safe handling of dead badgers.

3.1.2.2 Removal policy in the removal and buffer areas

Farm participation in the programme of badger removal was also voluntary. In the removal and buffer areas, except where permission was witheld by the landowner, a proactive programme of badger removal was carried out under licence on 2 to 3 occasions each year on all land fragments. This high frequency of removal was designed to maximise removal of all resident badgers and of any badgers that migrated into the area during the study period.

3.1.2.3 Removal policy in the reference area

In each of the reference areas, badger removal was entirely reactive. Badger removal was only conducted on a farm and its surrounds following severe outbreaks of tuberculosis in cattle herds (defined as outbreaks where 4 or more standard tuberculin reactors were disclosed) where the source could reasonably be attributed to badgers. In Ireland, an animal is considered a standard reactor if the reaction to bovine tuberculin in the single intradermal comparative tuberculin test is more than 4mm greater than the reaction to avian tuberculin, or there is oedema, exudative necrosis, heat and/or pain at the bovine tuberculin injection site and/or swelling of the related prescapular lymph node (DAF, 2003). All outbreaks were investigated by a Veterinary Inspector, and in each case where removal was undertaken, active badger setts were found on or in the vicinity of the farm-in-question only after all other sources of infection (residual, purchased and farm-to-farm spread) were considered unlikely. Although removal was generally limited to a single removal operation, removals were repeated if evidence of badger activity was subsequently detected.

3.1.2.4 Prior to the study

A number of badger removal operations were carried out prior to the study. Data relating to these operations, such as the number of badgers captured, sett location and gross *post-mortem* results, have been recorded since 1988.

3.1.3 Tuberculosis status

A gross *post-mortem* examination was conducted on all captured badgers following euthanasia at either the Central Veterinary Research Laboratory of the Department of Agriculture and Food, one of its Regional Veterinary Laboratories, or at the Irish Equine Centre. If gross evidence of tuberculosis was detected, all affected tissues were sent for histopathological examination and for culture. If no evidence of tuberculosis was found during the gross *post-mortem* examination, a pool of designated tissues (bronchial and mediastinal lymph nodes, retropharyngeal lymph nodes, a portion of each kidney and a portion of lung tissue) was sent for histopathological examination and culture. A badger was regarded as positive for tuberculosis if it was positive at histopathological examination and/or on culture.

3.2 Results

3.2.1 Sett surveys

There was a high level of co-operation and support from the farmers in each area. Permission to survey was refused on only one occasion, on a single farm of 19 hectares in county Cork.

During the initial survey, over 5,000 setts were identified, with a further 400 being found later in the study period. A total of 3,077 setts (620 main and 2,457 non-main setts) and 2,448 setts (508 main and 1,940 non-main setts) were located in the removal and reference areas, respectively (Table 3). The overall density of active main setts in the removal and reference areas was 0.45 and

0.46 active main setts per km², respectively. However, the density of active main setts varied by county; for example, the density of active main setts in the reference area in Cork was lower than in the corresponding removal area, while in Monaghan the reverse was the case.

Table 3 **Number of setts located in the removal and reference areas in Cork, Donegal, Kilkenny and Monaghan.**

County	Main setts	Non-main setts	Total	Active main setts	Active main setts per km²
Removal and buffer areas					
Cork	203	907	1110	193	0.63
Donegal	107	446	553	102	0.45
Kilkenny	162	564	726	115	0.37
Monaghan	148	540	688	139	0.38
Total	**620**	**2457**	**3077**	**549**	**0.45**
Reference areas					
Cork	110	319	429	94	0.47
Donegal	115	557	672	108	0.39
Kilkenny	128	383	511	112	0.44
Monaghan	155	681	836	150	0.54
Total	**508**	**1940**	**2448**	**464**	**0.46**

3.2.2 Badger removals

3.2.2.1 Prior to the study

Details of badger removals in the study areas during the pre-study period (1 September 1992 to 31 August 1997), and also several years prior to this, are presented in Table 4. There was no organised badger removal prior to 1988 in Ireland. There had been very little badger removal in counties Cork and Donegal during the pre-study period. In contrast, badger removal had occurred during the late pre-study period in county Kilkenny and during the mid pre-study period in county Monaghan. In the latter two counties, the average annual intensity of badger removal during the pre-study period was higher in the removal areas compared to the respective reference area.

Table 4 **Number of badgers captured during the pre-study period, and for several years prior to this in the treatment areas by year and county.**

Year	Cork	Donegal	Kilkenny	Monaghan	Total
Removal areas					
Prior to the pre-study period					
1988-Aug 92	31	118	0	3	152
The pre-study period					
1992/93	11	0	0	0	11
1993/94	9	0	0	34	43
1994/95	0	5	4	56	65
1995/96	0	4	148	123	275
1996/97	1	0	57	0	58
Total	**21**	**9**	**209**	**213**	**452**
Average annual removal intensity[1]	**0.02**	**0.01**	**0.17**	**0.14**	**0.09**
Buffer areas					
Prior to the pre-study period					
1988-Aug 92	16	0	0	0	16
The pre-study period					
1992/93	0	0	0	0	0
1993/94	0	0	0	7	7
1994/95	0	0	0	3	3
1995/96	2	0	0	1	3
1996/97	0	0	0	0	0
Total	**2**	**0**	**0**	**11**	**13**
Average annual removal intensity[1]	**0.003**	**0.00**	**0.00**	**0.03**	**0.01**
Reference areas					
Prior to the pre-study period					
1988-Aug 92	0	0	0	5	5
The pre-study period					
1992/93	0	0	0	0	0
1993/94	5	0	0	17	22
1994/95	4	1	55	0	60
1995/96	5	1	33	0	39
1996/97	3	4	4	0	11
Total	**17**	**6**	**92**	**17**	**132**
Average annual removal intensity[1]	**0.02**	**0.004**	**0.07**	**0.01**	**0.03**

[1] Removals per km², during the pre-study period.

3.2.2.2 During the study period

Again, there was a high level of support from farmers during the study period. Permission to undertake a programme of badger removal within the removal areas was only refused in one 19 ha. area in Cork where no survey could be conducted and at 13 surveyed setts (0.42% of those setts surveyed). These 13 setts were located in Cork (5 setts), Donegal (5) and Kilkenny (3).

There were 5,867 removal operations and 2,360 badger removals in the removal and buffer areas during the study period (Table 5); 50.1% and 41.2% of all removals in these areas occurred during the first 12 months, respectively. In the reference areas, a total of 258 badgers were removed following 64 severe outbreaks of bovine tuberculosis (as defined previously). This consisted of a total of 321 removal operations. Removal intensity in the removal and reference areas during the first 2 years of the study averaged 0.57 and 0.07 badgers/km^2/year, respectively.

The average annual removal intensity in the reference area during the study period (0.05 badgers removed per km^2 per year) was roughly similar to the intensity of badger removal in the removal areas (0.09) and in the reference areas (0.03) during the 5-year pre-study period, but substantially less than the intensity of badger removal in the removal areas (0.33) during the study period.

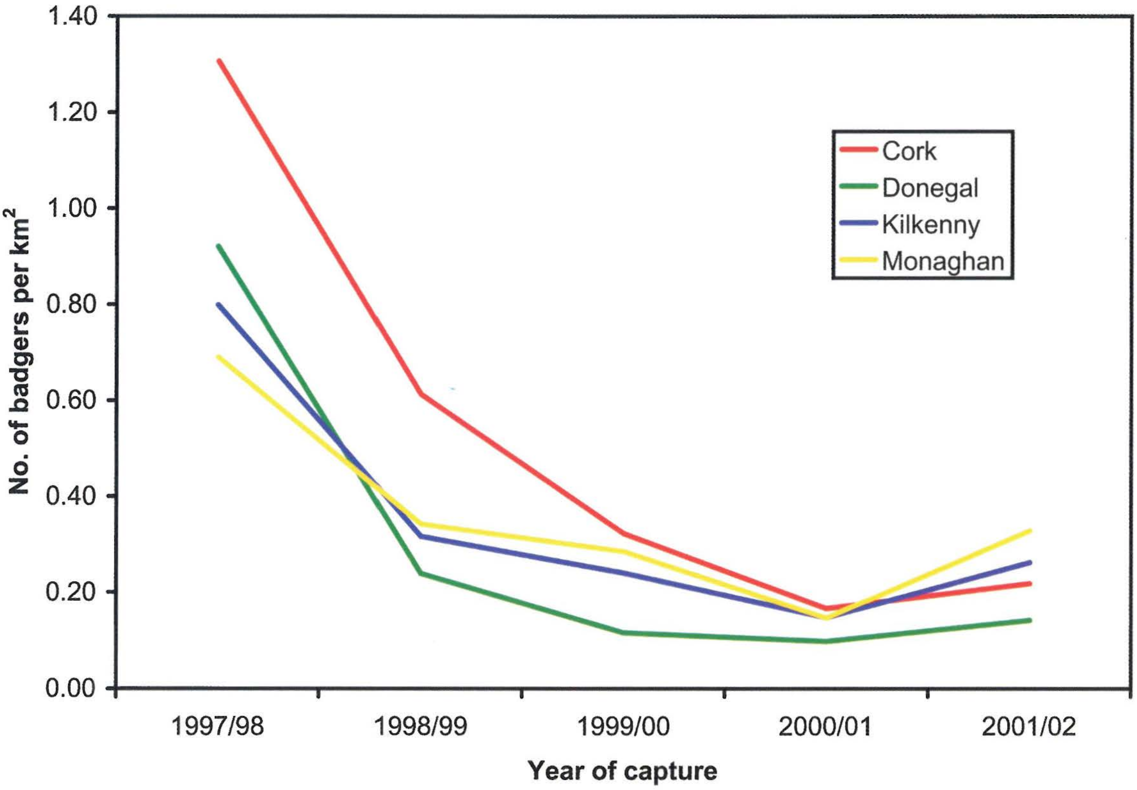
Figure 3 illustrates the annual removal intensity in the removal and buffer areas, and reflects the relative badger density throughout the study period, assuming uniform removal efficacy.

Table 5 Number of badgers removed, and the removal intensity (badgers removed per km²), in the removal, buffer and reference areas of counties Cork, Donegal, Kilkenny and Monaghan during 1 September 1997 to 31 August 2002.

Year	Cork		Donegal		Kilkenny		Monaghan	
	No. of badgers	Removal intensity (removals/km²)	No. of badgers	Removal intensity (removals/km²)	No. of badgers	Removal intensity (removals/km²)	No. of badgers	Removal intensity (removals/km²)
Removal areas								
1997/98	235	1.25	191	0.89	189	0.75	176	0.58
1998/99	103	0.55	38	0.18	83	0.33	84	0.28
1999/00	46	0.24	16	0.07	61	0.24	71	0.23
2000/01[1]	29	0.15	16	0.07	28	0.11	34	0.11
2001/02	36	0.19	16	0.07	49	0.19	78	0.26
Total	449	2.39	277	1.29	410	1.63	443	1.45
Buffer areas								
1997/98	166	1.39	17	1.55	61	1.00	78	1.24
1998/99	85	0.71	16	1.45	16	0.26	42	0.67
1999/00	53	0.45	10	0.91	14	0.23	34	0.54
2000/01[1]	22	0.18	6	0.55	18	0.30	20	0.32
2001/02	31	0.26	16	1.45	33	0.54	43	0.68
Total	357	3.00	65	5.91	142	2.33	217	3.44
Reference areas								
1997/98	18	0.09	0	0.00	7	0.03	4	0.01
1998/99	36	0.18	9	0.03	43	0.17	21	0.08
1999/00	23	0.12	0	0.00	3	0.01	17	0.06
2000/01[1]	14	0.07	4	0.01	16	0.06	10	0.04
2001/02	6	0.03	0	0.00	25	0.10	2	0.01
Total	97	0.49	13	0.05	94	0.37	54	0.20

[1] The number of badgers removed in the removal area in 2000/01 was low due to restrictions imposed because of the foot-and-mouth disease outbreak in Ireland.

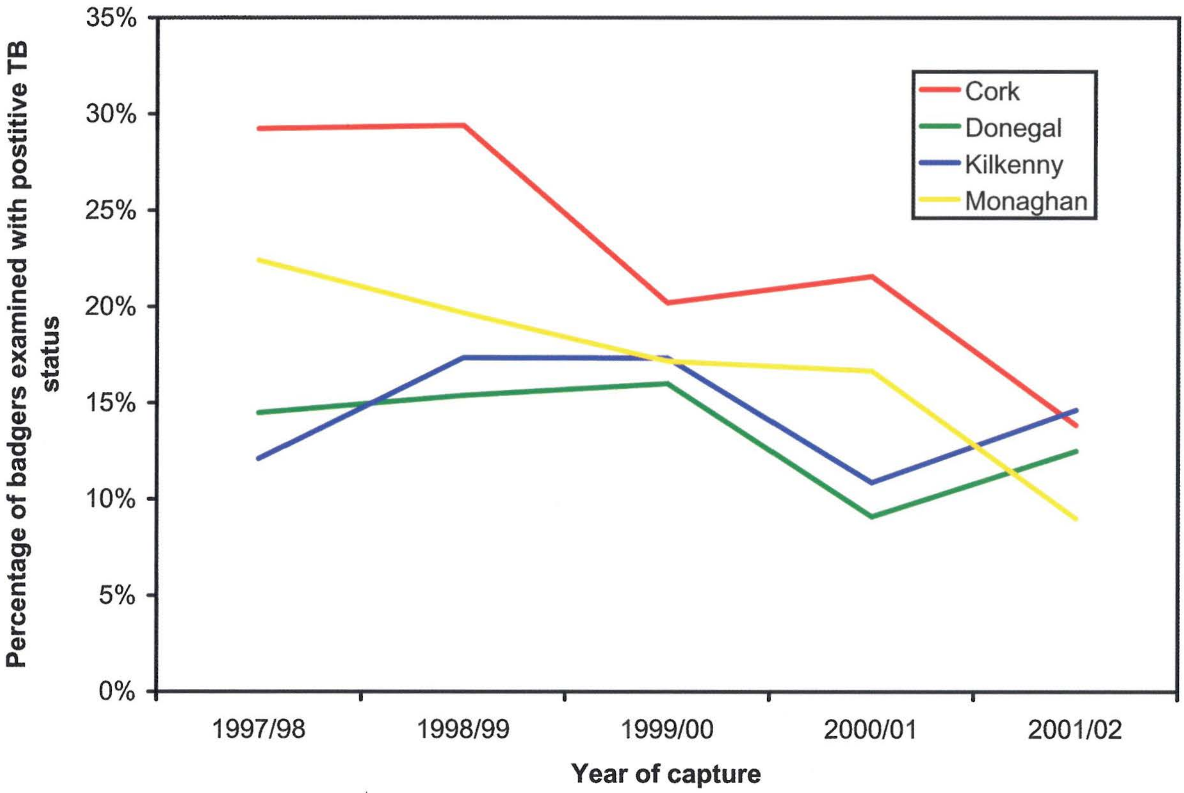
Figure 3 **Density of badger capture per km² in the removal and buffer areas by county and year of capture.**



3.2.3 Tuberculosis status

Of the 2,360 badgers captured in the removal and buffer areas during the study period, 2,310 (97.9%) were examined *post-mortem,* with samples being forwarded for culture and/or histopathology. The remainder, in error, were examined *post-mortem* only. Of the initial 2,310 badgers, 450 (19.5%) were considered positive for tuberculosis. During the first year of the study, tuberculosis among captured badgers was most prevalent in Cork (29%), followed by Monaghan (22%), Donegal (14%) and Kilkenny (12%). The prevalence of tuberculosis dropped during the study period in three of the four areas ranging from 9% in Monaghan to 14% in Cork in the last year of the study (Figure 4). In Kilkenny the prevalence was relatively stable during the course of the study, finishing at 15%. At the start of the study, the proportion of positive badgers in Cork was higher than in the other counties; however, this proportion dropped to 14% in 2001/2002 (Figure 4). There was a significant difference between the four counties in the proportion deemed positive in the removal and buffer areas (chi-square statistic = 41.79, $p < 0.001$). Cork had the highest proportion of tuberculous badgers (26%), while Donegal and Kilkenny each had the lowest infected badger population (14%).

Figure 4 **Proportion of examined badgers in the removal and buffer areas deemed positive for tuberculosis, by county and year of capture.**



Of the 258 badgers captured in the reference areas during the study period, 218 (84.5%) were examined at *post-mortem* with samples being forwarded for culture and/or histopathology. The remainder were examined *post-mortem* only. Of the former, 57 (26.1%) were deemed positive for tuberculosis. The prevalence of tuberculosis among captured badgers in the removal and buffer areas compared to the reference areas was significantly different (chi-square statistic = 5.52, p =0.02). In the reference areas badgers were only removed on or adjacent to farms with confirmed tuberculosis breakdowns.

4 The cattle population

4.1 Methods

4.1.1 The study herds

The 'study herds' included all herds wholly contained within either the removal or reference areas. Therefore, herds within a removal area, but with any land fragments elsewhere (either in a reference area, a buffer area, or elsewhere) were not considered in any subsequent analyses. The same was true for herds within a reference area, but with any land fragments elsewhere (either in a removal area, a buffer area, or elsewhere). The location of land, and identify of herd owners, was determined using the Land Parcel Identification Scheme (LPIS) maintained by the Department of Agriculture and Food (DAF).

4.1.2 Tuberculosis status

The national tuberculosis testing programme was conducted, without modification, in the study areas throughout the study period. Therefore, all herds were subjected to at-least annual testing, with animals being tested using the single intradermal comparative tuberculin test (SICTT). In accordance with the European Union Directive 64/432/EEC, an animal was deemed a 'standard reactor' if the increase in skin thickness at the site of injection of the bovine tuberculin was > 4 mm. in excess of the increase at the site of the injection of avian tuberculin. Further, the tuberculosis-free status of a herd was suspended and the herd was subject to animal movement restrictions, if an animal, having reacted positively to a routine tuberculin test, was deemed a reactor, or tuberculosis was diagnosed in a non-reactor animal at routine *post-mortem* examination. Following direct evidence of infection, herds remained restricted until 2 consecutive negative herd tests were subsequently achieved, the first at least 60 days and the second not less than four months after the removal of the last positive reactor. Typically the second test took place at 120 days. At this point the herd was derestricted. The tuberculin test was repeated again on the herd after six months; if this revealed no tuberculin reactors, the herd was not tested again for approximately twelve months and at yearly intervals thereafter. However, herds that had a major breakdown were tested at 6 monthly intervals for a period of two years following derestriction. In accordance with European Community legislation, official Veterinary Inspectors examine all slaughtered animals during abattoir surveillance, either routinely or following a positive herd test.

For the purposes of this study, a confirmed tuberculosis herd restriction was defined as a herd restriction at which a tuberculous lesion was detected in one or more animals at *post-mortem* examination at the time or during the course of the restriction. A major confirmed tuberculosis herd restriction is a subset of the above-mentioned, and was defined as a herd restriction at which a tuberculous lesion was recorded in one or more animals at *post-mortem* examination, and at least two standard reactors were recorded at a tuberculin test in the course of the restriction.

The schedule for the tuberculin testing programme along with the test interpretation used were identical in both the removal and reference areas and corresponded to those concurrently used in the national programme.

4.1.3 Descriptive statistics

Two measures were used to measure the level of tuberculosis in the study herds, namely the confirmed restriction risk and the number of standard reactors per 1,000 animals tested.

4.1.3.1 Confirmed restriction risk

The 'confirmed restriction risk' (CRR) is an annual measure defined as the number of newly confirmed restrictions per 100 herds per *annum* and was calculated as:

$$\frac{\text{Number of herds with a newly confirmed restriction within the year x 100}}{\text{Number of unrestricted herds at the start of the year}}$$

In this calculation, the denominator includes all herds that were officially tuberculosis-free (that is, unrestricted) prior to their first test within that year. The numerator includes all new confirmed herd restrictions within the year (that is, herds that were unrestricted prior to their first tuberculin test in that year). If a herd had a confirmed restriction more than once in a year, it was only counted once in the numerator. A year was defined as commencing on 1st September and ending on 31st August in the following year.

The (annual) confirmed restriction risk and the severity of restrictions were examined by time, county and treatment area. Data from before the start of the study were included in the analysis in order to permit a comparison of tuberculosis levels in the reference and removal areas prior to the study.

An average CRR was calculated for three time periods: the 'pre-study' period (from 1 September 1992 to 31 August 1997, inclusive) and two periods in the 'study' period (from 1 September 1997 to 31 August 2000 and from 1 September 2000 to 31 August 2002 inclusive). This measure was calculated by summing the number of confirmed restrictions per year and dividing by the sum of the number of herds per year, within each time period. It is therefore a weighted average.

4.1.3.2 Standard reactors per 1,000 animals tested

The number of standard reactors per 1,000 animals tested (SPT) was calculated as the number of standard reactors per county, treatment and year divided by the number of animals tested within a year. If an animal was tested more than once in a year, it was only counted once in the denominator. If there was only a part herd test carried out then the number of animals tested at the part herd test was used, otherwise the number of animals at the full herd test within the year was used. Note that the SPT is different to the APT (animals per thousand tests), which includes all (not just standard) reactors in the numerator and all tests during a year in the denominator (thereby potentially counting a single animal on more than one occasion).

4.1.4 Modelling

The study aimed to compare the impact of badger removal at two levels on confirmed restrictions in four different farming environments. Two outcome measures were chosen: (1) yearly confirmed herd restriction prevalence rate and (2) survival time to a confirmed herd restriction. Comparisons were made between the removal and reference areas in a county, between study and pre-study years in an area, and between counties. P-values less than alpha 0.05 (two-sided) are regarded as significant.

4.1.4.1 Data assembly

The data were assembled into a single database and edited at the Centre for Veterinary Epidemiology and Risk Analysis. In order to compare the reference and removal areas during the pre-study and study periods, a yearly confirmed restriction status was assigned to each herd in each year (from September 1 to the following August 31) for 1992/93 through to 2001/02. The final 5 years (i.e. beginning on September 1, 1997) covered the study period. Periods of permission to trade, trading restrictions due to tuberculosis, and periods without cattle were determined from the tuberculin test records of herds. Each period of restriction was then classified as confirmed (that is, tuberculous lesions were detected in 1 or more animals during abattoir surveillance, either routinely or following a positive herd test) or not. Following its first tuberculin test, a herd was considered depopulated during any between-test interval of more than 2 years, therefore providing missing values for the logistic regression analysis. For a between-test interval of less than 2 years the herd's trading status was known.

If the herd entered the year free of a confirmed restriction, then it was considered free of a confirmed restriction for the year if and only if it remained so throughout the year. If the herd entered the year with a confirmed restriction, but became and remained unrestricted during that year, it was also considered unrestricted for that year; otherwise it was considered to have a confirmed restriction that year. This leads to a confirmed restriction prevalence rate. In addition a survival time for each herd was calculated as the time from September 1, 1992 to a confirmed restriction, or August 31, 2002, whichever came first. In the latter case, the survival time was censored. In cases where no herd test was carried out in the 2 years prior to the end of the study or where a between-test interval is more than 2 years (see above), the survival time was censored at the time of the last herd test. Additional survival times from the end of a restriction period were calculated for herds with more than 1 restriction. The survival times were based on time to restriction (under the Irish testing programme), not time to infection (which is unknown).

A range of explanatory variables were included in the dataset, for subsequent modelling, including: TR, a factor with 2 levels denoting the removal and reference areas; herd size (time dependent), the number of animals tested at a full herd test; a factor CO with 4 levels denoting the counties, and a time dependent factor PH (previous history) with 2 levels denoting whether the herd had previously had a confirmed restriction. YEAR was used to denote a factor with 10 levels representing the years 92/93, 93/94, ... , 01/02. A time-dependent factor PERIOD with 2 levels corresponding to the pre-study and study (i.e. from 1 September, 1997) periods was used to summarise results.

4.1.4.2 Logistic model using a generalised estimating equation

A logistic model related the logit of the confirmed restriction prevalence to the 2 treatment areas, 4 counties, herd size, previous history and year. A generalised estimating equation (GEE) method was used to account for dependence in measures on herds with more than 1 restriction. No dependence is generated otherwise (Allison, 1995, page 223). Estimates using independence and first-order autoregressive correlation (AR1) structures were compared. Terms were assessed for inclusion in the model on the basis of the generalised score test (Boos, 1992). Consistent estimates of coefficient standard errors were obtained using the empirical covariance matrix of parameter estimates resulting from the GEE method.

The factor TR was regarded as nested within YEAR, by including terms YEAR and TR x YEAR in the model. These terms were further nested within CO, producing a model with 3 way interactions. Interactions involving PH, CO and TR were tested. An annual herd size for each herd was taken as the mean number of animals tested at all full herd tests during the year, or the number of animals tested at the previous such test if all tests during the year were partial. A variable H was then obtained by dividing by the sample average. Differences in the slope of log(H) by county and treatment were tested in the model by including the 2 and 3 way interactions between log(H), CO and TR. The analysis was carried out using the SAS procedure GENMOD (SAS Institute Inc., 1999).

Log(H) was checked for linearity by the inclusion of quadratic terms, and also by being supplemented by a categorical variable based on the percentiles and testing the extra term for significance. Tests were carried out to examine if the effect of YEAR was linear, before or during the study period. An assessment of the goodness-of-fit was obtained by examining residuals and by a Hosmer-Lemeshow test. The LOGISTIC procedure of SAS (SAS Institute Inc., 1999), which assumes an independence correlation structure on the repeated measures on a herd, was used for the latter.

4.1.4.3 Survival analysis

The Kaplan-Meier estimate of the survival function (Collett, 1994) was computed separately for the removal and reference areas within each county, and these were compared using the nonparametric Wilcoxon test.

A Cox regression model was constructed as described by Collett, 1994. In this model, interest was centred on the hazard of restriction at any time from September 1, 1992. Herd size and YEAR were entered into the model as time-dependent variables, changing with chronological time. To account for herds with multiple restrictions the time-dependent factor PH was included. The counting process form of a Cox model was used with the Anderson-Gill method for treating multiple events (Therneau and Grambsch, 2000). Thus the correct YEAR effects are used for second and subsequent survival times. Both the Wald and jacknife estimates of standard errors were examined (Therneau and Grambsch, 2000). The model included the terms TR, CO and PH and all 2 and 3 way interactions including those with YEAR. Terms were dropped from the model following hierarchical rules and using the likelihood ratio test. Note that the effect of YEAR is subsumed in the baseline hazard function but not interactions with YEAR. The model was checked by examining the martingale, influence and Schoenfeld residuals. The effect of herd size was examined for linearity.

A similar Cox model was also developed to model survival in the 5-year period prior to the study and the 5-year period during the study. Model terms were included and tested as in the 10-year model, with the factor PERIOD replacing YEAR. This model was used to estimate the overall hazard ratio between removal and reference areas and between periods.

4.2 Results

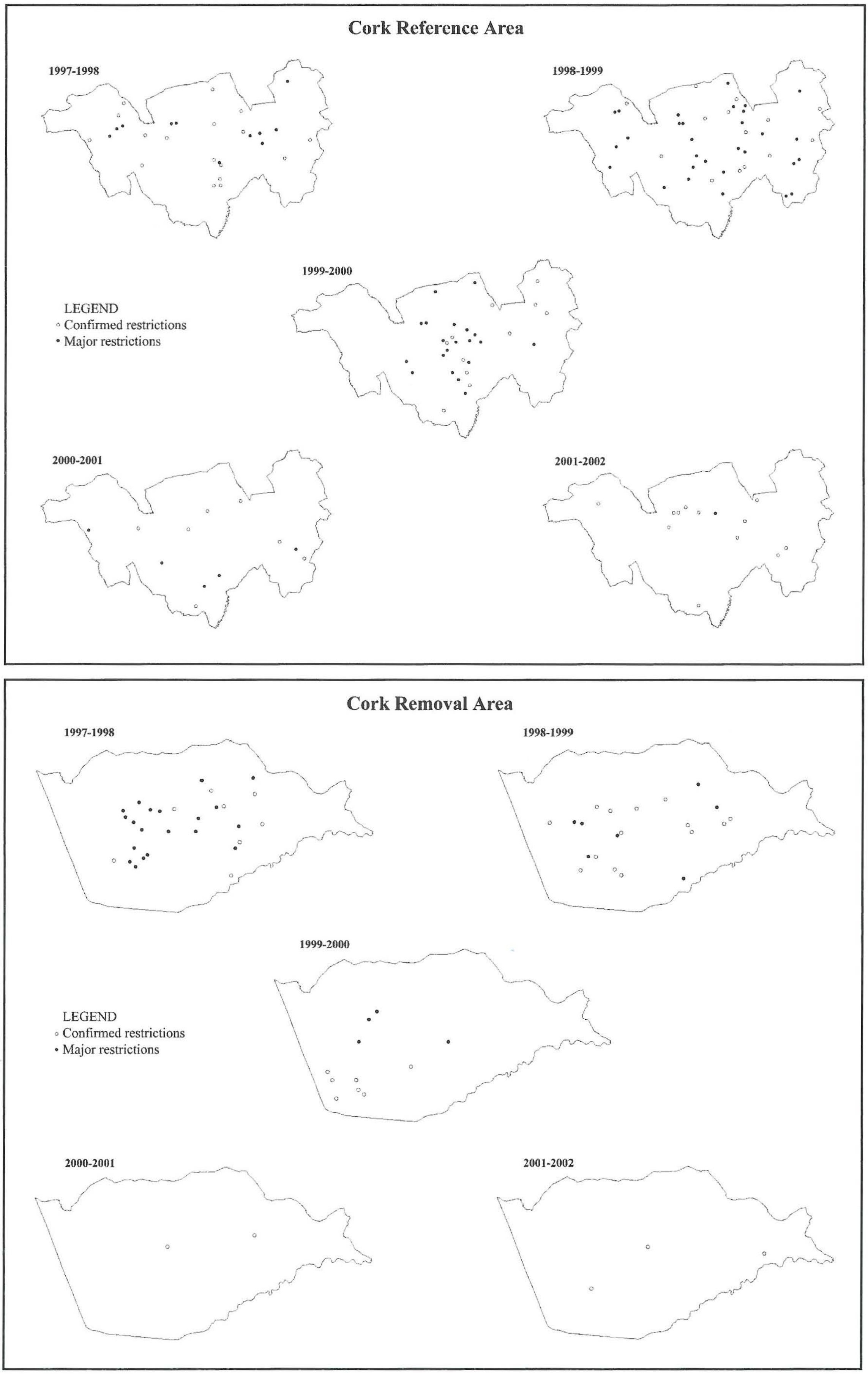
4.2.1 Descriptive statistics

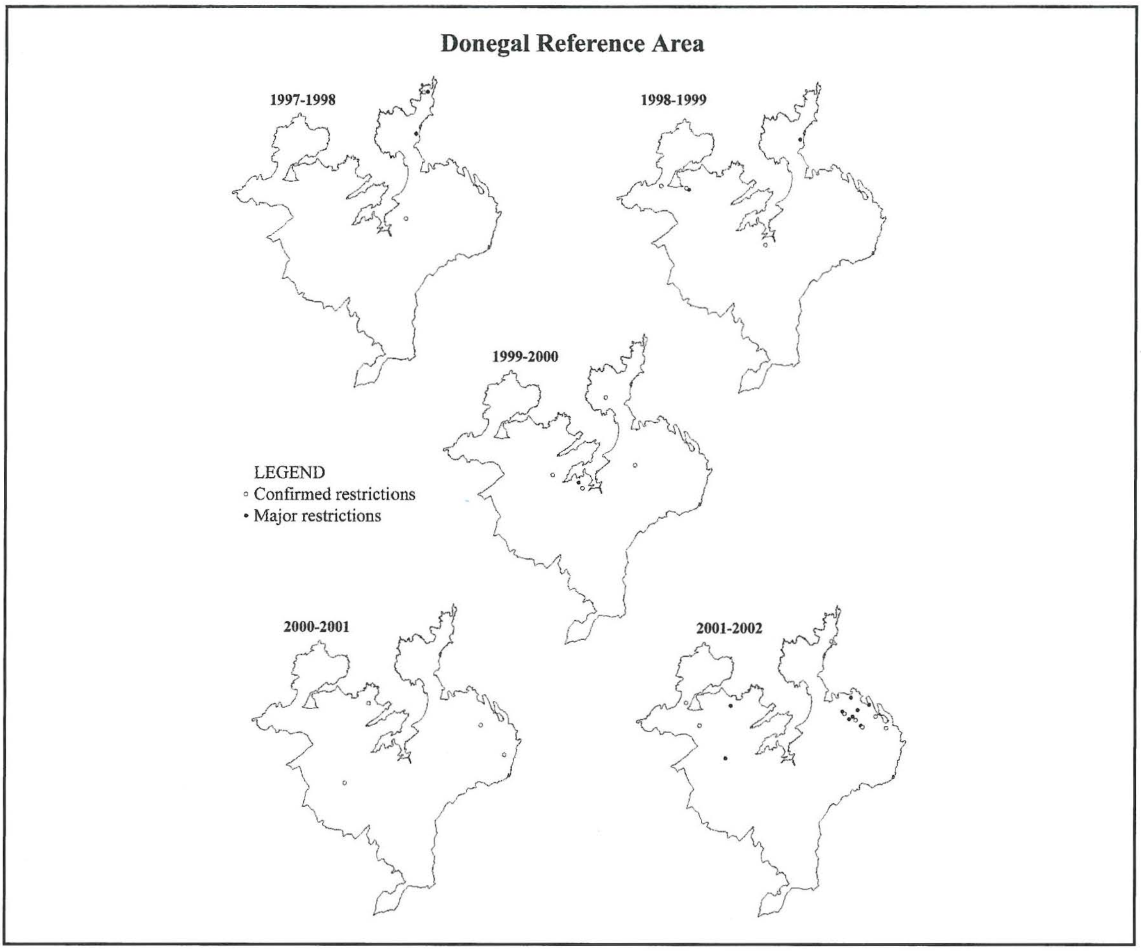
4.2.1.1 The herds

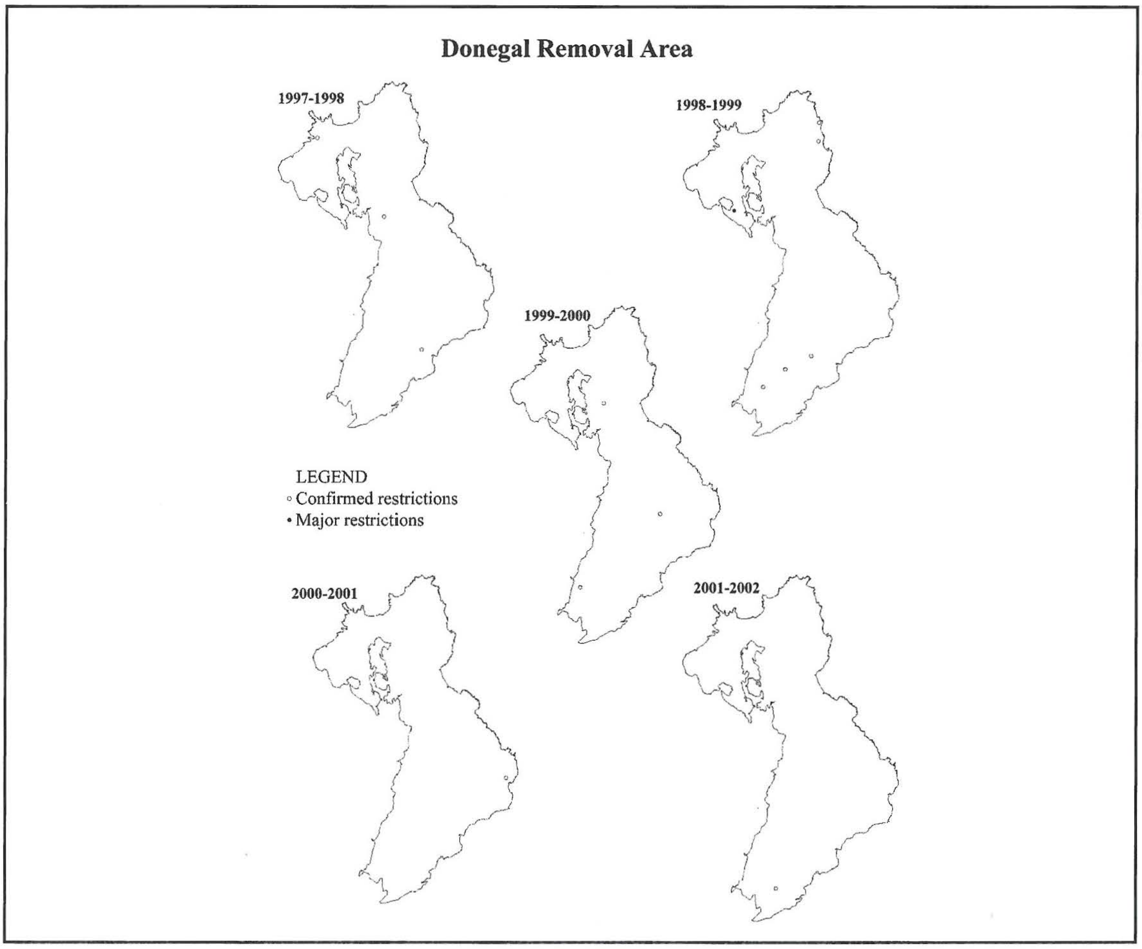
During the pre-study and study period, a total of 1,736 and 1,544 cattle herds were tested at least once in the removal and reference areas, respectively.

The locations of all farms that were the subject of a confirmed or major confirmed restriction during each year of the study period are shown in Figure 5. The location of a farm is represented as a point based on the centroid of the largest fragment of land owned by the farmer.

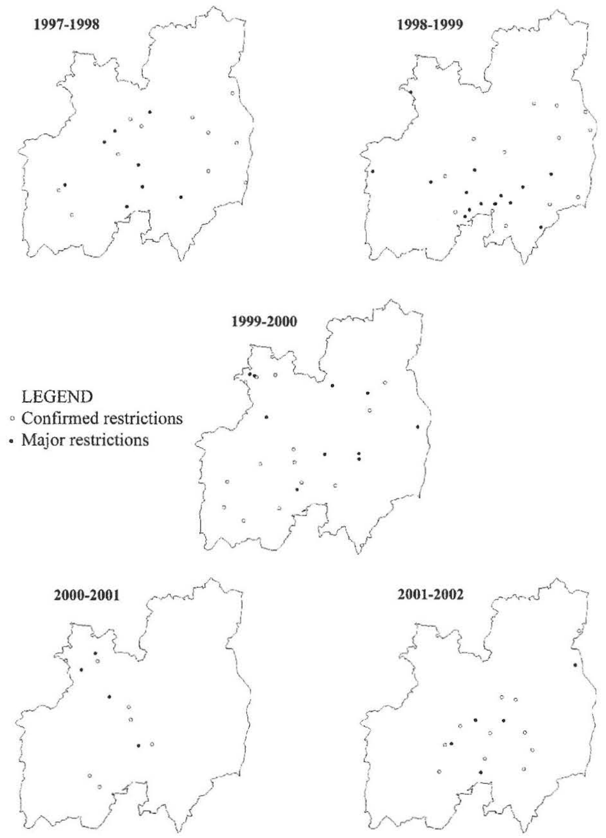
Figure 5 Location of farms that had a confirmed or major confirmed restriction during the study period.



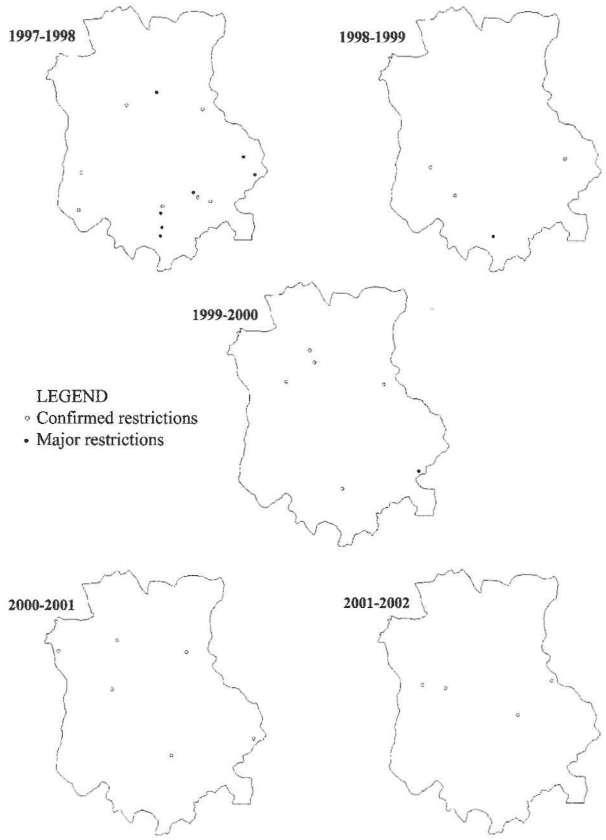

Donegal Reference Area
1997-1998
1998-1999
1999-2000
LEGEND
◦ Confirmed restrictions
• Major restrictions
2000-2001
2001-2002

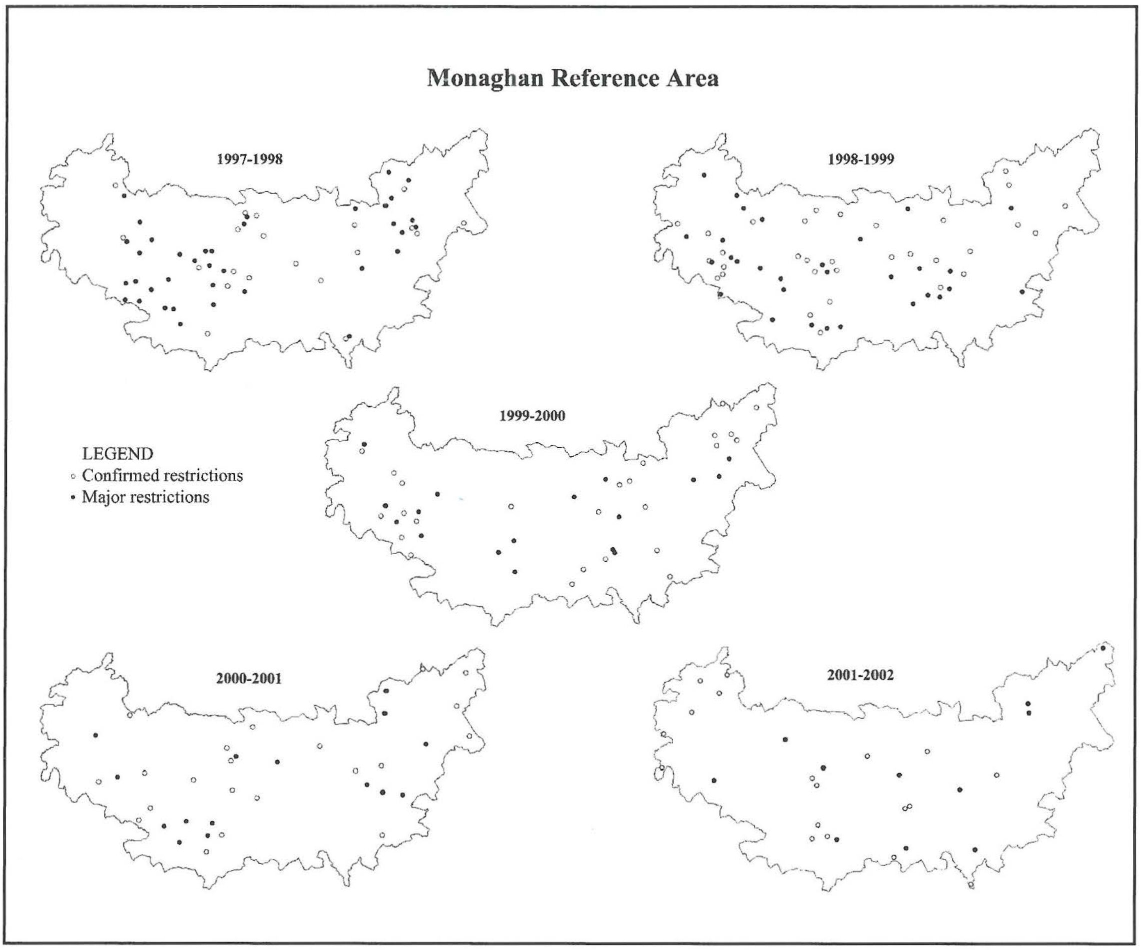

Donegal Removal Area
1997-1998
1998-1999
1999-2000
LEGEND
◦ Confirmed restrictions
• Major restrictions
2000-2001
2001-2002

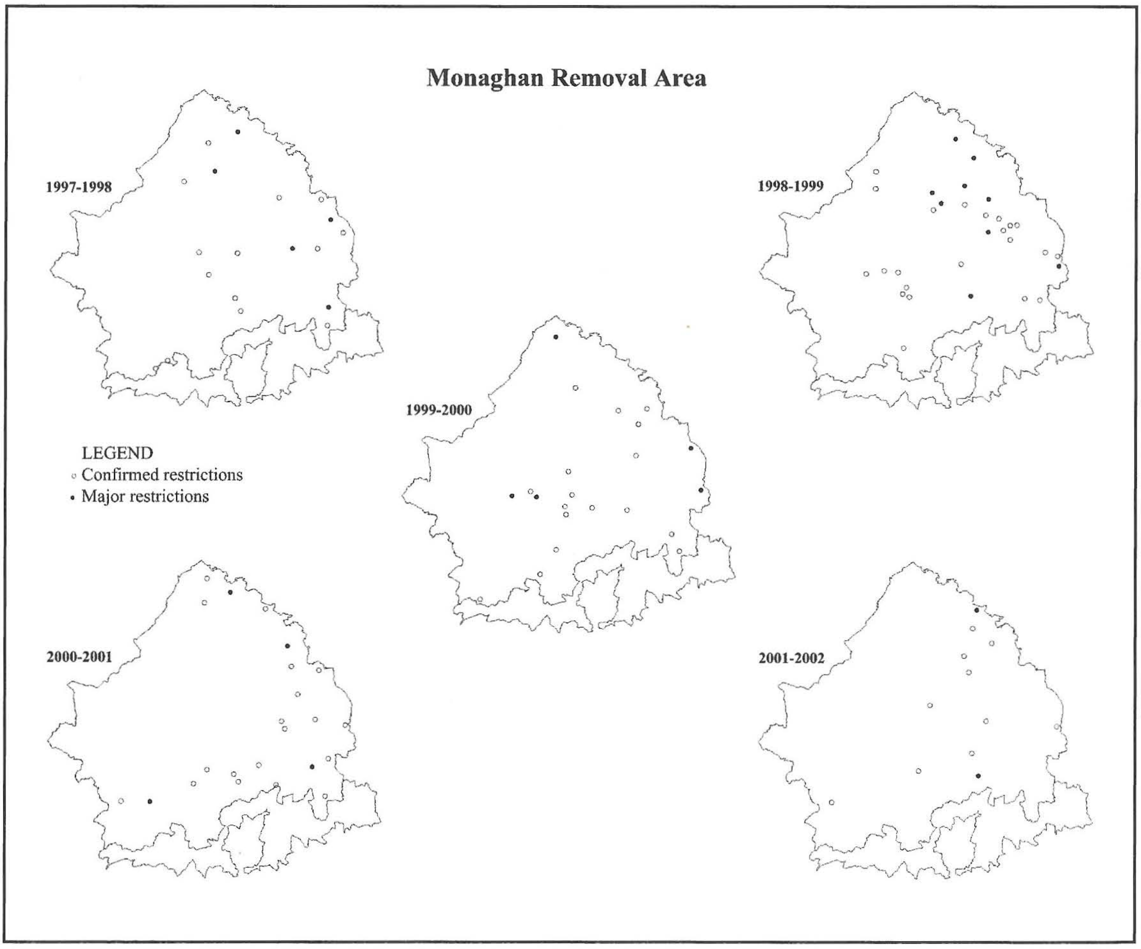
Kilkenny Reference Area



Kilkenny Removal Area




Monaghan Reference Area
1997-1998
1998-1999
1999-2000
LEGEND
Confirmed restrictions
Major restrictions
2000-2001
2001-2002


Monaghan Removal Area
1997-1998
1998-1999
1999-2000
LEGEND
Confirmed restrictions
Major restrictions
2000-2001
2001-2002

4.2.1.2 Tuberculosis status

During the pre-study period

The removal areas. During the pre-study period, the average annual apparent prevalence of tuberculosis, measured as the SPT, ranged from 4.27 to 8.75 (Table 6). In all counties, except Donegal where the difference was marginal, the average annual CRR was higher than the national average during the pre-study period (Figure 6).

The reference areas. During the pre-study period, the annual SPT ranged from 2.55 to 6.26 (Table 6). In all counties, except Donegal, the average annual CRR was higher than the national average CRR (Figure 6).

The removal areas in comparison to the reference areas. Prior to the study the average annual CRR was higher in the removal area compared to the reference area in Cork (11.1 vs. 8.2) and Donegal (3.8 vs. 1.7), whilst the CRR was higher in the reference area in Kilkenny (7.5 vs. 7.8) and Monaghan (7.2 vs. 8.9) (Figure 6). The SPT generally followed a similar pattern with the exception of Kilkenny, where the average annual SPT was higher in the removal area compared to the reference area (5.0 vs. 2.6).

During the study period

The removal areas. A total of 193 (11.7% of all) herds in the removal areas were the subject of a confirmed restriction on at least one occasion during the study period. In each of the four counties, there was a decrease in the average CRR in the removal areas between the pre-study and study periods (Figure 6). The greatest change was observed in Cork where the average CRR fell from 11.3 in the pre-study period to 1.0 in the last two years of the study period. The smallest change was observed in Donegal where the average CRR fell from 3.8 in the pre-study period to 0.3 in the last two years of the study period. In all counties the average CRR in the removal area during the last two years of the study period was below the national average (Figure 6). In addition, in the removal area of each county there was a general decline in the CRR throughout the study period (Figure 7). To illustrate, the CRR during 2001/02 (the final year of the study) was between 39% and 77% of the average CRR throughout the 5 years of the full study period. Further, the SPT in each removal area fell by between 49% and 98% during the study period, when comparing the final year of the pre-study and study periods (Table 6).

The reference areas. During the study period, 393 (26.7% of all) herds in the reference areas were the subject of a confirmed restriction on at least one occasion. In all counties, except Donegal, and in comparison to the pre-study period, the average CRR fell in the last two years of the study period. In all counties, except Donegal, the average CRR in the reference area during the study period was above the national average (Figure 6).

A comparison of the removal and reference areas. During the study period, there were differences between the removal and reference areas in terms of both the number and severity of tuberculosis breakdowns. During this period, 193 (11.7%) and 393 (26.7%) herds in the removal and reference areas, respectively, were the subject of a confirmed restriction on at least one occasion. There was a difference in both the CRR and SPT in each of the paired removal and reference areas (Figure 6, Table 6). During the study period, the average CRR was lower in the removal area compared to the reference area in all counties (Figure 6). The average CRR in the removal area in the last two years of the study for all counties was almost half that in the reference area (e.g. Cork 4.7 vs. 1.0, Donegal 3.6 vs. 0.3, Kilkenny 7.0 vs. 2.5, Monaghan 6.3 vs. 3.2,). The annual CRR was consistently lower in the removal area compared to the reference area in every year of the study period in every county (Figure 7). A similar pattern can also be seen for the SPT, with the SPT in the final year of the study ranging from 0.21 to 1.98 in the removal areas and from 1.73 to 9.66 in the reference areas (Table 6). The number of herd restrictions, by restriction type and county, during the pre-study and study periods is presented in Table 7. In each county and with respect to confirmed herd restrictions, the number increased in each of the reference areas and decreased in each of the removal areas during the study as compared to the pre-study period. With respect to unconfirmed herd restrictions, the pattern was less consistent. In the removal areas during the study as compared to the pre-study period, the relative drop in major confirmed restrictions was greater than when all confirmed restrictions were considered.

Table 6 **Number of standard reactors per 1,000 animals tested (SPT), by county, treatment and year.**

Year	Cork		Donegal		Kilkenny		Monaghan		National
	Reference	Removal	Reference	Removal	Reference	Removal	Reference	Removal	
1992/93	1.46	7.23	5.73	3.53	2.02	3.13	5.75	4.44	4.14
1993/94	6.44	5.50	1.99	4.78	2.92	2.16	7.78	5.13	5.01
1994/95	6.93	11.29	3.80	8.36	3.14	5.38	7.48	8.89	7.22
1995/96	5.02	8.67	4.14	3.59	1.46	9.92	7.24	4.02	5.70
1996/97	9.40	11.07	0.64	1.11	3.21	4.24	3.06	5.36	5.52
Annual average (all 5 years)	***5.85***	***8.75***	***3.26***	***4.27***	***2.55***	***5.00***	***6.26***	***5.57***	***5.52***
1997/98	4.90	8.04	2.33	0.60	3.97	2.65	7.87	1.87	4.63
1998/99	13.20	6.14	4.02	0.99	5.78	1.42	9.87	5.01	6.67
1999/00	9.48	2.37	3.40	0.52	3.91	0.98	5.48	3.33	4.11
2000/01	5.40	1.21	1.87	0.11	2.20	1.26	3.62	1.31	2.38
2001/02	1.73	0.21	9.66	0.57	3.28	1.30	3.38	1.98	2.32
Annual average (all 5 years)	***6.94***	***3.59***	***4.26***	***0.56***	***3.83***	***1.52***	***6.04***	***2.70***	***4.02***
Annual average (last 2 years)	***3.57***	***0.71***	***5.77***	***0.34***	***2.74***	***1.28***	***3.50***	***1.65***	***2.35***

Figure 6 **Weighted average of the annual confirmed restriction risk (CRR) in the removal and reference areas and nationally during the pre-study (1992-1997) and study (1997-2002) periods.**

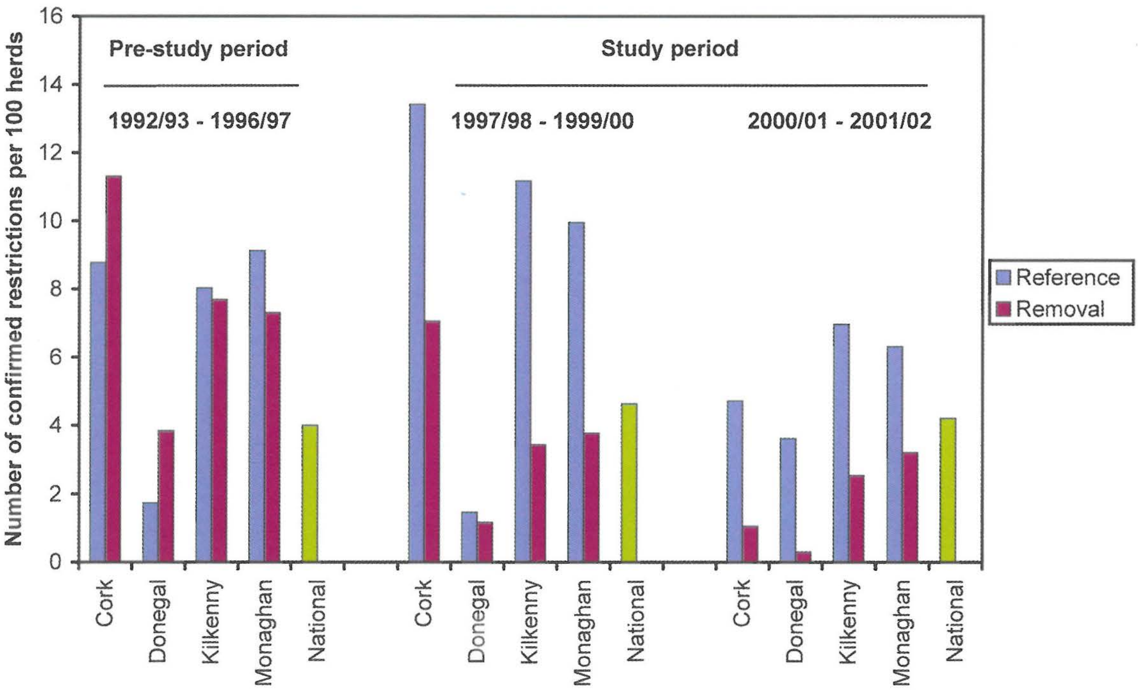
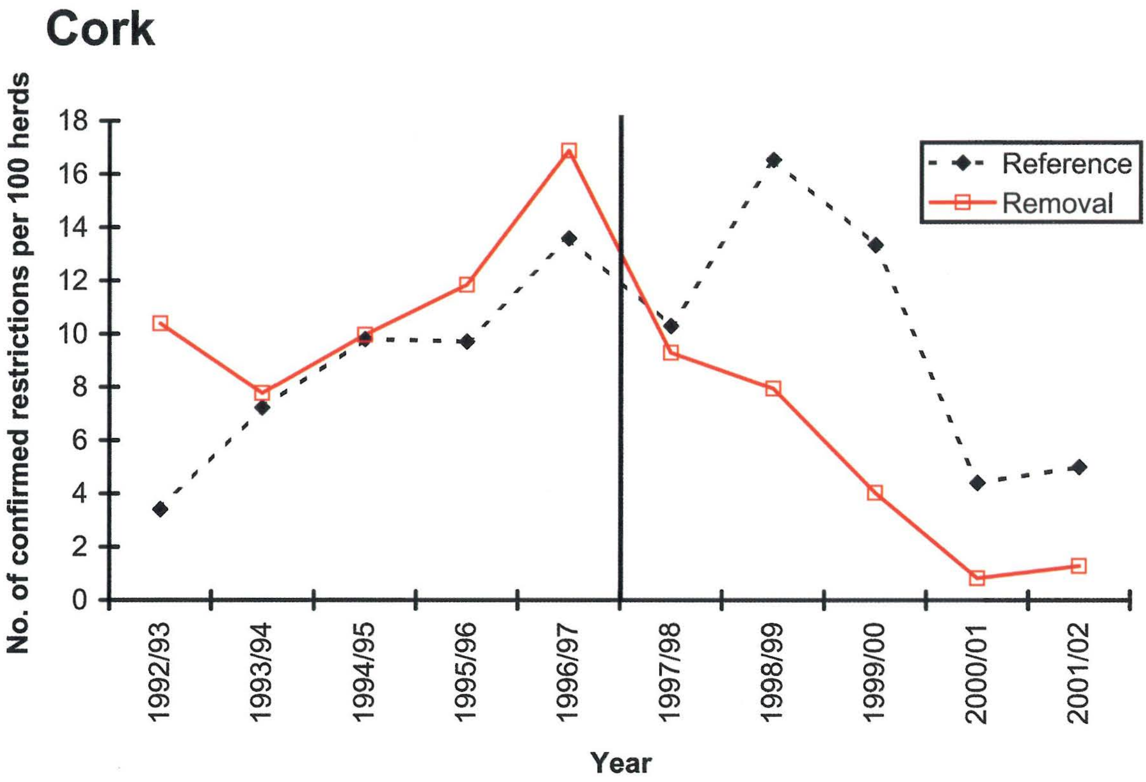
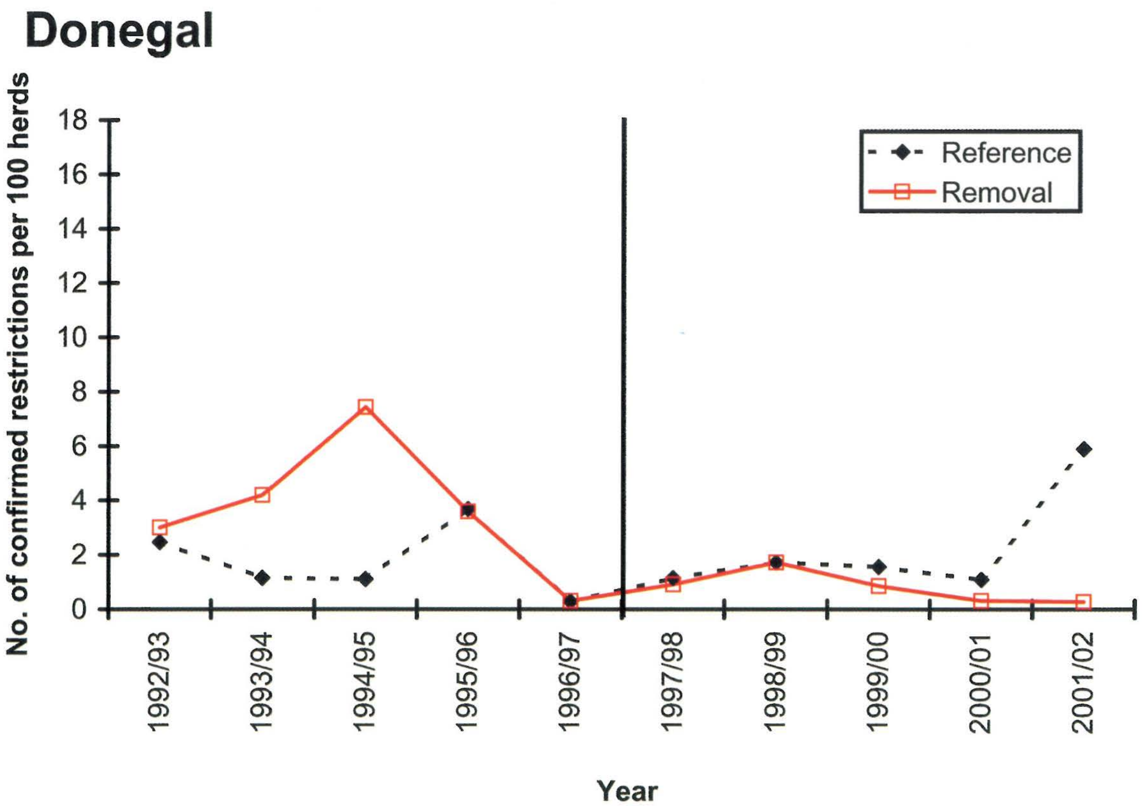
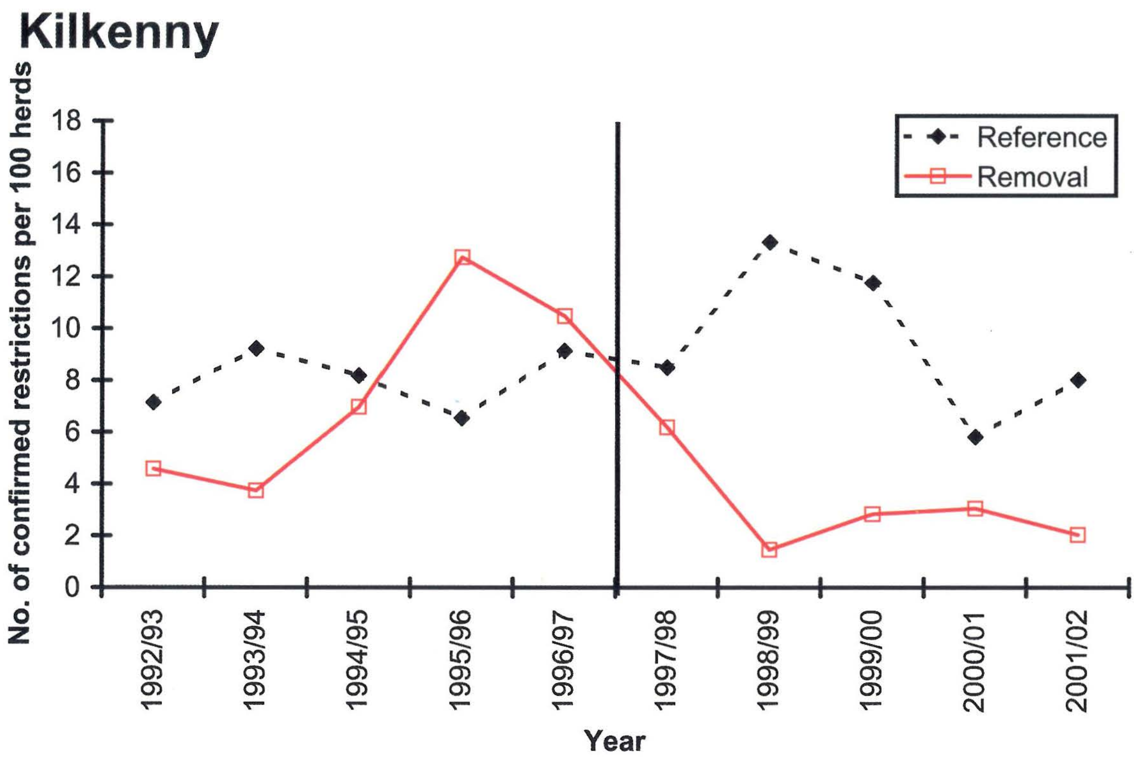


Figure 7 **Confirmed restriction risk (CRR) over time by county, in the removal and reference areas.**






Kilkenny
No. of confirmed restrictions per 100 herds
18
16
14
12
10
8
6
4
2
0
Reference
Removal
1992/93
1993/94
1994/95
1995/96
1996/97
1997/98
1998/99
1999/00
2000/01
2001/02
Year

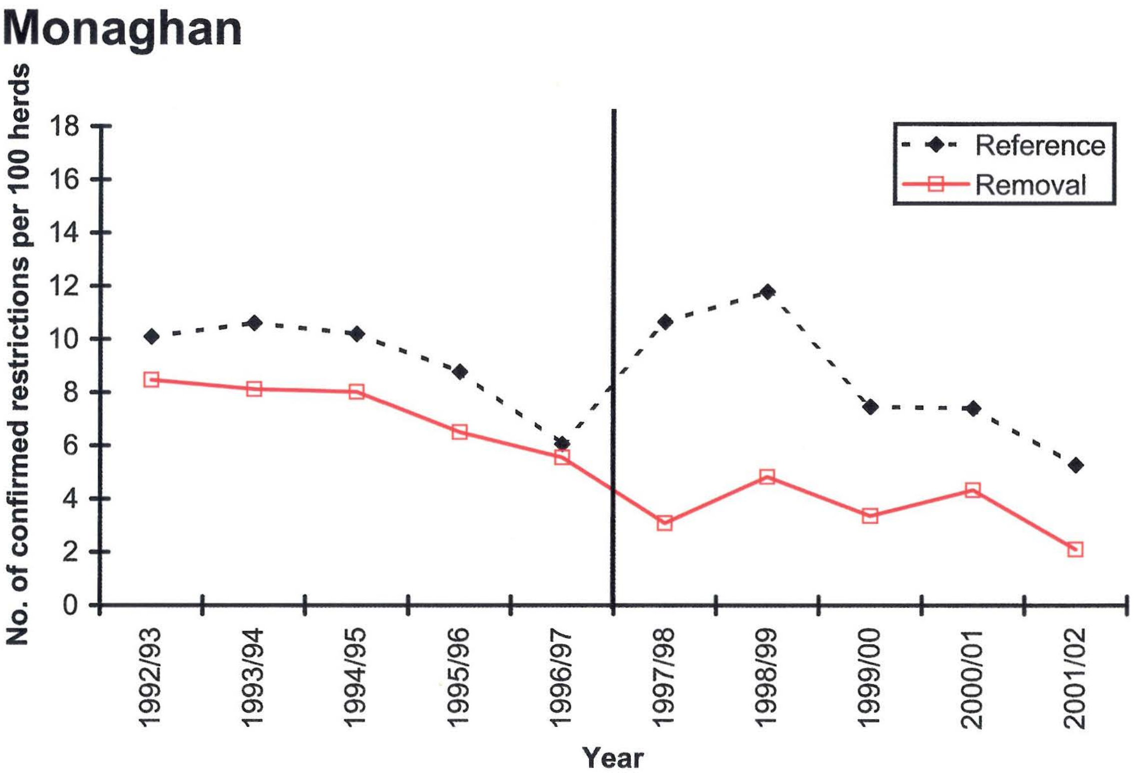

Monaghan
No. of confirmed restrictions per 100 herds
18
16
14
12
10
8
6
4
2
0
Reference
Removal
1992/93
1993/94
1994/95
1995/96
1996/97
1997/98
1998/99
1999/00
2000/01
2001/02
Year

Table 7 **Number of herd restrictions in the pre-study (1992-1997) and study (1997-2002) periods by restriction type* and county.**

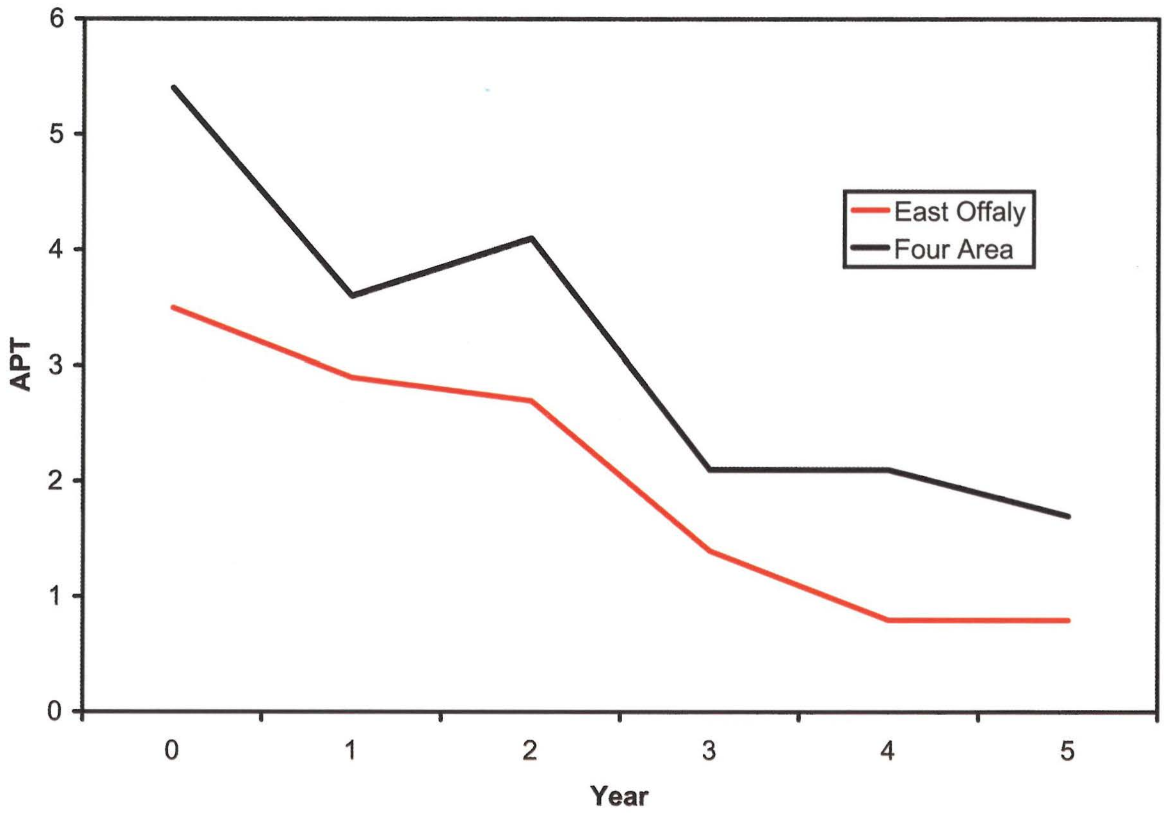
		Reference			Removal		
County	Restriction type	Pre-study period	Study period	Percent change	Pre-study period	Study period	Percent change
Cork	Confirmed	112	130	16%	158	66	-58%
	Major	62	68	10%	100	32	-68%
	Non-confirmed	41	59	44%	42	49	17%
	Number of herds	*278*	*282*		*300*	*294*	
Donegal	Confirmed	30	36	20%	73	14	-81%
	Major	14	14	0%	29	1	-97%
	Non-confirmed	28	46	64%	59	23	-61%
	Number of herds	*391*	*371*		*406*	*391*	
Kilkenny	Confirmed	82	100	22%	82	34	-59%
	Major	28	42	50%	49	9	-82%
	Non-confirmed	44	68	55%	55	56	2%
	Number of herds	*244*	*234*		*244*	*240*	
Monaghan	Confirmed	222	229	3%	224	108	-52%
	Major	88	110	25%	82	25	-70%
	Non-confirmed	123	73	-41%	108	61	-44%
	Number of herds	*568*	*583*		*713*	*720*	

**Note: Definitions of the restriction types are described in Section 4.1.2. Major restrictions are a sub-group of confirmed restrictions.*

Four-area results compared to the East Offaly study results

The number of reactors per 1,000 animal tests (APT) was used to measure tuberculosis levels in the East Offaly Study. The APT in the project area of the east Offaly study and in the removal areas of the four area study is shown in Figure 8. Although the studies were conducted in different areas under different time periods, the pattern of change in APT following badger removal is remarkably similar.

Figure 8 Comparison of the number of reactors per 1,000 tests (APT) in the removal areas of the East Offaly study and the Four Area study.



4.2.2 Modelling

4.2.2.1 Logistic Regression

Table 8 shows the number of herds at risk each year, and the proportion having a confirmed restriction. In the removal and reference areas of counties Cork, Kilkenny and Monaghan during the study period, there was a general decline in the percentage of herds with confirmed restrictions. Apart from 2001/02 in the reference area, there were few confirmed herd restrictions in the study areas of county Donegal. The observed prevalence of confirmed herd restrictions in the removal areas during the final year of the study ranged from 0.3% (Donegal) to 2.0% (Monaghan) compared with a range of 0.3% (Donegal) to 16.4% (Cork) in the year prior to study start. In contrast, in the reference areas the observed prevalence of confirmed restriction during the final year of the study ranged from 4.8% (Cork) to 7.8% (Kilkenny) compared with a range of 0.3% (Donegal) to 13.3% (Cork) in the year prior to study start (Table 8).

Table 8 Numbers of herds at risk and percentage with confirmed restrictions in each of the eight areas for the years 1992/93* through 2001/02*.

Year	Treatment	Cork		Donegal		Kilkenny		Monaghan	
		Total Herds	% Restricted	Total Herds	% Restricted	Total Herds	% Restricted	Total Herds	% Restricted
92/93	reference	265	3.4	369	2.2	215	7.0	533	9.8
	removal	290	9.3	392	3.1	215	4.2	658	7.6
93/94	reference	266	6.8	369	1.1	225	8.4	535	10.7
	removal	292	7.5	396	4.0	233	3.9	650	7.5
94/95	reference	270	9.6	374	1.1	231	6.5	538	8.9
	removal	294	10.2	394	7.6	232	7.3	653	7.5
95/96	reference	273	8.8	370	3.5	232	6.5	540	7.8
	removal	293	12.3	390	3.6	231	12.6	668	6.3
96/97	reference	270	13.3	362	0.3	232	8.2	545	5.5
	removal	292	16.4	379	0.3	229	9.2	680	5.3
97/98	reference	272	11.0	361	1.1	230	8.7	554	10.3
	removal	288	10.1	375	0.8	230	6.1	687	2.8
98/99	reference	271	16.6	349	1.4	222	12.6	565	11.0
	removal	285	7.7	375	1.6	230	1.7	701	4.6
99/00	reference	271	12.2	343	1.5	214	11.7	565	7.4
	removal	282	3.9	375	0.8	229	2.6	681	3.5
00/01	reference	274	4.4	334	1.2	213	5.6	559	6.8
	removal	270	0.7	370	0.3	225	2.7	661	3.6
01/02	reference	269	4.8	320	5.6	206	7.8	545	5.3
	removal	259	1.2	365	0.3	214	1.9	644	2.0

** Note that a year was defined as commencing on 1st September and ending on 31st August in the following year.*

There were a total of 3,242 missing values (9.9% of the total possible values), a consequence of herds not having any stock in the year in question. Of these, 3,048 occurred before the first or after the last herd record, so that 194 out of a possible 29,752 (0.65%) values were missing between the first and last record for a herd.

There was a significant CO x TR x YEAR (P <0.001) interaction indicating that the treatment effect varied by county and year. The interactions log(H) x CO x TR (P = 0.13), log(H) x CO (P = 0.32), log(H) x TR (P = 0.80) were insignificant, as were PH x CO x TR (P = 0.85), PH x CO (P = 0.35) and PH x TR (P = 0.43). No quadratic terms were required for log(H). Thus the effects of log(H) and PH were the same in all areas. These were significant (P < 0.001) with odds ratios (95% confidence limits) 1.25 (1.14, 1.37) corresponding to a doubling of herd size, and 1.38 (1.21, 1.57) for previous history over no previous history, respectively. The estimated correlation parameter from fitting a model containing an AR1 correlation structure was 0.003. Independent correlation structure gave very similar results in terms of the parameter estimates and standard errors.

The Hosmer and Lemeshow Goodness-of-Fit Test detected no lack of fit (P = 0.73). This test assumes an independence correlation structure but was considered appropriate in view of the similarity between estimates from this and a model with AR1 correlation structure. Pearson residuals were examined using both an index plot and a half-normal plot with simulated envelope (Collett, 2002). There were no indications that the model was inappropriate.

The AR1 model will be considered as the final model since it does account for the small correlation present in the data. This included the terms: CO x YEAR, CO x TR x YEAR, Log(H), PH.

The CO x TR x YEAR term (Table 9) compares removal and reference areas for all herd sizes and levels of PH. The parameterisation used means that a lower prevalence of restriction in the removal compared to the reference area corresponds to a negative term. During the 5 years of the study period, the odds ratios of prevalence of a confirmed restriction (from Table 9) were significantly less than 1 in at least 3 of the 5 years of the study period, the exception being Donegal where this was true of the last year. These results contrast with the pre-study period, where odds in reference areas were not significantly different from removal except in 2 years in Donegal and 1 year in Cork and Kilkenny, where the removal area had higher odds.

Table 9 **Estimates from the logistic GEE model, of the difference in the log odds and the odds ratio of a confirmed herd restriction in the removal area compared to the reference area for the counties Cork, Donegal, Kilkenny and Monaghan. Annual estimates during 1 September 1992 to 31 August 2002 are presented, and significant estimates (P <0.05) have been shaded. The constant effect of herd size (log(H)) and previous history (PH) are shown.**

Year	Cork				Donegal				Kilkenny				Monaghan			
	Estimate	S.E.	p-value	Odds ratio	Estimate	S.E.	p-value	Odds ratio	Estimate	S.E.	p-value	Odds ratio	Estimate	S.E.	p-value	Odds ratio
92/93	1.19	0.40	0.003	3.29	0.23	0.46	0.620	1.26	-0.38	0.44	0.389	0.69	-0.14	0.21	0.495	0.87
93/94	0.21	0.33	0.537	1.23	1.19	0.57	0.035	3.30	-0.66	0.42	0.117	0.52	-0.25	0.21	0.230	0.78
94/95	0.15	0.28	0.597	1.16	1.86	0.54	0.001	6.41	0.31	0.37	0.407	1.36	-0.04	0.21	0.870	0.97
95/96	0.44	0.28	0.114	1.56	-0.22	0.40	0.586	0.81	0.90	0.34	0.007	2.47	-0.08	0.23	0.738	0.93
96/97	0.34	0.24	0.157	1.41	-0.30	1.42	0.831	0.74	0.22	0.34	0.507	1.25	0.13	0.26	0.607	1.14
97/98	-0.03	0.28	0.914	0.97	-0.59	0.77	0.442	0.55	-0.28	0.37	0.445	0.75	-1.23	0.27	<0.001	0.29
98/99	-0.79	0.28	0.005	0.45	-0.14	0.61	0.820	0.87	-2.03	0.55	<0.001	0.13	-0.79	0.23	0.001	0.45
99/00	-1.16	0.36	0.001	0.32	-0.86	0.74	0.246	0.42	-1.44	0.47	0.002	0.24	-0.63	0.26	0.018	0.53
00/01	-1.77	0.77	0.022	0.17	-1.77	1.12	0.114	0.17	-0.61	0.51	0.232	0.54	-0.49	0.27	0.067	0.61
01/02	-1.40	0.65	0.031	0.25	-3.33	1.03	0.001	0.04	-1.35	0.57	0.017	0.26	-0.84	0.34	0.013	0.43
log(H)	0.58	0.03	<0.001	1.79												
PH	0.32	0.07	<0.001	1.38												

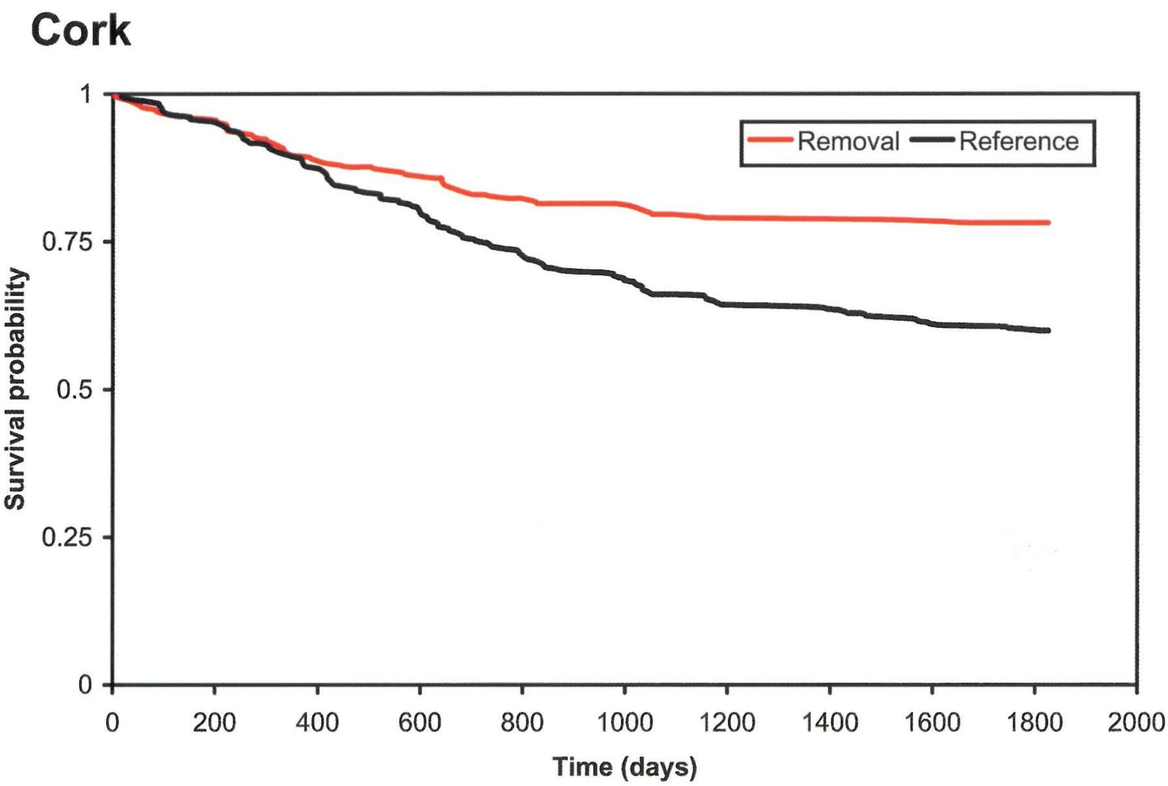
4.2.2.2 Survival Analysis

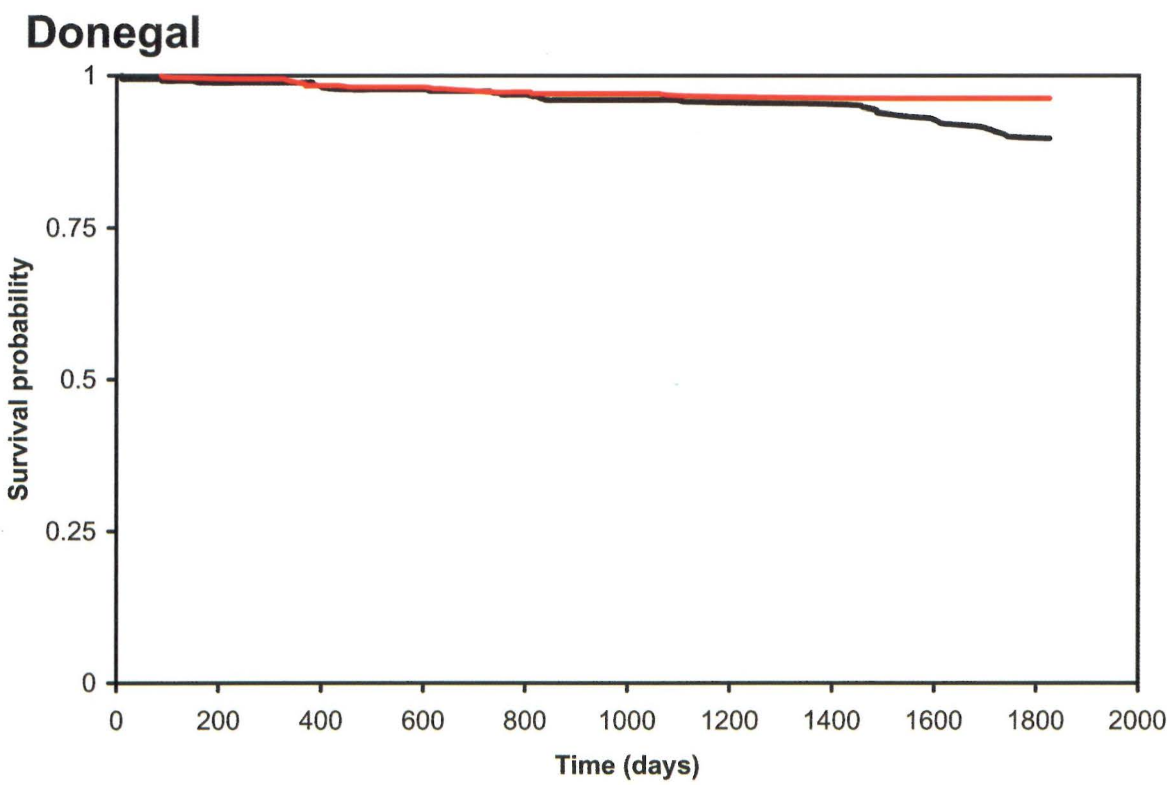
As an exploratory analysis, Figure 9 displays the Kaplan-Meier survival curves in each county for the removal and reference areas during the study period. Note these do not take herd size into account. In every county, there was a significant shortening of survival time ($P < 0.001$ using the Wilcoxon test) for the reference areas. Table 10 gives the estimates of the 5-year survival probability from these curves. In each removal area, the probability of surviving for 5 years without a confirmed restriction was higher than the corresponding reference area ($P < 0.001$ in all counties, Wald's test).

Table 10 Kaplan-Meier probability of surviving for 5 years without a confirmed restriction, by county and treatment, in the study period.

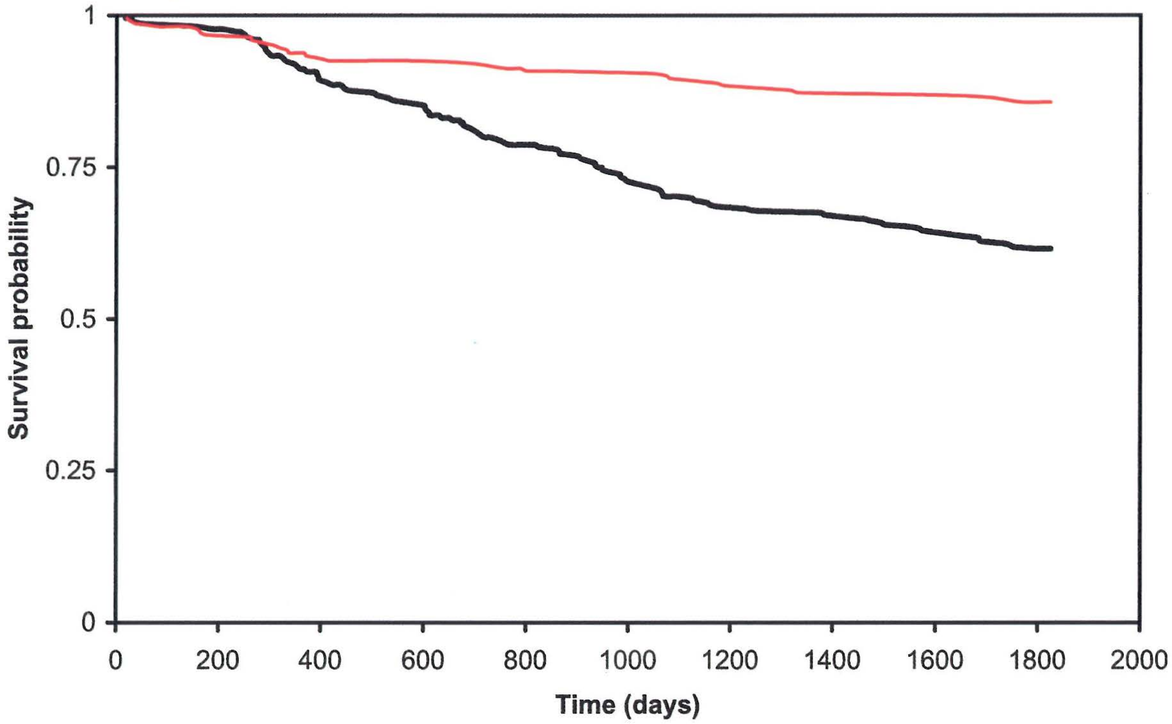
County	Reference area			Removal area		
	Survival probability	Standard error	No. in the risk set	Survival probability	Standard error	No. in the risk set
Cork	0.599	0.027	273	0.781	0.024	270
Donegal	0.897	0.016	331	0.963	0.010	370
Kilkenny	0.615	0.030	207	0.857	0.023	224
Monaghan	0.651	0.019	550	0.851	0.013	663
4 Areas	0.690	0.012	1360	0.865	0.008	1531

Figure 9 **Kaplan-Meier survival curves for each county during the study period.**

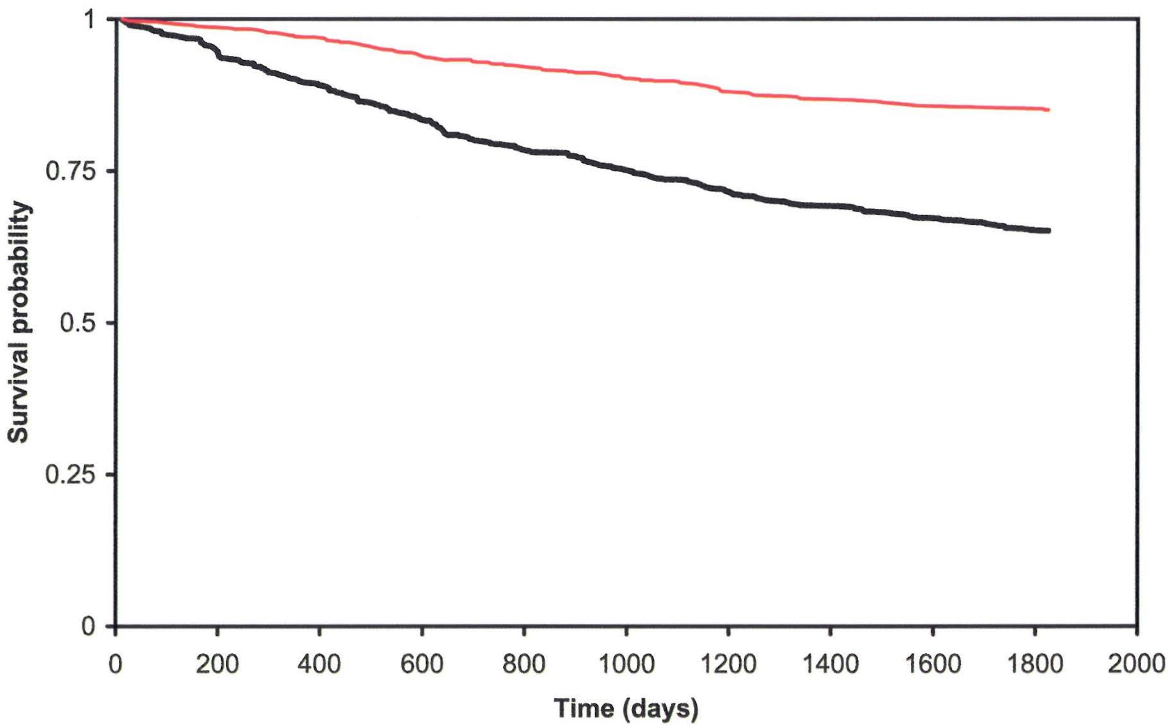




Kilkenny



Monaghan



The final Cox model contained the terms PH, log(H), TR, CO and the 2 and 3 way interactions between TR, CO and YEAR. The TR x CO x YEAR interaction was significant ($P < 0.001$); therefore, the effect of treatment varied over county and over year. The 2 and 3 way interactions between PH, CO and TR (PH x CO x TR $P = 0.86$, PH x CO $P = 0.24$, PH x TR $P = 0.96$) and log(H) with CO and TR (log(H) x CO x TR $P = 0.16$, log(H) x CO $P = 0.29$, log(H) x TR $P = 0.22$), were not significant. In addition, the interaction terms PH x CO x YEAR ($P = 0.19$), PH x TR x YEAR ($P = 0.87$) and PH x YEAR ($P = 0.16$) were not significant. The Wald and jackknife estimates of standard error did not differ correct to 2 decimal places, so Wald estimates were used as they reduced computational time by a third. Table 11 compares the removal and reference areas for each county and each year. For example, an estimate of 1.25 is the difference (removal - reference) in the log hazard function. Cork, Kilkenny and Monaghan all show significant effects of treatment during the study period, with hazard ratios < 1. Donegal shows a significant effect of treatment only in the final year of the study, although the hazard ratio is decreasing in the last 3 years. There were significant differences between removal and reference areas prior to the study period (with removal having a higher hazard) for 1 year in Cork and Kilkenny and 2 years in Donegal. In 1 year in Kilkenny the removal area had a significantly lower hazard. The effects of log(H) and PH were significant and positive ($P < 0.001$) (Table 11).

Table 11 **Estimates from the Cox model of the difference in the log hazard function, and the hazard ratio of a confirmed herd restriction in the removal area compared to the reference area in counties Cork, Donegal, Kilkenny and Monaghan. Annual estimates during 1 September 1992 to 31 August 2002 are presented, and significant estimates ($P < 0.05$) have been shaded. The constant effect of herd size (log(H)) and previous history (PH) are also shown.**

Year	Cork				Donegal				Kilkenny				Monaghan			
	Estimate	S.E.	p-value	Hazard ratio	Estimate	S.E.	p-value	Hazard ratio	Estimate	S.E.	p-value	Hazard ratio	Estimate	S.E.	p-value	Hazard ratio
92/93	1.25	0.40	0.002	3.48	0.13	0.46	0.768	1.14	-0.42	0.44	0.338	0.65	-0.05	0.21	0.809	0.95
93/94	0.23	0.31	0.448	1.26	1.17	0.56	0.035	3.23	-0.85	0.42	0.043	0.43	-0.14	0.20	0.487	0.87
94/95	0.05	0.28	0.852	1.05	1.72	0.53	0.001	5.56	0.31	0.37	0.409	1.36	-0.17	0.20	0.393	0.84
95/96	0.29	0.27	0.286	1.34	-0.23	0.39	0.550	0.79	0.75	0.32	0.020	2.12	0.00	0.22	0.985	1.00
96/97	0.35	0.22	0.119	1.41	-0.31	1.41	0.828	0.74	0.21	0.32	0.517	1.23	0.11	0.25	0.669	1.11
97/98	0.03	0.26	0.906	1.03	-0.59	0.76	0.438	0.55	-0.28	0.35	0.414	0.75	-1.20	0.27	<0.001	0.30
98/99	-0.75	0.27	0.005	0.47	-0.14	0.61	0.820	0.87	-1.90	0.54	<0.001	0.15	-0.82	0.22	<0.001	0.44
99/00	-1.04	0.35	0.003	0.35	-0.85	0.73	0.247	0.43	-1.44	0.45	0.002	0.24	-0.72	0.26	0.006	0.49
00/01	-1.83	0.76	0.016	0.16	-1.72	1.12	0.124	0.18	-0.59	0.51	0.247	0.56	-0.52	0.27	0.051	0.59
01/02	-1.40	0.64	0.029	0.25	-3.24	1.03	0.002	0.04	-1.34	0.56	0.017	0.26	-0.93	0.34	0.007	0.40
log(H)	0.52	0.03	<0.001	1.68												
PH	0.25	0.06	<0.001	1.29												

To summarise results, a Cox model was fitted with PERIOD replacing YEAR. The results are shown in Table 12. This reduced model contained the terms PH, log(H), TR, CO and the 2 way and 3 way interactions between TR, CO and PERIOD. Thus, the effect of treatment varied over counties and over period. The hazard ratios, removal over reference, in the study period ranged from 0.28 to 0.52 and were significantly less than 1 in every county. In the pre-study period, the hazard ratios, removal over reference, were significantly greater than 1 in Cork and Donegal, while not significant in Kilkenny and Monaghan.

Table 13 examines the difference between the pre-study and study period. In the reference areas, there was no significant change between the 2 periods for any county. In contrast, in the removal areas the hazard ratio in the study period compared to prior to the study was significantly less than 1 in every county, indicating that survival times for the removal area in every county were longer in the study period than before.

There was also a significant county effect ($P < 0.001$) in the reference areas, in the pre-study period and again in the study period, and in the removal areas in the pre-study period and again in the study period.

A plot of the martingale residuals *versus* the linear predictor was obtained for the Cox yearly model. The plot showed the usual distinction between censored and uncensored observations. There were no outliers. We note deviance residuals are only available for models with fixed covariates. Plots of the dfbeta residuals (influence residuals) for both PH and log(H) were examined. The influences were small, being no more than 1/15 of a standard error for PH and 1/9 of a standard error for log(H). Plots of the weighted Schoenfeld residuals *versus* the linear predictor, *versus* time and *versus* herd index were also examined and showed no evidence of model misspecification.

Table 12 **Estimates from the reduced Cox model of the difference in the log hazard function, and the hazard ratio of a confirmed herd restriction in the removal area compared to the reference area in counties Cork, Donegal, Kilkenny and Monaghan. The periods from 1 September 1992 to 31 August 1997 (pre-study period) and from 1 September 1997 to 31 August 2002 (study period) are presented, and significant estimates (P<0.05) have been shaded. The constant effect of herd size (log(H)) and previous history (PH) are also shown.**

Period	Cork				Donegal				Kilkenny				Monaghan			
	Estimate	S.E.	p-value	Hazard ratio	Estimate	S.E.	p-value	Hazard ratio	Estimate	S.E.	p-value	Hazard ratio	Estimate	S.E.	p-value	Hazard ratio
1992-1997	0.36	0.12	0.004	1.43	0.61	0.22	0.005	1.83	0.10	0.16	0.523	1.11	-0.07	0.10	0.480	0.93
1997-2002	-0.66	0.15	<0.001	0.52	-1.27	0.32	<0.001	0.28	-1.04	0.20	<0.001	0.35	-0.84	0.12	<0.001	0.43
log(H)	0.51	0.03	<0.001	1.67												
PH	0.25	0.06	<0.001	1.29												

Table 13 **Estimates from the reduced Cox model of the effect of period on the log hazard function, and the hazard ratio of a confirmed herd restriction in the study (1 September 1997 to 31 August 2002) compared to the pre-study (1 September 1992 to 31 August 1997) periods in the reference and removal areas of counties Cork, Donegal, Kilkenny and Monaghan. Significant estimates (P<0.05) have been shaded.**

Treatment	Cork				Donegal				Kilkenny				Monaghan			
	Estimate	S.E.	p-value	Hazard ratio	Estimate	S.E.	p-value	Hazard ratio	Estimate	S.E.	p-value	Hazard ratio	Estimate	S.E.	p-value	Hazard ratio
Reference	0.15	0.16	0.363	1.16	0.13	0.28	0.653	1.13	0.11	0.20	0.565	1.12	-0.15	0.16	0.363	0.86
Removal	-1.02	0.20	<0.001	0.36	-1.75	0.32	<0.001	0.17	-1.03	0.24	<0.001	0.36	-0.92	0.18	<0.001	0.40

5 Discussion

5.1 Study justification

The Irish bovine tuberculosis eradication programme began in 1954. Although there was initial programme success, with animal prevalence falling from 17% to 0.3% in 1965, progress has since stalled. Since 1965, the pattern of disease has remained remarkably stable, both in time and space, with herd prevalence at almost twice the national average in some counties. These findings are at odds with the British experience, where recently there has been a very substantial increase in herd incidence and geographic spread (DEFRA, 2004). During the period 1988 to 1992, and in addition to a comprehensive national disease eradication programme, the Irish government introduced, with limited success, a number of strategies to improve progress towards bovine tuberculosis eradication. On the basis of growing evidence of the role of wildlife in bovine tuberculosis in Ireland, the East Offaly project commenced in 1989 with the aim to critically evaluate the role of infected badgers as a source of tuberculosis on cattle farms in county Offaly. The current study, which has been conducted at four geographically-diverse sites throughout Ireland, is a logical extension of this earlier work.

5.2 Study design

Some concerns have been raised regarding the design of the East Offaly project (Ó'Máirtín et al., 1998b; Eves, 1999), including the opportunity (given the doughnut design) for continuing migration of badgers into the control area, and the need for greater geographical diversity. Although the former issue is of limited concern (noting that the inward migration of badgers will have had the effect of making it more difficult to detect a treatment effect, if one was present), each was addressed in the design of the current work. Where possible, the removal areas were bounded by natural geographic features (such as large rivers, mountain ranges and sea inlets) to limit inward migration of badgers during the study period. Because there are few sites in Ireland meeting this and each of the other selection criteria (higher-than-average disease prevalence, representative of the diverse Irish landscape), we elected to use purposive (that is, non-random) sampling to identify suitable removal areas and matched reference areas. In 3 of the 4 removal areas (all but Monaghan), immigration of badgers was minimised through effective geographic boundaries. Some limited immigration did continue during the study period, given the location of badger removals in the removal areas during the latter years of the programme, as well as the higher intensity of removal in the buffer as compared with the removal areas (Table 5). However, this was unavoidable due to the presence of road bridges across key rivers and badger movement across buffer areas. In the north east of the Monaghan removal area, the boundary was less-secure, being separated from Northern Ireland (where there was no official badger removal programme) by the narrow River Blackwater. As illustrated in Table 5, removal intensity during the last year of the study was higher in the Monaghan removal area than in the other counties. Regardless, the impact of limited immigration was minimal, due to the ongoing removal efforts throughout the study period. Any ongoing immigration of badgers (and associated herd breakdowns) in the removal areas will have had the effect, if any, of increasing the prevalence of bovine tuberculosis in each removal area, and thereby leading to an underestimation of the true effect of badger removal in this study.

Further, during each of the 5 years prior to study start in Monaghan, and in at least 3 of the 5 years prior to study start in Cork, Donegal and Kilkenny, there was no significant difference in the probability of, or time to, a confirmed restriction in the matched removal and reference areas (Tables 9 and 11). This was despite some reduction of the badger populations, particularly in the removal areas of counties Monaghan and Kilkenny, during the 12 months from mid 1995 to mid 1996 (2 year's prior to study start). During most years when there was an observed difference in the rate of herd restriction, the time to a confirmed restriction in each situation was significantly greater in the removal as compared with the matched reference area (Table 12). Therefore, if there were any residual differences between these matched study areas, they would have reduced the probability of detecting any treatment effect, if present. In each county, there was no significant difference in the probability of, or time to, a confirmed restriction between the matched areas during the full year (1 September 1996 to 31 August 1997) prior to study start (Tables 9 and 11).

The current study is based on an assessment of 2 different levels of badger removal on the prevalence of tuberculosis in cattle in Ireland. In the removal areas, badger removal is proactive (that is, the badgers were removed independent of and prior to any outbreak of bovine tuberculosis). Further, we sought to achieve as complete a removal as possible, and to sustain this throughout the study period. Although restraints do not effectively capture young badgers, this would not have adversely affected removal effectiveness, due to the ongoing efforts to remove adult badgers from each removal area. In contrast, badger removal in the reference areas was conducted reactively, in response to severe outbreaks of tuberculosis in cattle herds where the source could reasonably be attributed to badgers. In order to minimise capture intensity in these areas, the criteria for badger removal were more stringent than that routinely used throughout Ireland; in the reference areas, badgers were only removed if there were 4 or more standard reactors and badgers could be implicated, whereas throughout the rest of the Republic of Ireland (apart from the removal and buffer areas in this study) badgers were removed if there were 2 or more standard reactors and badgers could be implicated. Therefore, the badger population in the reference areas was less disturbed than throughout most of the rest of the Republic of Ireland. To illustrate further, during the first 2 years of the study period the intensity of badger removal in the reference area was equivalent to 0.07 badgers removed/km^2/year. In comparison and during the same period, the intensity of badger removal in the removal areas was 0.57 badgers/km^2/year (Table 5).

There are several reasons why we elected to utilise a reactive, rather than a no-removal, control. Reactive removal represented official government policy at the time. Therefore, use of a reactive, rather than no-removal, control is in keeping with standard scientific practice, where the comparison group should generally represent existing standard practice (Dohoo et al., 2003). Further, because it was contrary to official government policy and popular views about this disease, the use of a non-removal control may have encouraged the illegal removal of some badgers within the reference area. This latter problem, and the opposing effect of interference to removal, were extremely rare.

In order to minimise measurement bias, the matched removal and reference areas in each county were supervised by the same field people within the same administrative unit. In addition, the project was coordinated nationally, and all work was conducted in accordance with nationally-agreed protocols (for field and laboratory work). As part of national coordination, regular meetings were held among field staff from each of the project areas.

5.3 Study findings

5.3.1 Co-operation from farmers

The study attracted very high levels of farmer cooperation in all areas throughout the full study period. Although participation was entirely voluntary, refusal to provide permission to survey (a single 19 ha. holding in county Cork) and to capture following the sett survey (13 setts in 3 counties) was extremely rare. At least in part, this result reflects the dedication of field staff who liaised closely with all farmers throughout the study period. Further, ongoing reactive badger culling in the reference areas (in response to breakdowns, but where the criteria of intervention was considerably more-stringent than the national policy) was critical to ongoing farmer cooperation.

5.3.2 Badger population

5.3.2.1 Size of the badger population

The results from this study indicate that the overall size of the badger population in Ireland may be less than the estimate of 200,000 adult badgers provided in an earlier national survey, carried out between 1989 and 1993 Smal (1995). In the national survey, 729 1 km squares (1% of the land area) were surveyed to obtain an estimate of the overall density of active main setts in use. Population size was then estimated, based on the assumptions that the number of badger social groups was equivalent to the number of main setts, and that the average social group size was 5.9 adults. Based on these assumptions, we would expect 549 distinct social groups in the removal and buffer areas and an estimated badger population of 3,239 adults. However this is considerably higher than the number (2,360) of badgers that were actually captured in these areas during the study. Because it is reasonable to assume (certainly in counties Cork, Kilkenny and Monaghan where the removal area boundaries were not entirely secure) that many of the later captures were immigrant badgers, the number captured during the first two years of the study (1,580) may be a more accurate estimate of the size of the native population at the start of the study. Smal's estimate of social group size was very similar to reports from the UK (Cresswell et al., 1990; Wilson et al., 1997) and from East Offaly (O'Corry-Crowe et al., 1993), but at odds with studies from Northern Ireland (Feore and Montgomery, 1999), where average group sizes as low as 3.0 were reported. In order to reconcile these differences further studies are currently underway to investigate the size of the badger population in Ireland.

5.3.2.2 County differences

The observed badger density varied between counties, as estimated from the number of active main setts and the intensity of badger removal during the first year of the study. Some variation is inevitable, given county differences in terms of habitat composition. For example, pasture accounts for 89% of the total land area in county Cork, 73% in Monaghan, 71% in Kilkenny and 37% in Donegal (Hammond, 1997). However, other factors are clearly important, in view of the fact that the density of active main setts was higher in the removal and buffer areas of Donegal (0.45 setts per km^2; Table 3) than in the equivalent areas of Monaghan (0.38) and Kilkenny (0.37). In addition, the number of badgers removed from the Donegal study in the first year of the study period was $0.89/km^2$ compared to 0.75 and 0.58 for Kilkenny and Monaghan, respectively. In this case, badger density was partly influenced by removal history. In Kilkenny and Monaghan, there were official programmes of badger removal during the 3-4 years immediately prior to study start. In contrast, there was very little badger capture after August 1992 in Donegal.

The varying badger capture rates are also a reflection of varying levels of boundary security between counties. In the removal areas of Donegal, 69.0% of all badger removals occurred during the first year of the study (Table 5), whereas the equivalent capture percentage in counties Cork, Kilkenny and Monaghan was 52.3%, 46.1% and 39.7%, respectively. In Donegal, the removal area was sited on the Fanad peninsula, and opportunities for immigration were limited to movement through the 11 km^2 buffer area to the south and south-west. In contrast, the northern boundary in the removal area of county Monaghan was less-secure. On the eastern side, it was mainly formed by the river Blackwater which could be crossed by the undisturbed badger population (of Northern Ireland) at various points. On the western side, most of the boundary consisted of bogland and moorland. While this was not ideal badger habitat, some setts were found in this area and some badger immigration from Northern Ireland may also have occurred.

5.3.2.3 Distribution of tuberculosis amongst the badger population

In this study, the prevalence of tuberculosis in badgers (19.5% in the removal areas and 26.1% in the reference areas) was considerably higher than estimates from a range of previous Irish studies, including the East Offaly study (12% in the removal area (Ó'Máirtín et al., 1998b), routine examination of animals removed under licence (annual prevalence ranging from 12.2 to 13.3%; (O'Boyle, 1999, 2000, 2002; O'Boyle et al., 2003) and a study of road casualty accidents (11.6%; (O'Boyle et al., 2003). Although this increase appears dramatic, it is more likely a reflection of improved diagnostic methods rather than any change in actual disease prevalence (Costello et al., 1998). Several trends in disease prevalence are of particular interest. Tuberculosis prevalence was higher in the reference as compared to the removal areas, which may reflect the selective way in which badgers were removed in these areas. Equally the reducing rate in the removal areas may reflect changes in disease transmission in a declining population. Further, there were significant county differences in disease prevalence, with levels being highest in the Cork removal area (29%) and lowest in Kilkenny (12%). Again, disease prevalence may have been influenced by population density, noting that there had been an intensive programme of badger removal in the two years prior to study start in counties Kilkenny and Monaghan. However, there is currently little understanding of the spatial distribution of tuberculosis in badgers in Ireland; a better understanding of this may help to explain the differences that were observed.

5.3.3 Cattle population

During the study period, there was a significant difference between the removal and reference areas in both the probability of and the time to a confirmed herd restriction due to tuberculosis. To illustrate, in the final year of the study the odds of a herd restriction in the removal area in Cork was 0.25 (95% C.I. 0.07-0.88) that observed in the associated reference area. In Donegal the odds of a breakdown in the removal area was only 0.04 (0.00-0.27) that in the reference area. In Kilkenny the figure was 0.26 (0.08-0.79) and in Monaghan 0.43 (0.22-0.84) (Table 9). Further, the estimated probability of surviving 5 years without a confirmed restriction was between 7% (Donegal) and 24% (Kilkenny) higher in the removal over the reference area (Table 10). In the final year of the study, the hazard ratios (removal over reference) ranged from 0.40 to 0.04 or less (Table 11), that is, a 60 to 96 percentage decrease in the rate at which herds were becoming the subject of a confirmed restriction. These effects are consistent across all 4 counties, which is remarkable given known differences between each of these 4 areas. These differences include the varying levels of badger disturbance prior to study start (minimal in counties Cork and Donegal but recent in counties Kilkenny and Monaghan), varying levels of herd restriction in the pre-study period and the diverse farming environments and likely badger densities.

Additional information about the effect of treatment can be gleaned on the basis of description alone. Based on confirmed restriction rates, the level of bovine tuberculosis was lower in every year of the study period in the removal as compared to the corresponding reference areas (Figures 6 and 7). A comparison of the CRR in the removal area during the last year of the study with the weighted average annual CRR in this area throughout the study period indicated that the effect of treatment also appeared to increase over time (Figure 7), an outcome that was in agreement with results from the East Offaly study (Figure 8). In addition, the tuberculosis levels in cattle herds in each removal area were considerably lower in the study period than during the pre-study period.

The treatment effect in Donegal was consistent with, but somewhat smaller than, that observed in each of the other counties (Figures 6 and 7). To illustrate, in both the removal and reference areas, the percentage surviving 5 years in the study period was 90% and over. Further, there were very few confirmed restrictions in either area in the 6 years 96/97 through 01/02, with the exception of 18 restrictions in the reference area in 01/02. Low levels had been achieved in the 2 areas in the county prior to removal, and these persisted apart from this exception. Although Donegal is geographically-suited to a study of this type (being divided by a range of natural barriers, including peninsulas and mountains), bovine tuberculosis in this county prior to 1995 was more common on the Fanad peninsula (where the removal area was subsequently located) than elsewhere. Therefore, it is unsurprising that a treatment effect would be more difficult to detect in Donegal than in other counties. Despite this constraint, Griffin et al. (in press) detected a range of significant differences relating to the hazard ratio of a confirmed herd restriction in Donegal which were consistent with a positive treatment effect and with the broad study results in each of the other counties. There were significant differences between the reference and removal areas during the study period (with the risk being higher in the reference area), and in the removal area during the pre-study and study periods (with the risk being higher during the pre-study period). Further, there was no significant difference in the reference area during the pre-study and study periods. Although, there was also a significant difference between the reference and removal areas during the pre-study period, the risk was higher in the removal area (thereby making it harder to find an effect, if present).

In addition to the above-mentioned effect on breakdown frequency, there also appears to be a relationship between breakdown intensity and badger removal (Table 7). To illustrate, when comparing the pre-study and study periods, the relative reduction in major confirmed restrictions was consistently greater than the reduction in all confirmed restrictions across all four counties. For example, there was a 59 and 82% reduction in confirmed and major confirmed restrictions, respectively, in Kilkenny between the pre-study and study periods. This finding is consistent with anecdotal field evidence, and has previously been noted with respect to the East Offaly project (Eves, 1999). However, these are descriptive results and take no account of potential confounding by other variables; consequently, they should be interpreted with care.

Levels of disease in the reference areas need to be considered in some detail. Although there were fluctuations in disease incidence in the reference areas (Figure 7), there was no statistical difference in disease levels during the pre-study and study periods (Table 13). These findings have implications both in terms of the validity of the study (specifically whether the reference area was a valid control on which to evaluate any treatment effect; this is discussed later) and for the broader national programme. In terms of the latter, based on the results from the East Offaly and four area projects, Ireland is now seeking to achieve sustainable control of the disease in cattle in the medium term, pending the development of long-term strategies for disease control in badgers. The longer-term strategies are discussed later. In the medium-term, it is in the national interest to identify the minimal intensity of control that will be needed to sustainably maintain low levels of disease in cattle. This study adds to current understanding in this area. Although there was no statistical change in disease incidence in any of the reference areas, there was an increase in CRR in all counties during 1998/99, except Donegal (Figure 7). This finding may be spurious, given that it was coincident with increases in SPT and CRR throughout Ireland (Figure 6 and Table 6). Certainly and as discussed later, we can rule out any plausible biological link between reactive badger removal and the observed increase, in contrast to UK reports (Donnelly et al., 2003). As an alternative explanation this finding might suggest that the control of tuberculosis in the reference areas during the study period was slightly lower than optimal. It is important to emphasise that control intensity was lower in the reference areas (where the national control programme was applied, but the threshold for reactive badger removal was higher) than in all other areas not involved in the study. Logically and in agreement with the current downward trend in national disease incidence in cattle, the intensity of the current national programme (incorporating the current thresholds for reactive badger removal) may be close to optimal, in the medium term.

5.4 Statistical issues

We have used several different indices in the measurement of tuberculosis in cattle herds. In Ireland, the APT (the reactor disclosure rate per 1,000 animal tests) has been used for some years as the main measure of programme progress (Collins and Hammond, 2003). While convenient to measure, it does not differentiate surveillance and control, nor is it independent of the intensity of testing. As a herd-level measure, the CRR overcomes these concerns, and has been used here as our primary measure of breakdown frequency. Although of lesser importance in the current argument, we have used the SPT as a means of reflecting breakdown size. The SPT was preferred to the APT, given the above-mentioned concerns regarding testing frequency. Further, we have focused on standard (using the SPT) rather than all (using the APT) reactors, thereby minimising the misclassification of positive reactors.

The significant effect of county in modelling has reflected the clustered nature of the data. In this situation it is common to consider a random effect (McDermott et al., 1997). However, in this study the purpose-led selection of the 4 removal areas and the matching reference areas would not justify this approach. It would be unsafe to assume the county effect for the selected areas behaved like randomly selected areas from geographical areas in Ireland. In such situations, it is recommended that a fixed effect factor should be used (McCullogh and Searle, 2000, section 1.6). Schukken (2003) cites a similar example involving bovine herpes virus 1 data where 3 areas were selected purposively, and states that the use of random effects is not appropriate. Moreover, because there were only 4 areas, the estimation of variation at this level is questionable and can be unstable (Schukken et al., 2003). In addition, the purpose of the present study was to determine if there were circumstances in Ireland under which levels of herd restriction changed following badger removal. Results from individual areas are therefore important in suggesting where removal might be beneficial, and of conditions in Ireland or elsewhere where the control of *M. bovis* in badgers should be considered.

Logistic regression and survival analyses were both conducted to obtain estimates of odds and hazard ratios. These estimates were similar, showing consistency of results from these 2 analyses (Tables 9 and 11). This is to be expected (Allison, 1995, page 233; Therneau and Grambsch, 2000, page 185).

Although time to infection is preferred over time to restriction, the former data are not known in a field-based control programme. We elected to limit our analyses to confirmed (as opposed to all) restrictions to minimise the probability of false positives. For the logistic analysis, the prevalence (rather than incidence, as in the survival analysis) of confirmed restriction was used to avoid missing values. Incidence values were missing, and would not have occurred at random, for all herds that were restricted at the start of any year, and remain restricted for a further 12 months. Also, giving a confirmed restriction status to the herd acknowledged the ongoing presence of risk factors contributing to the continued restriction.

A range of factors are known to increase the risk of a herd breakdown, including the bovine tuberculosis history of the area of the country, herd size, and the past tuberculosis history of the herd (Olea-Popelka, 2002). In this study, we controlled for the first factor by using APT as a matching criterion during the selection of the removal and reference areas in each county, and the latter factors were controlled during analysis. In keeping with previous findings (Griffin et al., 1996; Ó'Máirtín et al., 1998b; O'Sullivan and O'Keeffe, 1998; Olea-Popelka, 2002), in this study increasing risks (both in terms of the probability of and time to a confirmed herd restriction) were associated with increasing herd size and with a history of a previous confirmed breakdown. Note that the relationship between breakdown risk and herd size is not entirely biological. When evaluating the status of herds based on imperfect tests applied to individual animals, there is an increased likelihood of at least 1 test-positive result in a disease-free herd as herd size increases (Martin et al., 1992).

5.5 Study validity

In a recent paper, Donnelly et al. anticipated the findings of the current study (Donnelly et al., 2003). These authors report an apparent increase in incidence of tuberculosis in cattle following reactive culling in the UK, and speculate that this effect may be associated with disruption of the social organisation of badgers leading, ultimately, to increased transmission of tuberculosis from badgers to cattle. Relevant to the current study, Donnelly et al. suggest that a similar effect may result in an over-estimate of the true effectiveness of widespread proactive culling. However, in our study, there is no evidence in support of such an effect. Firstly, although there was an initial increase in the average CRR in the first three years of the study, the average CRR was lower in the last two years of the study compared to the pre-study period in three of the four counties (Figure 6). In addition, after accounting for confounders, there was no statistically significant difference in the time to a confirmed restriction when comparing the pre-study and study period in the reference areas (Table 13). Secondly, throughout the study period the intensity of badger removal in the reference areas was very low. During the first 2 years of the study (when most badger removals occurred), removal intensity was 0.07 badgers/km^2/year, which equates with an annual average of 17.3 badgers per county or 1 removal per 14.5 km^2. It would seem improbable for there to be a biological association between bovine tuberculosis and badger removal at this level of removal intensity. Finally, it would be implausible for there to be a causal link between badger removal and bovine tuberculosis unless these events were lagged in time, sufficient to enable a defined chain of biological events to occur. These events would include disruption in badger social organisation leading (in a manner currently undefined) to increased transmission of tuberculosis among badgers, contact between cattle and the disturbed badger population leading to cattle exposure, the establishment of infection in cattle, the development of responsiveness to tuberculin following establishment of infection, the holding of the annual herd test (in the Republic of Ireland, each 12 months but at a time nominated by each farmer), the inspection of reactor animals at slaughter and laboratory confirmation of disease. Similar comments have been made elsewhere (Godfray et al., 2004). In our study, there was no evidence of a lagged temporal association between badger removal and confirmed restrictions in cattle in the reference area.

The study sites were not chosen randomly, for reasons given previously. Rather, we used a number of criteria during the selection of the study areas, including areas with recurrent problems of tuberculosis in cattle, sites that were suitable for the establishment of 'secure' removal areas, and areas that were reflective of the diverse farming environments found in Ireland. Consequently, the results from this study must be generalised with care. In Ireland, bovine tuberculosis is a clustered problem; to illustrate, 69% and 64% of standard reactors during 1998-2000 occurred in 32% and 28% of the agricultural land in the north and south of the Republic of Ireland, respectively (O'Keeffe et al., 2002). It would seem reasonable, given the absolute size of the study areas (covering 1,961 km^2 and representing 3.9% of the agricultural land area in the Republic of Ireland), the diversity of farming environments represented in this study and the general consistency of the key study results in each of the 4 areas, that these results can be generalised to other 'problem' areas of Ireland. These results may also be generalised, with care, to other regions after considering differences in farming systems and badger ecology, such as population densities and preferential sett location.

6 Conclusions

It is critical that this study is considered within a clearly-defined context. The Irish control programme is comprehensive, incorporating each of the accepted elements of disease control, including mandatory annual tuberculin testing of all animals in the national herd and early, ongoing removal of infected animals. It has long been suspected that a source of the bovine tubercle bacillus other than infected cattle is involved, given the lack of national progress towards eradication despite these efforts. These suspicions have now been confirmed, with the results from the four area (and earlier East Offaly) study clearly highlighting wildlife (and specifically transmission of infection from badgers to cattle) as a key constraint to disease eradication in Ireland. These findings are of national importance and provide compelling evidence of the linkage between proactive badger removal and tuberculosis in Irish cattle. Note that this linkage (and the consequent impact of proactive badger removal) would not have been as evident if the national control programme were less effective. As a direct consequence of these efforts, cattle-to-cattle transmission has become relatively less important in the epidemiology of bovine tuberculosis in Ireland. To illustrate, if cattle-to-cattle transmission were still common, differences in disease incidence between the removal and reference areas would not have been as marked. In the future, it is critical that Ireland initiate medium and long-term measures to minimise transmission from badgers, whilst maintaining existing measures (with additional enhancements, as appropriate) to control cattle-to-cattle transmission. Ongoing cooperation between government and industry will also be essential. The relative importance of cattle-to-cattle and wildlife-to-cattle transmission will depend on a range of circumstances, including the standard of animal husbandry, aspects of national disease control and badger ecology. Therefore, the results should be extrapolated to other regions with care.

In order to eradicate tuberculosis from the Irish cattle population, Ireland will need to sustainably control tuberculosis in badgers, with which cattle may come in contact (Gormley and Collins, 2000). However, this presents significant challenges for scientists and policy-makers (Gormley and Costello, 2003), including the international legal protection, and national status, afforded to badgers; the potential for increases in badger numbers, as a consequence of agricultural intensification and increase in productive pastures; the close physical proximity of badgers and cattle, given the preference of badgers in Ireland to locate setts in hedgerows (Hammond et al., 2001); and the high prevalence of disease among the Irish badger population (L. Corner, personal communication). Ireland is currently implementing a comprehensive strategy to address these challenges. In the short-term, the Department of Agriculture and Food is implementing a national programme for wildlife control when and where wildlife are implicated in on-farm breakdowns of bovine tuberculosis (O'Keeffe et al., 2002). These activities will be focused in areas of high disease prevalence. In these areas, badger removal will form the basis of temporary disease control (by minimising contact between cattle and infected badgers), and will also provide potential locations for vaccination trials and (later) usage (O'Keeffe et al., 2002). In the longer-term, Ireland is committed to the development of an effective badger vaccine and the implementation of a strategic programme of badger vaccination, with the aim to reduce *M. bovis* transmission between infected badgers and susceptible cattle (Gormley and Costello, 2003). The feasibility of such an approach was first considered in 1994, with input from scientists from both the Republic of Ireland and Northern Ireland (Ellis et al., 1994). Current work is focusing on the use of a live vaccine based on *M. bovis* BCG (Leigh Corner, personal communication), which might persist in the host and continuously prime the protective cellular immune response (Gormley and Costello, 2003). Results from early experimental studies have been promising (Leigh Corner, personal communication).

7 References

Allison, P.D., 1995. Survival Analysis Using the SAS® System: A Practical Guide, Cary, NC: SAS Institute Inc.

Boos, D., 1992. On Generalised Score Tests. The Am. Stat. 46, pp. 327-333.

Cheeseman, C.L., Wilesmith, J.W., Stuart, F.A., 1989. Tuberculosis: the disease and its epidemiology in the badger, a review. Epidemiol. Infect. 103, pp. 113-125.

Coleman, J.D., 1988. Distribution, prevalence and epidemiology of bovine tuberculosis in brushtail possums, *Trichosurus vulpecula*, in the Hohonu range, New Zealand. Aust. Wildl. Res. 15, pp. 651-663.

Collett, D., 1994. Modelling Survival Data in Medical Research. Chapman and Hall, London.

Collett, D., 2002. Modelling Binary Data. Second Edition. Chapman and Hall, London.

Collins, J.D., 2001. Tuberculosis in cattle: new perspectives. Tuberculosis (Edinb) 81, pp. 17-21.

Collins, J.D., Hammond, R.F. 2003. Selected papers 2002-2003. Veterinary Epidemiology and Tuberculosis Investigation Unit, University College Dublin, Dublin.

Cook, B.R., 1975. Tuberculosis in possums - Buller and Inangahua Counties. Animal Health Division Special Report, Ministry of Agriculture and Fisheries, Wellington, New Zealand, p. 13.

Costello, E., O'Grady, D., Flynn, O., O'Brien, R., Rogers, M., Quigley, F., Egan, J., Griffin, J., 1999. Study of restriction fragment length polymorphism analysis and spoligotyping for epidemiological investigation of *Mycobacterium bovis* infection. J. Clin. Microbiol. 37, pp. 3217-3222.

Costello, E., Quigley, F., O'Grady, D., Flynn, O., Gogarty, A., McGuirk, J., O'Rourke, J., Griffin, J., 1998. Laboratory examination of tissues from badgers and cattle from the four-area study for evidence of tuberculosis, In: Selected Papers 1997. Tuberculosis Investigation Unit, University College Dublin, Dublin, pp. 32-36.

Cresswell, P., Harris, S., Jefferies, D.J., 1990. The history, distribution, status and habitat requirements of the badger in Britain. Nature Conservancy Council, Peterborough.

DAF, 2003. Department of Agriculture and Food, Handbook: For the Veterinary Management of Herds Under Restriction due to Tuberculosis. DAFF, Ireland, p. 37.

DAFF, 1996. Department of Agriculture Food and Forestry, Badger manual. DAFF, Ireland.

DEFRA, 2004. Preparing for a new GB strategy on bovine tuberculosis: Consultation document. Defra Publications, London.

Dohoo, I., Martin, W., Stryhn, H., 2003. Veterinary Epidemiologic Research. AVC Inc., Charlottetown, PEI, Canada.

Donnelly, C.A., Woodroffe, R., Cox, D.R., Bourne, J., Gettinby, G., Le Fevre, A.M., McInerney, J.P., Morrison, W.I., 2003. Impact of localized badger culling on tuberculosis incidence in British cattle. Nature 426, pp. 834-837.

Downey, L., 1990. Ireland's TB problem - What can and must be achieved. ICOS with the support of the Agricultural Trust.

Downey, L., 1992. Bovine TB Programme. Review of ERAD Measures - Technical Audit. Eradication of Animal Disease Board, Dublin.

Ellis, W., Collins, J.D., Feore, M., Neill, S., Sheridan, M., Sleeman, D., Hughes, S., Rogers, M. 1994. The feasibility of developing a vaccine against tuberculosis for use in the badger *(Meles meles)* (Department of Agriculture, Food and Forestry (Republic of Ireland) and Department of Agriculture for Northern Ireland), p. 52.

Eves, J.A., 1993. The East Offaly Badger Research project: An Interim Report. The Badger. Proceedings of the Royal Irish Academy, Dublin, pp. 166-173.

Eves, J.A., 1999. Impact of badger removal on bovine tuberculosis in east County Offaly. Irish Vet. J. 52, pp. 199-203.

Feore, S., Montgomery, W.I., 1999. Habitat effects on the spatial ecology of the European badger (Meles meles). Journal of Zoology 247, pp. 537-549.

Godfray, C.J., Curnow, R.N., Dye, C., Pfeiffer, D., Sutherland, W.J., Woolhouse, M.E.J. 2004. Independent scientific review of the randomised badger culling trial and associated epidemiological research. Report to Mr Ben Bradshaw MP, 4 March 2004 (York, Central Science Laboratory).

Gormley, E., Collins, J.D., 2000. The development of wildlife control strategies for eradication of tuberculosis in cattle in Ireland. Tubercle and lung diseases 80, pp. 229-236.

Gormley, E., Costello, E., 2003. Tuberculosis and badgers: new approaches to diagnosis and control. J. Appl. Microbiol. 94, pp. 80S-86S.

Griffin, J.M., Martin, S.W., Thorburn, M.A., Eves, J.A., Hammond, R.F., 1996. A case control study on the association of selected risk factors with the occurrence of bovine tuberculosis in the Republic of Ireland. Prev. Vet. Med. 27, pp. 75-87.

Griffin, J.M., Williams, D.H., Kelly, G.E., Clegg, T.A., O'Boyle, I., Collins, J.D., More, S.J., in press. The impact of badger removal on the control of tuberculosis in cattle herds in Ireland. Prev. Vet. Med. In press.

Hammond, R.F., 1997. Variables used to characterise the four areas badger survey removal/reference areas. Tuberculosis Investigation Unit, Selected Papers 1996, University College Dublin., pp. 12-18.

Hammond, R.F., McGrath, G., Martin, S.W., 2001. Irish soil and land-use classifications as predictors of numbers of badgers and badger setts. Prev. Vet. Med. 51, pp. 137-148.

Hansard (House of Commons Daily Debates) 2004. Written answers to questions. In Environment, Food and Rural Affairs, United Kingdom Parliament (London, http://www.publications.parliament.uk/pa/cm200304/cmhansrd/vo040122/text/40122w01.htm).

Hickling, G.J., Pfeiffer, D.U., Morris, R.S., 1991. An analysis of the Epidemiology of *Mycobacterium bovis* infection in Australian brushtailed possums *(Trichosurus vulpeculas kerr)* in the Hauhungaroa Ranges, New Zealand. (Forest Research Contract Report FWE 91/25), Forest and Wildland Ecosystems Division, Forest Research Institute, Christchurch, New Zealand, p. 30.

Julian, A.F., 1981. Tuberculosis in possum *Trichosurus vulpecula.*, In: Bell, B.D. (Ed.) Proc. First symposium on Marsupials in New Zealand, (Zoology Publication No. 74), Victoria University, Wellington. pp. 163-174.

Krebs, J.R., 1997. Bovine Tuberculosis in Cattle and Badgers. Ministry of Agriculture, Fisheries and Food, London, UK, p. 191.

Martin, S.W., Shoukri, M., Thorburn, M.A., 1992. Evaluating the status of herds based on tests applied to individuals. Prev. Vet. Med. 14, pp. 33-43.

McCullogh, C.E., Searle, S.R., 2000. Generalized, Linear and Mixed Models. John Wiley and Sons Inc., New York.

McDermott, J.J., Kadohira, M., O'Callaghan, C.J., Shoukri, M.M., 1997. A comparison of different models for assessing variations in the sero-prevalence of infectious bovine rhinotracheitis by farm, area and district in Kenya. Prev. Vet. Med. 32, pp. 219-234.

Noonan, N.L., Sheane, W.D., Harper, L.R., Ryan, P.J., 1975. Wildlife as a possible reservoir of bovine TB. Irish Vet. J. 29, p. 1.

O'Boyle, I., 1999. Review of Badger *(Meles meles)* research licenses in 1998, In: Selected Papers 1998. Tuberculois Investigation Unit, University College Dublin, Dublin, pp. 10-14.

O'Boyle, I., 2000. Review of Badger *(Meles meles)* research licenses in 1999, In: Selected Papers 1999. Tuberculosis Investigation Unit, University College Dublin, Dublin, pp. 15-21.

O'Boyle, I., 2002. Review of Badger *(Meles meles)* research licenses in 2000 and 2001, In: Selected Papers 2000-2001. Veterinary Epidemiology and Tuberculosis Investigation Unit, University College Dublin, Dublin, pp. 19-25.

O'Boyle, I., Costello, E., Power, E.P., Kelleher, P.F., Bradley, J., Redahan, E., Quigley, F., Fogarty, U., Higgins, I., 2003. Review of Badger *(Meles meles)* research licenses in 2002, In: Selected Papers 2002-2003. Veterinary Epidemiology and Tuberculosis Investigation Unit, University College Dublin, Dublin, pp. 13-18.

O'Corry-Crowe, G., Eves, J.A., Hayden, T.J., 1993. Sett distribution, territory size and population density of badgers *(Meles meles L.)* in east Offaly., In: Hayden, T.J. (Ed.) The badger. Royal Irish Academy, Dublin, pp. 35-56.

O'Keeffe, J.J., Hammond, R.F., McGrath, G., 2002. Density maps highlight areas with chronic bovine tuberculosis and enable targeting of resources to eradicate disease, In: Selected Papers 2000-2001. Veterinary Epidemiology and Tuberculosis Investigation Unit, University College Dublin, Dublin, pp. 41-44.

Olea-Popelka, F.J., 2002. Studies on bovine tuberculosis in cattle and badgers in Ireland. Master of Science. The University of Guelph, Guelph.

Ó'Máirtín, D., Williams, D.H., Dolan, L., Eves, J.A., Collins, J.D., 1998a. The influence of selected herd factors and a badger-intervention tuberculosis-control programme on the risk of a herd-level trade restriction to a bovine population in Ireland. Prev. Vet. Med. 35, pp. 79-90.

Ó'Máirtín, D., Williams, D.H., Griffin, J.M., L., D., Eves, J.A., 1998b. The effect of a badger removal programme on the incidence of tuberculosis in an Irish cattle population. Prev. Vet. Med. 34, pp. 47-56.

O'Sullivan, M.C., O'Keeffe, J.J., 1998. Bovine tuberculosis: statistical modelling of single animal breakdowns, In: Selected Papers 1997. Tuberculosis Investigation Unit, University College Dublin, Dublin, pp. 43-49.

SAS Institute Inc. 1999. SAS OnlineDoc®, Version 8. Cary, NC: SAS Institute Inc.

Schukken, Y.H., Grohn, Y.T., McDermott, B., McDermott, J.J., 2003. Analysis of correlated discrete observations: background, examples and solutions. Prev. Vet. Med. 59, pp. 223-240.

Smal, C., 1995. The Badger and Habitat Survey of Ireland. Stationary Office, Dublin.

Therneau, T., Grambsch, P., 2000. Modelling Survival Data. Springer, New York.

Thornton, P., 1988. Density and distribution of badgers in south-west England - a predictive model. Mammal Review 18, pp. 11-24.

Wilson, G.S., Harris, S., McLaren, G., 1997. Changes in the British badger population 1988 to 1997. Peoples Trust for Endangered Species, London.

Centre for Veterinary Epidemiology and Risk Analysis
Faculty of Veterinary Medicine
University College Dublin

ISBN: 1-902277-97-X

Copi-Print Library Building UCD