Monitoring the efficacy of badger population reduction by controlled shooting during the first six weeks of the pilots

Report to Defra

AHVLA
Animal Health and Veterinary Laboratories Agency

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1. Introduction

1.1. As set out in Defra's policy statement published in December 2011[1], the Government's policy is to allow controlled culling and vaccination of badgers in areas of high incidence of bovine TB in cattle in a carefully regulated way for the purpose of controlling the spread of the disease. The requirements of the policy are set out in Defra's Guidance to Natural England: "Licences to kill or take badgers for the purpose of preventing the spread of bovine TB under section 10(2)(a) of the Protection of Badgers Act 1992" (Defra publication PB13692).

1.2. The Guidance sets out that in the first year of culling, a minimum number of badgers must be removed during an intensive cull which must be carried out throughout the land to which there is access, over a period of not more than six consecutive weeks. This minimum number should be set at a level that in Natural England's judgement should reduce the estimated badger population of the application area by at least 70% (para 10(c)(i) and (ii) of the Guidance).

1.3. The guidance also sets out that Natural England should aim to ensure that culling will "not be detrimental to the survival of the population concerned" within the meaning of Article 9 of the Bern Convention on the Conservation of European Wildlife and Natural Habitats. For that purpose Natural England should determine appropriate area-specific licence conditions, and set a maximum number of badgers to be removed from the licence area (para 12 of the Guidance).

1.4. Two pilot areas in southwest England were selected to test whether industry-lead badger culling, licensed in accordance with this policy, could be undertaken effectively, humanely and safely. During the summer of 2013 licensed badger culling operations were implemented in these areas.

1.5. Defra commissioned a programme of independent monitoring in order to estimate the proportion of the badger population from within the outer boundary of each pilot area that was removed by industry-led culling operations. A major challenge that this presented was identifying a monitoring method that was robust to interference, while offering estimates with a high degree of accuracy (see Donnelly and Woodroffe, 2012). High accuracy is required so that it can be confidently concluded whether industry-led culling removed 70% of the population, significantly more than 70% or significantly less.

1.6. Here we present the results of independent monitoring of the efficacy of badger removal during the first six weeks of the pilots. The underlying assumption of the primary analysis was that the proportion of badgers individually identified prior to culling that were subsequently observed in the cull returns provided an unbiased and relatively precise estimate of the proportion of the pilot area population that had been culled. This method of quantifying cull efficacy was agreed with the Independent Expert Panel.

1.7. A separate analysis requested by the Independent Expert Panel followed a more traditional capture-mark-recapture approach to provide an estimate of the population prior to the cull against which to compare the number of badgers reported culled. We analysed the frequency

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[1] https://www.gov.uk/government/uploads/system/uploads/attachment_data/file/69463/pb13691-bovinetb-policy-statement.pdf

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with which individual badgers were hair trapped in order to estimate the size of the population immediately before culling. This was compared with the number of badgers culled to estimate the proportion of the population removed by culling. It was expected *a priori* that this approach would produce estimates with greater confidence intervals.

2. Methods

2.1. We aimed to sample as many badgers as possible in 50 1km x 1km cells selected at random from a grid covering approximately 300km^2 in each of the two pilot areas. This aimed to provide a representative sample, covering 17% of cells and 12% of the population, assuming an even distribution and 70% trapping/sampling efficiency.

2.2. We deployed hair traps (short lengths of barbed wire suspended between two short stakes or trees) at all active setts and along badger runs associated with setts and adjacent to non-participating land, following the procedures described by Frantz *et al*. (2004). Hair samples were removed from all barbs daily for 18 days and each sample was stored in a uniquely coded plastic ziplock bag containing a sachet of desiccant. Following sample collection, hair traps were de-contaminated by flaming with a cigarette lighter. DNA from the bulb of a randomly-selected single guard hair from each hair trap was amplified and sequenced to provide a unique genetic finger print for each badger. DNA was extracted from hairs using a suspension of chelex resin (Frantz et al. 2004). The purified DNA was genotyped using 10 loci (Dawnay et al. 2008) on an Applied Biosystems *3130xl* Genetic Analyzer. Repeat samples from individuals were identified on the basis of all 10 loci matching (probability of identity approximately 1 in 100,000 based on observed allele frequencies).

2.3. If a profile including all 10 loci was not isolated from a hair, a further guard hair from the same sample was sequenced. In circumstances where no guard hairs were present within a sample all under-fur was pooled from the sample and these were amplified and sequenced. This allowed assessment of whether the sample constituted a single individual or multiple individuals. Only samples from single individuals were used in the estimates of efficacy. By sampling in this way across the 50 1km x 1km squares in each pilot we built a list of individual profiles to constitute the 'marked' population.

2.4. Tissue samples (ear tips) removed from every culled and retrieved badger were submitted by industry contractors in sealed tubes containing 5ml of ethanol for DNA profiling.

2.5. Profiles of culled badgers were matched to profiles of the 'marked' population to estimate culling efficacy as the proportion of the marked population that was identified in the cull in each pilot area (cull sample matching – see Appendix 1 for details of the analysis).

2.6. Profiles were also used to identify the frequency with which each hair-trapped badger was sampled in order to estimate pre-cull population size using a capture-mark-recapture approach (see Appendix 1 for details on how the impact of incomplete genetic profiles was addressed and Appendix 3 for details of the main analysis and results). The number of badgers culled, identified from the unique profiles submitted for genetic analysis, was compared with this population estimate in order to estimate the proportion of the population culled.

3. Results

3.1. All ranges quoted in this section are 95% confidence intervals.

3.2. From cull sample matching (the primary method) we estimate that the cull in Gloucestershire removed between 27.5 and 39.1% of the population by both cage trapping and shooting (Table 3.1). This is not consistent with removal of at least 70% of the population.

3.3. The number removed by shooting was 543 and was 165 by cage trapping, giving an estimated shooting efficacy of 25.3 to 37.1% from cull sample matching and 16.7 to 39.0% from capture-mark-recapture.

3.4. Dividing the number of badgers culled in Gloucestershire by the proportion estimated to be culled by cull sample matching (Table 3.1) gives a pre-cull population estimate for Gloucestershire of 1811 to 2575.

3.5. The Gloucestershire population estimate based on the capture-mark-recapture analysis and a survey of setts in 2012 was between 1394 and 3242 badgers immediately before the cull (Appendix 3). Removal of 708 badgers (Table 3.1) from this population estimate results in an estimated removal of 21.8% to 50.8%.

3.6. From cull sample matching we estimate that the cull in Somerset removed between 34.5 and 48.1% of the population by both cage trapping and shooting (Table 3.1). This is not consistent with removal of at least 70% of the population.

3.7. The number reported to be removed by shooting was 398 and was 467 by cage trapping, giving an estimated shooting efficacy of 14.6 to 24.8% from cull sample matching and 20.9 to 46.8% from capture-mark-recapture.

3.8. Dividing the number of badgers culled in Somerset by the estimated proportion culled (Table 3.1) gives a pre-cull population estimate for Somerset of 1802 to 2512 with 95% confidence.

3.9. The Somerset population estimate based on the capture-mark-recapture analysis and a survey of setts in 2012 was between 850 and 1905 immediately before the cull (Appendix 3). Removal of 866 badgers (Table 3.1) from this population estimate results in an estimated removal of 45.5% to 101.9%.

3.10. The robustness of the efficacy estimates can be assessed from whether the assumptions on which they were based were met or violated (Table 3.2).

Table 3.1. Summary of survey effort, culling effort and measurements contributing to the cull sample matching estimates of efficacy for each pilot area.

	West Gloucestershire	West Somerset
Number of 1km by 1km grid squares with hair traps (number of original, randomly-selected survey squares in parenthesis)	71 (40)	78 (46)
Number of setts hair trapped	93	130
Number of hair traps at setts	408	444
Number of hair traps away from setts	114	137
Total number of hair samples (counted as one per hair trap per night)	615	801
Number of unique hair profiles	233	216
Contractor effort (number of contractor-shifts combined for cage trapping and shooting)	1063 over 34 nights	1243 over 41 nights
Number of badgers reported culled	708	865
Number reported shot with rifles (and shotguns)	543 (0)	387 (11)
Number reported cage trapped	165	467
Number of ear tip samples received	710	875*
Number of unique ear tag-genetic profile combinations from ear tips	708	868
Number of matches among ear tips (one match = a pair of matching ear tips)	0	2
Number of badgers identified from ear tips	708	866
Number of ear tips matching hair profiles	80	87
Number of matches shot with rifles (and shotguns)	67 (0)	42 (0)
Number of matches cage trapped	13	45
Estimated Cull efficacy (proportion of population removed by cull using both methods; 95% confidence interval)	0.275 to 0.391	0.345 to 0.481

*Five samples were sent in duplicate. Two samples were from road-killed badgers and were subsequently removed from all analyses.

Notes: 1) Cull efficacy cannot be estimated by dividing the number of ear tips matching hair profiles by the number of unique hair profiles because these figures are not corrected for false negatives or population churn (Appendix 1, 5.2 to 5.15 and 5.26). 2) The numbers of badgers that we conclude were culled is taken from the number of badgers identified from ear tips and not the number reported culled because we have stronger evidence for the former (*i.e.* an ear tip sample).

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Table 3.2. Assumptions underpinning estimates of efficacy

Assumption	Evidence
Up to 10% of the population (including marked animals) within 3km of the outer boundary of the pilot area move out of the area and are replaced by badgers moving in.	Rogers *et al*. (1998) found that up to 10% of badgers moved from their social group in Woodchester Park, and moved up to 3km away. Therefore, simulating up to 10% replacement is very conservative (10% is worst case). This adds uncertainty to the efficacy estimates.
Equality in the probability of being culled between individual hair-trapped and non-hair trapped badgers.	The proportions of the marked population that was taken by cage trapping and by shooting were much the same as for the un-marked population. This equivalence between marked and un-marked badgers for two different techniques is consistent with the assumption. Failure to meet this assumption would lead to bias.
Receipt of a genetic sample from every badger culled.	All badgers in the cull data base were represented by at least one sample received by the laboratory. Badgers culled prior to hair trapping or from elsewhere would have no effect on the efficacy estimates. Failure to submit genetically marked badgers would bias the efficacy estimates low.
The hair trapped sample population was representative of the wider population within each area.	Hair trapped badgers were a random sample from a random sample of selected locations. A non-random sample could lead to biased estimates.
Culling operations were not spatially correlated (positively or negatively) with hair traps.	Currently no evidence. This needs further exploration since this association could bias results.
The additional effect of spatial variation in culling efficacy was small relative to other sources of variation.	The mean of proportions of the marked population returned per sample square and the total proportion returned are approximately equivalent (Appendix 2). Differences may mean that our confidence intervals were too tight.

4. Discussion

4.1. The culling of badgers is a highly sensitive issue, which tends to polarize opinions. We anticipated that activities employed to provide evidence to evaluate Government policy on badger population control would experience interference. Consequently we developed a rapid, robust approach to estimate the proportion of the badger population that was removed by industry-lead culling operations in each of the two pilot areas. We aimed to sample badgers in 50 1km x 1km cells selected from a grid covering approximately 300km^2 in each of the two pilot

areas. This aimed to provide a representative sample, covering 17% of cells and 12% of the population, assuming an even distribution and 70% trapping/sampling efficiency.

4.2. The primary method of efficacy estimation (cull sample matching) required far fewer assumptions and data manipulations to produce estimates of cull efficacy and population size than did the secondary method (capture-mark-recapture). Nevertheless, both estimates relied on reliable reporting of the number of animals culled (including provision of samples from all culled badgers) and several other assumptions.

4.3. Sampling of badgers prior to the start of culling was from within and around 1km squares that were randomly selected from all those lying wholly within the outer boundary of each pilot area. From the number of unique genetic profiles collected by hair sampling, we might have sampled somewhere between 8 and 13% of the population in pilot areas at least once. It is reasonable to assume that the samples constitute a representative sample of the population.

4.4. The key assumption affecting the accuracy of the primary efficacy estimates is that there was no spatial association between culling operations and our hair traps. If contractors had invested more effort at hair trapped sites, our primary efficacy estimates would be biased high. If contractors invested less effort at hair trapped sites, our estimates would be biased low. Anecdotal reports were seen on protestor websites indicating that they did focus nocturnal activities at setts, but we do not have access to information on which setts received attention from activists nor when such activities occurred. To assess whether interference or any other influence on culling activities impacted our efficacy estimates we would need spatially precise data on each contractor's activities over time in order to test for correspondence with our hair trapping. The Independent Expert Panel may wish to consider whether this or an alternative analysis is possible and required to assess whether this and other assumptions were met.

4.5. Analysis of the proportions of marked badgers returned from each survey square indicated that variation in returns per square contributed very little additional uncertainty to the efficacy estimates over-and-above that associated with other sources of uncertainty, such as sample sizes, genetic sample mis-match rates, and replacement of genetically marked badgers with un-marked badgers. Therefore, it is likely that the confidence limits of our estimates are appropriate (*i.e*. have good coverage; Appendix 2).

4.6. In the Gloucestershire pilot area a total of 708 badgers were removed during the first six weeks of culling, with an estimated cull efficacy of 27.5 to 39.1% from cull sample matching and 21.8 to 50.8% from capture-mark-recapture analysis. The number removed by shooting was 543 and was 165 by cage trapping, giving an estimated shooting efficacy of 25.3 to 37.1% from cull sample matching and 16.7 to 39.0% from capture-mark-recapture analysis. The minimum cull target for Gloucestershire was 2856 from an estimated population of 2656 to 4080 badgers (Anon. 2013a).

4.7. In the Somerset pilot area a total of 866 badgers were removed during the first six weeks of culling, with an estimated cull efficacy of 34.5 to 48.1% from cull sample matching and 45.5 to 101.9% from capture-mark-recapture analysis. The number reported to be removed by shooting was 398 and was 467 by cage trapping, giving an estimated shooting efficacy of 14.6 to 24.8% from cull sample matching and 20.9 to 46.8% from capture-mark-recapture analysis. The

minimum cull target for Somerset was 2081 from an estimated population of 1972 to 2973 badgers (Anon. 2013a).

4.8. Confidence intervals produced using the primary method were tighter than those commonly produced when estimating the size of wildlife populations at similar scales to the pilot areas (see for example Parrott *et al*. 2012). This is in part due to the large sample sizes provided by the cull (approximately 27 to 48% of the population was in the final sample). Confidence intervals produced using the secondary method were consistent with the width of those commonly produced when estimating the size of wildlife populations at similar scales to the pilot areas (see for example Parrott *et al*. 2012). However, since the lower confidence limit of the secondary population estimate for Somerset was lower than the number culled, it is now clear that at least that confidence limit is not credible.

4.9. Investigation of the dispersion of efficacy estimates between survey squares from the primary method indicated that spatial variation added little uncertainty to the primary efficacy estimates (Appendix 2).

4.10. From the results presented above we conclude that industry-lead controlled shooting of badgers during a six-week period did not remove at least 70% of the population inside either pilot area. In both areas significantly fewer than 70% were removed by controlled shooting. The combined approach of controlled shooting and cage trapping also did not remove at least 70% of the population inside either pilot area; substantially fewer than 70% were removed in both areas.

5. Appendix 1. Statistical analysis to estimate the efficacy of culling in the pilot areas from cull sample matching.

Principle of the efficacy estimation

5.1 DNA profiles were taken from hair samples to form a database of individual profiles. The proportion of these samples that are present in the DNA profiles from badger carcasses submitted by contractors gives an estimate of the proportion of the population culled.

5.2 This method offers high accuracy because it is much less susceptible to biases caused by interference or falsified returns than are methods of estimating cull efficacy from population estimates, and offers high precision, in part due to the due to the large sample sizes provided by the cull (over 70% of the population may be in the final sample if the target is achieved).

False negatives (failures to match)

5.3 A 'false negative' would occur if hair from an individual was trapped and profiled, but when that badger was subsequently culled its genetic profile did not produce a match with its hair-trap profile on the database. Frantz et al (2006) produced 749 profiles without such problems. Hence, the false negative prior to the study the probability was estimated to be low because of the high quality of profiles from ear samples. If this is incorrect, estimates of the efficacy of badger removal may be lower than the true efficacy.

5.4 However, failure to match within hair samples is also an issue for efficacy because it leads to an overestimation of the population size, and if not corrected, an underestimation of the cull efficacy.

5.5 The algorithm for matching DNA profiles is designed to provide a low false positive rate (approximately 10^{-5}) based on allele frequencies in the sample of hairs and ears. That is a match is detected where the probability of observing two samples from within a population with the allele frequencies observed in the sample of hairs and ears is less than 1 in 100,000. Because the false positive rate is fixed, the effect of lower quality (incomplete) DNA profiles tends to be expressed as false negatives rather than false positives.

5.6 Ear genetic profiles are, in general, of good quality (complete) since they contain much good quality genetic material. These maintain low false negative probabilities for matching while giving the fixed low false positive probability for matches against ears.

5.7 It is assumed that the set of hair profiles with a matching ear profile is a random sample from the population of hair profiles. The false negative rate for matching DNA profiles among hairs is estimated by examining hair profiles that are found to match ear profiles. The false negative rate is estimated as the number of matches that should be made between hair profiles that matched ears, but which do not match each other, and the number of observed matches between hairs.

5.8 The number of missing matches among hairs that are used to estimate population size is estimated from the negative binomial distribution with size equal to the observed number of matches and probability equal to the probability of detecting a match. The effect of missing these matches is accounted for in the estimate by adding the estimated missing number of matches at random to the observed matches.

5.9 Matches are counted in one direction only from the first hair profile in a sequence of matches. This reflects the method for generating matches whereby profiles are sequentially checked against a database once.

5.10   The effect of missed matches on efficacy (and the value of the factor to correct for the effect) is estimate from the binomial proportion of the number of individuals as counted by ears against the number of individuals as counted by distinct profiles. The factor reduces the estimated number of marked badgers.

5.11   **Example**

A DNA database of 21 hair samples produces the following matches (Table 5.1).

Table 5.1 Example of a database of DNA matches between hair samples.

					Matches
HAIR1	HAIR2	HAIR3	HAIR4	HAIR5	4
HAIR6	HAIR7	HAIR8			2
HAIR9	HAIR10	HAIR11			2
HAIR12	HAIR13				1
HAIR14	HAIR15				1
HAIR16					0
HAIR17					0
HAIR18					0
HAIR19					0
HAIR20					0
HAIR21					0
				total	**10**

Including ear profiles gives

These hair samples match 9 ear samples as follows (Table 5.2).

Table 5.2 Example of a DNA database of hair samples matching ear samples.

						Matches
EAR1	HAIR1	HAIR2	HAIR3	HAIR4	HAIR5	4
EAR2	HAIR6	HAIR7	HAIR8			2
EAR3	HAIR9	HAIR10	HAIR11			2
EAR3	HAIR12	HAIR13				1
EAR4	HAIR14	HAIR15				1
EAR5	HAIR16					0
EAR6	HAIR17					0
EAR7	HAIR18					0
EAR8	HAIR19					0
EAR9	HAIR20					0
EAR6	HAIR21					0
					total	**10**

(2 missing matches, 1 missing matches + 1 missing between rows)

1 missing match between rows

Here we can see that some hair samples (e.g. HAIR9,10,11 and HAIR12,13) match the same ear sample (EAR3), but do not match each other. Hence, a table of matches among hair profiles corrected by the more reliable ear profiles gives the following (Table 5.3).

Table 5.3 Example of a DNA database matching

EAR1	HAIR1	HAIR2	HAIR3	HAIR4	HAIR5
EAR2	HAIR6	HAIR7	HAIR8		
EAR3	HAIR9	HAIR10	HAIR11	HAIR12	HAIR13
EAR4	HAIR14	HAIR15			
EAR5	HAIR16				
EAR6	HAIR17	HAIR21			
EAR7	HAIR18				
EAR8	HAIR19				
EAR9	HAIR20				

5.12   The probability of detecting a match among hair profiles is estimated by the binomial proportion 10/15.

5.13   The factor to convert from the number of marked individuals based on distinct hair profiles to the true number of marked individuals is estimated by the binomial proportion 9/11.

5.14   The population of badgers in setts from which hairs are sampled is estimated by applying the TIRM model to observations of captures (see Appendix 3). Here, 22 individuals (based on matching profiles caught between 1 and 7 times; Table 5.4):

Table 5.4 Example of hair profiles captured over seven capture events.

HAIR1	HAIR2	HAIR3	HAIR4	HAIR5	HAIR6	HAIR7
HAIR8	HAIR9	HAIR10	HAIR11	HAIR12		
HAIR13	HAIR14	HAIR15	HAIR16	HAIR17		
HAIR18	HAIR19	HAIR20	HAIR21			
HAIR22	HAIR23	HAIR24				
HAIR25	HAIR26	HAIR27				
HAIR28	HAIR29					
HAIR30	HAIR31					
HAIR32	HAIR33					
HAIR34	HAIR35					
HAIR36	HAIR37					
HAIR38	HAIR39					
HAIR40	HAIR41					
HAIR42						
HAIR43						
HAIR44						
HAIR45						
HAIR46						
HAIR47						
HAIR48						
HAIR49						
HAIR50						
captures	1	2	3	4	5	6	7
individuals	9	7	2	1	2	0	1

5.15   Here the central estimate for the population is 31 individuals. The effect of missing matches is estimated, in this example, by producing a single Monte Carlo estimate of the number of individuals.

5.16   **Monte Carlo estimate**

Number of observed matches = 28

Probability of detecting matches (random sample from binomial 10/15) = 0.91

Number of missing matches (random sample from N.B. 28, 0.91) = 2

Missing matches are between the following pairs of individuals (selected at random, identified by first HAIR ID): missing match 1 HAIR42 − HAIR38

Re-estimated capture profile Table 5):

Table 5.5 Example of a re-estimated capture profile following correction for failures to match.

captures	1	2	3	4	5	6	7
individuals	8	7	3	1	3	0	1

Here the central estimate for the population remains 31 individuals.

False positives (mis-matches)

5.17   A false positive would occur if the genetic profile from a returned carcass produced a match in the database even though no hair from that individual had been trapped initially. Frantz et al. (2004) reported a 1% probability of *siblings* being identified as a single individual in Luxemburg badgers using DNA profiles from hair trap samples. Franz et al. (2004) noted that Luxemburg badgers may be less genetically diverse than British badgers. Dawnay et al. (2008) reported an 'average probability of identity' of 2.18×10^{-7} (1 in 4.6 million) estimated using ear-snip and blood DNA from British badgers.

Effect of false positives (mis-matches) on efficacy estimates

5.18   False positives could inflate the value of the estimated efficacy, but were corrected for using the estimated mis-match rate. Given a population N_p badgers of which N_m are in the database and N_n are not; cull efficacy p_t; and a mis-match probability p_f, (Figure 5.1):

Figure 5.1: Expected numbers of observed matched and not-matched culled badgers
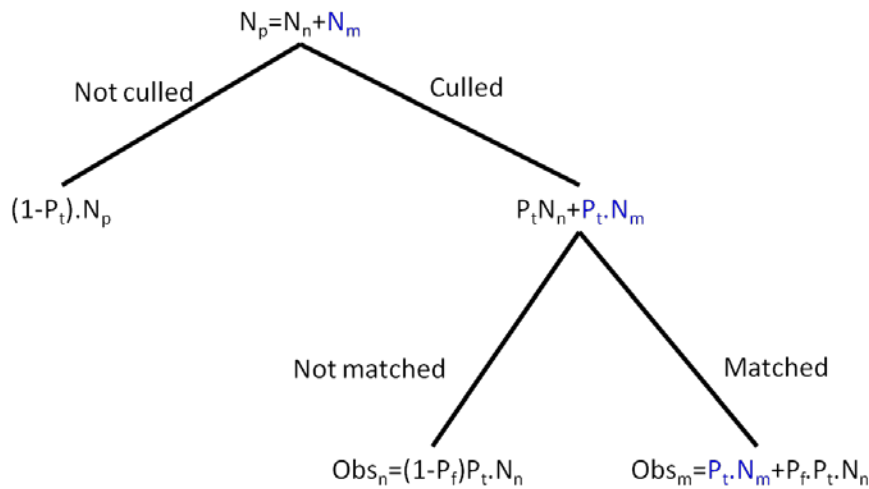
then the estimated cull efficacy Obs_{pt} is given by

$$Obs_{p_t} = \frac{Obs_m - \dfrac{p_f . Obs_n}{1 - p_f}}{N_m}$$

<div align="right">Equation 1</div>

5.19   Where Obs_m is the observed number of culled badgers in the database and Obs_n is the observed number of culled badgers not in the database.

5.20   The value of p_f depends on the probability of identity p_i, and the number of samples in the data base n_d

$$p_f = 1 - (1 - p_i)^{n_d}$$

<div align="right">Equation 2</div>

Estimating limits for the number of mis-matches during the pilot cull

5.21   The expected number of mis-matches between the culled badgers and the database, and its uncertainty, were estimated from the observed number of matches within the samples from culled badgers, all of which must be mis- matches. This removed the need to extrapolate a mis-match rate from other studies.

5.22   Given N_c culled badgers, and a probability of identity p_i, then the expected proportion p_0 of $N_c - 1$ culled badgers that do not match with any other culled badgers is:

$$p_0 = \frac{N_0}{N_c - 1} = \sum_{j=1}^{j=N_c-1} \frac{(1 - p_i)^j}{N_c - 1}$$

<div align="right">Equation 3</div>

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5.23   If p_0=1 (no culled badgers match any other culled badgers), then with 95% confidence the probability of a culled badger not matching any other culled badger is at least (Brown et al. 2001).

$$L_{p0} = 0.05^{1/(N_c - 1)}$$

Equation 4

5.24   And for other observations a 95% confidence interval for the probability that a badger matches no other culled badgers is given by the 2.5[th] and 97.5[th] quantiles of the $beta(N_0 + 0.5, N_c - 1 - N_0 + 0.5)$ distribution (Brown et al. 2002).

5.25   Hence, lower and upper limits for the probability of identity for badgers in the pilot cull that are consistent with the observed mis-match rate in culled badgers can be estimated by finding values of p_i that satisfy Equation 3 for upper and lower limits for p_0.

5.26   For example if 840 badgers are culled with no matches between them, then the best estimate for p_0 is 1 with a lower value of 0.99644 with 95% confidence (Equation 4). If 351 badgers are matched to a database containing 500 unique badger profiles then:

- the probability of identity p_i for badgers in the pilot cull would be estimated to lie between zero and 8.51×10^{-6} (Equation 3);
- the false match probability would be estimated to lie between zero and 0.00424 (Equation 2). Hence the number of observed matches is reduced by applying this factor to the number of observations

Estimating the proportion of marked badgers that may leave the cull are and be replaced by another badger

5.27   A third factor that may affect the estimation of efficacy is the replacement of marked badgers by unmarked badgers (population churn). Formally, this has the same effect as overestimating the number of marked badgers in the population. Hence it is treated in the same way as the effect of false negative matches on the number of marked badgers: as a factor that reduces the effective number of marked badgers. The value of this factor is not easy to determine precisely. However, its lower limit is zero and its upper limit is estimated to be equal to the approximate rate at which badgers from different social groups have been found in 'home' social groups (10%, Rogers *et al*. 1998) and the number of hair traps at setts within 3km of the boundary as a proportion of all hair traps at setts. This is a conservative estimate of this quantity. The probability of exchange is treated as a uniform distribution from zero to the estimate (10% of animals sampled at hair traps within 3km of the outer boundary).

Estimating efficacy

5.28   The proportion of badgers removed is estimated by the proportion of marked badgers returned after correction by the estimated false positive and false negative matching rate, and also a correction for population churn. This is implemented as a second order Monte Carlo estimate with the following structure:

Estimate a distribution for the false negative probability FN from the mismatch between ears and the number of distinct hair profiles

Estimate a distribution for the false positive probability FP

Estimate a distribution for the probability of exchange (population churn) FE

Select independent random quantiles from each of the distributions for the proportions FN, FP, FE

> Select independent random values from binomial distributions as realisations of the effect of FN, FP,FE on the number of marked badgers n and the number of returned badgers x (eFP, eFN.FE).
>
> Fit a beta-binomial distribution to the 'observed' proportion (x- eFP)/(n-eFN.FE) for each square to estimate the mean of the proportions in each of the squares and the effect of between-square variation in the proportion returned.
>
> Estimate the proportion returned from the pilot area as a random quantile from the binomial proportion (x- eFP)/(n-eFN.FE)
>
> Repeat estimates to provide a range of estimates for the proportion returned.

Estimate a 95% confidence interval for the proportion returned from the 2.5[th] and 97.5[th] percentiles of Monte Carlo estimates.

6. Appendix 2. Observations of the proportions returned from each survey square

The primary measure of efficacy is the proportion of badgers returned in the cull. This is estimated by the proportion of previously DNA-profiled (synonymous with 'marked') badgers returned in the cull (Appendix 1)

We also present the estimated proportion returned from each square (often with considerable uncertainty) and the mean of these proportions. The uncertainty associated with this mean of proportions and its alignment with the primary measure of efficacy gives an indication of the effect of between-location variation on the primary efficacy estimate. Here we report the observations used to make these estimates.

Estimates of the average of proportions returned from each square and the estimate of the total proportion returned across the entire area were very similar (Glos P = 0.55; Soms P = 0.38) and the dispersion associated with estimates was similar in both areas (Table 6.2 and 6.4, Fig 6.1 and 6.2). From this we conclude that variation in returns between squares does not add much uncertainty over-and-above that associated with the sample size and other sources of uncertainty such as false positive rate, false negative rate and uncertainty about population churn.

This observation only applies to those squares that we hair trapped, and cannot be extrapolated to the whole pilot area.

Table 6.1 The number of badgers marked and returned by square in Somerset. 'Both methods' is the number of badgers culled in that square using controlled shooting and cage trapping. 'Shooting' is the number of badgers culled for controlled shooting only. 'Interference' indicates a square in which we detected protestor interference during hair trapping.

Square	Number marked	Both methods	Shooting	Interference
1	1	0	0	no
2	1	0	0	yes
3	1	0	0	no
4	1	0	0	no
5	1	1	0	no
6	1	1	0	no
7	2	0	0	no
8	2	0	0	no
9	2	0	0	no
10	3	0	0	no
11	3	2	0	no
12	4	2	1	no
13	4	4	1	no
14	4	2	2	no
15	4	1	0	no
16	5	1	0	no
17	5	2	0	no
18	5	3	1	no
19	6	2	2	no
20	6	1	0	yes
21	8	6	6	no
22	10	3	1	no
23	11	7	5	no
24	12	6	1	no
25	12	8	5	no
26	15	6	5	no
27	24	12	3	yes
28	29	8	2	no
29	34	9	6	no

Missed matches: 87 ears were found to match with 90 distinct hair profiles

False positive matches: 2 matching pairs were found within 868 DNA profiles from ears

Population churn: between 0 and 3.5%

Version 2. 31st January 2014

Table 6.2 Somerset efficacy estimates for controlled shooting and cage trapping combined.

Estimate	Lower 95% confidence limit	Upper 95% confidence limit
Confidence interval for the mean of the estimated proportion removed in each square, using data from all survey squares	0.3487	0.5215
Confidence interval for the mean of the estimated proportion removed in each square, including only those setts at which protestor interference was detected	0.0426	0.768
Confidence interval for the mean of the estimated proportion removed in each square, excluding setts at which protestor interference was detected	0.333	0.5228
Confidence interval for the estimated proportion removed within the pilot area, using data from all squares	0.3448	0.4807
Confidence interval for the estimated proportion removed within the pilot area, including only those setts at which protestor interference was detected	0.3057	0.6981
Confidence interval for the estimated proportion removed within the pilot area, excluding setts at which protestor interference was detected	0.3336	0.4716

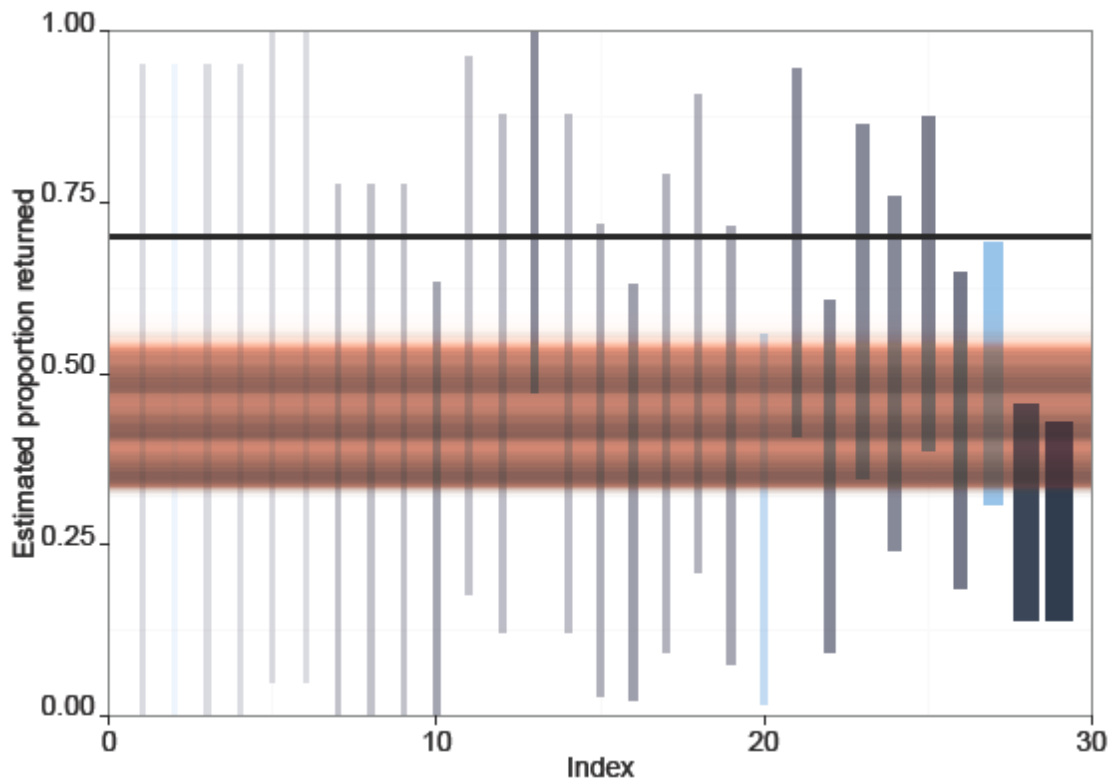Significance of the effect of interference on the estimate: $P = 0.296$

Figure 6.1 Proportions of marked badgers returned by controlled shooting and cage trapping combined in each square in Somerset.

In Figure 6.1 the vertical bars show the estimated proportion returned from that square. The individual estimates displayed here are not adjusted for factors such as the estimated rate of missed matches. Estimates are arranged in order of the number of badgers marked in the square. The width of the bar is proportional to the number of badgers marked. Grey bars indicate squares that contain setts at which interference was not reported. Blue bars indicate squares that contain at least one sett at which interference was reported. The depth of shading is proportional to the average probability density within the interval. The pink horizontal bar shows the estimated average of proportions returned across squares. The width of the bar is a measure of uncertainty caused by the sample size, the variation in the proportion returned between squares and the uncertainty caused by factors such as potential exchange of badgers from the cull area and the mismatch rate. The grey horizontal bars are estimates of the proportion of the population returned based on the proportion of marked badgers returned out of all marked badgers. The fuzziness of the bars represents the uncertainty caused by factors such as population churn and the mismatch rate. The distance between the upper and lower grey bar represents the uncertainty associated with the proportion caused by the sample size. The vertical bar is set at 70% of population size.

Table 6.3 Somerset efficacy estimates for controlled shooting only.

Estimate	Lower 95% confidence limit	Upper 95% confidence limit
Confidence interval for the mean of the estimated proportion removed in each square, using data from all survey squares	0.1327	0.291
Confidence interval for the mean of the estimated proportion removed in each square, including only those setts at which protestor interference was detected	0.0346	0.3374
Confidence interval for the mean of the estimated proportion removed in each square, excluding setts at which protestor interference was detected	0.1222	0.2971
Confidence interval for the estimated proportion removed within the pilot area, using data from all squares	0.1457	0.2477
Confidence interval for the estimated proportion removed within the pilot area, including only those setts at which protestor interference was detected	0.0343	0.3263
Confidence interval for the estimated proportion removed within the pilot area, excluding setts at which protestor interference was detected	0.1578	0.2779

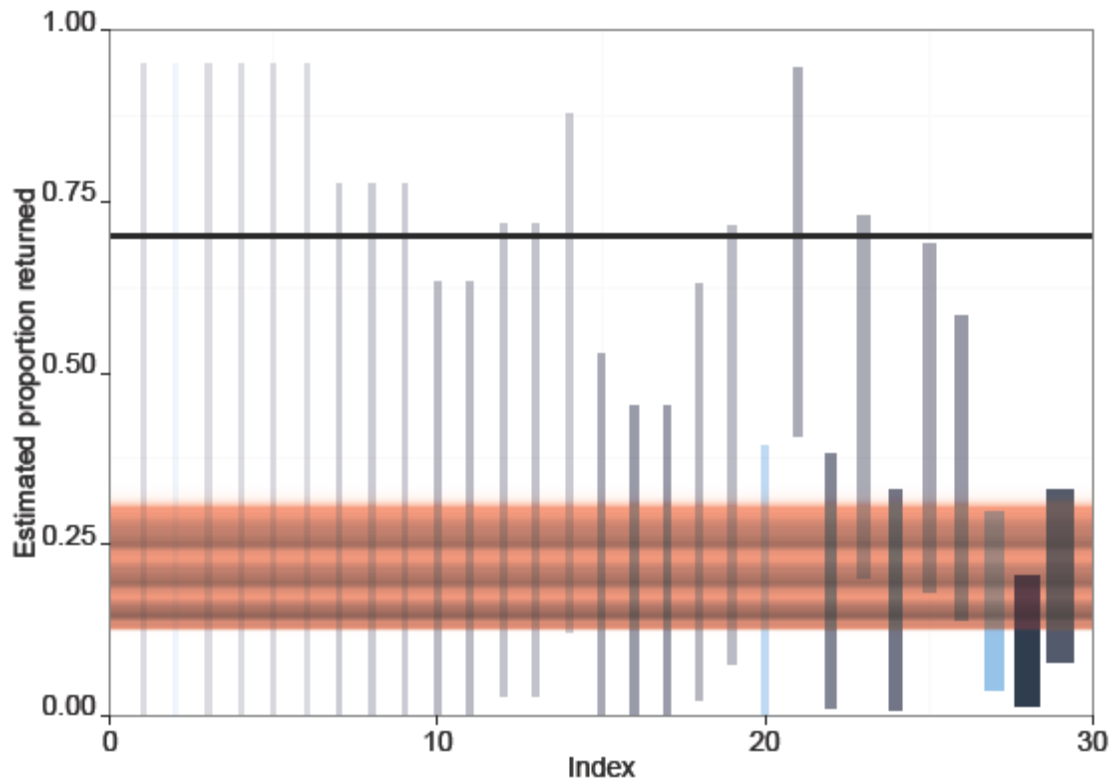Significance of the effect of interference on the estimate: $P = 0.262$

Figure 6.2 Proportions of marked badgers returned by controlled shooting in each square in Somerset. Symbols are as for Figure 6.1

Table 6.4 The number of badgers marked and returned by square in Gloucestershire. 'Both methods' is the number of badgers culled in that square using controlled shooting and cage trapping. 'Shooting' is the number of badgers culled for controlled shooting only. 'Interference' indicates a square in which we detected protestor interference during hair trapping.

Square	Number marked	Both methods	Shooting	Interference
1	1	0	0	no
2	1	0	0	no
3	1	1	1	yes
4	1	1	0	no
5	1	1	1	no
6	1	1	0	no
7	1	0	0	no
8	2	0	0	no
9	2	0	0	no
10	2	0	0	no
11	3	0	0	no
12	3	1	1	no
13	4	2	0	no
14	5	0	0	no
15	6	1	1	no
16	6	2	2	yes
17	6	0	0	no
18	6	3	3	no
19	7	3	3	yes
20	8	3	3	no
21	8	3	1	no
22	8	1	0	no
23	9	3	3	no
24	11	2	2	no
25	14	2	0	no
26	14	0	0	no
27	15	8	6	yes
28	15	8	8	no
29	15	4	2	no
30	22	9	8	yes
31	35	22	22	no

Missed matches: 81 ears were found to match with 84 distinct hair profiles

False positive matches: No matches were found within 708 DNA profiles from ears

Population churn: between 0 and 6.5%

Table 6.5 Gloucestershire efficacy estimates for controlled shooting and cage trapping combined.

Estimate	Lower 95% confidence limit	Upper 95% confidence limit
Confidence interval for the mean of the estimated proportion removed in each square, using data from all survey squares	0.2381	0.4231
Confidence interval for the mean of the estimated proportion removed in each square, including only those setts at which protestor interference was detected	0.2468	0.5686
Confidence interval for the mean of the estimated proportion removed in each square, excluding setts at which protestor interference was detected	0.2206	0.4377
Confidence interval for the estimated proportion removed within the pilot area, using data from all squares	0.2749	0.3906
Confidence interval for the estimated proportion removed within the pilot area, including only those setts at which protestor interference was detected	0.2501	0.5699
Confidence interval for the estimated proportion removed within the pilot area, excluding setts at which protestor interference was detected	0.2774	0.4016

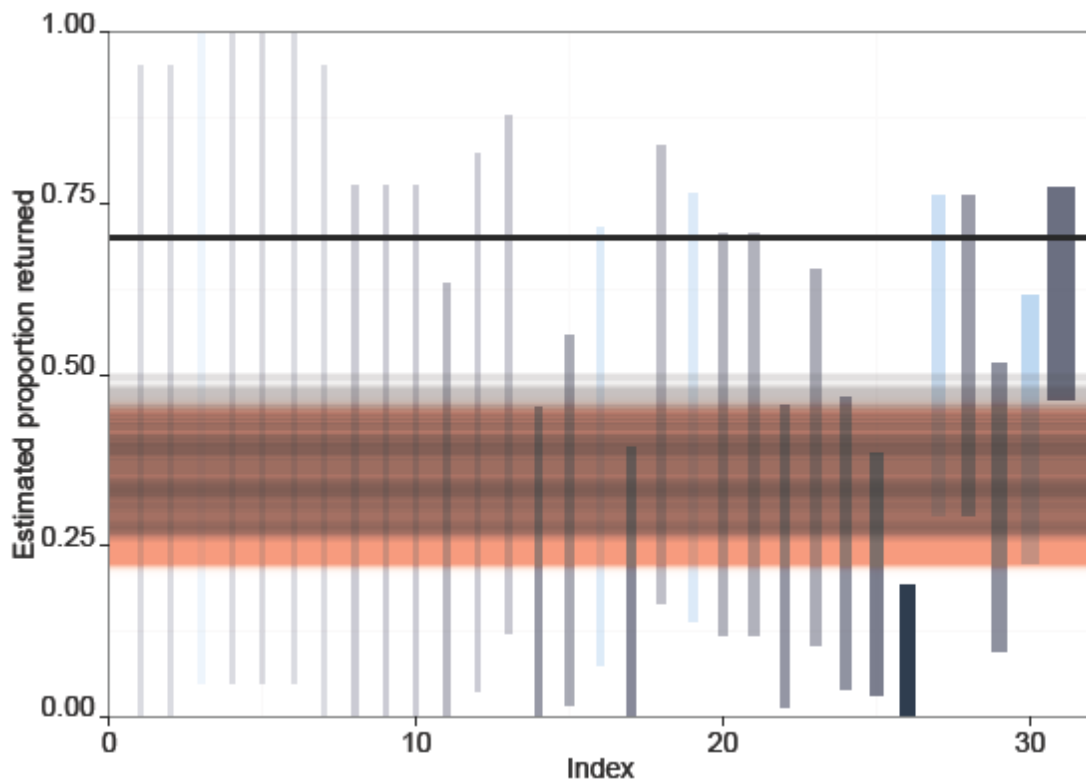Significance of the effect of interference on the estimate: P = 0.791

Figure 6.3 Proportions of marked badgers returned by controlled shooting and cage trapping combined in each square in Gloucestershire. Symbols are as for Figure 6.1

Table 6.6 Gloucestershire efficacy estimates for controlled shooting alone.

Estimate	Lower 95% confidence limit	Upper 95% confidence limit
Confidence interval for the mean of the estimated proportion removed in each square, using data from all survey squares	0.1608	0.3611
Confidence interval for the mean of the estimated proportion removed in each square, including only those setts at which protestor interference was detected	0.1528	0.4718
Confidence interval for the mean of the estimated proportion removed in each square, excluding setts at which protestor interference was detected	0.1444	0.3639
Confidence interval for the estimated proportion removed within the pilot area, using data from all squares	0.2531	0.3712
Confidence interval for the estimated proportion removed within the pilot area, including only those setts at which protestor interference was detected	0.1535	0.4696
Confidence interval for the estimated proportion removed within the pilot area, excluding setts at which protestor interference was detected	0.2526	0.3838

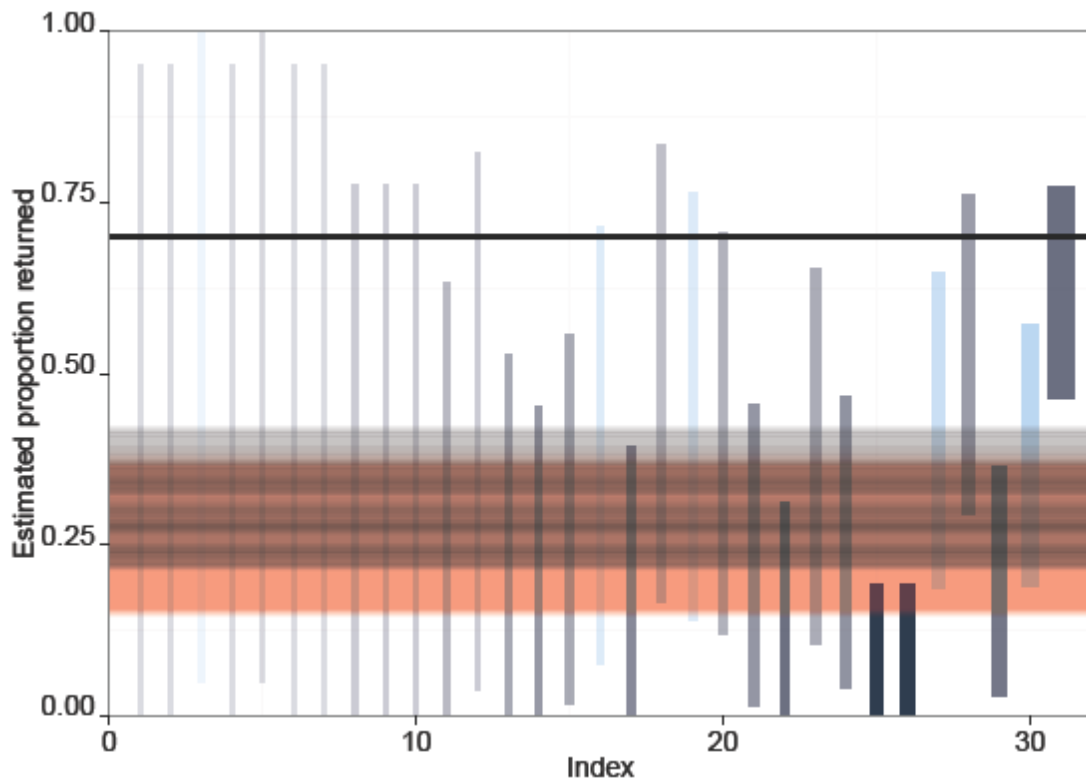Significance of the effect of interference on the estimate: $P = 0.724$

Figure 6.4 Proportions of marked badgers returned by controlled shooting alone in each square in Gloucestershire. Symbols are as for Figure 6.1

7. Appendix 3. Estimates of the population size in the Gloucestershire and Somerset pilot areas by hair trapping and sett survey

Summary

7.1 Here we describe how sett surveying, hair trapping and genetic profiling were used to estimate the badger population sizes within the pilot areas during 2013.

7.2 Estimates of the average number of badgers per active sett for each area during each year were multiplied by the estimates of the number of active setts within the pilot areas to produce estimates of population size with a measure of uncertainty.

7.3 Surveys to estimate the number of active setts were undertaken in 2012. These 2012 results were also used in 2013 under the assumption that the number of active setts was the same in 2013 as in 2012. Estimates of the number of badgers per active sett were obtained in 2013 using hair trapping data collected to measure the efficacy of badger culling.

7.4 Population size was estimated between 862 to 1948 in Somerset and 1394 to 3242 in Gloucestershire, with 95% confidence.

Method

7.5 Each study area was overlaid with a grid of 1km squares, and a number of these were randomly selected for hair trapping. Not all land within each randomly-selected square was accessible so accessible land in adjacent squares was used when this was the case. Hair trapping was undertaken from 6 to 30 August 2013 for two purposes:

a) To genetically identify as many badgers as possible to provide a cull efficacy estimate from the number of known badgers returned by the cull.

b) To provide an estimate of the pre-cull population size by an analysis of the mark-recapture profile of badger identities.

7.6 The primary objective required the identification of as many individual badgers as possible, whereas the secondary objective required the identification and re-sampling of badgers within defined sampling area associated with setts. Sett location and activity status was assigned during a survey of setts within the survey areas undertaken from 17 August to 21 September 2012 in Gloucestershire and 5 August to 1 October 2012 in Somerset. The purpose of the survey was to provide an estimate of the number of active setts in each of the pilot areas. The mean number of active setts per nominal 1km square was used to estimate the number of active setts in the pilot areas and the observed between-square variation in the number of setts was used to estimate the uncertainty of the estimate. The survey included an expert review of photographs of putatively active holes at setts assessed to be active by surveyors, in order to exclude from further analysis any setts that appeared to be mis-identified, and to apply a correction to the estimated number of active setts in the pilot areas.

7.7 Hair traps consisted of a loop of barbed wire fixed to wooden stakes, on fence-lines or natural objects such as logs and suspended approximately 20cm above the ground. They were placed at active setts and areas of obvious badger activity such as runs crossing land boundaries and at latrines. Each hair trap was given a unique alphanumeric identifier and its location taken with a GPS unit. Samples from hair traps were collected on each day for up to 18 days. During the first three days hair traps were moved or additional hair traps were placed to maximise sample

collection. Only samples from the last 15 days were used to estimate population sizes. Each sample consisted of hairs from a single tuft. Where a hair trap had tufts on multiple barbs all tufts were taken and stored in separate plastic ziplock bags.

7.8   Hair samples from a hair trap were placed into a uniquely coded bag which was matched with the time of collection and trap location. DNA was extracted from hairs using a suspension of chelex resin (Frantz et al. 2004). The purified DNA was genotyped using 10 loci (Frantz et al. 2004; Dawnay et al. 2008) on an Applied Biosystems 3130xl Genetic Analyzer. Repeat samples from individuals were identified on the basis of sufficient loci matching to provide a probability of identity approximately 1 in 100,000 based on observed allele frequencies).

7.9   The profile of captures expressed as the number of individuals hair-trapped once, twice, three times etc was analysed with the mark-recapture CAPWIRE package in R. (Miller et al. 2005) using its 'two intrinsic rates model' (TIRM). This model is designed to estimate population size from sparse datasets where the majority of individuals are only captured once. It is particularly suitable for estimating population size of badgers, which vary in capture probability according to age/sex class (Valiere 2002).

7.10   A second order Monte Carlo model was used to estimate the effect of missed matches (as described in Appendix 1) and the uncertainty associated with TIRM estimates via a parametric bootstrap.

7.11   The estimates are based on the assumption that the populations were closed both geographically and demographically (*i.e.* no dispersal or mortality) over the trapping periods, with two sub-sets of individuals that have higher and lower trap probabilities due to some individuals being more easy to sample than others. We assumed closure was met by the short sampling period and by locating hair traps close to setts because badgers tend to defend territories within which their setts are located. The subsequent trapping probability of an individual is assumed not to be affected by being previously hair trapped. The model is a two-probability mixture model version of Chessel's equation (Valiere 2002; Frantz and Roper 2006).

7.12   The sett at which a hair trap was deployed was recorded or else it was recorded as not associated with a sett. Population estimates required estimation of the number of badgers per active sett from those individuals closely associated with active setts at which hair traps were deployed. Consequently, data from hair traps deployed away from setts (deployed as part of the effort to estimate the proportion of the population removed by culling) were excluded from this analysis.

7.13   Estimates of the average number of badgers per active sett were converted into estimates of the number of badgers within each of the pilot areas by multiplying by the estimated number of active setts in each pilot area as described in Anon (2013b).

Results

Active setts

7.14   All sett surveying was undertaken during 2012. In Gloucestershire 183 setts were identified as active by observers, but 10.3% of the setts assessed during the photograph review were judged as misidentified, so were excluded from further analysis.

7.15   In Somerset 275 setts were surveyed as active, but 27.3% of the setts assessed during the photograph review were judged as misidentified as active badger setts, so were excluded from further analysis.

Hair trap and sample numbers

7.16   A total of 850 hair traps associated with setts yielded 758 putative samples, of which 535 produced viable genetic profiles, representing 274 individuals (Table 6.3). The average number of alleles per locus was 9.24 (range 4 – 10). Genetic profiles were obtained from 57 of the 93 active setts trapped in Gloucestershire and 60 of the 130 active setts trapped in Somerset. Despite failure to collect hair samples from many setts, the inability to sample every individual from every sett means it is not possible to conclude that the identification of these setts as active was incorrect.

7.17   Data from five setts in Gloucestershire and three setts in Somerset were excluded from analysis because their hair traps were operative for fewer than six days before being disturbed by third parties.

Table 6.3. Hair trapping effort, numbers of samples, genetic profiles and individuals contributing to the estimates of the number of badgers per sett

Location	Hair traps	Average trap/sett	Putative samples	Genetic profiles	Individuals
Gloucestershire 2013	406	4.4	359	265	150
Somerset 2013	444	3.4	399	270	124

Estimates of the number of badgers

7.18   In both Gloucestershire the ratio of individuals caught once to those caught on multiple occasions was 1.7:1 and in Somerset it was 1.6:1 (Table 6.4). Table 6.5 presents the estimates of the number of badgers per active sett. Table 6.6 presents estimates of the population of badgers in the pilot areas during 2013.

Table 6.4. Capture profiles: number of badgers sampled once, twice, three times etc.

Area	Number of individuals by number of times sampled															
	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16
Glos	94	31	9	8	3	1	3	1	0	0	0	0	0	0	0	0
Som	77	19	7	8	3	4	0	2	2	0	0	0	1	0	0	1

The rate of missed matches was estimated to be 7 per 186 observed matches in Somerset. In Gloucester the rate of missed matches was estimated to be 10 per 111 observed matches.

Table 6.5. TIRM estimates of the average number of badgers per sett.

Location	Setts	Badgers per sett	(95 CI)		RSE (%)
Gloucester	87[a]	3.323	3.209	4.337	0.1607
Somerset	127[a]	1.595	1.474	2.129	0.1703

[a] setts trapped for six or more days

Table 6.6. Population estimates for the two pilot areas

	Gloucestershire	Somerset
Survey year	2013	2013
Total area (km^2)	311.00	256.05
Squares (nominal km^2) surveyed	80	67
Area surveyed (km^2)	77.96	62.82
Active setts found	183	275
RSE between location(%)	14.51	11.39
Photo reliability	89.7	72.7
RSE photo reliability (%)	2.3	3.5
Mean badgers per sett	3.323	1.595
RSE badgers per sett (%)	0.1607	0.1703
Average density (80% one-tailed interval) (number per km^2)	7.00 (5.70 to 8.19)	5.08 (4.18 to 5.91)
Population range as 95% confidence interval	1394 to 3242	850 to 1904

RSE = Relative Standard Error

Discussion

7.19   Two badgers in Somerset were sampled a surprisingly high number of times (13 and 16 times). They were both sampled at the same sett on every occasion. The badger sampled 13 times was trapped at six different hair traps on eight different nights. The badger sampled 16 times was trapped at eight different hair traps on nine different nights. Removal of these two individuals resulted in an estimate of the number of badgers per sett of 1.61 (RSE = 20.0%).

7.20   Re-running the estimate while setting the missed match rate to zero produced values of 1.69 badgers per sett (RSE = 17.7%) in Somerset and 3.59 badgers per sett (RSE = 16.1%) in Gloucester. The difference between these values and the estimated number of badgers per sett shows the effect of missed matches on the population estimate.

8. Appendix 4. Estimation of the effort required to deliver a cull of at least 70%

Background

8.1 Industry-lead culling removed significantly fewer than 70% of the population during the six week culling period. The target was to remove at least 70% of the population, a quantity that is higher than the average of the estimate of 70% of the population. Here we use data collected by industry on effort invested in culling and the number of badgers culled to estimate the effort that they may have needed to invest to achieve their target. These data were not audited and therefore of unknown quality in terms of their accuracy, completeness and reliability.

Method

8.2 Data were received in a spreadsheet, one for each pilot area, from the National Farmers Union (NFU). Each row contained information on one contractor for one shift. We defined a shift *post hoc* as one continuous block of time during which the contractor was engaged in culling duties, such that each row of data constituted one shift. Fields were as follows:

Date – the date on which a contractor was operating.

User code – a unique identifier for each contractor.

Day start – Time and date of the contractor's start time.

Day end – Time and date of the contractor's end time.

Amount of time – 'Day end' minus 'Day start'. For cage trapping this included all time from the setting of a trap to trap checking or submission of the carcass to the carcass collector, and hence included some time when the contractor was not operative.

Total carcases – Total number of carcases removed by a contractor during a shift.

Method – The method used to cull badgers (R = Rifle, S = Shotgun, CT = Cage trap).

8.3 To provide comparability of effort invested in cage trapping and shooting, effort was described as 'contractor-shift' such that the total effort expended was equal to the number of rows in the spreadsheet. Day start, Day end and Amount of time were used only to quantify the duration of shifts, but were not used to quantify effort.

8.4 On shifts when no badgers were culled the method that was intended to be used (rifle or cage trapping) was not recorded. Consequently it was not possible to determine total effort expended using any one technique. Thus effort was assessed for both methods combined, and entries with no record of Method and Total carcases were assumed to represent the taking of zero badgers.

8.5 The shift cull rate (*r*) was calculated for each contractor from the following equation:

$$r = \left(\frac{A}{P}\right)^{\frac{1}{t}} - 1$$

8.6 Where *A* is the estimated population remaining following culling (i.e. population size minus the number culled by that contractor), *P* is the estimated pre-cull population, and *t* is time expended by the contractor, measured in nights.

8.7 A simple model was constructed in a spreadsheet to estimate the effort required to achieve the target for each pilot area. The model evaluated a column of increasing values for effort, ranging from 0 to 15000 contractor-shifts, in steps of 50, with 0 being the last day of culling in the spreadsheet of cull returns provided by the NFU. The number of badgers likely to remain (*A*) for each level of effort was estimated by rearranging the above equation to:

$$A = P(1 + r)^t$$

8.8 The number of badgers predicted to be culled for each level of effort was estimated as the difference between the starting population (*P*) and the estimated number remaining (*A*). This approach assumes a constant proportion of the population is removed for each level of effort, such that the number of badgers culled per unit effort declines with increasing effort.

8.9 The level of effort at which at least 70% of the population had been removed, was taken as the effort required to achieve the target.

8.10   Shift cull rates varied between contractors, and the population estimate was uncertain. Therefore, a Monte Carlo procedure was used to draw one population point estimate. This was drawn from a triangular distribution, with the minimum, mean and maximum defined from the range of population estimates derived from the primary efficacy estimate. Fifty contractors' shift cull rates were then drawn from the data (with replacement) and applied to the number of badgers remaining. This last step was repeated until 15000 contractor-shifts were invested and the whole process iterated 1000 times. The amount of effort (in steps of 50 contractor-shifts) to achieve the target was then calculated. The target was estimated from the Monte Carlo sample of the primary efficacy estimate. The target was taken as 70% of the 80th percentile of the population point estimates.

Results

8.11   Data were received from NFU covering 34 nights of culling in Gloucestershire and 41 nights for Somerset. Effort per contractor was broadly similar in both areas (Table 8.1). However, data on the duration of shifts were questionable, ranging from 15s to over 13 days per shift in Somerset, with 164 shifts recorded as being less than 1 hour duration, and ranging from 28s to over 34 days in Gloucestershire, with 83 shifts recorded as being less than 1 hour duration.

8.12   Cage trapping produced more badgers in Somerset, and controlled shooting produced more in Gloucestershire (Table 8.1).

8.13   From the model we estimate that under the same conditions as during the first 34 nights in Gloucestershire and 41 nights in Somerset, an additional 4000 to 10000 contractor-shifts (median = 6200 contractor nights) would have been needed in Gloucestershire and 1950 to 5200 contractor-shifts (median = 3050 contractor-shifts) in Somerset to remove at least 70% of the population.

Table 8.1. Contractor effort and cull returns.

	Gloucestershire	Somerset
Total effort (contractor-shifts)	1063	1243
Median number of shifts per contractor (range in parentheses)	14 (2 to 36)	12 (1 to 49)
Median number of badgers culled per contractor (range in parentheses)	5 (0 to 40)	5 (0 to 42)
Number of shifts badgers culled by rifle	288	229
Number of shifts badgers culled by cage trapping	63	292
Number of shifts with no method recorded	712	732
Mean number of badgers culled per contractor-shift (range in parentheses)	0.573 (0 to 9)	0.658 (0 to 8)

Discussion

8.14   From the simulations we predict that in Somerset an additional 1950 to 5200 contractor-shifts and in Gloucestershire an additional 4000 to 10000 contractor-shifts may have resulted in removal of at least 70% of the population.

8.15   These predictions rely on several assumptions including:

- The data used in the simulations were accurate, complete and reliable. The data did not cover the full 42 days of culling, data on Day start, Day end and Amount of time appear inaccurate, casting doubt on the reliability of the dataset.

- The same contractors would undertake culling using the same methods in the same way and each would invest effort in the same proportion as during the first six weeks. Some contractors produced many more carcasses than others and these highly productive contractors may be used in preference for future culling.

- The probability of any one badger being culled was no different between the first six weeks and any subsequent culling. Behavioural changes caused by culling operations or a change in the weather, or the possibility that the remaining animals, by their nature, have a lower probability of capture, would violate this assumption.

8.16   Industry-lead culling was undertaken under very specific circumstances using a mix of methods and with no record of relative use of each method reported. Therefore the estimates of effort required to remove at least 70% of the pilot area populations are unlikely to reflect the effort likely to be required to reduce other populations by controlled shooting.

8.17   The Independent Expert Panel may wish to consider whether the data on contractor effort provided by the NFU could be analysed in an alternative way that could provide greater clarity on the effort required.

9. Appendix 5. The effect of hair trap presence on numbers of badgers culled

Introduction

9.1 We used wire hair traps to collect genetic samples from badgers in the pilot areas, and we used this information to estimate the proportion of the badger population removed by industry contractors (efficacy). The pilots encountered disturbance from protestors, and badger culling activities by the contractors were not evenly spread throughout the areas. While these may have influenced the overall efficacy of the pilots, they may also have impeded our ability to accurately measure efficacy, for example if the areas where hair sampling took place were not representative of the pilot area badger population or the pattern of badger culling. During monitoring activities some hair traps were disturbed, for example either having hair samples apparently removed from the wire, or the wires themselves being removed. Such activity is likely to have reduced the number of genetic profiles in the efficacy analysis and the frequency with which each badger was sampled, but these effects will not have directly biased the estimates. However, disturbance from protestors might have influenced contractor behaviour, potentially impeding culling at locations with hair traps which could have biased estimates of efficacy. Here we test the null hypothesis that hair trapping was not associated with a lower badger removal rate.

Methods

9.2 Data on the locations at which each badger was culled in both pilot areas were received from industry. We are not aware of industry's quality control procedures and could not independently verify the quality of their data. The data consisted of a unique badger identification number, time and date on which it was culled, a code for the landholding(s) over which the cull contractor was working on the night on which the badger was culled, an OS grid reference for the centroid of that landholding(s), and a code for the culling method used (cage trap, rifle, shotgun).

9.3 These data were linked to information on land holding boundaries, on the locations of every hair trap deployed and data on the number of genetic profiles collected at each hair trap, within a GIS.

9.4 We identified three issues with the data that could limit the extent of appropriate interpretation of results arising from their analysis. Firstly, in instances where a contractor visited multiple landholdings on a single night, any resultant carcasses were recorded as having been taken across all the landholdings covered. Thus a carcass could not be allocated to the landholding on which it was taken, and was instead allocated across all the landholdings covered by that contractor on that night. Secondly, there were instances where the centroid of one or more landholdings fell outside of the landholding. This was caused by the shape of the landholding(s), e.g. the centroid of a crescent lies outside the crescent. In these instances we corrected the grid reference of the cull returns to place it inside the landholding(s) described by the unique code for the landholding(s). Finally, some landholdings were split across multiple land parcels, each surrounded by other landholdings owned by other landowners. In these instances a carcass was allocated across the combined land parcels for a landholding.

9.5 Following data correction, a zero-inflated negative binomial model was fitted to observations of the number of carcasses from each holding, the area of the holding and the presence of hair

traps on the landholding. Landholdings were used because this was the scale at which the cull data were recorded.

9.6 The model provided estimates of four values: 1) the effect of 'area' on the expected number of badgers culled from those landholdings where the conditions required to cull badgers were in place (e.g. presence of badgers and contractors), 2) the variation in this quantity between landholdings, 3) the probability that the conditions required to cull badgers were not in place, 4) the size of the effect of the presence of hair traps in a landholding on both the expected number of badgers culled from a landholding where the conditions required to cull badgers were present and the probability of those conditions not being present.

Results

9.7 In both Gloucestershire and Somerset the expected number of badgers culled was not statistically significantly different between landholdings that contained hair traps and those that did not (Tables 1 and 2), although the average expected number of carcasses was higher for landholdings that contained hair traps in Gloucestershire only.

Table 9.1. Model parameters for Gloucestershire: Estimates of the effects of area and hair trap presence on numbers of badgers culled on landholdings.

Count model coefficients (negbin with log link):				
	Estimate	Standard error	z value	P (>|z|)
(Intercept)	1.38021	0.13989	9.866	< 2e-16 ***
log(Area_km2)	0.72657	0.13517	5.375	7.65e-08 ***
Traphere1	0.14284	0.23649	0.604	0.546
Log(theta)	0.01988	0.26305	0.076	0.940

Zero-inflation model coefficients (binomial with logit link)				
	Estimate	Standard error	z value	P (>|z|)
(Intercept)	-0.6358	0.2938	-2.164	0.0305 *
log(Area_km2)	-0.6059	0.2262	-2.678	0.0074 **
Traphere1	-1.6069	1.1089	-1.449	0.1473

Significance codes: 0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1

Table 9.2. Model parameters for Somerset: Estimates of the effects of area and hair trap presence on numbers of badgers culled on landholdings (no area).

Count model coefficients (negbin with log link):

	Estimate	Standard error	z value	P (>|z|)
(Intercept)	2.19771	0.14330	15.336	<2e-16 ***
Traphere1	-0.16616	0.27094	-0.613	0.540
Log(theta)	-0.09633	0.26304	-0.366	0.714

Zero-inflation model coefficients (binomial with logit link)

	Estimate	Standard error	z value	P (>|z|)
(Intercept)	0.2214	0.1961	1.129	0.259
Traphere1	-0.4723	0.3960	-1.193	0.233

Discussion and conclusion

8.8 While the possibility of a small effect cannot be precluded, there is no strong evidence of an effect of hair trap presence on the number of badgers culled on a landholding in either the Gloucestershire or Somerset pilot areas (Figures 9.1 and 9.2). The direction of the (non-significant) trend in Gloucestershire was opposite to what might be expected if our monitoring activities resulted in culling being impeded. If there was an impact of protestor activity or contractor behaviour on our estimates of efficacy, the effect would most probably be small. We conclude that our efficacy estimates were unlikely to have been significantly biased due to protestor activity or changes to contractor behaviour associated with our monitoring activities.
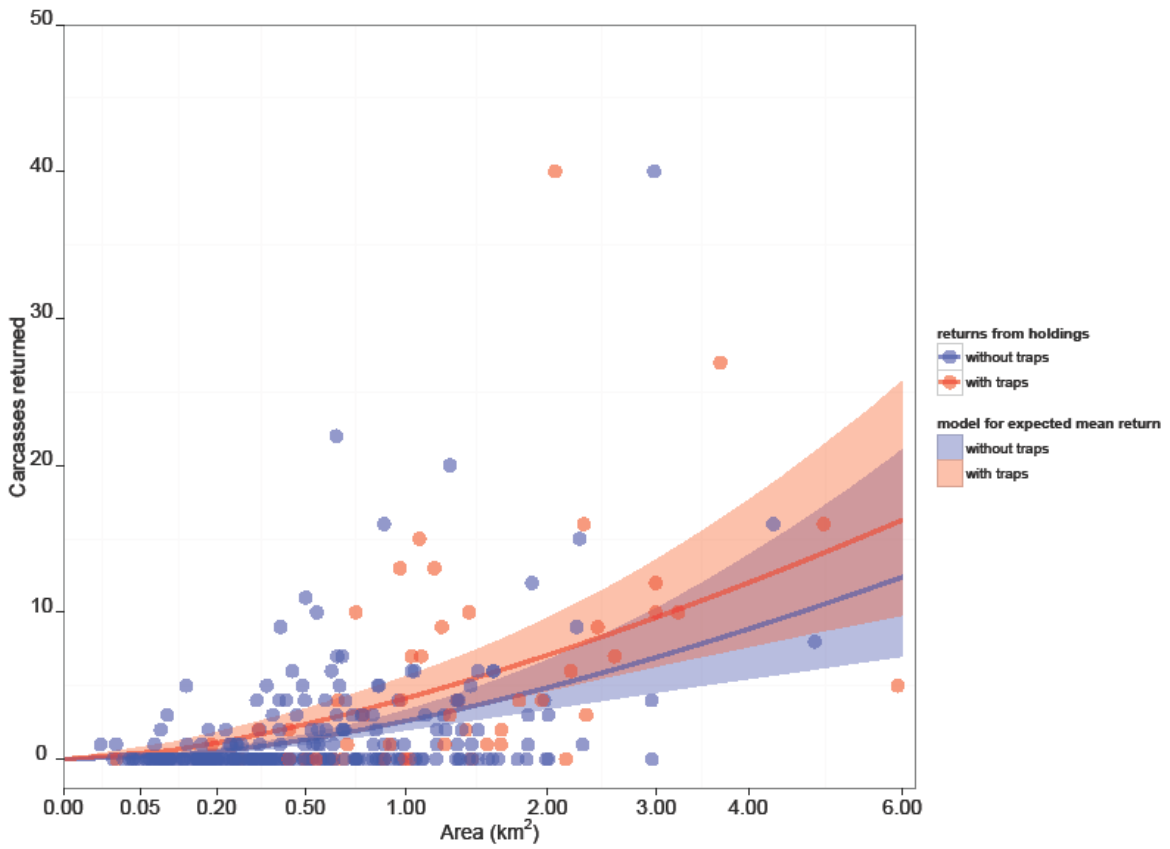
Figure 9.2. Relation between the number of badgers culled, the area and the presence of hair traps on a land holding in Gloucestershire.
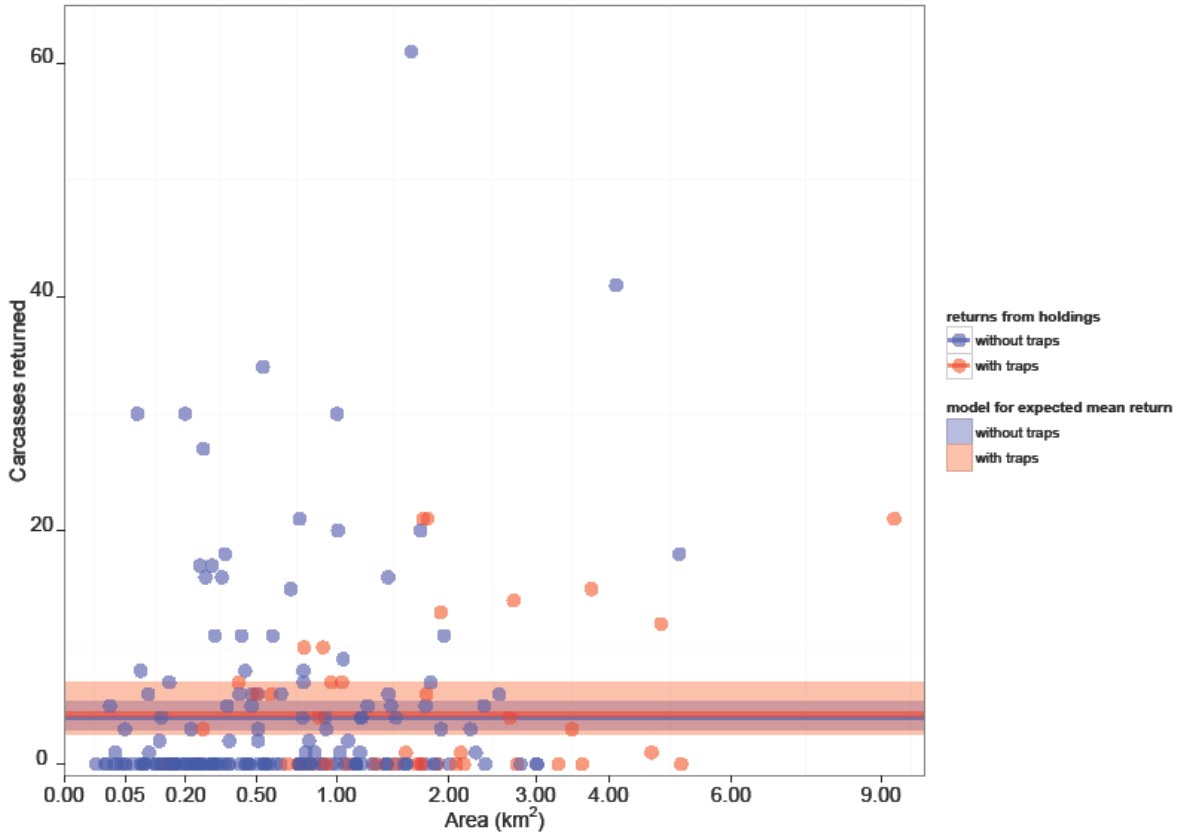
Figure 9.2. Relation between the number of badgers culled, the area and the presence of hair traps on a land holding in Somerset.

10. **Appendix 6.** Quality assurance

Methods

10.1   All survey methods, data to be collected and data analysis methods were reviewed, finalised and approved by the Independent Expert Panel before data collection started.

Staff training and auditing

10.2   Most staff engaged in hair trapping activities were experienced hair trappers who received one day of training in the use of the relevant standard operating procedures. Less experienced staff were paired with experienced staff during field data collection. In addition, staff received two days of training and 5 days of practical experience in sett surveying and hair trapping before starting hair trapping in the field. Adherence by the research team to the standard operating procedures was independently assessed and verified by an experienced surveyor during visits to the pilot areas. An independent assessment of surveying, data recording and manipulation, sample handling and laboratory processes was undertaken by an experienced external auditor. Errors identified by the auditor were corrected before final estimates were calculated. One member of the Independent Expert Panel reproduced all of our calculations from our raw data. Discrepancies were explained or corrected as appropriate before production of final results.

Peer Review

10.3   Numerically competent staff and members of the Independent Expert Panel selected by Defra reviewed the assumptions used to underpin analyses, calculations and interpretation. Senior members of staff and the Independent Expert Panel reviewed this report. Recommendations to improve data collection, analysis and reporting were followed. The reviewers accepted the final version of this report.

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11. **Appendix 7.** References

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