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ORIGINAL ARTICLE

Weather influences trapping success for tuberculosis management in European badgers (*Meles meles*)

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Abstract European badgers (*Meles meles*) in Ireland and the UK are a reservoir for *Mycobacterium bovis*, the causative agent of bovine tuberculosis (TB). A number of interventions have been evaluated in attempts to control bovine TB within badger populations, and many of which rely on the capture of badgers. One strategy being implemented within Ireland is intramuscular vaccination using Bacillus Calmette-Guérin (BCG), as an alternative to badger culling. The success of vaccination as a disease control strategy depends on the ability to capture badgers and administer vaccines; thus, trapping success is crucial to effectively vaccinate the population (maximize vaccine coverage). A field vaccine trial was conducted in County Kilkenny, Ireland, from 2010–2013. We used data from this trial to evaluate the association between weather (precipitation and temperature data), badger sett characteristics, and badger trapping success. Approximately 10% of capture efforts resulted in a badger capture. Our results indicate that badger captures were the highest in drizzle, rain, and heavy rain weather conditions, and when minimum temperatures ranged from 3–8 °C. Badger captures were the highest at main setts (large burrow systems), and when sett activity scores were high (qualitative classes 4 or 5). Using local precipitation and temperature data in conjunction with observed sett characteristics provides wildlife managers with guidelines to optimize trapping success. Implementing capture operations under optimal conditions should increase the trapping success of badgers and allow for increased delivery of vaccines to manage bovine TB.

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Introduction

Managing endemic diseases in free-ranging wildlife relies on interventions intended to control or eradicate the disease (Wobeser 2002). When controlling disease, vaccination of wildlife is considered under certain circumstances, particularly in offering protection against diseases that threaten livestock production or wildlife species of conservation concern (Cross et al. 2007). Vaccination programs may be useful in the control of wildlife diseases such as bovine tuberculosis (TB). Bovine TB affects livestock and a number of wildlife species around the world and is an important disease of cattle in the Republic of Ireland (More and Good 2015). The European badger (*Meles meles*) is an important wildlife reservoir implicated in bovine TB persistence, which hampers disease eradication efforts. In Ireland, badgers are listed as protected species under the Irish Wildlife Act; thus, their conservation is an important consideration in disease management (Byrne et al. 2012b). Bovine TB management in Ireland has included targeted culling of badgers in areas of cattle TB outbreaks (O'Keeffe 2006). Culling is not a long-term sustainable management strategy of a protected species; thus, vaccination of badgers against bovine TB has been proposed as an alternative. Vaccination has the dual benefits of controlling disease without reducing badger populations, while lessening the morbidity and mortality in badgers due to TB disease. The Bacillus Calmette-Guérin (BCG) vaccine has been shown to be safe (Lesellier et al. 2006) and efficacious (Lesellier et al. 2011; Chambers et al. 2011) in badgers. However, a considerable portion of a given badger population must be immunized for vaccination to effectively replace culling as a management strategy (Wilkinson et al. 2004; Byrne et al. 2012a).

An intramuscular BCG vaccine is currently available for use in badgers, which requires capture and handling for administration. Maximizing trapping success will therefore be crucial to an effective vaccination program. Live-capture rates are low among carnivores. Capture success of red foxes (*Vulpes vulpes*) has been reported in the range of 1.5–1.8 captures/100 trap-nights (Baker et al. 2001) or 0–3.4 captures/100 trap-nights (Ruette et al. 2003) and for stone martens (*Martes foina*) and pine martens (*Martes martes*), 0.6–7.8 captures/100 trap-nights (Ruette et al. 2003). Badgers are nocturnal and fossorial, which further reduces capture opportunities. A study in Atlantic Spain showed that a minimum of 40 traps had to be set per sampling period per sett to trap 93.18% of adult badgers (Acevedo et al. 2014). Byrne et al. (2012a) showed mean badger trappability during a vaccine trial in County Kilkenny, Ireland to be 34–35% across the population, with variation by season and age-class. Examining specific factors that improve trapping success of badgers can provide wildlife managers with information to optimize trapping efforts and, in doing so, guide wise allocations of resources to protect badgers and livestock from TB.

Trapping success is influenced by factors related to trapping methods, environmental variables, and species characteristics (Pawlina and Proulx 1999; Tuyttens et al. 1999). Few mammal trapping studies have examined the role of weather. Temperature and time since rainfall affected trapping success of Valley pocket gophers (Cox and Hunt 1992) and rainfall and lower temperatures were positively correlated with captures of Western red-backed voles (Maguire 1999). In the United Kingdom (UK), temperature and precipitation have been shown to influence the efficiency of cage-trapping badgers (Noonan et al. 2015). However, that study in the UK was conducted over a small area with a discrete, systematically trapped population using bait and a different trap style than that employed in Ireland. Thus, the objective of this study was to examine the effect of local weather (temperature and precipitation), season, as well as sett type and sett activity, on badger trapping success in disease management in Ireland.

Methods

Study area

This study used data from the Kilkenny Vaccine Trial; the study area and capture protocol have been previously described by Byrne et al. (2012a). Briefly, the study area is approximately 755 km^2 located in the northwest of County Kilkenny, Ireland, and encompasses pasture land with extensive hedgerows (Fig. 1). This area was divided into three zones (A, B, and C) for different treatments of the vaccine trial.

Capture protocol

Badgers were captured in six sessions from February 2010–December 2013. Trapping occurred during all months of the year, but most heavily from March–June and October–November and infrequently during July–August. Badgers were captured using stopped wire restraints (for details on these restraints and their impact on trapped badgers see: Byrne et al. 2015b). In each zone, active setts were targeted each week for trapping, and 1–35 restraints were laid at each sett. The number of restraints laid was subjectively determined by signs of activity, number of openings available, and badger passes or paths available for restraints to be set. Setts were classified as main setts (those used for breeding and overwintering; Smal 1995) or non-main setts. Starting in February 2011, at the beginning of the week, setts were assigned activity scores ranging from 0–5 (Table 1). Trapping was conducted at setts with activity scores ≥3. Trapping occurred at selected setts over a period of eight nights. A sett-night is defined as all trapping effort at one sett over one trap-night. All traps were checked daily prior to 12 pm.

In each zone, minimum and maximum temperatures were recorded using a maximum/minimum thermometer (AgriHealth, Monaghan, Ireland) for each 24-h period from morning to the time when traps were checked the following morning. Precipitation scores were assigned on a scale of 1–6, where 1 = dry, 2 = drizzle, 3 = light rain, 4 = rain, 5 = heavy rain, and 6 = snow. A single precipitation score, representative of conditions overnight when badgers were expected to be active, was assigned by the field staff for each 24-h period.

Statistical analyses

Descriptive statistics (counts, frequencies, proportions, means, and standard deviations) were calculated to evaluate the data distribution. The temperature data revealed a nonlinear relationship between minimum and maximum temperature and badger trapping success. To further explore this relationship, minimum and maximum temperatures were separated

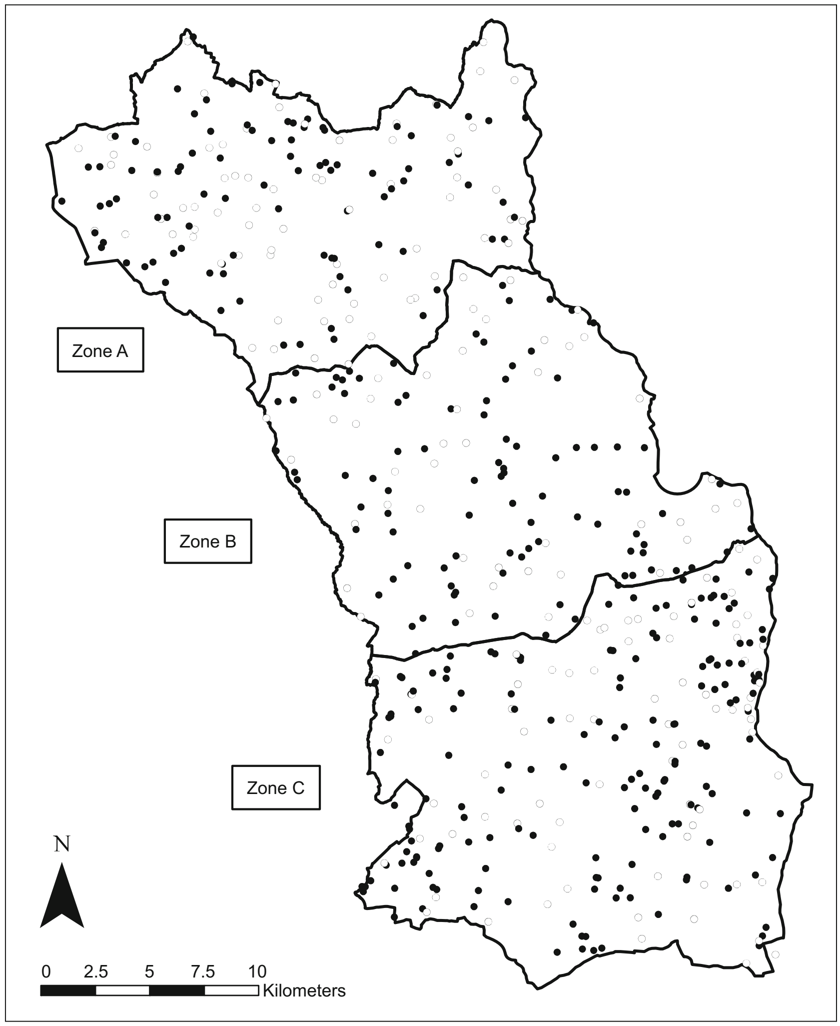

Fig. 1 Map of badger vaccine trial area and zones with County Kilkenny, Ireland. *Black dots* are main setts and *white dots* are non-main setts where trapping occurred from 2010–2013

into four categories based on quartiles. Logistic regression modeling was used to assess trapping success, which was considered as a binary event (badger captured or not) in a given sett/night.

Table 1 Standardized badger sett activity scoring system used in Ireland

Score	Description
0	No activity; openings closed or partly closed by clay, leaves, etc. No fresh paths or tracks are visible leading to or between openings. Old existing paths are overgrown and beginning to disappear. Grass or scrub growing around openings and on the spoil heap.
1	Beginning of movement; first signs of activity, with paths leading to the openings. Openings however are not cleaned out. Could not be sure if paths are badger or non-target species.
2	Possible badger activity; distinctive paths leading to openings. Openings may or may not be cleaned out. No fresh spoil heap. Possible footprint. Impression is that the badger is traveling around different setts rather than setting up home.
3	Badger activity; opening cleaned out but spoil heap not fresh. Paths can be visibly seen leading to and from openings. Bottom of opening is clean where animal is moving in and out of the sett.
4	Definite badger activity; paths can be clearly seen leading to and between openings. Openings cleaned out with fresh spoil heaps, possibly with or without bedding. Bottom and side of openings are clean and shiny in appearance where badger is moving in and out of the sett. Fresh latrine pits in the vicinity of the openings.
5	Definite badger activity; as above at number 4 but at a main sett.

Univariable logistic regression models were used to assess the association between variables (sett type, sett activity score, precipitation score, minimum and maximum temperature categories, number of traps per sett, season, year, and zone) and whether or not a badger was captured. All variables found to be significant (using a significance threshold of $p < 0.15$) in the univariable analysis were considered for inclusion in a multivariable model. Continuous variables were assessed for collinearity using pairwise Pearson correlation, and categorical variables were assessed for collinearity using Spearman correlation. When collinearity was detected in a pair of variables, only the variable with higher correlation to badger trapping success was retained.

A series of ten logistic regression candidate models were developed using variables from the univariable analysis. Two-way interaction terms between weather and season were also investigated in some candidate models. Using a full fixed effects logistic regression model, model fit was assessed using the Hosmer-Lemeshow goodness-of-fit test and a receiver operating characteristic curve. To control for lack of independence from repeated observations within setts, the candidate model set was tested using three-level mixed logistic regression models with setts nested within zones. An information-theoretic approach with Akaike's Information Criterion (AIC) was used to perform model selection (Burnham and Anderson 2002). The model with the lowest AIC (and highest weight) was considered the preferred model, and models with ΔAIC <2 were considered equally parsimonious. The candidate model set is shown in Table 2. All candidate models contained season, year, and number of traps set as controls. To ensure comparability of AIC values by using the same number of observations for all models (Burnham and Anderson 2002), model selection was performed on a subset of the data (13,860 of 19,196 total sett-nights) for which no covariate data was missing. All analyses were performed in Stata 13.1 (StataCorp 2013).

Results

Trapping occurred at 561 unique setts over 19,196 sett-nights from 2010–2013. The number of trapping events at main and non-main setts was approximately equal, with 9316 trap-nights at main setts and 9880 at non-main setts. Number of restraints per sett ranged from 1–35 (mean 7.8, SD 3.3). Sett activity was not quantified in 2010 or early 2011 (before February). Of the 14,272 sett-nights where sett activity was recorded, 54.5% were scored 3, 24.2% were scored 4, and 21.3% were scored 5. Using observer precipitation scores, there were 7526 sett-nights with dry weather, 2721 sett-nights with drizzle, 2848 sett-nights with light rain, 3274 sett-nights with rain, 1941 sett-nights with heavy rain, and 262 sett-nights with snow. Minimum temperature ranged from −12 to 16 °C (mean 5 °C, SD 4.5). Maximum temperature ranged from −3 to 30 °C (mean 12.4 °C, SD 4.9). The majority of sett-nights (17,394/19,196; 91%) did not result in capture of any badgers. A total of 1802 sett-nights resulted in trapping success; most successful sett-nights (1623) resulted in one badger captured, but 167 sett-nights resulted in two badgers captured and 12 sett-nights resulted in three badgers captured. The overall trapping success rate was 9.5 badgers/100 sett-nights.

Univariable logistic regression analysis indicated significant (at $p < 0.15$) differences in badger trapping success for sett type, sett activity, precipitation score, minimum temperature category, maximum temperature category, number of traps set, season, and year (Table 3). Minimum and maximum temperatures were highly correlated, and minimum

Table 2 Candidate models and model statistics for mixed effects logistic regression models of badger trapping success

Model	LL	K	AIC	ΔAIC	w_i
Main Activity Weather MinTemp Traps Season Year	−4028.453	20	8096.906	0	0.79
Activity Weather MinTemp Traps Season Year	−4031.012	19	8100.025	3.12	0.17
Main Weather MinTemp Traps Season Year	−4134.651	18	8305.301	208.40	0.00
Main Activity Weather Traps Season Year	−4034.823	17	8103.646	6.74	0.03
Activity Weather Traps Season Year	−4037.215	16	8106.429	9.52	0.01
Main Activity MinTemp Traps Season Year	−4039.411	15	8108.821	11.92	0.00
Activity MinTemp Traps Season Year	−4041.986	14	8111.971	15.07	0.00
Main Activity Traps Season Year	−4051.036	12	8126.073	29.17	0.00
Main Activity Weather MinTemp Traps Season Year Weather*Season	−4024.328	30	8108.656	11.75	0.00
Activity Weather MinTemp Traps Season Year Weather*Season	−4026.878	29	8111.756	14.85	0.00

K number of parameters, *LL* log likelihood, *AIC* Akaike's information criterion, *ΔAICc* difference in AIC from minimum AIC model, w_i Akaike weight

Table 3 Results from univariable logistic regression analysis of sett characteristics, weather variables, and other predictors of badger trapping success in Co. Kilkenny, Ireland 2010–2013

Variable	Category	OR	95% CI	*p* value
Main	Non-main	REF	–	–
	Main	1.79	1.62–1.97	<0.001
Sett activity	3	REF	–	–
	4	2.64	2.28–3.06	<0.001
	5	4.56	3.97–5.24	<0.001
Weather	1 (dry)	REF	–	–
	2 (drizzle)	1.37	1.18–1.59	<0.001
	3 (light rain)	1.17	1.00–1.36	0.041
	4 (rain)	1.52	1.33–1.74	<0.001
	5 (heavy rain)	1.63	1.39–1.91	<0.001
	6 (snow)	0.70	0.41–1.18	0.178
Minimum temperature	≤2 °C	REF	–	–
	3–5 °C	1.36	1.19–1.55	<0.001
	6–8 °C	1.08	0.94–1.23	0.26
	≥9 °C	0.74	0.63–0.86	<0.001
Maximum temperature	≤9 °C	REF	–	–
	10–12 °C	1.07	0.94–1.22	0.28
	13–16 °C	0.88	0.77–1.00	0.049
	≥17 °C	0.62	0.53–0.72	<0.001
No. Traps	N/A	1.13	1.12–1.15	<0.001
Season	Spring	REF	–	–
	Summer	0.47	0.38–0.57	<0.001
	Autumn	1.01	0.89–1.14	0.92
	Winter	1.36	1.20–1.53	<0.001
Year	2010	REF	–	–
	2011	1.14	1.00–1.31	0.06
	2012	1.06	0.92–1.22	0.42
	2013	0.92	0.80–1.07	0.29

REF reference, *No.* no preference

temperature was retained for inclusion in multivariable models based on its higher correlation with badger trapping success. Analysis of Spearman correlation coefficients for categorical variables did not show strong correlations ($p > 0.7$).

The full logistic regression model had adequate performance under the ROC curve (AUC = 0.71), and the Hosmer-Lemeshow goodness-of-fit test did not reveal a lack of fit in the model ($p = 0.70$). AIC of the mixed effects logistic regression models revealed a single most parsimonious model, the full model containing sett type, sett activity, precipitation score, and minimum temperature (Table 2, Fig. 2). When controlling for the combined effect of all other variables, there was a difference in badger trapping success between sett types, with captures more likely to occur at main setts than non-main sett (OR = 1.23, 95% CI 1.03–1.48). Badger captures were more likely at setts with activity scores of 4 (OR = 2.58, 95% CI 2.18–3.06) and 5 (OR = 3.04, 95% CI 2.54–3.64), compared to setts with an activity score of 3. Captures were only marginally higher at setts with activity scores of 5 compared to 4 (OR = 1.18, 95% CI 0.95–1.46). Captures were more likely in drizzle (OR = 1.20, 95% CI 1.00–1.43), light rain (OR = 1.08, 95% CI 0.89–1.3), rain (OR = 1.29, 95% CI 1.29–1.53), and heavy rain (OR = 1.47, 95% CI 1.21–1.79), compared to dry weather. Captures were less likely in snow than dry weather (OR = 0.41, 95% CI 0.13–1.31). Badger captures were more likely in minimum temperatures of 3–5 °C (OR = 1.33, 95% CI 1.12–1.59), 6–8 °C (OR = 1.20, 95% CI 1.01–1.43), and ≥9 °C (OR = 1.05, 95% CI 0.86–1.30) compared to minimum temperatures ≤2 °C. As the number of restraints set increased by 1, the odds of capturing a badger increased 6% (OR = 1.06, 95% CI 1.04–1.08). Badger captures were more likely in spring (OR = 1.78, 95% CI 1.38–2.31), autumn (OR = 1.9, 95% CI 1.46–2.42), and winter (OR = 2.4, 95% CI 1.81–3.13), compared to summer. Badger trapping success varied little in 2012 (OR = 0.98, 95% CI 0.84–1.14) and 2013 (OR = 0.98, 95% CI 0.83–1.13) compared to 2011.

Discussion

In this study, the proportion of trapping events resulting in capturing at least one badger was low with <10% of sett-nights resulting in a badger captured, highlighting the importance of determining factors associated with trapping success for implementing a vaccination program. Our results indicate that sett type, sett activity, weather, number of restraints set, and season all influence badger trapping success.

Sett characteristics proved to be important predictors of trapping success. Badger captures were more likely at main setts than non-main setts (Byrne et al. 2013a). Main setts are typically larger and more active than non-main setts (Smal 1995) and therefore have more badgers present or more entrances available for trapping (Byrne et al. 2013a). Trapping success also increased marginally with each additional restraint set, which is related to some degree to the number of sett entrances and paths available for trapping. Badger captures were more likely at setts with higher activity scores, and previous work has shown sett activity can provide a crude indication of badger presence (Wilson et al. 2003). Although the relationship between trapping success and sett activity was not surprising, the magnitude of the differences in capture odds among activity scores was notable. It is clear that setts with a score of 4 or 5 should be prioritized for maximizing trapping success, given odds ratios 2.6–3 times higher for scores of 4 or 5 as compared to 3. Sett activity was the most important factor (the highest odds ratios) contributing to badger captures in this study.

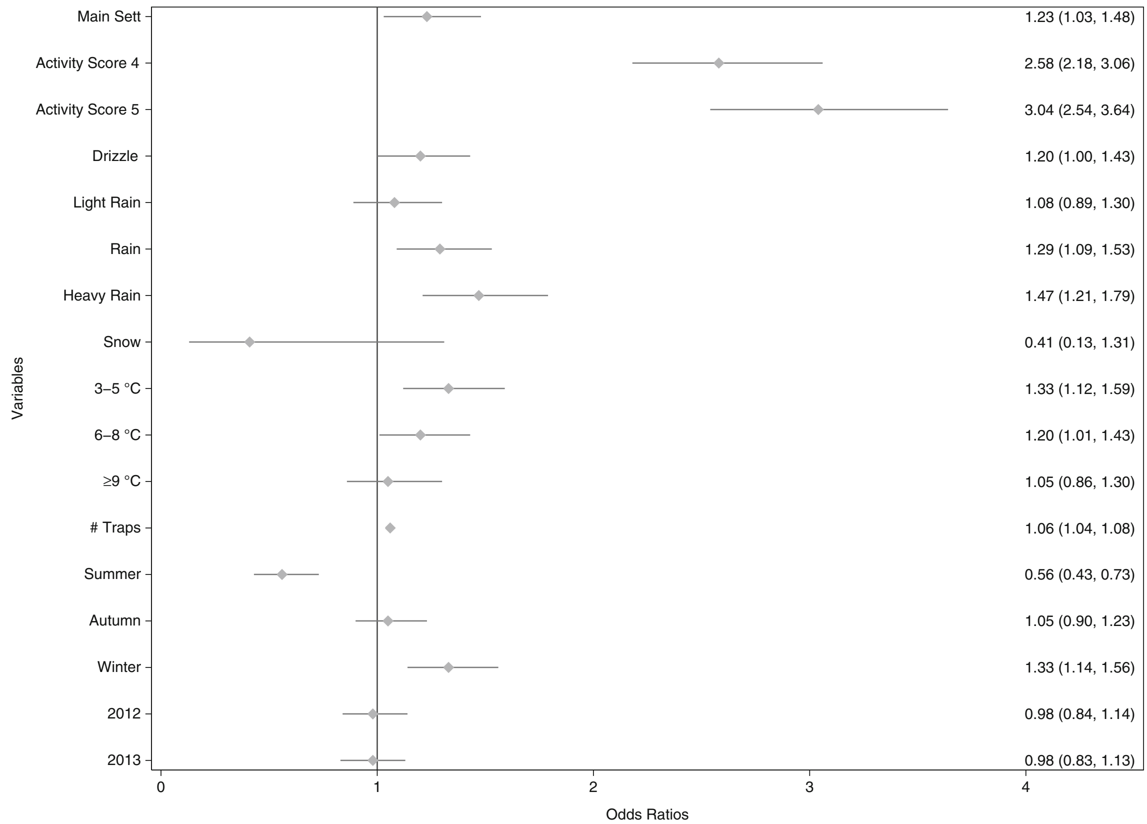

Fig. 2 Forest plot of odds ratios and associated 95% confidence intervals for variables in the top logistic regression model of badger capture success in County Kilkenny, Ireland. Values for odds ratios and 95% confidence intervals are reported on the right side of the plot. Reference groups for variables (given in parentheses) are as follows: non-main sett (sett type), activity score 3 (sett activity score), dry (precipitation), ≤2 °C (minimum temperature), spring (season), and 2011 (year)

Anecdotal reports in Ireland indicated badger captures might increase after nights with rain or wind. Our analysis supports this idea, with all but one category of rainy weather associated with increases in badger captures. Two factors may be driving the relationship between rainfall and trapping success. First, earthworms are an important food source for badgers and are reported in numerous studies of badger diet in Ireland (reviewed by Byrne et al. 2012b) and elsewhere (reviewed by Goszczyński et al. 2000). Badgers are likely to emerge after rainfall to take advantage of emerging earthworms, an abundant and easily obtained protein source. Elliott et al. (2015) reported that badgers in a study site in Ireland tended to make smaller foraging trips during wet weather. This was interpreted to mean that food resources (primarily earthworms) were more plentiful, and thus, badgers did not have to forage as far from their setts to find prey. Indeed, recently research from Ireland has found that badger body mass is significantly, and positively, affected by precipitation (Byrne et al. 2015a). Badgers appear to gain weight in the months following above long-term average rainfall, indicating that badgers are indeed gaining physiologically through increased access to food resources (Byrne et al. 2015a). The second hypothesis relates to badgers having a strong sense of smell and typically being wary of human scent, some to the point of failing to emerge from a sett overnight if the sett has been visited by a person during the day (Roper 2010). Rain may reduce human scent outside setts and around restraints, making badgers less wary of emerging from setts or approaching restraints. Frequent rainfall in Ireland offers ample opportunities for improved trapping success.

Badgers were most likely to be captured when minimum temperatures were in the 3–8 °C range and during winter compared to other seasons. The 3–8 °C temperature range comprised the interquartile range of the observed minimum temperature data in our study, indicating a preference for cooler and moderate temperatures. This observation is supported by anecdotal evidence from field staff, who reported poor perceived trapping success in warm weather and weather cold enough to produce frost or snow. Badgers do not hibernate in Ireland, but their activity levels are known to decrease during winter in northern latitudes, consistent with a type of torpor or winter lethargy (Fowler and Racey 1988; Roper 2010; Newman et al. 2011). It may be difficult for badgers to forage in frozen soils. Badgers experience a net negative energy balance and increased heat loss (Fowler and Racey 1988) despite a decrease in resting metabolic rate (McClune et al. 2015), with weight dramatically decreasing during winter months (Byrne et al. 2015a). Badgers may reside outside of the sett and sleep above ground during high temperatures (Roper 2010). Badgers may become less trappable during warm nights when they are away from their setts, as stopped restraints are predominantly set near sett entrances (Byrne et al. 2013b).

In a study of badgers in Wytham Woods, England, time-lagged temperature and precipitation contributed to trapping efficiency (Noonan et al. 2015). Noonan et al. (2015) also found a nonsignificant positive effect of rain on trapping efficiency during summer months, but a significant negative effect during spring trapping. Our data did not provide strong support for models with an interaction between weather and season. Season has been shown to affect badger trappability elsewhere (Tuyttens et al. 1999; Byrne et al. 2012a; Byrne et al. 2013a). Badgers in our study were most likely to be captured in winter, followed by autumn and spring. This finding is in agreement with prior studies in Ireland that found more badgers captured in autumn/winter (Byrne et al. 2012a) or winter/spring (Byrne et al. 2013a) and with field staff perceptions of optimal badger trapping during November–March. In England, trappability was found to be the lowest in autumn (Tuyttens et al. 1999), with some evidence of low trappability in winter from another study (Wilson et al. 2003). It is likely that the differences in seasonal trappability between Britain and Ireland relate to the predominant trap used (stopped restraints in Ireland and cage traps in Britain; Byrne et al. 2012a) and how these traps operate. Restraints rely on the ability to go undetected by the badger and are placed near sites through which badgers are known to move (sett entrances and along runs; Byrne et al. 2013a). In Ireland, restraints are not used very frequently during summer months, as vegetation growth can obscure badger setts (Byrne et al. 2013b; Byrne et al. 2013a). Restraints have been specifically designed to capture adults, not cubs (Sleeman et al. 2009), and in the spring, cubs may emerge from setts and disturb restraints, preventing adults from being captured. In contrast, cage traps are baited (typically with peanuts), so badgers are drawn towards the trap and can be placed away from badger setts, for example, near border latrines.

Trapping a significant proportion of badger populations is essential for reaching herd immunity via vaccination, the threshold where the infection is unable to establish in the susceptible population (Begon 2009). The basic reproductive ratio of a disease (R_0) must be less than one for disease eradication, although the entire population need not be vaccinated to achieve this (Begon 2009). The exact number of badgers that must be vaccinated to induce herd immunity is currently unknown. Simulations of an oral vaccination strategy based on data from England suggested at least 40% of badgers needed to be immunized annually to eradicate TB (Wilkinson et al. 2004), and benefits of vaccination are most likely with long-term annual vaccination programs (Hardstaff et al. 2013). Another simulation study using data from Ireland suggested that vaccination success depends on population density and prevalence of TB in badgers (Abdou et al. 2016). Trapping efforts must be prioritized at setts and under conditions most likely to yield badger captures.

We conclude that efforts should be concentrated on main setts and setts with activity scores of 4 or 5 and under rainy weather conditions when minimum temperatures range from 3–8 °C. The factors investigated in this study are advantageous in that all can be determined easily and inexpensively, allowing managers to make informed decisions about when and where to prioritize trapping efforts. Tailoring capture operations to optimal conditions should increase the trapping success of badgers and allow for increased vaccine delivery. An effective badger vaccination program will move Ireland closer to the goal of bovine TB eradication.

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Compliance with ethical standards

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Conflict of interest The authors declare that they have no conflict of interest.

Ethical approval All badger captures were conducted under licenses issued by the Irish Department of Health & Children and approved by the University College Dublin animal ethics committee. All applicable international, national, and/or institutional guidelines for the care and use of animals were followed. This article does not contain any studies with human participants performed by any of the authors.

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