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Comparison of badger (Meles meles) population density estimates among camera trap, hand-held and drone-based thermal imagery survey methods

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Comparison of badger (*Meles meles)* population density estimates among camera trap, hand-held and drone-based thermal imagery survey methods.

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Abstract

Accurate and reliable estimates of wildlife densities are fundamental for effective management, particularly of conflict species. The Eurasian badger (*Meles meles*) is such a species, serving as a wildlife disease reservoir implicated in the spread of bovine tuberculosis (bTB) in domestic livestock. Rigorous population data are essential to inform invasive management interventions. Indirect population assessments can be limited in their reliability, but the advent of high quality, affordable thermal imaging can transform density estimations, especially for nocturnal species. This study compared five non-invasive population estimation methods in a relatively well-enclosed focal badger population using: i) camera-trap Random Encounter Models (CT-REM), ii) camera-trap Distance Sampling, iii) thermal binocular point-transect Distance Sampling, iv) thermal binocular viewshed counts and v) thermal drone counts. Concurrent estimated badger densities in the location varied 21-fold (by 2000%) among methods, from 0.83 badgers km^{-2} using CT-REM, to a minimum number alive (MNA) of 18 badgers km^{-2} using thermal drone surveys. A significant negative relationship between badger density and viewshed area was revealed, converging on thermal drone estimates at a viewshed area of 0.32 km^2, which we thus recommend as a minimum area for thermal binocular surveys. Thermal equipment consistently recorded higher badger detections and reliable, repeatable counts. Our highest badger density estimate was 2-6 times higher than

previous indirect estimations. Thermal imaging, especially drone-based surveys, offer a rapid, non-invasive method that maximises detectability of nocturnal mammals. In the case of the badger, this would strengthen the scientific basis for bTB management, conservation and human-wildlife conflict mitigation strategies.

Keywords: Density estimation; Eurasian badger; *Meles* meles; Human-wildlife conflict; Thermal binoculars; Thermal drones.

Introduction

Human-wildlife interactions increasingly manifest as conflict worldwide, a trend that is expected to intensify as anthropogenic pressures on ecosystems grow (Can, 2021). The term “human-wildlife conflict” may itself be a misnomer, as many disputes arise between groups of people holding contrasting values and priorities regarding wildlife conservation and land use (Redpath et al., 2015). Such conflicts are often amplified by a global “state of emergency” in biodiversity conservation (McHugh et al., 2021), driven by rapid ecological change which accelerates biodiversity loss, thus resulting in challenges in monitoring population trends and assessing competing conservation outcomes (Leung and Gonzalez, 2024).

Ensuring global food security and ecosystem resilience requires integrated management of wildlife and their habitats within agricultural systems (Atwoli et al., 2021). However, such management is complicated by competing human interests and diverse ecological contexts. Human-wildlife conflict is particularly evident in the agricultural sector, involving a wide range of taxa from bumblebees to geese (Cope et al., 2003; Osgathorpe et al., 2011) and issues such as crop damage (Gill, 1992) and pathogen transmission (Boehm et al., 2007; Simpson, 2008). Climate change is further modifying the dynamics of disease transmission and species distributions, intensifying these challenges (Dash et al., 2021; Dutra et al., 2023).

Among the most critical areas where human-wildlife tensions intersect with economic and public health concerns is the management of wildlife reservoirs of infectious disease. Such reservoirs contribute to livestock morbidity and mortality, productivity losses, large compensation costs, trade restrictions and social controversy, particularly when legally protected species are involved. A prominent example is bovine tuberculosis (bTB), caused by *Mycobacterium bovis*, which persists in wildlife such as the Eurasian badger (*Meles meles*), protected to various degrees by wildlife conservation law, but contributing to disease transmission and thus acute and chronic human-wildlife conflict in agricultural landscapes (Gortazar et al., 2012; Akhmetova et al., 2023).

Effective wildlife management responses depend on accurate estimates of population densities. Population estimation is most robust when individuals can be readily detected, identified and re-identified (Burton et al., 2015), or at least not double counted. Camera trapping, for instance, has been successfully used to estimate

population size of uniquely marked species such as tigers, *Panthera tigris* (Karanth and Nichols, 1998). However, estimating populations of cryptic, nocturnal species whose individuals are not easily distinguished remains particularly problematic (Harley and Eyre, 2024). In such cases, laboursome genetic or other high-cost techniques may be necessary to ensure accuracy (Treloar et al., 2024).

Badgers present particular challenges for population estimation. Recent research has sought to refine "minimum number alive (MNA)" methodologies (Ross et al., 2022), while intensive capture-mark-recapture (Garrote et al., 2021; Allen et al., 2022) and technological advances in detection and automated recognition, for example, using camera trapping (Howe et al., 2017; Bedson et al., 2021), are subject to methodological bias and statistical uncertainty. Indirect indices are used, but these typically measure relative abundance over space or time rather than true density estimates, underscoring the need for clarity in distinguishing between abundance indicators and estimators (Ross et al., 2022).

Accurate population density estimates are particularly critical for species at the centre of management controversy, such as the badger, due to their epidemiological importance (Gortazar et al., 2012). Although bTB has been eradicated in many regions (Allen et al., 2018), it continues to affect cattle welfare and agricultural livelihoods in the UK and Ireland (AFBI, 2014b). The persistence of bTB is a complex, multifactorial issue (Allen et al., 2018; More, 2019) with cattle-to-badger transmission likely more common than badger-to-cattle, yet even limited wildlife-to-cattle transmission can substantially amplify herd infection (Akhmetova et al., 2023).

Effective management of badger populations must, therefore, be underpinned by reliable density estimations. This is especially important when evaluating interventions such as culling, vaccination, or test-vaccinate-remove (TVR) programmes. In Northern Ireland, a proposed non-selective cull was overturned following judicial review, reflecting both social opposition and the need for evidence-based decision-making (Cullen, 2023). Consequently, a TVR approach remains the most acceptable management option to non-farming stakeholders (DAERA, 2018), aligning with recommendations from the Chief Veterinary Officer's (CVO) review of bTB control (CVO, 2024). The efficacy of any intervention, however, revolves around accurate badger population size estimation and

105 the effectiveness of the intervention including trapping success and/or the proportion of
106 the population removed or vaccinated.
107 Previous efforts to estimate badger density and activity have included sett
108 enumeration (Feore, 1994; Reid et al., 2012), cage-trapping (AFBI, 2014a) and camera-
109 trap surveys (O'Mahony, 2015; Campbell et al., 2019). The Northern Ireland TVR
110 programme based on capture-mark-recapture methods reported densities at 5.3-6.3
111 badgers km^{-2} (Menzies et al., 2021), largely comparable to previous sett survey
112 extrapolations (Reid et al., 2012). However, mark-recapture has many assumptions that
113 can often be violated (e.g. random animal mixing), and multiplying sett number by
114 estimated social group size is sensitive to sett detection error and variation in social
115 group size (Jacquier et al., 2021). Continued refinement of survey and analytical methods
116 is therefore essential to improve the precision and reliability of badger population
117 estimates, enabling science-based management of this ecologically and politically
118 significant species.
119 Thermal detection devices such as binoculars and drone-mounted units have
120 emerged as a relatively new and transformative approach to population estimations,
121 becoming much more capable at discriminating among species at a distance, day and
122 night (Witczuk et al., 2018; Beaver et al., 2020). With equipment quality increasing and
123 costs decreasing, thermal imaging is being increasingly used across ecology (Williams,
124 2023). This study aimed to compare a range of population estimation methods,
125 traditional and novel, to capture the variability in population estimates, determine
126 population density in an area of high badger activity, and drive methodological
127 improvements. The first objective was to compare: i) camera trap Random Encounter
128 Models, ii) camera trap Distance Sampling, iii) thermal binocular imagery point transect
129 Distance Sampling, iv) thermal binocular imagery viewshed counts and v) thermal
130 imagery drone counts; all utilising an enclosed focal study area of known high badger
131 density. Secondly, the effect of survey area on thermal binocular density estimations was
132 examined in relation to drone counts. Such comparison will inform future survey
133 methods and intervention strategies by allowing identification of methods with realistic
134 and reliable badger detection rates.
135
136 ***Methods***

Study site

Badger surveys were conducted within a walled 3.8km^2 site within Mount Stewart Estate, Ards Peninsula, County Down, Northern Ireland (centroid latitude, longitude: 54.556712, -5.595461), managed by the National Trust (Fig 1).

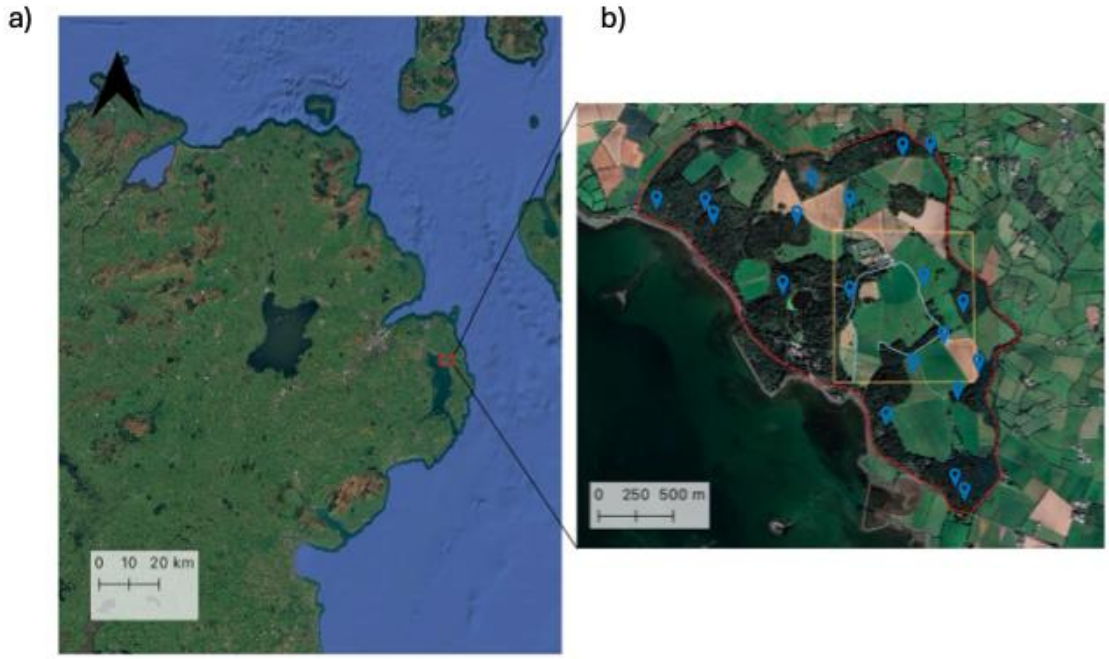


Fig. 1 a) Mount Stewart Estate, Northern Ireland. **b)** The Estate boundary in red, with the focal square in yellow. Locations of the camera traps are denoted by the blue markers and the transect by the cyan line

Land cover mainly consisted of broadleaved mix and yew woodland and improved grassland, mixed with arable and horticulture and neutral grassland (Morton et al., 2024). Lowland grassland in County Down has the highest badger density of any landscape in Northern Ireland (Reid et al., 2012), whilst mixed mature woodland and farmland is ideal habitat for excavation of setts and foraging respectively (Byrne et al., 2012). Within this site, a focal survey square of 1km^2 was selected to directly compare daylight sett surveys, thermal binocular imagery point transect Distance sampling, thermal imagery viewshed counts and thermal imagery drone counts, with viewshed referring to the area able to be surveyed from a viewpoint with thermal binoculars. A camera trap survey was completed across the whole study site to try and gather an estimate for the whole population in this area, as well as to sample different habitats. Habitat within the focal square consisted

157 approximately of 50% improved grassland, 25% arable and horticulture and 25%
158 broadleaved mix and yew woodland. While individual badgers can have home ranges
159 around 2.5 km^2 (Gaughran et al., 2018), it is estimated that group territories are around
160 500 m^2 (Murphy et al., 2011), therefore, in the context of capturing thermal detections of
161 badgers whilst foraging in fields to compare methods, a focal square of 1km^2 was
162 deemed logistically and ecologically appropriate.
163
164 *Number of setts*
165 Badger density in this area based on land-class (Drumlin farmland) was expected to be
166 5.17 badgers km^{-2} (95% CI 2.99- 7.86), average social group size of 6.05 individuals (95%
167 CI 5.1-7) and sett density of 0.85 active setts km^{-2} (95% CI 0.59 -1.12) (Reid et al., 2012).
168 However, our study site was an area of known high badger density, with Mount Stewart
169 rangers estimating a population of around 40 badgers with 10 known setts, equating to
170 an approximate badger population density of 10.5 badgers km^{-2} and a sett density of 2.65
171 setts km^{-2}. Upon completion of a daylight survey of the focal square, three setts were
172 detected indicating a baseline badger density, based on mean group size and setts
173 detected within the focal square, of 18.15 badgers km^{-2}.
174
175 *General methods*
176 Camera trapping utilised Bushnell HD Trophy Cams deployed as randomly placed point
177 transects with a minimum distance of 100 m between points throughout the whole study
178 site (Figure 1a, b). This randomised approach resulted in 47% of the cameras being in
179 areas of woodland, 26% being in fields and 26% being on the boundaries of fields and
180 wooded areas (Fig 1b). Cameras were mounted on vertical structures 40-100 cm
181 aboveground and operated on night mode, restricting sampling to match the
182 predominately nocturnal behaviour of badgers. Where camera height was above
183 estimated badger height it was angled downwards to minimise the risk of missed
184 detections due to height (Moeller et al., 2023). Cameras were set to record a 'snapshot
185 moment' of two consecutive photos 1 second apart. At deployment, bamboo canes were
186 used to mark a distance of 10 m at 1 m intervals directly in front of each camera for a
187 reference photo to be taken before the canes were removed. Subsequently, a 1x1 m grid
188 was generated, morphed to the ground topography, upon which animal detections were

superimposed with the radial detection distance estimated following Caravaggi et al. (2016), who reported a test accuracy of ±20 cm where error was random, such that subsequent density estimates were not positively or negatively biased. Camera traps were left *in-situ* for one week, whilst the thermal binocular transect survey was ongoing. All footage was processed manually, identifying individual badger detections, group size and detection distances.

Survey techniques

1. Camera trap Random Encounter Model

Following Rowcliffe et al. (2008), a Random Encounter Model (REM) was created using camera trap detections and survey effort (hours of observation) from 19 placed cameras. Average badger movements per unit time was derived from Redpath et al. (2023), who GPS-tracked badgers in County Down, giving a nightly distance travelled of 3.31 km. The radius of the camera detection zone was 0.014km, as tested in the field, and the angle 0.873 radians. Density was derived following Palencia et al. (2021) as:

$$D = \frac{Y}{H} \cdot \frac{\pi}{v \cdot r \cdot (2 + \Theta)}$$

Where D was the population density, Y the number of camera trap detections, H the total survey effort in hours, v the average nightly distance travelled by a badger, r the radius of the camera trap detection zone and Θ the angle of the camera trap detection zone in radians.

2. Camera trap Distance Sampling

Camera trap data were also analysed in R version 4.5.2 (R Core Team, 2026), using the '*Distance*' package (Miller et al., 2019), following the methodology outlined by Howe et al. (2023). The proportion of time that the target species was available to be detected was estimated from a detection function generated using the package '*Activity*' (Rowcliffe, 2023) to restrict density estimates to badger peak period of activity (between the hours of 2000 and 0600). A 'snapshot' approach allowed camera trap effort to be derived from the number of seconds cameras were available to observe (Howe et al., 2017). Distances

were binned into three categories: 0-3 m, 3-5 m and 5-6 m, being right-truncated at 6 m. Detection shoulder model selection assumed uniform cosine, half-normal cosine and hazard-rate simple polynomial candidate models evaluated using Akaike Information Criterion (AIC).

3. Thermal point transect Distance Sampling

A 2 km transect was walked, the observer stopping at 20 point transects spaced 100 m apart, before using Pulsar Merger LRF XP50 thermal imaging binoculars to make a 360° observation. Due to the nocturnal nature of the fieldwork and concerns with crossing fields with challenging terrain as well as fields occupied by livestock in darkness, the chosen transect was along roads and paths within the focal square. Whilst the use of paths can introduce a bias due to animal movement (Thomas et al., 2010), it did cover all three types of land-cover within the 1km^2 square and provided a suitable viewshed for the use of thermal binoculars. The radial distance from the observer to each detected badger was estimated using a built-in laser range finder. The observer took care to avoid double counting by only recording a detection if they were confident it was a novel individual based on its positioning. This survey was repeated once per night in the same order for 7 nights throughout early August 2023 as weather allowed, commencing an hour after sunset. Distances were binned into six equal 80 m interval categories out to 480 m after which the data were right-truncated. Detection shoulder model selection was the same as above, fitted using the software 'Distance for Windows 7.5' (Thomas et al., 2010).

4. Thermal viewshed Minimum Number Alive

Using the same thermal binoculars as above, observations were conducted from elevated points, such as high seats, selected for a view of the surrounding landscape, particularly fields, in order to observe and record badgers foraging after they emerge from their setts (viewsheds). Due to limited range of detection, observations were carried out by two observers at two different viewsheds where possible. There were 5 viewsheds within a focal 1 km^2 square (Irish grid reference J5570) within optimal foraging agricultural habitat within the study site, and all viewsheds were visited at least twice except for one which was deemed to overlap too much with another viewshed and thus only visited

once. Viewshed area was estimated using Google Earth 10.59.0.2 (Google Earth, 2024) based on maximum detection distances estimated using a laser range finder and visual lines of sight during the day; these areas varied among observation points, ranging from 0.08-0.28 km^2. Upon arrival at the observation point a settling in period of approximately 20 minutes was observed, after which observations were begun, with observers remaining at the observation point for approximately three hours, carrying out scans every 10 minutes to observe badger foraging. Due to the slow average speed of badgers (0.86 km/h (Redpath et al., 2023)), and 10-minute intervals between scans, within which theoretically badgers would move approximately 143 m based on a speed of 0.86 km/h, a distance which the thermal binoculars can easily see, it was assumed that double counting would be low with this method. Individuals were able to be tracked as they moved across a landscape and novel badgers only recorded as such when it was definite e.g. could be seen within the same scan as individuals already counted, or observed as appearing from a different direction/area to individuals already counted. The absolute badger count was taken as the minimum number alive (MNA) within each viewshed reported as a density per km^2. It should be noted that small parts of the focal 1 km^2 square were unsurveyed i.e. woodland and behind elevated terrain, thus the MNA was a lower bound. Nevertheless, as viewsheds were chosen to provide optimal vantage points of agricultural grassland, the badgers optimal foraging habitat, it is quite plausible that most active animals aboveground may have been detected.

5. Thermal drone Minimum Number Alive

Aerial surveys were conducted using a DJI Mavic 2 Enterprise Advanced drone fitted with a thermal imaging camera. Flights were based on a linear transect using a 'lawnmower' sampling design following Olsen et al. (2023) within the same focal 1 km^2 square sampled using the viewsheds above and, as pre-programmed lines were flown, the pilot was consistently carrying out 360° scans. Again, visual lines of sight permitted coverage of open agricultural grassland but detection was not possible under woodland canopy, yet 75% of the survey square was covered using 5.75 km of flown line transect lines with 100 m between parallel lines. Due to limitations of the battery life the focal square was split into three 'drone transects' each with a different launch site, with the pilot remaining static throughout individual drone transects but changing position between them for

optimal signal strength between the drone and the controller. Surveys were repeated over 3 nights with the order of drone transect randomised each time. The drone flew at a speed of 6 m/s at an altitude of 50 m. Badgers have been reported to remain undisturbed by drones at an altitude of 60 m (Larsen et al., 2023), a pilot survey within this site revealed that most individuals did not demonstrate any disturbance until the drone had lowered to 30m, while at 50m consistent positive species identification could be made and was chosen for the study. When an animal was detected the flight plan was paused and the drone lowered until a confident species identification could be made. As with the viewshed methodology, with the consideration of badger speed and slow foraging behaviour, as well as the vast area the drone could monitor with a variable camera angle along the transect lines, it was determined that double counting was unlikely. This was due both to the drone being faster than a foraging badger, and the ability of the drone controller to show where the drone has already been on the display; if a badger was observed in an area the drone had already seen it was not counted as a novel individual, with novel individuals only recorded where the pilot could be certain i.e. due to multiple badgers in one scan and the directions from which the observed individuals came from, and the spots within which they were foraging. From these surveys the absolute count was taken as the MNA.

Thermal viewshed-drone comparison

Estimated badger density derived from viewsheds, where badger densities were extrapolated based on area observed, was plotted against viewshed area using a 2-parameter exponential non-linear regression in Sigmaplot 15. The convergence of estimates derived from thermal drone MNA was then established, giving the viewshed area necessary to produce comparable badger density estimates of thermal binoculars and thermal drones.

Results

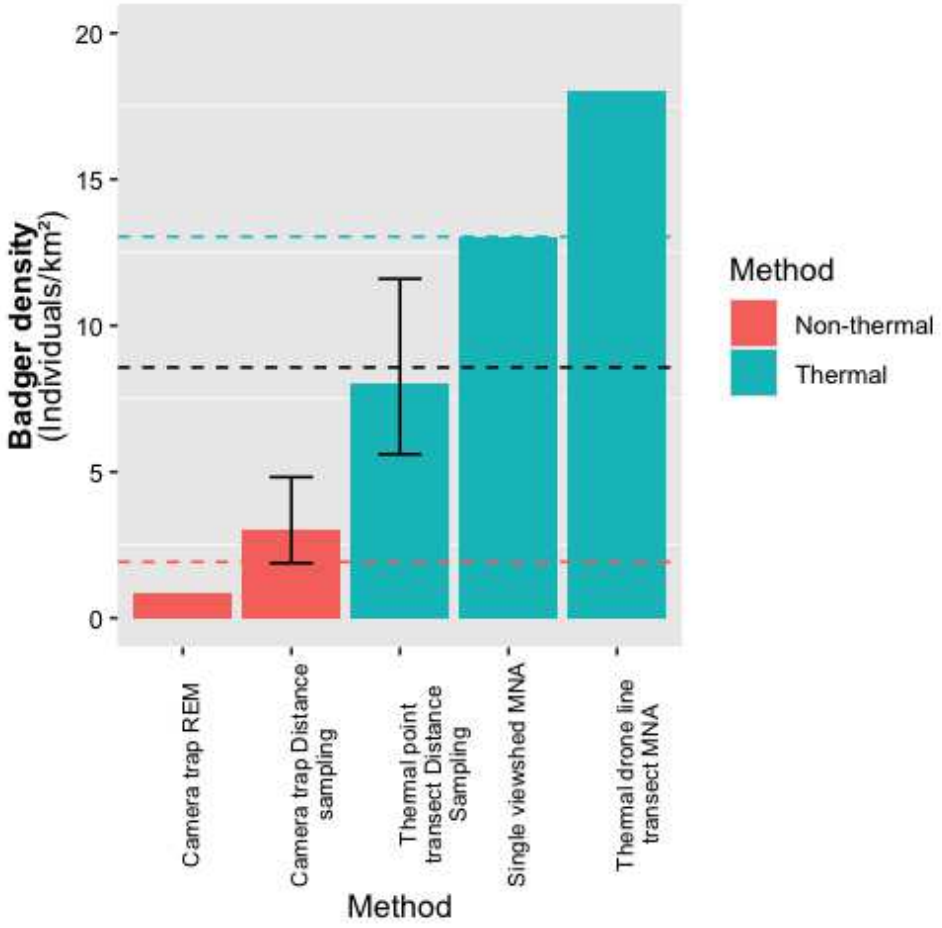


Fig. 2 Comparison of badger density estimates derived from five different survey methodologies. Whiskers denote 95% confidence intervals where applicable, whilst the other bars are absolute estimates. The dashed red line is the mean density estimates from all non-thermal methods, the black dashed line is the mean density estimate across all methods and the blue dashed line is the mean density estimate from all thermal-supplemented methods

1. Camera trap REM

The REM was calculated from 56 badger detections across 1,596 hours of camera trapping effort, yielding an estimated density of 0.83 badgers km^{-2} (Figure 2). Badgers were detected at five of the 19 placed cameras.

2. Camera trap Distance Sampling

A uniform cosine model was selected (Fig. 3a) supported by a goodness-of-fit test (AIC = 102.46, CV = 0.24) derived from 56 detections (with a mean of 8 badger detections/night across all cameras) yielding an estimated badger density of 3.00 (95% CI 1.88 - 4.82) badgers km^{-2} (Figure 2).

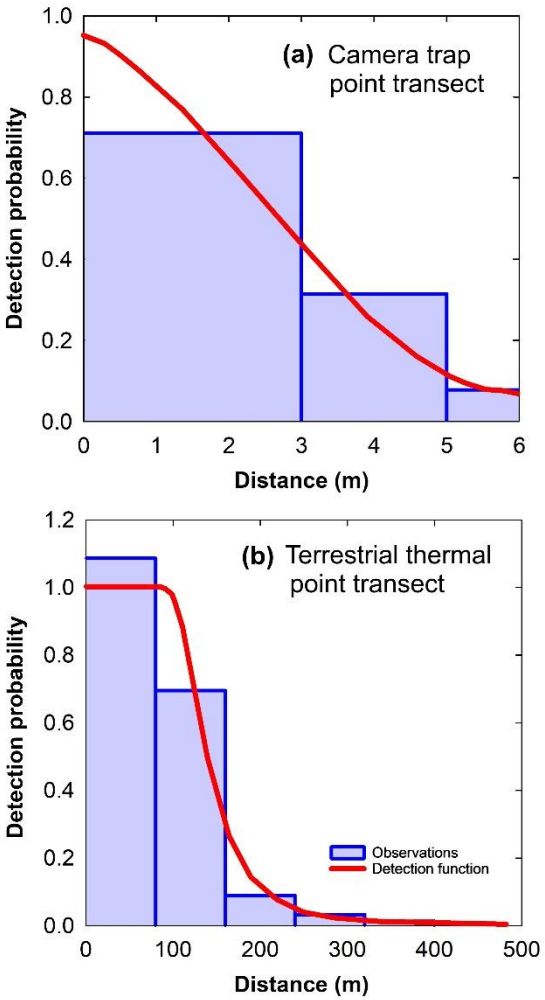


Fig. 3 Distance Sampling probability detection functions (red lines) fitted to badger observations (blue bars) using **a)** a hazard-rate simple polynomial model for 80m equal intervals derived from terrestrial thermal point transects and **b)** a uniform cosine model for unequal intervals derived from camera trap point transects

3. Thermal point transect Distance Sampling

A hazard-rate simple polynomial model was selected (Fig. 3b) supported by a goodness-of-fit test (AIC = 1147.63, CV = 18.28) derived from 91 detections (with a mean of 13 badger detection/night; range 9 - 19), yielding an estimated badger density of 8.02 (95% CI 5.57 - 11.55) badgers/km^{-2} (Figure 2).

4. Thermal viewshed Minimum Number Alive

A total of 89 badger detections were recorded across 5 viewsheds on a total of 12 observer nights yielding a mean of 7.42 badgers/night (range 4 - 13). Thus, the highest MNA during any one night was 13 badgers within the focal 1km^2 survey square (Figure 2).

5. Thermal drone Minimum Number Alive

A total of 42 badger detections were recorded across 3 nights from drone line transects yielding a mean of 14 badgers/night (range 10 - 18). Thus, the highest MNA during any one night was 18 badgers within the focal 1km^2 survey square (Figure 2).

Method comparison

There was a significant negative relationship between estimated extrapolated badger density derived from viewsheds and viewshed area ($F_{df=1,4}$= 72.250, p=0.003, R^2= 0.924; Figure 4). Small viewsheds yielded unrealistically high densities from abundance counts (up to *ca*. 77.28 badgers km^{-2}), declining as viewshed areas increased in size to *ca*. 23.33 badgers km^{-2}, with this modelled relationship converging with the thermal drone MNA estimate of 18 badgers within the focal 1km^2 survey square at a viewshed area of 0.32 km^2 (Figure 4).

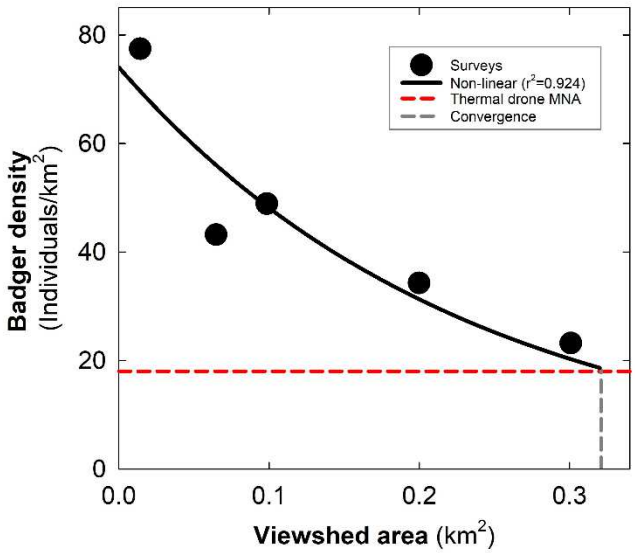


Fig. 4 Badger density estimates with thermal binoculars across five surveyed viewsheds of varying area suggest a minimum viewshed survey area of 0.32km^2 is required to converge on the thermal drone MNA

The five different methods generated highly variable estimates of badger density and/or MNA, from 0.83 badgers km^{-2} across the whole 3.8 km^2 survey site (i.e. *ca*. 3 badgers within the Mount Stewart study site) using the camera trap REM, to 18 badgers km^{-2} as the minimum number alive within the focal 1 km^2 survey square derived from the direct counting of badgers with the thermal drone (Figure 2). As thermal was introduced into methods, the resulting density estimations increased, from the transect survey, to the singular viewshed observations, to finally the aerial thermal surveys. This resulting MNA of 18 badgers in the focal square suggests that the total number throughout the entire site is likely a much higher number.

In terms of badger detections as a function of survey effort, the thermal drone approach was the most efficient with the highest rate of detections per night and the lowest relative effort (Table 1), with only the drone and the thermal binocular viewshed methods able to give an idea of social group numbers in an area.

Table 1- Survey dates and effort across methods alongside metrics of badgers detected

Method	**Dates surveyed**	**Total effort (hours)**	**Average distance from which badger was observed (metres)**	**Average badger detections/night**	**Recorded badger groups**
Camera traps	03/08/2023 - 10/08/2023	1596	3.625	8	NA
Thermal binocular transects	01/08/2023, 02/08/2023, 05/08/2023, 06/08/2023, 07/08/2023, 09/08/2023, 10/08/2023	14	124	13	NA

Thermal binocular viewsheds	11/05/2023, 02/08/2023, 16/08/2023, 23/08/2023, 04/10/2023, 30/01/2024, 22/02/2024	21	201	12.86	3
Thermal drone	14/11/2024, 03/12/2024, 14/01/2025	6	NA	14	3

382

383

384 **Discussion**

385 Effectively monitoring animal populations is vitally important in mitigating areas of
386 human-wildlife conflict (Walters et al., 2024; Smith et al., 2026). The present study was a
387 comparison of traditional methods of population estimation with novel thermal-
388 supplemented techniques to derive population densities of a nocturnal, elusive species,
389 the Eurasian badger, *Meles meles*. Concurrent survey methods estimated densities that
390 varied up to 2000% across methods, with traditional, indirect methods being
391 substantially lower than estimates from thermal-supplemented methods, with thermal
392 drone surveys estimating densities of 18 badgers km^{-2} in this badger hotspot. Such
393 findings could be applied to future national surveys and would be useful in increasing the
394 precision and addressing uncertainty of animal censuses in areas of high badger density
395 due to the increased detectability of badgers when using thermal imaging.

396 Within camera trap methods, estimates ranged from 0.83 badgers km^{-2} using a
397 camera trap REM to 3 badgers km^{-2} from camera trap-distance sampling. The randomised
398 nature of the camera trap placement successfully sampled different habitats across the
399 study site, indeed, where badgers were detected by camera traps, 60% of the detections
400 occurred in woodland areas, 20% in area of pasture and 20% on the border of pasture
401 and woodland. Badgers were detected on the first night of camera-trap placement, this
402 National Trust property is well visited both by civilians and wildlife documentarians, likely
403 resulting in a fairly human-tolerant badger population. The minimum number of 50

detections was obtained, in the future if methods were to be repeated, a greater sample size would increase the power (Palencia and Barroso, 2024; Wiegers et al., 2026). Camera trap REM produced the lowest density estimates, consistent with previous evidence that REMs tend to underestimate populations of species exhibiting non-linear or localized movement patterns (Rowcliffe et al., 2008; Palencia et al., 2021). Badger foraging behaviour, characterized by intensive local activity and frequent pauses, likely violated the assumption of constant movement speed central to the REM framework. Consequently, the REM-derived estimate when applied to a species such as the badger should be regarded as unrealistically conservative.

Camera trap Distance Sampling yielded a higher badger density estimate (3.00 badgers km^{-2}), aligning more closely with densities reported in previous Northern Ireland studies derived from sett-based extrapolations and capture-mark-recapture approaches of 2.51 badgers km^{-2} and 5.8 badgers km^{-2} respectively (Reid et al., 2012; Menzies et al., 2021). The approach includes direct distance estimation but remains constrained by detection range and habitat complexity, particularly where vegetation or terrain obscures individuals from view. Camera trap methods demonstrate the feasibility of using static sensors for abundance estimation, but their reliability depends heavily on detection modelling and behavioural assumptions (Howe et al., 2017). In general, where camera traps are used with *M. meles* as a focus species, unless camera traps are placed to specifically monitor setts, they can be a challenging species to survey using this method due to having a relatively low proportion of detection availability (Mason et al., 2022).

Within thermal-supplemented methods, estimates ranged from 8 - 18 badgers km^{-2}. Population estimates from thermal imaging drone surveys were 2-6 times higher than previous estimates for badger population density locally (Reid et al., 2012; Menzies et al., 2021). These results highlight the variability inherent in population estimation techniques and the importance of method selection when informing management decisions for cryptic, nocturnal species. Further, the advent of high-quality, low-priced thermal equipment is clearly a highly useful tool to use in such population estimations, particularly at night.

Thermal approaches for direct badger observation and enumeration consistently produced higher population estimates, with high confidence due to direct badger observations carried out in real time. Point-transect Distance Sampling yielded a density

of 8.0 badgers km^{-2}, within the upper range of previous estimates from similar habitats (Feore, 1994; Menzies et al., 2021), the examination of such nocturnal point transects was, at its core, an investigation into the suitability of thermal imaging technology in using transect distance sampling for a nocturnal species. This increased detection rate likely reflects enhanced thermal visibility under nocturnal conditions and the broader field of view compared with stationary camera traps. The viewshed and drone-based methods, which estimated minimum numbers alive of 13 and 18 badgers km^{-2} respectively, indicated that non-thermal approaches may substantially underestimate true local densities. Thermal viewshed counts demonstrate the utility of thermal imaging to monitor individual setts or territories which can increase knowledge on group size in an area, and thus be applied to sett extrapolation counts to improve precision. Singular thermal viewsheds can be limited by the small area that they are able to observe, and thus their application to density estimates across larger areas might be limited. However, the use of man-made elevated viewpoints to increase viewshed, as well as the addition of secondary observers surveying with thermal binoculars from non-overlapping viewpoints can easily mitigate this issue where terrain or viewshed is challenging. Additionally, drones do not experience this limitation.

Drone-based counts, provide rapid, wide-area coverage and capture unique foraging individuals across open grassland habitats, suggesting high detection efficiency with minimal disturbance consistent with observations by Larsen et al. (2023). Moreover, due to the speed of drone flight over landscapes and the reasons detailed in the drone methodology, double-counting is highly unlikely, and the resulting detection rates are also unlikely to substantially under-count. Drones, depending on the model, can be limited by battery life, affecting flight time, although the purchase of additional batteries for use in these drone surveys mitigated this. This type of surveillance excels in areas of open habitats such as grasslands, and while nocturnal drone surveys can be challenged by topographical factors such as steep terrain, alterations to the flight plan, including programmed waypoints where drone altitude can be changed, or manual flight by the pilot can mitigate these difficulties in the field. Additionally, for *M. meles* where foraging in such agricultural habitats is a constant ecological pattern, focusing on these habitats creates a snapshot within which their availability for detection is relatively high, with survey methods taking advantage of their style of foraging to increase detectability.

Utilising the number of individual badgers detected aboveground as an effective MNA due to it being a direct count across an area.

There was an observed gradient in estimated densities across methods, with thermal viewshed and drone surveys appearing particularly suited to estimating badger population densities. Whilst many surveyors may have access to thermal binoculars, fewer will have access to high spec, costly thermal drones. Here, we show that the viewshed area over which thermal binocular observations are made is critical. Surveying small areas with thermal binoculars can produce unlikely high density estimates when animals are detected and estimates extrapolated. We found that badger density estimates declined significantly with increased viewshed area, converging on more realistic estimates directly comparable to thermal drone estimates when 0.32km^2 was surveyed with thermal binoculars. Thus, in this landscape, this likely represents the minimum recommended survey area when using thermal binoculars for direct observation. Such methods can produce reasonable minimum number alive estimates per unit area, yet these represent lower bounds as parts of the landscape may not easily be observed using direct observation. Thus, incorporating formal detection function modelling (e.g. Distance Sampling) into viewshed and drone methods could yield confidence intervals providing some measure of statistical confidence.

Our maximum badger density (18 badgers km^{-2}) at this badger hotspot area was 2.9-3.4 times (186-240%) higher than the capture-mark-recapture estimates of 5.8 (5.3-6.3) badgers km^{-2} from the Northern Ireland DAERA test-vaccinate-remove (TVR) programme (Menzies et al., 2021) conducted within a 100 km^2 area elsewhere in County Down (2014-2018); and 2.3-6.0 times (128-500%) higher than the sett extrapolation estimates of 5.2 (3.0 - 7.9) badgers km^{-2} for Drumlin farmland in County Down from the last Northern Ireland Badger Survey in 2007/08 (Reid et al., 2012). The badger densities estimated from the drone were almost exactly in line with estimates from the local sett surveys completed as part of this study. Sett detectability at this site was reliable due to it being a National Trust managed site with experienced rangers knowing the land well, of the estimated 10 setts across the entire property, 30% were in the focal square. This study shows that where local knowledge is great, and sett detection rate is known to be high and group size informed (as thermal methods can successfully inform), drone survey counts can be exceptionally accurate. This indicates both the value drone surveys can

provide as a check for sett extrapolation methods, as well as the potential of drone methods in providing expected population numbers for an area, which in turn, could guide daylight survey methods, particularly as sett detectability over large areas- specifically in cases where land-owner knowledge to inform sett detection may be unavailable- can be uncertain, in such instances thermal drones provide a reliable alternative.

Accurate population estimates are critical for evidence-based management of badgers, particularly in regions affected by bovine tuberculosis (Gortazar et al., 2012; Allen et al., 2018). Under- or overestimation of badger density can directly influence the perceived efficacy and ethical justification of interventions such as culling and test-vaccinate-remove (TVR) programmes (DAERA, 2018; CVO, 2024). The highest densities reported here using direct observation thermal methods, especially those from night-time drone surveys, suggest that badger populations in favourable lowland habitat may greatly exceed previous estimates based on sett count extrapolations from land-class type and capture-mark-recapture data at the county level, and highlights the importance and limitations of local sett surveys based on sett detectability as well as the value of additional methods in informing local population estimates. This has serious implications for both disease transmission modelling and resource allocation for vaccination and/or population control operations. That said, previous estimates were derived from much larger areas i.e. the TVR capture-mark-recapture estimate was conducted throughout a 100 km^2 area elsewhere in County Down (Menzies et al., 2021), while sett extrapolations from the Northern Ireland Badger Survey were derived from 212 x 1 km^2 squares spread uniformly throughout County Down (Reid et al., 2012). These studies will, therefore, have more representatively estimated average density across landscapes incorporating suboptimal habitats, while the current study focused solely on a small 3.8 km^2 study site of ideal badger habitat. On the other hand, neither the sett extrapolation nor the mark-recapture studies recorded anything in the region of the higher badger densities captured in the present study; indeed, the former studies may have suffered low sett detection and/or low social group size estimates, while mark-recapture has notoriously strict assumptions that could seriously underestimate badger densities when violated. While camera trap sampling in the present study was, by necessity of the method, spread throughout the total extent of our study site, thermal

methods were focused on a 1 km^2 square, where reliable and repeated badger foraging behaviour could be observed to facilitate population counts. It is perhaps therefore, unsurprising that with thermal equipment we report markedly higher densities than previous studies, yet these data evidently demonstrate that maximum badger density locally may well be substantially higher than previous estimates, with implications for bovine tuberculosis epidemiology and management interventions. Future work could consist of a longer-term, more intensive camera-trap investigation across this site to compare more rigorously with thermal supplemented methods in this area, as well as the application of thermal-supplemented methodologies across larger areas.

Thermal detection technologies clearly offer distinct advantages for monitoring cryptic nocturnal mammals, including non-invasive sampling, reduced observer disturbance and rapid spatial coverage (Cilulko et al., 2013; Bushaw et al., 2019). With the construction or selection of elevated viewpoints and multiple observers surveying non-overlapping areas, line-of-sight constraints can be mitigated, and in terms of species recognition thermal sensors are now of such quality that this is rarely an issue from a reasonable distance. Drone-based thermal surveys diminish these challenges further through systematic coverage and altitude control. As with most data collected in the field, regulatory permissions, operator training and consideration of weather need to be taken into account, but upon these acquisitions and field-appropriate weather the drone can efficiently cover large areas of land, particularly if multiple batteries are used to extend flight time. Future thermal surveys should representatively sample the landscape while integration with automated image analysis and detection probability modelling frameworks could further enhance representativity, accuracy and reproducibility.

This study demonstrated that non-invasive, thermal based surveys, particularly drone-based methods, can detect substantially higher numbers of badgers than other survey approaches. These findings underscore the importance of method selection in ecological monitoring and suggest that thermal imaging can serve as both a complementary and standalone tool for estimating population size in nocturnal species. Incorporating such approaches into routine wildlife surveys could improve the reliability of density estimates, thereby strengthening the scientific foundation for wildlife management and conflict mitigation in agricultural and other landscapes.

Statements and declarations

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Competing interests

The authors declare no competing interests

Data availability statement

Meles meles are a protected species in the UK under the Wildlife and Countryside Act 1981, as such, data is available upon request.

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