Effects of supplementary feed for game birds on activity of brown rats *Rattus norvegicus* on arable farms

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Abstract

Brown rats are widespread in agroecosystems, but our understanding of factors affecting their activity is incomplete due to cryptic, nocturnal behaviours. Indirect monitoring methods include tracking plates and camera traps. Supplementary feeding of game birds may provide resources for rats away from farm buildings, allowing them to persist in winter when there is little other food available. Developing reliable methods to monitor such populations will facilitate landscape-scale studies of rat populations in farm environments and aid ecologically based approaches for controlling rats on farms. We compared camera traps and tracking plates to monitor brown rat activity near game bird feeders at a mixed farm in Northumberland, UK. Generalized linear models (GLM) were used to compare rat incidence estimated from camera traps and tracking plates. A strong positive relationship was found between the two methods, although tracking plate estimates were less reliable when rat activity was very low. Factors that affected populations of brown rats near game bird feeders were assessed via linear mixed-effect models (LMM) of monthly tracking plate data (October 2017 to September 2018). Populations were highest at the feeders (0 m) compared with further away (10 m, 20 m) and were also higher in periods of cold, wet weather and when more food was available from the feeders. Rodenticide application near feeders did not significantly affect activity, nor did land cover 100 m around each feeder. A highly significant relationship was detected with food supply, suggesting that the use of game bird feeders could potentially have major impacts on rat population dynamics.

Keywords Brown rat · Bird feeder · Tracking plates · Supplementary food · Environment factors

Introduction

Game birds such as pheasant *Phasianus colchicus* L. and red-legged partridge *Alectoris rufa* L. are economically important farm birds in the UK, with over 40 million gamebirds reared

and released into the wild annually (Bicknell et al. 2010; Natural England 2009; Roos et al. 2018). Game bird shooting is worth up to £1.6 billion to the UK economy (PACEC 2014) and is therefore an important additional source of income for many farmers and landowners. However, in intensively managed agroecosystems, there are often insufficient food resources during the winter for the released pheasants and partridge to survive; therefore, many farmers and gamekeepers use artificial feeders to supplement their diets. These game bird feeders are usually placed in field margins where game birds and songbirds live or are found (Parish et al. 1995), and feeders are usually filled with grain in winter to early spring (October to April) to provide food for both released and wild game birds (Sanchez-Garcia and Buner 2017). The additional food resources from feeders also aid many songbird populations as availability of other foods such as invertebrates is reduced in winter as the latter overwinter as eggs, larvae or pupae (Knight 2017). Benefits of supplementary feeding in winter include maintenance of good gamebird body condition, increased breeding success the following spring, reduced

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gamebird dispersal away from a farm and hence enhanced net economic returns from shooting (Sanchez-Garcia and Buner 2017). Additional beneficial side effects on songbirds include better overwintering survival rates (Siriwardena et al. 2008) and improved breeding densities (Stoate and Szczer 2001).

Unfortunately, pest species, including brown rats *Rattus norvegicus* (Berkenhout, 1769), also consume the additional food from game feeders, which may result in an increase in their numbers on farmland. For example, 54% of camera-trap images ($n = 160,000$) taken from 259 bird feeders were of non-target species such as rats, mice, crows and magpies (Sánchez-García et al. 2015). The beneficial effects that arise from provision of supplementary food for game birds may be reduced if the feeders attract pest species such as brown rats, which are also predators of game bird eggs and chicks (Duron et al. 2017). Despite this, there have been relatively few farm studies that have investigated the relationship between the activity of non-target small mammals, especially brown rats, and provision of supplementary food via game bird feeders (Brakes and Smith 2005; Sánchez-García et al. 2015).

Methods to assess small mammal populations include mark-recapture techniques (which requires use of live-capture traps) and camera traps. The former is very labour intensive and may be biased by ‘trap-happy’ or ‘trap-shy’ individuals (Nichols et al. 1984); hence, the use of camera-traps has become widespread in recent years. Camera traps provide data on absolute presence, estimated abundance and activity from the images of animals (O’Connel et al. 2011; Swann et al. 2011). Unfortunately, camera traps are relatively expensive, with the costs of most models £150 to £300, and often considerable time is needed to process large volumes of imagery, in which the camera trap may have been triggered by ‘non-target’ species such as birds. This makes camera traps challenging to deploy over large areas, and tracking plates have the potential to provide an inexpensive alternative (less than £1.50 each). It is important to know if the estimated rat population derived from tracking plates can be confidently used by researchers. In contrast, camera traps provide images of animals, and hence presence/absence data can be derived directly. In theory, camera traps only record presence data, but in practical use, a large number of empty images are also recorded, where no animal is visible. It is important to recognize, however, that neither tracking plates nor camera traps have been validated for rats away from farm buildings, where their population densities are likely to be low. They have been successfully used in urban slum areas in South America (Hacker et al. 2016), which suggested a strong relationship between rat activity, as measured by tracking plates, and overall rat infestation levels. Without robust data on population size (e.g. from removal trapping), it must be acknowledged that agreement between tracking plates and camera traps increases our confidence in the precision, but not necessarily accuracy, of population indices.

The activity of small mammals such as brown rats may also be affected by landscape composition (Heroldová et al. 2007), especially the availability of different semi-natural habitats, across a farm and especially the vicinity of bird feeders. Meteorological conditions, such as temperature and rainfall, also change during the year and are known to affect small mammal activity (Vickery and Bider 1981). Some farmers may also deploy pest control measures such as rodenticides near bird feeders in an attempt to reduce their numbers and activity. Our overall aim is to understand spatial and temporal dynamics of brown rats in relation to food supply from game bird feeders and in relation to temperature, rainfall, pest control and land cover at a mixed farm in Northumberland, UK. Our specific objectives were to, first, quantify the relationship between population estimates of brown rats from tracking plates and incidence (presence/absence) records from camera traps and, second, determine the primary local small-scale drivers of estimated brown rat populations, derived from tracking plates, at different distances from game bird feeders over 12 months.

Materials and methods

Sampling site

The study was undertaken at Nafferton Farm, Northumberland (54.9857° N, 1.8990° W), which is a 320-ha mixed agricultural farm managed by Newcastle University. The soil is sandy clay loam over glacial till deposits, forming Cambic stagnogleys and stagnic cambisols. Average January and July temperatures are 2.4 and 14.2 °C, while January and July monthly rainfall averages 62.3 and 57.8 mm, respectively. Six bird feeders at two fields, with three feeders per site (winter cereals with grass margins), were chosen for this study, with the feeders filled with wheat from October 2017 until April 2018. Camera trap and tracking plate surveys were undertaken monthly for 12 months from October 2017 until September 2018. Average daily temperature and rainfall at Nafferton Farm each month were available from a weather station running at the farm. Rodenticide was placed near to two sites in December 2017 and April 2018 at the discretion of the farm’s gamekeeper, although not directly on or adjacent to bird feeders.

The amount of food (wheat grain) in each bird feeder was visually recorded on a monthly basis on a 4-point scale as a proportion of food capacity (0, 0.33, 0.67, 1.00), at the same time that camera traps and tracking plates were checked (below). The bird feeders at Nafferton Farm each consisted of a large plastic drum to contain the grain (approximately 100-l capacity) fitted with a plastic lid, with a release mechanism at the base positioned approximately 40 cm above a solid concrete surface. The release mechanism consisted of a steel

spiral (approximately 2 cm diameter by 15 cm length) from which grain was easily dislodged by animals. Note that other designs of game bird feeders are also used in UK farms.

Geographical information system (GIS) maps of Nafferton Farm were available at 1:10,000 scale, indicating all the positions of all field boundaries, tracks and crop types across the farm. The spatial distribution of uncultivated semi-natural or natural vegetation were obtained from the Centre for Ecology and Hydrology Land Cover Map of Great Britain 2015 (CEH 2017) supplemented with field surveys at Nafferton Farm. All the spatial data was stored in ESRI ArcGIS 10.5 for subsequent analysis.

Data collection with camera traps and tracking plates

The activity of brown rats around each of the six bird feeders was estimated using both camera traps and tracking plates. Bushnell camera traps (Bushnell Trophy Cam E2 Essential, Model no. 119836, Kansas, USA) were mounted on a stout wooden stake at approximately 30 cm height and within 2 m of the base of each bird feeder. The exact distance of the camera trap from the bird feeder varied slightly between feeders, depending on immediate vegetation, as it was important to obtain a clear view of the concrete feeding platform below each feeder. The camera was set to take three shots when initiated by motion, with a pause of 30 s before it could be initiated by another movement in order to minimize the risk of repeat photos from the same animal that had initiated the previous shot (Lambert et al. 2018). Camera traps were deployed at the same time as tracking plates (see below).

Original pilot studies into the use of tracking plates by Quay et al. (1993) had counted footprints of rats, but this was not always practicable as they frequently encountered high rat population densities making it difficult to count individual footprints. They therefore calibrated the tracking plate method using a categorical scoring system based on the percentage of the tracking plate surface covered by rat footprints. This calibrated tracking plate technique was successfully used to determine the effectiveness of rat management strategies on farms in Southern England (Quay et al. 1993). We followed the methods of Brown (2007) using tracking plates made from Marley floor tiles (Tarkett Marley Floors Ltd., Lenham, Kent, England) cut to 200 mm × 100 mm. These were painted with a mixture of 100% industrial methylated spirit (IMS) and activated carbon powder (Norit powder: Lancaster Synthesis, Morecambe, UK) or pure activated charcoal ultra-fine powder (Regency Organics, Cheshire, UK) mixed at 40 g per litre. After a few minutes, the IMS evaporated leaving the carbon powder adhering to plates' surface. One advantage of tracking plates is that they can be used in many weather conditions: Shepherd and Greaves (1984) noted that they are waterproof except under a constant drip or flow of water.

Plates were used at a standard density of four plates per 10 m² ensuring repeatability between surveys (Quay et al. 1993). The plates were placed on well-determined runs where rats most likely would walk at each of the sampling distances. Each plate was placed on a different run to reduce the chances of double-counting the same rat. An initial pilot study did not detect any evidence of rat footprints on tracking plates beyond 20 m from a bird feeder; therefore, four tracking plates were positioned in the immediate vicinity of each feeder (0 m) and an additional four at 10 m and 20 m (in a straight line parallel to the field margin) from both sides of the bird feeder. Plates were placed for three consecutive nights and checked daily. The plates were left 24 h and then observed and scored according to the methods of Quay et al. (1993). If there was sign of animal footprint or the carbon was wiped off, the plate was repainted with carbon and IMS mixture. Footprints of brown rats were distinct from other species usually present in these contexts, such as wood mice (*Apodemus sylvaticus* L.) and common shrew (*Sorex araneus* L.).

Data analysis

Tracking plates were left for three consecutive nights and scored daily as follows (Quay et al. 1993):

Unmarked plates 0

Plates with 25% or less coverage of rat prints 1

Plates with between 26 and 95% coverage of rat prints 2

Plates with 96% or more coverage of rat prints 3

The mean score across 3 days, for each set of 4 tracking plates, was then multiplied by 1.56 to obtain a relative index of the rat population estimate for each survey site (Lambert 2003).

Generalized linear modelling (GLM) was used in R studio 3.5.2 to determine the relationship between presence and absence data of brown rats from the camera trap data (total over 3-day survey period in each month) and brown rat relative population estimate from tracking plates positioned at the 0 m position around the bird feeders. A binomial family error was used, as the camera trap data were in the form of presence/absence records.

Linear mixed-effect models (LMMs) were used to determine spatial (0, 10, 20 m) and temporal (survey month) patterns in estimated populations of brown rats at the bird feeders (Pinheiro and Bates 2000) via the R 'nlme' library. A mixed-effects model can be expressed as:

$$y_i = X_i\beta + Z_ib_i + \varepsilon_i \quad (1)$$

$$b_i \sim N_q(0, \psi) \quad (2)$$

$$\varepsilon_i \sim N(0, \sigma^2 \Lambda_i) \quad (3)$$

where $y_i = n_i \times 1$ vector of observations (estimated population of brown rats) in the i th group, $X_i = n_i \times 1$ model matrix of fixed-effects regressions for observations in group i , $\beta = p \times 1$ vector of fixed-effects coefficients, $Z_i = n_i \times q$ matrix of regressors for random effects for observations in group i , $\varepsilon_i = n_i \times 1$ vector of errors for observations in each group, $\Psi = q \times q$ covariance matrix for random effects and $\sigma^2 \Lambda = n_i \times n_i$ covariance matrix for errors in group i . This type of model formulation is relatively flexible, and we used bird feeder code within field as nested random effects grouping variables.

The area of each land cover type around each bird feeder was determined by buffering 100 m around the location of the feeder in ArcGIS and calculating the proportion of each of the habitat types present. However, for any given buffer around a point, as the percentage of one habitat type increases, the others decrease: this is sometimes known as the ‘unit sum constraint’ (Kucera and Malmgren 1998). This means that individual land covers cannot be reliably used as separate predictors in a model due to collinearities between them. Several methods have been proposed to resolve this problem (Aebischer et al. 1993; Robertson 1994), and one approach is to process the matrix of land covers by sites through unconstrained ordination such as principal components analysis (PCA) or non-metric multidimensional scaling (NMDS) (Borges-Matos et al. 2016; Sheen 2004). The first (and sometimes second) ordination axes can then be used as predictors in a linear (mixed-effects) model as by definition they are orthogonal to each other. Within the ordination plot, sites close to each other are more similar in their habitat composition, and vice versa. Initial analyses indicated that PCA produced a strong ‘arch effect’ (Legendre and Legendre 2012) but NMDS proved more robust and used in subsequent analyses (Chen et al. 2007).

Tracking plate position (0, 10 and 20 m), any rodenticide usage and food level in bird feeder were used as fixed effects. Additional fixed effects included in the model were mean monthly temperature and rainfall (and their interaction) and NMDS axes 1 and 2. Bird feeder and field were treated as random effects, with bird feeder nested within field. Models were tested with and without a first-order autoregressive correlation structure (Pinheiro and Bates 2000) via the ‘correlation = corAR1()’ option in R. As data were collected monthly, it is possible that the rat population in 1 month was not independent of that observed in the preceding month. The autoregression structure corrects for such correlations in the data, if they exist, and the Akaike information criterion (AIC) of models with and without the autoregressive correlation structure was compared. Lower AIC values indicate better models (Akaike 1974).

Results

Quantify the relationship between population estimates of brown rats from tracking plates and presence/absence records from camera traps

Binomial GLM indicated a highly significant relationship between the brown rat relative population estimate derived from tracking plates scores and presence/absence data from camera traps (GLM) (AIC = 59.08, z-value = 0.162, $p = 0.001$). However, tracking plates underestimated the true abundance of rats, in that even when the tracking plate gives an estimate of zero, there are still some rats detected in the camera traps (Fig. 1).

Understand the primary drivers of brown rat relative population index associated with feeders for game birds

Brown rat footprints were found at all six bird feeders. The highest mean estimated population was adjacent to the bird feeders (0 m), which was 4.131 ± 0.464 , while the lowest was at 20 m; 0.047 ± 0.030 . The maximum estimated population was 15.08, while the lowest was zero. The estimated population of brown rats was influenced by several variables such as distance of tracking plates from bird feeders, survey month and food level in bird feeders.

The NMDS ordination results are summarized in Fig. 2, with the first axis showing a trend from woodland/scrub-dominated areas through to permanent pasture and cereals such as winter barley. There was no significant difference in linear mixed-effects models with and without a first-order autocorrelation function (AIC values 402.53 and 403.06 respectively; log-likelihood ratio test = 1.47, $p = 0.225$). This suggests that the rat population estimates for 1 month could be

Fig. 1 Relation between estimated relative brown rat population index from tracking plates and presence/absence records from camera traps at bird feeders. Jittered points represent observations; line is fitted model

Fig. 2 NMDS analysis of land cover at six bird feeders at 100 m buffer (stress = 0.041). BF indicates individual bird feeders

treated as independently from those of the previous month with no serial dependency between months. Therefore, we only report the results for the simpler model, without the autocorrelation function (lower AIC).

The results of the linear mixed-effects model are summarized in Table 1 (AIC = 402.53). In a simple comparison solely to temperature there appeared to be a decline in rat activity at higher temperatures (Fig. 3a); however, once other covariables were considered, plus the nested structure of the data, and were accounted for via the linear mixed-effects models, activity appeared to increase with temperature. (Table 1; $t = 2.410$, $p = 0.017$). Note, however, that the effect size was relatively small and the data were relatively noisy. Rat activity increased with rainfall (Fig. 3b; Table 1 $t = 3.480$, $p = 0.001$), while the rainfall $\times$ temperature interaction term was marginally non-significant (Table 1; $t = -1.930$, $p = 0.055$). Land cover and rodenticide usage did not appear to have any effects on the rat activity recorded on the tracking plates, but activity was strongly positively associated with proximity to the bird feeder (Table 1; $t = -5.455$, $p < 0.001$) and food availability (Table 1; $t = 7.793$, $p < 0.001$). While

there was no autocorrelation in the residuals from the linear mixed-effects model from 1 month to the next, there were significant differences in the estimated rat populations between months, which were highest in November 2017 and lowest in March 2018 (Fig. 4; Table 1; t value = -2.340 , p value = 0.020). Within-group variability among bird-feeders within fields, and between the fields, was relatively low (within-group standard deviation fields = 0.00045 , bird feeders = 0.00088).

Table 1 Linear mixed-effect model result between estimate population of brown rats with land cover, temperature, rainfall and interaction of temperature and rainfall, position of tracking plates, rodenticide usage and food level in feeder (AIC = 402.53)

	Value	t value	p value
Land cover axis 1	0.028	0.455	0.694
Land cover axis 2	-0.045	-0.474	0.682
Temperature ($^{\circ}\text{C}$)	0.021	2.410	0.017
Rainfall (mm)	0.028	3.480	< 0.001
Temperature: Rainfall	-0.002	-1.930	0.055
Position (0, 10, 20 m)	-0.032	-5.455	< 0.001
Rodenticide	0.127	0.913	0.322
Food level (0, 0.333, 0.667, 1)	1.200	7.793	< 0.001

Fig. 3 Relationship between estimated relative populations index of brown rats. **a** With temperature ($r^2 = 0.011$, p value = 0.064), **b** with rainfall ($r^2 = 0.028$, p value = 0.008). Error bars are SE, $N = 72$

Fig. 4 Estimated relative brown rat population index scores (means $\pm$ SE) derived from tracking plates scores at each month

Discussion

Quantify the relationship between population estimates of brown rats from tracking plates and presence/absence records from camera traps

Passive activity measurements from tracking plates (Quy et al. 1993) have been reported to be reliable guides of brown rat relative population indices (Taylor et al. 1981). The plates are inexpensive and easy to lay out with weatherproof coating, which make the method suitable to measure rat activity and estimate their population. However, while camera traps are more expensive, unlike tracking plates, one advantage is that they do not need to be checked daily (Quy et al. 1993) and are therefore easier for long-term observation and monitoring. While tracking plates have been calibrated against known population size (Quy et al. 1993), it was important to understand the relationship with similar data from camera traps, especially in field settings away from farm buildings.

Our study has demonstrated that estimated brown rat populations from tracking plates were strongly positively related to rat presence/absence records from camera traps. While tracking plates failed to detect the presence of rats at low population densities, the results nevertheless suggest that tracking plates can be used as a low-cost alternative to camera traps to assess rat populations. This result is consistent with other comparisons, which found a positive correlation between activity indices of brown rats from tracking plates and camera traps at 10 livestock farms in North Yorkshire (Lambert et al. 2018) where the rats were living in and around farm buildings. Lambert et al. (2018) also reported that the index of rat activity at one site appeared disproportionately low compared with camera trap data, possibly due to an influx of rats from elsewhere on the site that were detected by cameras but not tracking plates. There is also the risk that even non-immigrant rats may avoid new objects in an environment, such as tracking plates, although other studies undertaken by the authors (unpublished data) suggest that this is not a major

problem. Tracking plates are usually placed on established rat runs, which recent immigrants may not be using; hence, it is recommended that tracking plates are used when populations are relatively stable, which they are likely to be when food resources are predictable and easily available. The results presented here confirm a link between food availability at game feeders and rat activity, and it is likely that rat populations are relatively stable around game feeders while they are in use, but at the start and towards the end of the game season, food levels in feeders may become less stable and hence results from tracking plates may be less reliable. They suggested that if the sampling points are positioned outside typical preferred habitats of a target species, the indices from the daily average of scores from the tracking plates are likely expected to underestimate the population size and hence an index based on daily sum of scores (as recommended by Quy et al. 1993) is likely more reliable where survey points may be outside the preferred habitats (as zeros have no effect on the index).

Understanding the primary drivers of brown rats associated with feeders for game birds

Brown rats are known to be attracted to places with food (Meerburg et al. 2004; Musso 2016). Game bird feeders on farms are usually filled regularly with food in colder months over winter from October to April. In this study, availability of food in the bird feeders, as measured by the proportion of the bird feeder containing food, was a key factor that increased the population of rats around the feeders compared with the background numbers across the farm (unpublished data). Rats were attracted to bird feeders because whole wheat was the food in the feeders at Nafferton Farm: although rats are omnivorous (Takács et al. 2018), they have a known preference for cereals such as wheat (Humphries et al. 2000; Meehan 1984). Furthermore, lower temperature and higher rainfall during the winter months could have reduced the availability of alternative food supplies, and thus increased the relative attraction of brown rats to the bird feeders. At Nafferton Farm, the four coldest months, November, January, February and March, were also among the wettest; thus, it is difficult to separate their individual effects. Nevertheless, even after accounting for time of year (and hence, indirectly temperature and rainfall), there was still a strong effect resulting from the presence of food from the bird feeders.

Rat relative population index was not changed by rodenticide application. This was maybe because rodenticide was applied by the local gamekeeper twice (December 2017 and April 2018) at only two feeders throughout the 12 months of sampling. Brown rats tend to avoid new items in their environment as they are neophobic (Modlinska and Stryjek 2016), and it is also likely that the rates of rodenticide application were too and low infrequent, resulting in low or sub-lethal uptake by rats. Most anticoagulant rodenticides have

relatively low acute toxicity, and hence a single application of bait may not allow sufficient opportunity for rats to overcome their initial reluctance to feed and to then acquire a lethal dose. Therefore, subject to an environmental risk assessment, it is usually recommended that a surplus of bait is maintained until the population has been controlled (or control failure for other reasons is suspected). Furthermore, when rodenticide was applied, the feeders were still providing food, and this can reduce bait uptake (game feeders provide feed from October until April). Rodenticides are known to be less effective in mice when alternative foods are available, which they consume in preference to the rodenticide (Schmolz 2010).

Estimated rat populations were highest when the bird feeder was full and immediately around the feeder (0 m) compared with 10 and 20 m away from the feeder. This probably simply reflects the much higher food availability for rats near the feeders, meaning that they did not need to forage in other places. This behaviour has been reported in a pig farm in Denmark where rat presence was higher in the immediate vicinity of automatic feeders (Leirs et al. 2004). In this study, it was suggested that the unlimited access to the feeder, with a continuous supply of food, resulted in rats staying in close proximity to feeders all day. It is clear that a balanced approach is required in farm management to prevent the beneficial effects of supplementary feed for birds being outweighed by negative effects from attracting rats (Quy et al. 2003). Ironically, even ‘wildlife-friendly’ approaches, such as game cover strips and wildlife corridors, can sometimes increase rat populations (Lambert et al. 2008). If using rodenticides, a balance is necessary between efficacy and safety, especially given the adverse effects of rodenticides on some predators of rats, especially birds of prey.

Disturbance at Nafferton Farm was relatively low, with the feeders not moved at all across 12 months of study, which may have given the rats an opportunity to establish near or under feeders. Some feeders had rat burrows under them especially when the feeders were filled with food or at harvesting time (pers. obs.). It would be preferable to move the feeders frequently as brown rats are neophobic in that they tend to avoid new things or new places (Modlinska and Stryjek 2016). This is also recommended by Sánchez-García and Buner (2017) who suggested that feeders need to move every 7–10 days within 20–50 m so that the target species (gamebirds and songbirds) still can find the feeder in the site. Given that rats can move 50 m or more, it may, however, be necessary to regularly relocate feeders + 100 m, although this would impose additional practical difficulties. This would also decrease infestation of other non-target species, especially pest rodents such as rats.

Land cover near to the feeders did not appear to have a direct effect on estimated rat populations. This accords with a study in Southern Sweden where activity of rodents was also not affected by surrounding habitat or landscapes (Tschumi et al. 2018). Nevertheless, brown rats were more abundant in

cultivated land and grass and less abundant in forested areas in Hunan Province, China (Xiao et al. 2018). Furthermore, in contrast to the results from Nafferton Farm, brown rats have been reported as responding to landscape changes in Thailand, Laos and Cambodia (Morand et al. 2015). The difference may have arisen due to higher levels of human settlements in the Southeast Asia study and/or because of that the overriding effect of food availability in feeders at Nafferton Farm was a stronger driver than the land cover immediately around the feeders.

In conclusion, brown rats are an important, but difficult to study, component of agroecosystems, and tracking plates can be used as an inexpensive method to estimate populations of brown rats, especially when populations are moderate or high. Estimates from tracking plates are less reliable at very low population densities. Brown rat populations thrived at bird feeders where there is constant food supply especially in autumn and winter, which may have implications for the economic benefits of game bird rearing versus increased pest incidence. Rat populations varied at different times of the year, and highest levels of abundance were associated with lower temperatures and higher levels of rainfall. Subject to regulatory requirements, rodenticides for pest control need to be applied routinely, and systematically, throughout the period when bird feeders are being used; otherwise, they are unlikely to have any effect on pest numbers. Given the importance of food availability in affecting rat activity, and the potential for impacts of rodenticides on non-target species, farmers may also need to implement ecologically based pest management strategies to minimize spilt grain and other sources of food and shelter to reduce rat numbers.

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Compliance with ethical standards

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

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