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Making the invisible visible: Determining an accurate national distribution of *Elater ferrugineus* in the United Kingdom using pheromones

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Abstract.

1. To date, conservation-status saproxylic beetle species in the United Kingdom have been monitored by chance findings or by monitor-based observational studies. Here, using *Elater ferrugineus* as our target species, we present the first national distribution survey carried out. in the UK or across mainland Europe on such a species using chemicals produced by the insect.

2. Over three years, mark release recapture studies were performed across the UK, using 416 lured (pheromone) traps monitored by volunteer recorders; the first survey in Europe to do so. Traps were baited with 7-methyloctyl- (Z)-4-decenoate, a compound previously identified as a female sex pheromone.

3. The results were used to plot a distribution map and investigate factors that may influence the distribution, including summer temperatures, possible habitat availability and larval food source.

4. The survey revealed a south-eastern distribution of *E. ferrugineus* in the United Kingdom, which was suggested by previous casual studies.

5. A correlative model was fitted to the data, indicating that 55% of the variation in the distribution of *E. ferrugineus* was explained by climatic variables (temperature and wind speed).

Keywords. *Elater ferrugineus*, pheromone, saproxylic, national distribution, veteran trees, aerial traps

Introduction

Schemes to effectively conserve endangered species must be able to reliably measure the current status of the organism, and then continue to monitor changes in its abundance and to manage its habitat (Hopkins & Freckleton, 2002; Svensson *et al.,* 2012). Such monitoring programmes ideally need to be carried out simultaneously across the whole of the range of the organism. Furthermore, for insect species where conservation funding is limited, surveys should be designed so that both skilled and previously untrained volunteers can readily and accurately carry them out. Surveys should avoid counting the same individuals more than once, which would artificially inflate population estimates. Methods should also be relatively inexpensive and ideally not require the constant presence of the monitor, especially where the habitat is not easily accessible, or is vulnerable (Tikkamäki & Komonen, 2011).

Throughout the United Kingdom, monitoring of Coleoptera of conservation concern is largely carried out by entomologists, recording sightings as part of commissioned projects or private surveys; results may be held by County recorders and/or placed upon the National Biodiversity Network website (NBN Gateway, 2016). Such recording may be haphazard, requires many man-hours and registration of results is not compulsory, therefore precise distributions of the majority of species are largely unknown. The impact of such recording could lead to conservation efforts based on speculation, rather than accurate data. At best this could result in unnecessary work, and at worst, with insufficient knowledge of the biology of the species, result in too little effort being made too late. Saproxylic beetle species provide excellent examples of the aforementioned problems with monitoring.

National monitoring of a saproxylic beetle species within the UK has thus far previously been best represented by the Great Stag Hunts carried out by the People’s Trust for Endangered Species for *Lucanus cervus* L.*,* in 1998 (Percy *et al.,* 2000), 2002 (Smith, 2003) and 2006-7 (Smith, 2011). Using media-based appeals for public records of the species, these surveys yielded a large database of records and confirmed the distribution of the beetle as largely south eastern in the UK, with population hotspots in the New Forest, Suffolk and London areas. Similar work across Europe enabled a pan-European comparison of its habitats and enabled recommendations for conservation strategies (Harvey *et al.,* 2011a). However, recruitment of volunteers to record such a charismatic and visible species is relatively easy, compared to some of the more cryptic species, whose distributions may be largely outside of the public field of view (Harvey & Gange, 2011). Moreover, despite such surveys raising the general profile of these species and providing an opportunity for education of the public of their importance, it is difficult to avoid the effect of ‘monitoring the monitors’ that such a survey can produce. It can also reflect the effects of monitor fatigue when surveys are carried out more than once, and be influenced by weather, with poor weather resulting in lower numbers which may, in part at least, reflect the behaviour of the surveyors. Even where such systems are effective, they are highly impractical for species whose habitats are associated with deciduous woodland or wood pasture where public presence is limited. Furthermore, the cryptic nature of many saproxylic species and the limited knowledge of their biology would hinder potential success of such surveys. Up to 2010, when in this study pheromones were first used to detect the presence of a conservation status saproxylic beetle species in the UK, many anecdotal records of rare saproxylic beetle were based on findings of larvae, the search for which inevitably leads to habitat disturbance. It is further hindered by the difficulty of accurate identification except by the relatively few people with an expert knowledge of larval morphology (Gouix & Brustel, 2012). The provision of an effective nationwide survey method in the United Kingdom could inform methods of surveying across other regions of the species range, in mainland Europe, where citizen based pheromone surveys could be employed to give an accurate distribution of the species across its entire range.

The lack of obvious economic importance of conservation species means that insect monitoring has concentrated on pest species, consequently resulting in a lack of effective monitoring schemes for the former. The use of chemical attractants that lure pests to a trap has a long and successful history in agriculture and horticulture (Borden *et al.*, 1983; Campion, 1984; Witzgall *et al.*, 2010; Sharma *et al.*, 2012; Vuts *et al.*, 2014). However, while species-specific volatiles used in the natural life cycle have been identified and utilised for monitoring wood-feeding and saproxylic species (Larsson *et al.*, 2003; Tolasch *et al.*, 2007; Larsson & Svensson, 2009; Svensson *et al.*, 2012; Wong *et al.*, 2012; Pajares *et al.*, 2013), such monitoring has been limited in scope and geographical distribution. This technique has not, to date, been used in the United Kingdom or elsewhere for nationally monitoring conservation-status saproxylic beetle species.

The use of pheromone monitoring of adults of cryptic species may thus offer a novel way of counteracting the recording problems identified above. One conservation-status saproxylic beetle for which a lure has been developed and utilised to monitor presence in some countries across mainland Europe is *Elater ferrugineus* L.(Larsson & Svensson, 2009; Svensson *et al.,* 2012). Colloquially known as the rusty red click beetle, *E. ferrugineus* is, at 15-24mm long, the largest click beetle present in the UK. It has a life cycle of around 6 years, with annual adult emergence and mating between July and August (Harvey *et al.*, 2017). Believed to inhabit hollows in old deciduous trees, of *Quercus sp*.(Svensson *et al.*, 2004; Svensson & Larsson, 2008; Larsson & Svensson, 2009, 2011), *Fagus sp.* (Zauli *et al.*, 2014)and occasionally *Aesculus, Ulmus* and *Fraxinu*s sp. in the larval stage (Allen, 1966; Alexander, 2002) (it is non-feeding in its adult stage), it has near-threatened status across most of its northern temperate range (Nieto & Alexander, 2010), attributed by Tolasch *et al.* (2007) and Nieto & Alexander (2010) to habitat loss and fragmentation. Despite its bright red colouration and diurnal flight behaviour (Barševskis & Nitcis, 2011), only 35 records were collected over the 112 years preceding 2010 (the start of this study) for *E. ferrugineus* in the UK, all centred around south-eastern England (NBN Gateway, 2016). Where available, data available from the national recorders were incorporated into the records form the NBN to obtain a complete a distribution as possible. Restricted dispersal probably contributes to its apparent rarity (Oleksa *et al.,* 2015), through real effects on its biology (such as limited mating possibilities and limited gene flow between populations) and a reduced likelihood of chance observation records.

Tolasch *et al.(*2007) identified four compounds produced by the female of *E. ferrugineus*, which proved behaviourally active in the field, trapping males of the species. Svensson *et al.* (2012) further investigated this mixture, using electro-antennography to identify one compound, 7-methyloctyl- (Z)-4-decenoate, as the active volatile. This compound has been successfully trialled across mainland Europe in Sweden (Svensson *et al.,* 2012), Poland (Kadej *et al.,* 2014) and Italy (Zauli *et al.,* 2014), demonstrating its efficacy in establishing the presence of the species. However, none of the above have used the pheromone on national distribution survey.

Here, we present data from the first national monitoring scheme of a saproxylic species using pheromone trapping in the UK. Our main aim with this study was to determine whether such a method could be used to produce an accurate nationwide distribution of the species. We hypothesised that the current methods for estimating distribution, such as habitat searching and casual observation, result in a distorted view of the species and its distribution and habitat requirements. We therefore compared our results with the existing records logged on the National Biodiversity Network Gateway. Our survey is the first of its kind to use citizen science, involving volunteer members of the public, to monitor such a cryptic species in a nationwide distribution study. A secondary aim of this survey was therefore to determine the feasibility of using unskilled volunteers in such studies.

We then compared these beetle data with maps of both possible prey species and tree habitat species to investigate two possible explanatory factors for the observed distribution. Since flight in insects is the most demanding physiological process in terms of energy requirements (David *et al.,* 2015) and all insects must allocate available resources to maximise reproductive success, we hypothesised that a lack of feeding behaviour in adults and fragmentation of habitat has prevented the beetle from extending its range. Although it has been suggested that the larvae can feed solely on wood mould (Tolasch *et al.,* 2007; Oleksa *et al.,* 2015), Barševskis & Nitcis (2011) and Svensson *et al.* (2004) suggest that the larvae of *E.ferrugineus* are predatory, or at least facultative predators, on the larvae of the families Lucanidae and Scarabaeidae. However, because of the rarity of the species, it would be very difficult to collect sufficient larvae from the field to carry out laboratory-based feeding experiments. A feasible alternative approach is to map the distribution of *E. ferrugineus* together with species reported as possible larval food sources. Of these species, the only ones present in the UK are *Dorcus parallelipidus* L, suggested as a possible food source by Alexander, (2002),and(Allen, 1966) and *Gnorimus sp* (Oleksa *et al.,* 2015)*.* The genus *Gnorimus* has two species in the UK, *G. nobilis* L. and *G. variabilis* L. We have therefore compared the distribution of these with that of *E. ferrugineus*.

Methods

*Monitoring surveys*

Volunteers were recruited across the UK by contacting professional and amateur entomologists via internet-based focus groups, non-governmental organisations such as Wildlife Trusts, local natural history societies, and National Trust properties, to provide as complete a nationwide representation as possible. To ensure that monitors were correctly able to identify the species, they were sent a coloured photograph and size guide, and were asked to send a photograph of any species that were caught in a trap to confirm identification. Many monitors were secure in their identification of the adult beetle prior to the survey and where possible the same monitors were used over the three years. Monitors were advised where possible to carry out their surveys where old trees were present, predominantly *Quercus sp*, as these have been suggested as the habitat for larval *E. ferrugineus* (Tolasch *et al.,* 2007; Oleksa *et al.,* 2015). In total, three surveys were carried out, during 2011, 2013 and 2014. A survey was planned for 2012 but was impractical because of poor weather.

For the first survey in July 2011, 200 hanging traps (modified from Harvey *et al.,* 2011b) were distributed across the country, from Yorkshire in the north of England to Sussex and Hampshire in the south, and from Norfolk in the east to Anglesey and Devon in the west. This included traps to cover the historic distribution of *E. ferrugineus* as suggested by Stephens (1830) as well as that suggested by the NBN data (NBN Gateway, 2014). Trapping was started on 8th July, a date identified as near the start of the season following a pilot survey carried out in 2010. Traps were monitored for three weeks, to coincide with the activity of the species, without requiring excessive effort on the part of volunteers taking part in the study. Each trap contained a 0.2ml PCR tube (Starlab l1402-8100) pierced horizontally through the body of the tube with a small needle and suspended from copper wire through the closed lid with 2µl of 7-methyloctyl- (Z)-4-decenoate, synthesised by EH, placed in the upper holding container. Monitors were advised, where possible, to hang traps at a height of 2m (as determined by pilot work by Harvey *et al.*, 2016). Traps were checked daily, beetles removed and released 10m from the site of capture. Recorders were asked to mark captures on the pronotum with a permanent marker, and to supply Ordnance Survey (mapping) coordinates of the trap position and a record of the vegetation in the area. Repeat surveys in 2013 and 2014 followed the same methodology. However, in 2013 emphasis was placed on covering the areas that had yielded negative results in the previous survey, and 94 traps were set. The final survey in 2014 (120 traps) was carried out to target the extremes of the range and check geographical gaps identified from the two previous studies, including Edinburgh, as the most northerly distribution, Cornwall to the west and the Isle of Wight to the south.

Trap contents were examined for presence and absence of *E. ferrugineus* across all regions. These data were then plotted and compared with plots of potential explanatory factors (see below).

*Comparison of mapped distribution with possible explanatory factors*

NBN records (NBN Gateway, 2016) for *E. ferrugineus* up until the time of the first survey (2011) were collated and mapped alongside the records achieved by trapping, to determine whether distribution of the species had declined or expanded. Additionally, the level of individual records of beetles collated over each decade from 1830 (representing the first records) was examined.

In order to investigate one possible explanation for the distribution established for *E. ferrugineus*, the presence/absence data for each year were then compared with distribution maps of veteran or old trees (*Quercus* *robur* and *Fagus* *sylvtica*; Ancient Tree Hunt, 2015- though it should be noted these records are compiled by volunteers and so may not represent all of such trees in the UK). Using data from the NBN Gateway, the number of oak and beech of all species were calculated for 10km squares to determine a density for tree type –including both veteran and non-veteran trees, and the data examined to see if the number of trees in a 10km square could predict the presence of *E. ferrugineus*. Chi-squared tests were carried out to determine whether there was an association between the occurrence of veteran oak and beech trees and *E. ferrugineus*, and t-tests to compare recorded tree density in areas of *E. ferrugineus* presence and absence.

As the flight season is virtually confined to July, monitoring records were also overlain on a map of the United Kingdom showing maximum mean temperature in July averaged across the years 1981-2010.

Finally maps overlaying the range of possible larval prey species (*D. paralellipipidus*, *G. variabilis* and *G.* *nobilis*; NBN Gateway, 2014) with that of *E. ferrugineus* were also plotted to determine whether larval food source could be an explanatory variable for the species’ distribution.

*Predictive modelling of distribution*

In order to produce a predictive model for the distribution of *E. ferrugineus,* presence/absence data were compiled across the 132 10 km squares in which trapping took place throughout the study. Climate parameters were determined from historical local weather data for each square (Met Office, 2016). Variables considered were mean winter (November-January) and summer (June-August) figures for wind speed, average temperature, minimum temperature, maximum temperature, precipitation, humidity, and atmospheric pressure. These data were inspected and Moran’s I computed (ns *p* = 0.33), indicating that there was no evidence of spatial auto-correlation, therefore the predictive modelling method used was considered to be appropriate (Dormann *et al.*, 2007).

A binomial generalised linear model was applied to the data (following e.g. Gillingham *et al.*, 2012), with all climatic variables entered as predictors and presence/absence of *E. ferrugineus* in each 10km square as the outcome variable. An R2 value was computed for the resulting model using the formula R2 = 1 – (residual deviance/ null deviance) (Faraway, 2016).

Results

*Presence/absence results (2011-2014)*

In 2011, from the 200 traps and lures sent out, 108 reports (54%) were returned of which 69 gave null results and 39 gave positive results (other traps were not reported on by surveyors). Where positive results were obtained and volunteers were unsure of identification these were verified by photographic evidence. In 2013, of the 94 traps sent, 47 (50%) returned results, 24 of which were positive and 23 were negative. In 2014, 120 lures were sent out, 29 (24.1%) yielded positive results, 82 (68.3%) negative with 9 null returns. The total number of catches for any one trap did not exceed 5 per day in any locality, with most results being single records. The exceptions to these were in Berkshire and in Cambridgeshire, where captures were 54 maximum and 12 maximum respectively. Recaptures were reported by only three of the monitors across all traps and years, with two of the three limited to single specimens, therefore no population estimates could be calculated.

[Figure 1 around here]

Fig. 1 shows the 10km squares in which trapping took place, combined with trap success. It shows clearly that the insect has a south-eastern distribution in the UK. Over the three years of monitoring, 132 10km squares were monitored of which 38 gave positive results. Of these, 28 were new records and 10 overlapped with previous records in the NBN Gateway database. The new records extended further south, including two localities in Sussex and further east, extending into Norfolk. There was no evidence of decline in range from the historic records. Thus, the number of individuals recorded per decade from 1830 to the present was low - below 10 specimens for 9 of the decades preceding 2010. From 2010 onwards, the number was over 1,500 specimens, a total higher than all other decades tallied. Figure 2 indicates that the beetle was not captured evenly across the different sites, with most localities having low and similar numbers of beetles. However, some localities produced considerably more than others, suggesting that its abundance is patchy.

[Figure 2 around here]

*Comparison of mapped distribution with possible explanatory factors*

Fig. 3 shows the distribution of veteran *F. sylvatica* and *Q. robur* across the UK compared to that of *E. ferrugineus*, with coincident distribution in 9 of the 132 10km squares for oak and none for beech (total number of squares occupied by oak was 178 and beech was 68). *E. ferrugineus* were found in 34 10km squares with no oak recorded and 38 x10km squares with no beech recorded. Comparing presence/absence of all oak and beech in 10km squares showed no significant association (χ2 = 1.87, df = 1, p > 0.05) between oak and *E. ferrugineus*, and similarly between beech and *E. ferrugineus* (χ2 = 0.08, df = 1, p > 0.05). The density of trees in 10km squares where *E. ferrugineus* was present or absent was also compared, showing no difference in either oak (*t* = 0.95, *df* = 129, *p* > 0.05) or beech (*t* = -1.43, *df* = 129, *p* > 0.05) tree density.

[Figure 3 around here]

A map of average mean July temperature with *E. ferrugineus* records superimposed upon them demonstrates that the beetle is restricted to the areas delineated by an average maximum daily temperature of greater than 21oC (Fig. 4).

[Figure 4 around here]

When plotted on 10km square maps, distributions for *E. ferrugineus* and *Gnorimus* sp. only overlapped by one square with *G. nobilis*, one with *G. variabilis* as well as one with both species (see Figure 5a). The majority of the range of *G. nobilis* falls outside of that of *E. ferrugineus* (no association in distribution; χ2 = 1.31, df = 1, p > 0.05) and *G.variabilis* is only present in three 10km squares across the whole of the United Kingdom with only one coincident square. *E. ferrugineus* and *D. parallelipidus* overlapped in 22 squares of their range (see Figure 6b). However, the range of *D. parallelipipdus* extends beyond that of *E. ferrugineus*, and there is no association in their distributions (χ2 = 0.47, df = 1, p > 0.05). However, if one restricts the analysis to encompass just the range of *E. ferrugineus*, there is an association between the species (χ2 = 12.73, df = 1, p < 0.05); suggesting that *D. parallelipidus* might be a possible larval food source for *E. ferrugineus*.

[Figure 5b around here]

*Predictive modelling of distribution using climatic variables*

Winter and summer wind speed and summer average and minimum temperatures were demonstrated to be significant coefficients in the model (see Table 1). Presence of *E. ferrugineus* was associated with lower winter and higher summer wind speeds, and with higher average but lower minimum summer temperature. A Hosmer and Lemeshow goodness of fit test indicated the suitability of this model, with no significant difference between observed data and the model (*χ*2(8) = 0.78, *p* = 0.99). A pseudo R2 value was calculated for this model (Faraway, 2016), indicating that the model explained 55.4% of the variance in the distribution of *E. ferrugineus.*

[Table 1 about here]

Discussion

Here we present the results of the first UK national survey of a conservation-status saproxylic beetle species using pheromones. In a survey which has enabled us to simultaneously investigate large areas of the country, we have produced an updated distribution map for the species. This has demonstrated a more extensive range than previously reported, with 38 x 10km2 positive records of the species, of which 28 are new. It was not possible to survey the entire country, but the distribution of observers was untargeted and as wide as possible with a number sufficient to reduce bias to a minimum. Since this survey was carried out over three years with most areas targeted more than once, we consider that our survey has produced a much more complete distribution of the species.

This work demonstrates the valuable role that citizen science can play in such surveys, allowing annual distributions of a species to be determined in a fraction of the time spent on previous recordings. Furthermore, the survey used scientifically rigorous techniques that do not rely on chance sightings, nor cause disturbance of habitats. The result was an increase in recorded specimen numbers from less than 40 to nearly 2000. In addition, carrying out the monitoring over three years allowed us to confirm areas that provided null returns initially to reduce the possibility of false negatives. We did not obtain positive records from any 10km square where a previous negative had been obtained, suggesting that this methodology would be a sound technique if only employed for just a single year. We suggest however, that as a conservation effort it should preferably be repeated for at least at the length of the species life cycle, in this case every six years (Tolasch *et al.*, 2007), so that a decline in range can be identified and appropriate action taken before the species becomes extinct. Such action should include habitat assessments, especially to determine the number of hollow trees in the landscape which have been described as key habitat for the species in the UK, coupled with targeted population monitoring in areas where the species was recorded in this study. Moreover, our results demonstrate how a species that is believed to be extremely rare can be more widespread than is apparent from recordings based on chance sightings. However, the data suggest that the majority of records come from south east England. The limited abundance records obtained in this study nevertheless provide a strong indication that most local populations contain very few individuals, compared to catches obtained in other studies of the species carried out in Sweden and Poland (Svensson *et al.*, 2012; Andersson *et al.*, 2014; Kadej *et al.*, 2014;).This in turn suggests a considerable threat to many of the UK populations, leading to possible extinction in a more fragmented population where larval habitat is scarce (Pilskog *et al.*, 2016).

Our original aim was to obtain population estimates of the beetle through mark-release-recapture. However, this proved impossible, since recaptures were so limited. This is also in stark contrast to results from other studies (Svensson *et al.*, 2012), which is disappointing from a demographic point of view. This could be worrying if, as suspected, populations are very low, but is also partly encouraging, since it shows that beetles were not attracted to the same trap. When this occurs, the potential exists for dispersal, mating and oviposition to be disrupted, meaning that trapping might have a detrimental effect on small populations. However, extensive searching of the literature has not revealed any conclusive evidence that trapping may have such an effect. This result therefore adds to our confidence in pheromone trapping as a suitable non-destructive method in insect conservation.

Pheromones produced by individual species have proved to be extremely valuable in monitoring of coleopteran pest species (Anderson *et al.,* 2012; Hanks & Millar, 2012; Reddy *et al.,* 2012). The technique has, to date, not been widely used to monitor non-pest species in general and saproxylic species in particular. This might be in part due to the cost of developing such schemes in species which have no perceived economic impact, since developing monitoring schemes for individual species requires a relatively large initial cost. As a result of lack of accurate monitoring schemes and inadequate management of habitats, many saproxylic beetle species may now be at risk of extinction both in the United Kingdom and across Europe (Nieto & Alexander, 2010). However, as the successful use of pheromones for saproxylic species monitoring increases, more species specific pheromones may be forthcoming and the technique become more widely available (Larsson & Svensson, 2009).

In the last few years pioneering work by several authors (Larsson *et al.*, 2003; Tolasch *et al.*, 2007; Larsson & Svensson, 2011; Svensson *et al.*, 2012; Oleksa *et al.*, 2015) has opened up the possibility of such work as a valuable monitoring technique in the field of insect conservation. For any species where the biology is largely unknown and the habitat is out of the public eye, monitoring using pheromones allows a constant approach that will avoid missing the crucial activity period, does not disturb or destroy habitats and allows for extensive surveys to be performed quickly, avoiding monitor bias. The surveys carried out here have largely confirmed the distribution of *E. ferrugineus* across the UK predicted by searching, but have additionally identified sites from which the beetle had not been previously recorded. It is undoubtedly true that habitat searching remains the only way for many species to be monitored when pheromones are not available, but the evidence for the use of volatiles in monitoring of conservation-status saproxylic insects is compelling and will provide a valuable tool for widespread surveying, that workers developing conservation strategies might use.

It must also be acknowledged that national pheromone monitoring, over a period of weeks, provides an accurate state of species distribution mapping that habitat searching cannot achieve, without employing an unrealistically large number of expert monitors. Data collation sites, such as the NBN Gateway, which predominantly report individual records collated by chance over many years, and many give no information as to whether these were adults or larvae, or the precise habitat nor any indication of numbers. Numbers of a species could therefore fall dangerously low before appropriate conservation efforts were put in place, if such distributions were used by conservation agencies to predict necessary effort. All this information can be collated within a season where pheromones are being used.

Although considerable effort is initially required to recruit monitors for a survey, the generation of results encourages more interest thereby making the task easier. It also promotes an interest among them, enhancing the possibility of initiating monitoring schemes for other cryptic groups and provides an opportunity for raising public awareness of such organisms, utilising the goodwill of citizen science schemes. Such schemes have already proved successful such as for *L. cervus* (Percy *et al.,* 2000; Harvey *et al.,* 2011b; Smith, 2011), ladybirds (Adriaens *et al.,* 2015) and more generally (Silvertown, 2009).

To date, much of the literature suggests that *E. ferrugineus* requires veteran oak and beech trees (i.e. those whose features include rot holes, water pockets, dead wood, hollowing, and fungal fruiting bodies; Fay, 2007) for breeding success (Tolasch *et al.*, 2007; Svensson & Larsson, 2008; Schimmel & Tarnawski, 2010; Andersson *et al.*, 2014; Pilskog *et al.*, 2016). Our study suggests that in the UK at least, the beetle is not limited to veteran trees of these species; we found no association between *E. ferrugineus* records those of veteran oak or beech, although we acknowledge that the Ancient Tree inventory is a citizen science project and the results may not be a complete survey. Furthermore, when we compared documented density of oak and beech trees we found that there was no significant difference in the densities in 10km squares where the beetle is present compared to where it is absent. This possible difference in habitat requirement between mainland Europe and the UK is not unprecedented, the stag beetle (*L. cervus)* being predominantly urban in the United Kingdom but a woodland insect across mainland Europe (Harvey *et al.,* 2011a). Such differences may be anticipated, since distribution of insects cannot be determined by a single trait, but rather is a combination of life traits (Gu *et al.,* 2006).

The surveys here have established that this beetle is largely restricted to the south-east of the UK. Such limited distribution is not unique and has been recorded for other species, including *L. cervus*, (Smith, 2011; Smith, 2003; Percy *et al.,* 2000), and *Gnorimus variabilis* (NBN Gateway, 2016). Correlative modelling suggests that presence of *E. ferrugineus* is predicted by climatic variables, with over half of the variation in their distribution accounted for by a model including wind speed and temperature. In particular, presence was associated with lower winter and higher summer wind speeds, and with higher average but lower minimum summer temperature. Our results demonstrate that the range of the species falls within that of a mean average greater than 21oC for July. This finding is consistent with the distribution of the species in Poland reported by Kadej *et al.* (2014). Such a temperature threshold requirement is crucial for insects, influencing distribution and abundance (Manzoor *et al.,* 2016). Such knowledge facilitates monitoring adults in the field and the development of phenology models (Jarošík & Honěk, 2011; Manzoor *et al.*, 2016). High summer wind speed may facilitate the spread of pheromone plumes, but further laboratory based wind tunnel experiments would be needed to determine whether this is the case, and whether there is a threshold above which the species finds it difficult to fly.

The literature contains references to *E. ferrugineus* being predatory, or at least a facultative predator, in the larval stage (Barševskis & Nitcis, 2011; Svensson *et al.,* 2004), with the former report suggesting that the main food sources are *Osmoderma eremita* Scop., *Gnorimus* species and larvae from the Lucanidae. Indeed, Larsson *et al.* (2003), Svensson *et al.* (2004) and Svensson & Larsson (2008) showed that the male sex pheromone of *O.eremita* acts as a kairomone of the female *E. ferrugineus.* However, this species is not present in the UK so we restricted our mapping to *G. nobilis*, G. *variabilis* and *D. parallelipipidus.* Our results suggest that neither *Gnorimus* species forms a major food source for *E. ferrugineus* in the UK, since the range of *G. nobilis* falls largely outside of its range, with only one 10km square in which the species do overlap. *G. variabilis* appears to have a very restricted distribution in the UK, with records from only 3 x 10km squares, one of which overlaps with *E. ferrguineus*. Twenty-two 10km squares of the 38 occupied by *E. ferrugineus* overlap with those of *D. paralellipipidus* suggesting that this might be a larval food source. This suggestion however needs substantiating by further laboratory investigation of larval food choice in the United Kingdom and, ideally, a comparative study across the Europen range.

One area that has not been explored here but has a range of far-reaching possibilities is using *E. ferrugineus* (as a now easily identifiable species, even to the inexperienced monitor) as an indicator species for the success of other species and available habitats in an area (Andersson *et al.,* 2014; Oleksa *et al.,* 2015). Such a scheme has been trialled in Sweden by Andersson *et al.* (2014), and utilised the pheromone monitoring of *E. ferrugineus* and *Osmoderma eremita* to monitor other less conspicuous species that share a habitat. This is because if the indicator is present then there is suitable niche available for species that share the same habitat. This could either precede presence studies by habitat searching or ideally be developed as part of a wider pheromone identification scheme. Such an approach could be used to monitor other species of beetle associated with hollow trees, such as *Limoniscus violaceus* Müller(Gouix *et al.,* 2015), *Megapenthes lugens* Redtenbacher, *Ampedus nigerrimus* Boisduval & Lacordaire, and *Ischnodes sanguinicollis* Panzer, all of which are believed to coincide with that of *E. ferrugineus* over some of their range (NBN Gateway, 2014).

Here we have demonstrated that the use of pheromones is an invaluable technique for monitoring a rare saproxylic beetle, providing a quick and efficient method that can be carried out by amateur entomologists and, with minimal training, people with little or no knowledge of the species. The cost of equipment could limit the success of a citizen science monitoring project but here we used traps designed by Harvey *et al.* (2011b), which were both cheap to construct and lightweight. We have shown that it can rapidly allow a more extensive distribution to be realised and in a time frame that is shorter and less destructive than could be achieved by habitat searching. It can also provide a valuable tool for determining the presence of more cryptic species where the habitat is outside public access and where flight times are unknown. However, such a technique can only ever form part of a conservation strategy for a species, which would also need to include habitat assessment in terms of quality and availability. The lack of continuity of suitable hollow trees for the species, as is the case in many modern landscapes, is undoubtedly detrimental to the endurance of saproxylic species and something which cannot be addressed by even the best pheromone monitoring system. Nevertheless, pheromone monitoring can potentially identify locations of rare species, thereby allowing habitat assessments to be correctly. Such knowledge, coupled with research into flight distances would provide valuable contribution to planned habitat surveys. We have also attempted to determine factors that could account for species distribution, as an indicator towards future research on the biology of the species. In this case a number of environmental factors are likely to interact in determining the distribution. Most importantly, the use of pheromones has allowed us to improve our knowledge of the distribution of the species in the UK and will guide further work to ensure the success of this and other similar species.

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Authors’ contributions

DJH devised the study, collected and analysed the data, and wrote the manuscript. HH, PF, and ACG assisted with data analysis and manuscript preparation. MCL and GPS advised on study design and gave feedback on manuscript. EH manufactured and supplied pheromone and gave feedback on manuscript.

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Figure legends

Fig. 1 – 10km square UK distribution map showing presence and absence results of nationwide monitoring surveys in years 2011-14. Some squares had more than one trap placed, determined by individual monitors.

Fig. 2 – Number of captures per trap per day recorded in each 10km2 area.

Fig. 3 - Distribution map of veteran and ancient trees across the UK: a) beech b) oak plotted with positive records of *E. ferrugineus.*

Fig. 4 – Map of mean maximum temperature for July 1981-2010 with *E. ferrugineus* distribution superimposed. Temperature map reproduced with permission from the Met Office.

Fig. 5 - Distribution of a) *Gnorimus nobilis* and *G.* *variabilis* and b) *Dorcus parallelipipidus* in the UK plotted alongside distribution of *Elater ferrugineus.*

*Table 1. GLM coefficients for the predictive model of distribution using climatic variables*

|  |  |  |  |
| --- | --- | --- | --- |
| Variable | Season | Estimate | P |
| Wind speed | Winter | -3.34 | 0.01\* |
|  | Summer | 3.86 | 0.01\* |
| Average temperature | Winter | 7.93 | 0.53 |
|  | Summer | 21.38 | 0.04\* |
| Minimum temperature | Winter | 2.43 | 0.73 |
|  | Summer | -11.14 | 0.02\* |
| Maximum temperature | Winter | -11.12 | 0.12 |
|  | Summer | -6.85 | 0.13 |
| Precipitation | Winter | -0.07 | 0.21 |
|  | Summer | -0.01 | 0.87 |
| Humidity | Winter | 0.75 | 0.19 |
|  | Summer | 0.41 | 0.43 |
| Atmospheric pressure | Winter | -3.91 | 0.19 |
|  | Summer | 6.06 | 0.09 |

\* Significant coefficient in model *p* < 0.05