

Using citizen science to examine the nesting ecology of ground nesting bees

Stephanie Maher^{1,2*}, Fabrizio Manco¹, Thomas C. Ings¹

¹Applied Ecology Research Group, School of Life Sciences, Anglia Ruskin University,
Cambridge, UK

²Dept. of Botany, School of Natural Sciences, Trinity College Dublin, Dublin 2, Rep. of
Ireland

*Corresponding author:

Address: Watts building, Dept. of Botany, Trinity College Dublin, Dublin 2, Rep. of Ireland

Email: smmaher@tcd.ie

Abstract

Suitable nest sites are a crucial habitat requirement of ground nesting bees, but empirical studies of fossorial solitary bee nesting ecology in the UK are few in number. This study used a citizen science approach to overcome the logistical and temporal barriers associated with this type of research and to gather data on the abiotic environment associated with the nesting aggregations of four fossorial solitary bee species in the UK. Three hundred and ninety-four records were submitted by the public between March and November 2017. Sixty percent (236) of these records were verified as indicative of active nesting aggregations of the target species. Overall, the species in this study demonstrated the capacity to nest within a broad range of environmental variables. Although *Colletes hederæ* (Schmidt and Westrich, 1993) was often reported from sloped, unshaded sites, and *Andrena fulva* (Müller in Allioni, 1766) was regularly associated with flat, shaded locations. This study demonstrated the efficacy of a citizen science approach in surmounting the intrinsic difficulties associated with studying solitary bee nest sites, which are both ephemeral and cryptic structures in the landscape.

Keywords: Solitary bees, citizen science, nesting ecology, ground nesting bees

Introduction

Solitary bees constitute roughly 250 species of wild bee in the UK, but there remain significant knowledge gaps with regard to their ecology (Wood et al. 2016). This group encompasses many important pollinators, including those of high value crops such as apples (Garratt et al. 2016), but is facing diversity loss (Biesmeijer et al. 2006) declines in relative abundance (Bartomeus et al. 2013) and extinctions (Ollerton et al. 2014). There are two principal resources that solitary bee populations require in order to survive and proliferate: suitable and robust nest sites for their offspring to successfully mature in, and sufficient forage material both for their own survival and to provision their young. The foraging requirements of bees have been well studied (Strickler et al. 2007; MacIvor et al. 2014; Dicks et al. 2015; Wood et al. 2016) as they are believed to be the principal limiting resource. However, within a landscape, Gathmann and Tscharnkte (2002) have speculated that nest sites may be a limiting factor for solitary bees more often than forage, although it is clear that these resources must work in tandem. There is a lack of empirical research regarding the nesting requirements of fossorial solitary bees in the UK (but see Potts and Willmer, 1997). Although there are multiple reasons for this gap, the difficulties associated with finding sufficient nest sites in the field and the lack of robust experimental methods are two of the most significant barriers. These issues are further compounded by the short flight seasons of many UK solitary bees, which result in only a narrow window of time when active nest sites can be discovered and examined.

There are two main types of empirical study performed on ground nesting bees' nesting ecology; those studies that focus on single species (Potts and Willmer, 1997; Wuellner, 1999; Julier and Roulston, 2009; Xie et al. 2013) and those that examine the effects of nest site suitability on wider metrics such as species richness, abundance and

community composition (Martins et al. 2018, Sardinas and Kremen, 2014, Grundel et al. 2010). When the species-specific studies are taken together, it is clear that there may be significant interspecific diversity in solitary bee nest site preferences with regards to key environmental characteristics. Within the UK, Potts and Willmer (1997) empirically examined *Halictus rubicundus* (Halictidae) (Christ, 1791) nest aggregations and identified a preference for softer soils with a moderate slope and southern aspect. Wuellner (1999) showed that the North American bee *Dieunomia triangulifera* (Vachel, 1897) preferentially nests in areas of bare, compacted soil with a warm soil surface temperature and close to visual landmarks. A study in Chinese *Camellia oleifera* (Abel) orchards found that *Andrena camellia* (Wu, 1977) preferred loose, moist and low temperature soil conditions (Xie et al. 2013). The abundance of *Peponapis pruinosa* (Say, 1837), a specialist pollinator of pumpkin in the U.S., has been shown to be negatively related to soil clay content and positively related to soil irrigation (Julier and Roulston, 2009). In all these studies, nest temperature seems to be an important characteristic and comes through either directly, in that individuals are observed nesting in areas with particular soil temperatures (Wuellner, 1999; Xie et al. 2013), or indirectly, where they are observed nesting at sites whose physical characteristics can potentially confer thermal benefits (Potts and Willmer, 1997). Although the direction of preference appears to be mixed. A similar pattern emerges with respect to the physical characteristics of the soil, where these attributes appear to be uniformly important, but the specifics of what is preferred seem to vary on a species to species basis.

Across geographical contexts, the availability of ground nesting resources has been shown to be a strong predictor of bee abundance (Potts et al. 2003; Sardinas and Kremen, 2014), species richness (Grundel et al. 2010) and community composition (Potts et al. 2005; Grundel et al. 2010). A recent study from Quebec, Canada, showed that bee diversity in

apple orchards, blueberry and raspberry fields was influenced by the presence of suitable nesting resources (Martins et al. 2018). Again, the important characteristics of the nesting resource varies, but the availability of bare ground (Potts et al. 2005), sloped terrain (Sardinas and Kremen, 2014), sandy soils (Cane, 1991) and soils with low organic matter content (Grundel et al. 2010) are factors that have proven to be important in at least some contexts.

Collectively, these studies show that nesting resources are important for the survival and proliferation of ground-nesting bees. But, due to geographical differences in community composition and interspecific differences in nest site preferences, a ‘one size fits all’ approach will not be sufficient in this context. This conclusion was also reached by Kim et al (2006) who found that across agricultural landscapes, ground nesting bee density was impacted by proximity to semi-natural habitat and edaphic factors of the individual sites. However, species differed in their response to the specific measured variables.

In this study, we use a citizen science approach to circumvent the logistical and temporal issues associated with in-situ solitary bee nesting research and attempt to identify and examine nesting aggregations on a national scale. Citizen science is an effective method of up-scaling research projects, both temporally and spatially, by capturing far more data than could be achieved by one individual (Pocock and Evans, 2014). It is also an excellent way to engage and educate the public about their local wildlife and scientific research (Kremen et al. 2011). Bees are currently enjoying a popular status both in the media and with the wider public, although this interest tends to centre around honeybees and, to a lesser extent, bumblebees. This zeitgeist presents us with the opportunity to test the limits of this interest and investigate whether people are willing to learn about and invest in lesser-known bees at a large scale.

This project set out to address three questions:

1. Can citizen science be used to examine the nesting aggregations of solitary bee species?
2. Do *Andrena fulva*, *Andrena cineraria* (Linnaeus, 1758), *Halictus rubicundus* or *Colletes hederæ* exhibit any associations with environmental characteristics in choosing a nest site?
3. Do broad scale environmental variables affect the nest aggregation size of these four solitary bee species?

Methods

Project design

Citizen science data can vary in quality (Aceves-Bueno et al. 2017), so this project was designed to optimise the chances of receiving high quality data based on the citizen science literature. This involved three fundamental design decisions. Firstly, the study was narrowed to four distinctive species (Delaney et al. 2008). Second, the participants were asked to record simple data that could be gauged by eye. Finally, the protocol did not require the participant to make a large time commitment (Pocock and Evans, 2014; Birkin and Goulson, 2016)

A ‘process of elimination’ protocol was used to identify four ground nesting solitary bee species for inclusion in the project. Within this selection process, we aimed to identify species that were already recorded by the public, nest in aggregations and have been recorded in the East of England. The October 2015 to October 2016 UK solitary bee iRecord (brc.ac.uk/iRecord) submissions were examined according to these

criteria and the following ten species were pulled out: From the Colletidae family *Colletes hederæ* and *Colletes succinctus* (Linnaeus, 1758), from the Andrenidae *Andrena clarkella* (Kirby, 1802), *Andrena fulva* and *Andrena cineraria*, from the Halictidae *Halictus rubicundus*, *Halictus tumulorum* (Linnaeus, 1758), and *Lasioglossum morio* (Fabricius, 1793), from the Melittidae *Dasypoda hirtipes* (Fabricius, 1793) and from the Apidae *Anthophora bimaculata* (Panzer, 1798). From this list of ten, four species with differing flight periods and that could be identified from photos, were chosen. In addition, *H. rubicundus* was chosen because empirical, U.K. based data on nest site preferences for it is available (Potts and Willmer, 1997) and this project could build upon that knowledge. *Colletes hederæ* was already the subject of a large-scale citizen science project run by the Bee, Wasps and Ants Recording Society (BWARS).

Once these four species were identified, a simple protocol for recording nesting aggregation data was designed. A project-specific website (thesolitarybeeproject.org) was created and launched both as an information tool and a portal for record submission. The website provided training instructions for participants. It also contained further context detailing what participants should look for, how to identify bee nests and aggregations and, described potential confusion structures such as worm casts. It also provided descriptions and photographs of each of the four target species and links to further resources. The project focussed on three principal environmental variables which have been shown to impact nest site suitability: shade (Potts and Willmer, 1997), slope (Sardinas and Kremen, 2014) and ground cover (Wuellner, 1999). A printable information sheet (S1), which included details on how to identify each of the four species and quantify the nest site characteristics, was provided to participants via the

website (including example photographs of the three different categories of shadiness and diagrams depicting the three levels of slope). Participants were asked to upload a photograph of the bee and the nest site for validation purposes. This was not made compulsory so as not to deter participants confident with bee identification. Participants were also provided with space to add additional commentary or detail to the record. The project ran from the 3rd of March to the 3rd of November 2017. Participants were asked to answer the following multiple-choice questions and to identify on a map where the aggregation occurred:

1. How many nests were there?
 - a. 1-10
 - b. 11-30
 - c. 31-50
 - d. 51+
2. How sloped was the ground the aggregation was on?
 - a. Flat
 - b. Sloped
 - c. Vertical
3. How shady was the aggregation?
 - a. Aggregation was completely in the open
 - b. Aggregation was adjacent to trees or buildings that could provide shade
 - c. Aggregation was completely shaded by trees or other structures
4. What was the ground cover like?
 - a. Bare earth
 - b. Lawn

- c. Under mulch
- d. Other

Data validation

Verification of citizen science records by a trained expert increases the accuracy of the data (Gardiner et al, 2012) and so records in this project went through a process of expert validation before being accepted for analysis. Records submitted with a photograph were accepted if the specimen in the image was accurately identified and the bee had been observed at a nest site. Records without photographs were only accepted if there was adequate descriptive commentary that established that the bee had been observed nesting and that the species identification was correct. Due to these criteria, many submissions without photographs were ultimately rejected because they lacked enough detail to establish validity. Records were also immediately rejected if there were any missing data from the submission.

Participant recruitment

Immediately preceding and proceeding the launch of the project, it was advertised through BWARS and through the personal contacts of those involved in the project. This resulted in the project being ‘target marketed’ either to those with a professional interest, e.g. university contacts, or amateurs who are members of a wildlife recording society and are accustomed to wildlife recording. At the beginning of June 2017, three months into the project, a press release was circulated to local and national media outlets by the university press office. This press release resulted in a number of local and national radio and television appearances and newspaper articles about The Solitary

Bee Project. In this way, the project was marketed to a much wider group of potential participants from this point on.

Data analysis

A random forest algorithm was developed as a classification model (500 trees) to attempt to predict the number of nests in an aggregation (categorical outcome of 1-10; 11-30; 31-50 or 51+ nests) based on the species, shade, slope and ground cover. Random forest is a machine learning approach that iteratively uses a different subset of the data to create multiple decision trees. In this way, it combines many classifications trees in order to produce more accurate classifications and is a robust method of examining variable importance and modelling interactions between variables (Cutler et al. 2007). We added a random variable of numbers between 1 and 100, generated by R to the model so that the relative contributions of the other variables could be examined. All analyses were carried out in R version 3.5.1 (R Core Team 2015). The R package ‘randomForest’ was used for the random forest analysis (Liaw and Wiener, 2002).

Results

Summary of records

In total, The Solitary Bee Project collected 394 records from across the UK and Ireland in 2017. Two hundred and thirty six of these records were assessed as being accurate and indicative of an active nesting aggregation (Figure 1). There was substantial variability in the number of accurate records submitted per species. Close to ten times more accurate records were received for *A. fulva* compared with *H. rubicundus* (105 and 11 accurate records respectively). There were also marked interspecific differences in the proportion of accurate

records submitted, where again *A. fulva* had the highest proportion (74% of records were accurate) and *H. rubicundus* the lowest (21% of records were accurate) (Table 1).

Solitary bee nest sites

Records were used to build a picture of the areas in which the four species were nesting in terms of their shade (Figure 2), slope (Figure 3) and ground cover (Figure 4).

Andrena fulva

The ground cover of *A. fulva* aggregations was reported to be grass in 56% of aggregations and bare in 34% of aggregations. Eighty two percent of records reported this species to be nesting in flat ground with no slope. The records also indicated that *A. fulva* has a broad tolerance for shade with 68% of aggregations reported to be experiencing at least partial shade. However, only 10% of aggregations were reported to be in full shade.

Andrena cineraria

Fifty three percent of *A. cineraria* aggregations were reported to be fully in the open and 44% were reported to experience some shade. Just 3% of aggregations were reported as fully shaded. Sixty seven percent of *A. cineraria* aggregations occurred on flat ground and 30% were sloped. Sixty four percent of aggregations were reported to be in a grassy area and 30% occurred in bare ground. This reflects a very similar pattern to *A. fulva*.

Halictus rubicundus

From the 11 accurate records of *H. rubicundus* aggregations, 54% occurred on flat ground and 36% on sloped ground. Most records (74%) specified that the ground was bare. No strong trend manifested in terms of shade with 45% of records specifying the aggregation was in the open and a further 45% specifying the aggregation to be in partial shade.

Colletes hederæ

A majority (74%) of *C. hederæ* aggregations were reported to be fully exposed to sunlight while no aggregations were in full shade. Aggregations occurred equally on flat ground and on sloped ground. Sixty two percent of recorded aggregations reported grass as the primary ground cover, with 36% recorded as bare.

Participant reach

The media attention three months into the project resulted in what might be considered a ‘high quantity, low accuracy’ scenario where in the first month post-press 230 of the 394 total records were submitted. In the first three months of the project, a total of 95 records were received, of which 82% were verified as accurate and 70% included one or more photographs (Table 2). In comparison, of the records submitted in the three months post media, only 49% were validated and taken through for data analysis. Not only were many of the records removed from the analysis, the percentage of records with accompanying images dropped to 33% (Table 2).

Predicting the aggregation size

The random forest algorithm could not successfully predict the size of an aggregation and had an ‘out of the bag’ error rate of 57.63%. This value represents the average of the errors associated with each iteration (classification tree) and is based on the correlation between the observed aggregation size and the predicted aggregation size. The variable importance plot shows that the random variable inserted into the model was the main driver of the model (Figure 5). Therefore, none of the measured variables are considered to be useful predictors of the number of nests in an aggregation.

Discussion

The Solitary Bee Project collected 236 accurate records of solitary bee nest site locations of four species from across the UK. Although the resolution of the data was not fine enough to identify any influence of environmental factors on aggregation size, the project did reveal some interesting trends in terms of where these four species nests in a landscape. All species were found to have broad tolerances for the measured environmental characteristics, but they did exhibit some significant interspecific differences in nest site characteristics. Furthermore, these results suggest that interspecific differences may be reduced when species are closely related and have similar flight seasons. This study took a novel approach to overcoming the logistical barriers associated with solitary bee nesting research and showed that citizen science can be an effective tool in this context, although data resolution would benefit from some methodological changes in the future. There was substantial engagement with the project and the near 400 submitted nest site records reflect the engagement the public had with this lesser known but important group of bees. The data collected by this study are indicative of presence only and future research could be strengthened by the explicit collection and consideration of absence data. However, this would be difficult to achieve

using a citizen science approach as it would require systematic and repeated surveying of specific geographic areas whether bees were present and nesting or not. This burden of effort would likely deter potential participants.

Shade

Nest sites that are in full sun are understood to be attractive to ground nesting species as they experience increased soil temperature (Brockmann, 1979; Potts and Willmer, 1997). *Colletes hederæ* followed this trend and was most often reported from sites that experienced no shade (Figure 2). However, there was evidence that all species could tolerate some level of shade, including *H. rubicundus* which has previously been found to show a strong preference for sites in full sun (Potts and Willmer, 1997). In fact, *A. fulva* was found to nest in open spaces in very few cases (Figure 2), which indicates that there may be benefits to nesting in a shaded site that outweigh the disadvantages. In this study, a number of participants reported *A. fulva* to be nesting near, and in some cases, directly beneath, trees. Although *A. fulva* is polylectic, a study of their pollen loads in Cardiff, Wales found that females were primarily foraging on flowering trees such as maple and cherry (Paxton, 1991), and so the tendency of *A. fulva* to nest in shaded areas may be a function of their decision to nest in close proximity to forage material. As *A. fulva* is active in early spring, when flowering plants are scarce, there may be more pressure on it than summer flying species to construct a nest close to abundant foraging resources. Trees can also alter the soil environment in ways that may facilitate nesting. For example, fossorial insects do not nest in hard-packed soil (Gliński et al. 2011; Srba and Heneberg, 2012) but tree roots can break up compacted or hardened soil layers, which may make the area habitable. Trees also help to mitigate extremes in soil

surface temperature (Edmondson et al. 2016), which may be beneficial to larvae developing underground (Potts and Willmer, 1997).

Slope

Sloped, south-facing ground experiences higher soil temperatures and this is thought to confer significant benefit to species that nest in these areas (Potts and Willmer, 1997). In this study, the majority of *C. hederæ* nesting sites were reported to be on sloped ground, in line with previous findings for this species (Bischoff et al. 2004; Falk, 2015). Conversely, most *A. fulva* nesting sites occurred on flat ground (Figure 2), a tendency that has previously been noted for other *Andrena* species that occur in North America (Youssef and Bohart, 1968). Neither *H. rubicundus* nor *A. cineraria* demonstrated a trend for any particular terrain gradient. This mixed picture is not unusual. When Srba and Heneberg (2012) examined the nest sites of five species of digger wasp (four Sphecids and one Crabronid), they also identified interspecific differences in the slope of the nesting areas, noting that there were preferences for both sloped and flat terrain. Potts and Willmer's (1997) study of *H. rubicundus* nesting aggregations found that across sites there was no correlation between slope and nesting density, however, within a site this species nested at higher densities in areas with steeper slopes. So, although these species possess the capacity to nest in variously sloped ground, these may not represent optimal nest sites and further study is required to untangle this relationship.

Ground cover

Seventy four percent of *H. rubicundus* nest sites were found in bare ground, but for the other three species (*A. fulva*, *A. cineraria* and *C. hederæ*), grass was reported as the primary

ground cover of the aggregation in the majority of records. Bare ground has been shown to encourage solitary bee nesting (Gregory and Wright, 2005; Dicks et al. 2010), but the results of this study show the capacity of some species to nest in grassy areas. For *A. fulva* and *A. cineraria*, many participants reported the aggregations to be in mown lawn or grazed grass, indicating that these species can tolerate significant anthropogenic disturbance to the surface area of the nest site. This is supported by the fact that many of the aggregations recorded in bare ground occurred on footpaths with frequent pedestrian or vehicular traffic. These findings are in line with descriptions of “typical” nesting sites for these species as detailed in field guides and species’ profiles (e.g. Falk (2015)). Although little work has been done on the impact of disturbance on solitary bee nest sites, Ullmann et al (2016) found that tilling the soil to a depth of 40 cm delayed the emergence of the squash bee *P. pruinosa* in an agricultural landscape. However, roughly 50% of the bees survived the management and so these results, taken with the results of this study, suggest that highly disturbed landscapes in both rural and urban landscapes can potentially contribute to the persistence of ground nesting solitary bee populations. This may indicate that these species have a broad tolerance for the surface characteristics of the ground they nest in and that other factors are more important for optimising their nest site location. Srba and Heneberg (2012) studied the nest site characteristics of five species of digger wasp and found a general trend of preference for low vegetation cover with some species more strongly selecting for this than others. However, they noted that one species showed no preference for vegetation cover and dug nests in areas with up to 80% cover. The authors did identify strong interspecific differences in the wasps’ soil requirements. Evidence shows that edaphic factors such as soil particle size (Cane, 1991) and organic matter content (Grundel et al. 2010) can drive the presence and density of fossorial bees and wasps and so it is possible that the subterranean

environment is a more dominant feature compared to the surface characteristics for some species.

Interspecific similarities and differences

Overall, *A. fulva* and *A. cineraria* nest sites exhibited similar trends in terms of their environmental characteristics. Furthermore, these two species were sometimes reported to be nesting together, a scenario observed by the authors of this paper. This, taken with previous work (Youssef and Bohart, 1968) suggests that these closely related species with strongly overlapping flight seasons favour similar nesting conditions. This pattern has also been identified in the Colletidae family, where steep, south-facing, sandy slopes are preferred (Bischoff et al. 2004). This tentatively suggests that phylogenetic relatedness could potentially play a role in defining the nest site requirements of a species, but more research with the specific aim of testing this hypothesis is required.

There seemed to be some inter-familial differences, with the majority of *C. hederæ* and *A. fulva* nest sites having values for slope and shade in opposite directions. Furthermore, *H. rubicundus* was the only species for which bare soil was identified as the primary ground cover in the majority of records. Summarising previous work on species from different families demonstrates some divergences in their preferred nest site characteristics (Potts and Willmer, 1997; Wuellner, 1999; Julier and Roulston, 2009; Xie et al. 2013). These differences may have originally manifested for many reasons. Although all species have a common goal of finding a nest site that is suitable for larval development and subsequent survival of offspring, they may differ significantly in what constitutes optimal soil for digging and what is the optimal position for forage. There is a high degree of morphological diversity within the ground nesting solitary bees, particularly with regards to body size.

Smaller bees are likely to have shorter foraging ranges (Greenleaf et al. 2007) and so may be more restricted in requiring a nest site in close proximity to suitable food resources. Furthermore, monolectic and oligolectic species may be constrained by the presence of their food plants. Body size may also impact the ability of an individual to excavate nests in harder soils. Indeed, Cane (1991) found that larger bees tend to nest in soils with higher clay content, and nesting in these conditions results in higher energy costs (Srba and Heneberg, 2012). Species' flight periods may also play a role. Spring flying species such as *A. fulva* and *A. cineraria* have to cope with lower soil temperatures which will alter the digging conditions (Xie et al. 2013). For example, soils with larger particles, such as sand, freeze more easily than those with a higher proportion of fine particles such as clay. In this way clay rich soils may be easier to dig in the spring, whilst in the summer months sandy soils represent a lower energy excavation. The closely related digger wasps *A. pubescens* and *A. sabulosa* have been shown to preferentially nest in areas where the soil has a low gravel content (Srba and Heneberg, 2012).

Although there is evidence to suggest that phylogenetic relatedness can help determine nesting requirements, Cane (1991), found that ground nesting bees exhibit substantial variability in their preferences for soil grain size. They also noted that the species with more similar preferences did not necessarily align along taxonomic relationships. The resolution may be that in certain families e.g. Colletidae and Andrenidae, taxonomic relatedness does help to delineate nesting preferences, but this is not true for all fossorial families. Looking ahead, significantly more research is required to gain a clear understanding of how these factors interact.

Aggregation size

The data collected did not distinguish any differences in environmental conditions for different sized aggregations. This may have been due to the broad nature of the questions asked, which is an inherent risk when designing hypothesis-led citizen science projects. There is a careful balance to be struck between establishing complexity in the methods for scientific robustness but maintaining simplicity in order to encourage participation and ensure accurate reporting. The categorical nature of the questions seemed to have a negative effect on data resolution as the categories were constrained. This was especially apparent with the *C. hederæ* data for which 77% of records reported the nest site to consist of more than 51 nests (the highest category). A separate, fine scale study of a subset of the aggregations revealed a wide range in the mean number of nests per square metre (Maher, Manco and Ings, unpublished data). For example, *A. fulva* had a mean highest nest density of eight nests per square metre and *C. hederæ* 49 nests per square metre. So, measuring the number of nests in an aggregation on a continuous scale would likely have improved the resolution.

Participant recruitment

There have been inherent and long-standing difficulties with the communication of science in mainstream media (Bell, 1994; Barron and Brown, 2012; Mehr, 2015) and the drop in accurate records following the national media attention of this project demonstrates some of the issues that can arise. However, the project's appearance in the media did, overall, result in a higher number of accurate records being submitted in absolute terms. The impact of media coverage can possibly be tempered by careful planning of the project, for example by simplifying the actions and by having clear, concise and readily available instructions. The records collected in this project were submitted anonymously and so there was little

opportunity to engage directly with participants or to offer feedback on their submissions through the website. However, participants could engage with project researchers via email or through social media profiles that were set up specifically for the project. These profiles also offered a way for participants to keep track of the project and its progress and were regularly updated with distribution maps of the submitted records. Social media has been acknowledged as an important tool for citizen science endeavours for engaging participants and creating a ‘sense of community’ around a project (Stafford et al. 2010; Dickinson et al. 2012). We found that exploiting social media platforms as forums in which potential participants could ask questions and clarify instructions with researchers directly was of great help. In some cases, participants would share a potential record with researchers via social media to get feedback before submitting the data through the website proper, rendering these records more accurate. That said, whether or not citizen science data are accurate, greater engagement represents more people learning about, and becoming aware of, solitary bees, which is in itself an important function of citizen science.

For future endeavours, we have found that citizen science can be a useful tool for the study of solitary bee nesting ecology and this exact approach could be enlisted for any distinctive species that can be accurately identified from photographs. However, the variability in the number and quality of records for the different species in this study raises an important consideration. *Andrena fulva* was the most successful species, while *H. rubicundus* performed poorly. This is most likely a reflection of the fact that *A. fulva* is a relatively large and physically distinctive species, which is easy for amateurs to become familiar with and identify in the field whereas *H. rubicundus* is smaller and far less charismatic. This indicates that for the many solitary species which are difficult to identify, it may be useful for participants to be able to submit specimens to researchers for

identification. In cases where this is not possible, citizen science can still be used to examine nesting ecology in general terms without specific connection of the nesting site to individual species'. Furthermore, the capacity of the public to find and record active nesting aggregations could be harnessed to develop databases of nest site locations for further investigation by scientists, thereby removing one of the most significant logistical barriers associated with studying this topic.

Conclusion

This study represents the first instance of using citizen science as a tool to examine solitary bee nesting ecology and illustrated the efficacy of a citizen science approach in this context. On the whole, this study demonstrated the capacity of the four target species to tolerate a broad range of environmental variables, although questions remain around whether these conditions impact the nesting density of bees. Srba and Heneberg (2012) in their study of digger wasp nesting found that some variables may be used to identify usable nesting areas and that others are important for determining nest density at a suitable site and the results from this study may be a reflection of this process. Most *C. hederæ* nest aggregations occurred at sloped sites in full sun, whereas the majority of *A. fulva* sites were found in flat, shaded areas. The distance to forage and phylogenetic relatedness may play a role in determining the nest site requirements of a ground nesting species, but more empirical research is required. Despite not being able to discriminate the effects of the measured environmental variables on aggregation size, we believe that by calculating the total number of nests or nest density on a continuous scale the data resolution required for this analysis could be achieved. The location, size and nesting density of solitary bee aggregations are likely determined by complex interactions between the abiotic environment, foraging

resources, phylogeny, parasite load and natal nest site fidelity and more empirical studies are needed to elucidate these forces. A better understanding of solitary bee nesting ecology will assist us in developing robust conservation practices and policy going forward as, in order to protect anything, we must first understand what needs protecting.

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Table 1: Summary of records by species

Species	Total records	Accurate records
<i>A. fulva</i>	142	105 (74%)
<i>A. cineraria</i>	128	81 (63%)
<i>H. rubicundus</i>	53	11 (21%)
<i>C. hederæ</i>	71	39 (55%)

Table 2: Summary description of submitted records

	No. of records	No. of valid records	No. of records with photos
Overall	394	236 (60%)	174 (44%)
Before media	95	73 (82%)	62 (70%)
After media	299	125 (49%)	84 (33%)

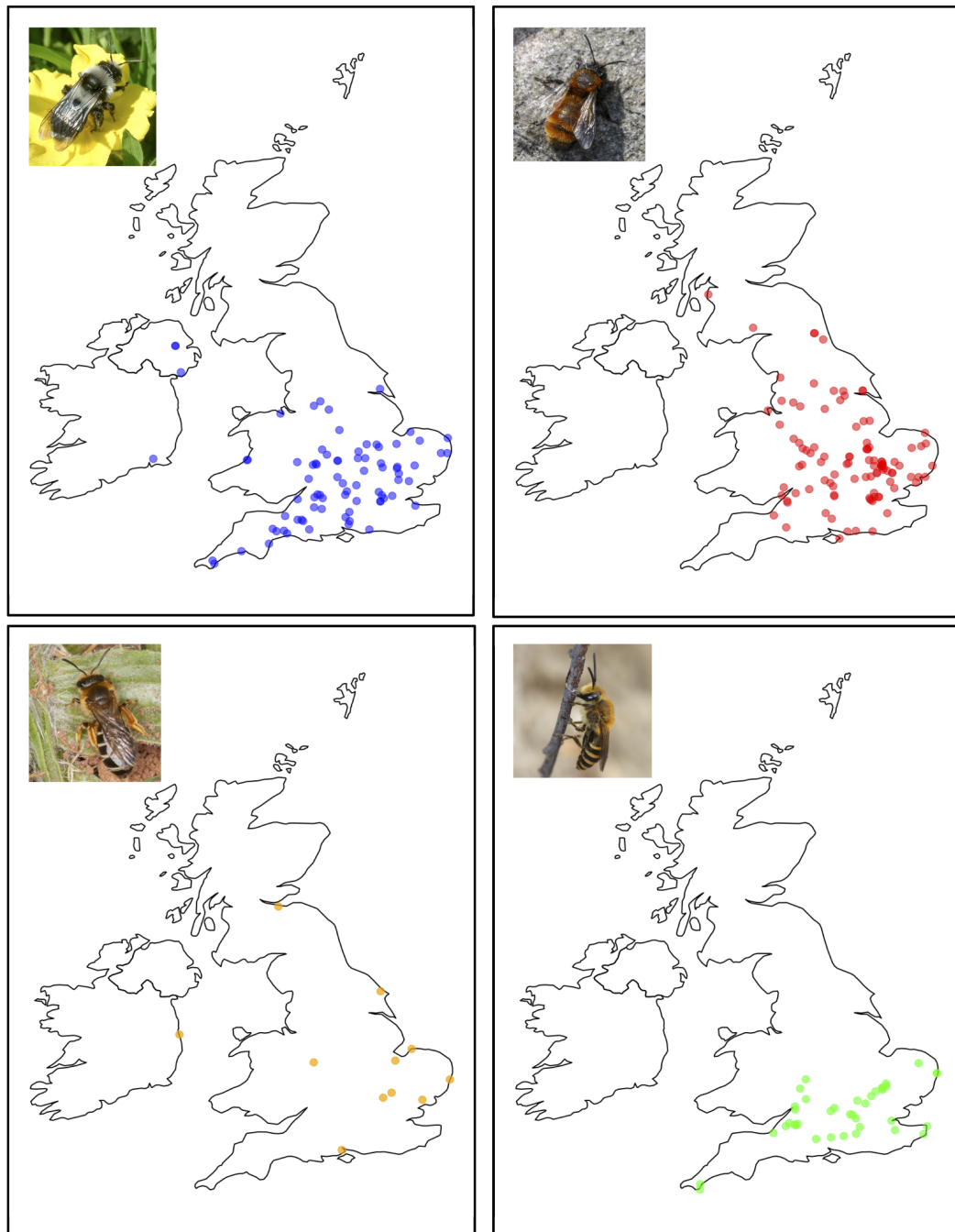


Figure 1: Distribution maps for the records submitted for each species: *A. cineraria* – blue dots (n=81); *A. fulva* – red dots (n=105); *H. rubicundus* – orange dots (n=11); *C. hederæ* – green dots (n=39) Photos: Thomas Ings.

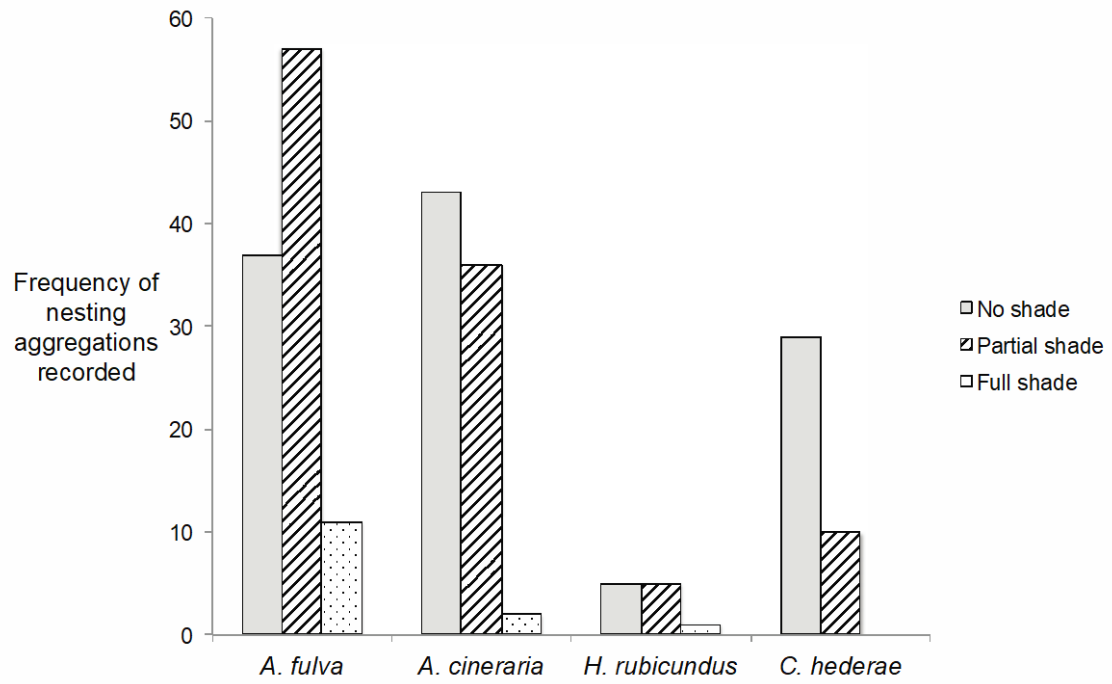


Figure 2: Frequency distribution of the number of verified records of nesting aggregations in shade, partial shade and full shade for each of the four study species (n=236).

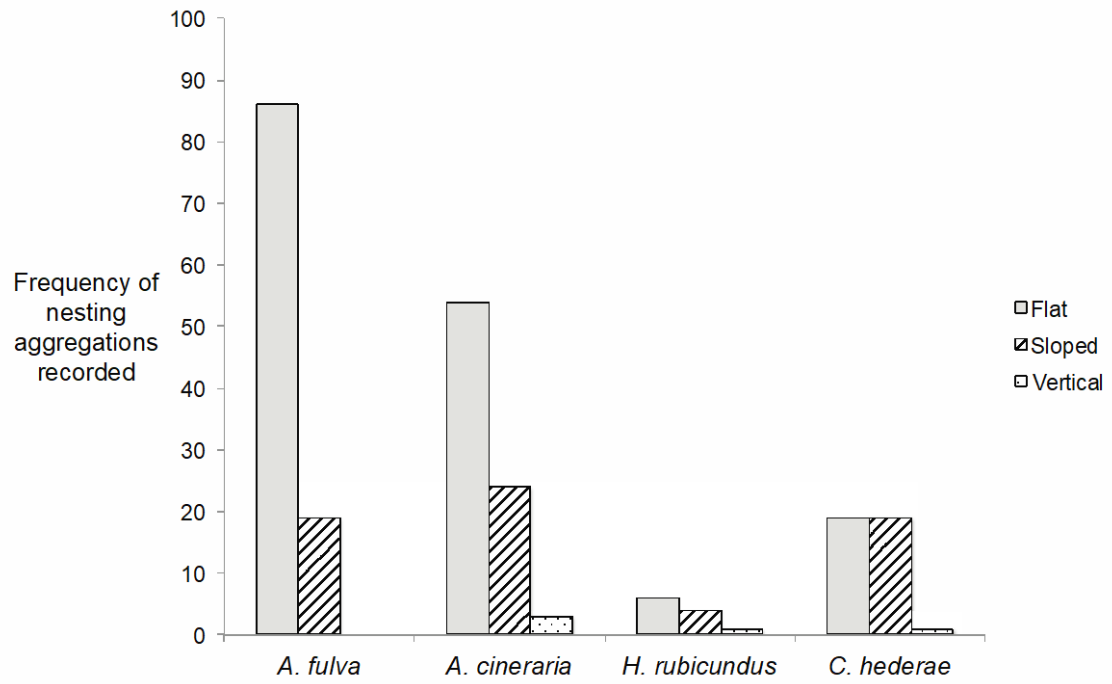


Figure 3: Frequency distribution of the number of verified records of nesting aggregations in flat, sloped and vertical terrain for each of the four study species (n=236).

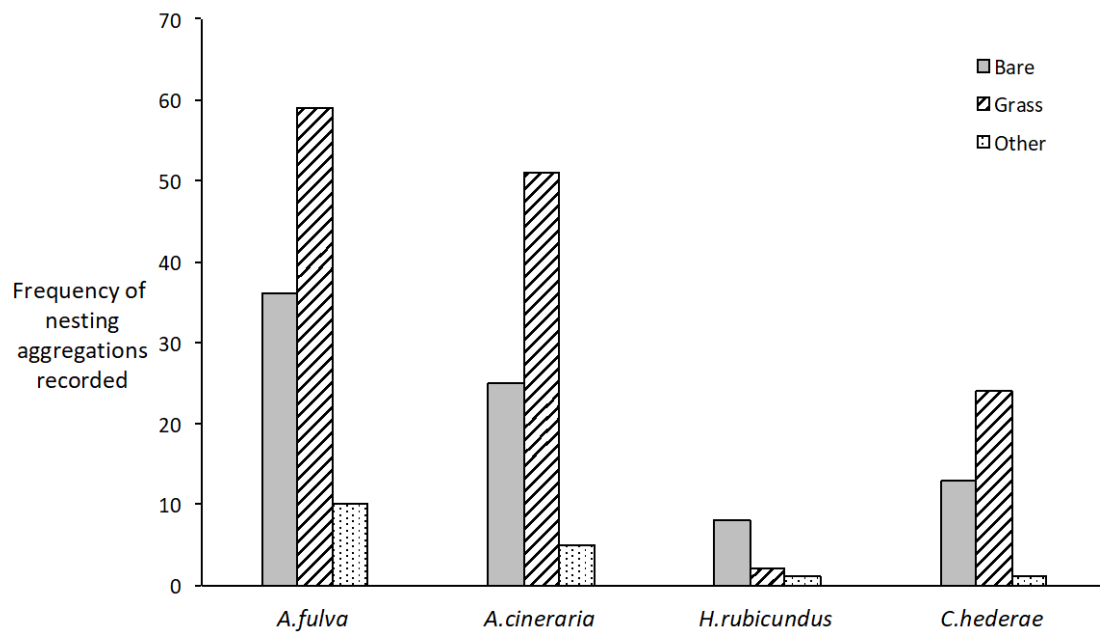


Figure 4: Frequency distribution of the ground cover (bare, grass, other) of the verified records of nesting aggregations for each of the four study species (n=236).

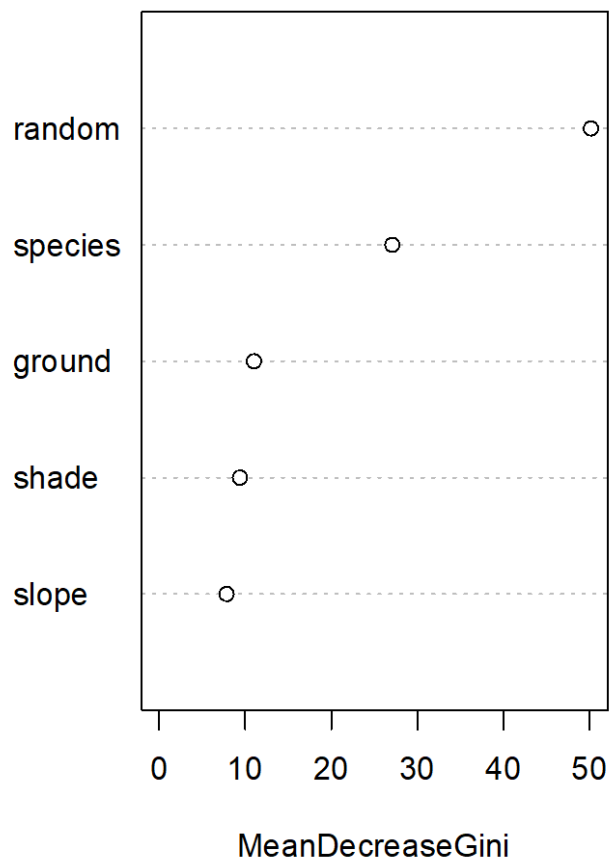


Figure 5: Variable importance plot. This plot illustrates a list of the most predictive variables in descending order. In this case, the random variable, which is listed first, contributes the most to the model.