MRes Ecology thesis

1. The effect of agri-environment schemes on bees on Shropshire farms

2. The effect of agri-environment schemes on bumble bee colony success

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Chapter 1.

The Effect of Agri-Environment Schemes on Wild bees on Shropshire Farms

Abstract

The decline of bees and other invertebrate pollinators is cause for global concern, endangering the stability of ecosystems and economic markets. Modern intensive agriculture has been identified as a key driver causing this decline, through the loss of foraging and nesting habitats and agrochemical applications. Alterations to land management techniques and farming styles through Government-run agri-environment schemes (AES) have the potential to restore the local landscape to benefit wild bees. Bee abundance and species richness were surveyed over a season, along with forage plant usage, on 18 farms in Shropshire (UK) to assess the effectiveness of AES in conserving and restoring local bee communities. Farms were classified into three treatment groups: (i) Conventional (intensive farming with little to no input into "wildlife-friendly" farming actions), (ii) Entry-Level Stewardship AES (ELS: broad, flexible, non-competitive admission), and (iii) Higher-Level Stewardship AES (HLS: strict, high-input options, competitive admission), covering a range of farm types. Bee abundance and species diversity were significantly higher on AES-compliant farms when compared to Conventional farms. AES-compliant farms also showed greater flowering plant diversity used as foraging resources. Small non-significant differences in abundance and species richness were identified between ELS and HLS, with ELS slightly higher in mean species diversity and HLS slightly higher in overall abundance. This study highlights that set-aside of uncultivated field margins, hedgerow restoration, late-cut meadows and the sowing of nectar-rich flower mixes are effective AES options to improve the agricultural landscape for bee communities. Flowering plants currently considered agricultural weeds are important forage resources for bees throughout the season and can benefit local bee communities.

Introduction

Intensification and advances in agricultural technologies over the past 50 years have led to the current drastic declines in wildlife species formerly associated with the British countryside (Kremen et al. 2002; Rundlof et al. 2008). Estimates suggest that up to 50% of all species within Europe depend on agricultural ecosystems at some level, including a number of threatened species (Stoate et al. 2009). The trade-off between local biological diversity and increases in yield has resulted in a ten-fold decline in economically and environmentally valuable taxa, many of which can be considered directly beneficial to agricultural production (Klein et al. 2007).

Two key factors have been identified as the main drivers of this decline: i) habitat loss and fragmentation (Rundlof et al. 2008; Bartlett et al. 2016); and ii) the introduction and extensive use of agrochemicals i.e. pesticides and fertilisers (Carvell et al. 2006; Lima et al. 2016). At the field scale, farmland biodiversity is directly affected by alterations to modern farming practice, specifically large-scale fast-moving machinery, and reductions in crop rotation cycles and conventional tillage systems (Holzschuh et al. 2006). With farmland making up more than 70% of the UK landmass (Department for Environment, Food and Rural Affairs, 2017), an increase in the area of monoculture, the lack of non-crop or semi-natural habitats and further reductions of connectivity between remaining pockets of semi-natural land, have all contributed to the drastic alterations of Britain at the landscape level (Garrett et al. 2017). Although the consequences of global climate change cannot be ignored in regard to overall biodiversity decline, the current level of agricultural influence can be more readily researched, and changes made to achieve relatively immediate results.

Agricultural systems rely heavily on ecosystem services to function successfully and yield beneficial products. Ecosystem services refer to physical elements and processes provided by functioning ecosystems which are advantageous to humans directly and indirectly (Tratalos et al. 2016). Such services that are provided by and contribute towards healthy, productive ecosystems include soil maintenance, biological control, nutrient cycling and pollination (Power, 2010). Intensive farming to produce high crop yields can be considered to trade-off with holistic ecosystem well-being. It degrades the environment and the associated services through increased soil erosion, organic nutrient removal, and runoff, increase of greenhouse gas emissions and escalation in environmental toxicity (Zhang et al. 2007; Pamminger et al. 2018). Although ecosystem services are the underlying driver to production and environmental regeneration in agricultural systems, research suggests a significant lack of understanding from farmers regarding how direct land management can manipulate ecosystem services, identifying the growing need for conservationists to work with farmers to increase the biodiversity of farmland (Teixeira et al. 2018).

Historically the Common Agricultural Policy had been a driver for agricultural intensification through its subsidies and financial support despite market fluctuations (Stoate et al. 2009). Environmental considerations triggered reform in this policy, changing its aims toward land productivity and the production of quality food products, rather than high agrochemical input to obtain maximum production. Later additions to the policy include actions working towards reducing pressures on the environment and implementing land set-aside (Stoate et al. 2009; Franks, 2016).

The UK Agri-Environment Schemes (AES), first implemented in the 1980s, aimed to increase the recruitment of farmers into “wildlife-friendly” farming through small to moderate alterations to

management activities, reducing production intensity and promoting the setting aside of areas of land for nature (Pywell et al. 2006). The two main levels of Countryside Stewardship AES are administered by Natural England, the Department for Environment, Food, and Rural Affairs (DEFRA) and the Rural Payments Agency. Entry-level Stewardship (ELS) is a widespread and flexible scheme involving various alterations for organic and upland farming. This scheme is currently being replaced with an alternative Mid-Tier Countryside Stewardship scheme during 2018. The Higher-level Stewardship (HLS) is a more rigorous complex scheme, which targets specific natural elements within farmland landscapes and requires high levels of commitment to changing land management methods and loss of cultivatable land. This scheme can be applied to both organic and non-organic farms (Hodge & Reader, 2010; Baker et al. 2012). Farmer's obligations within these schemes encompass adherence to "wildlife-friendly" and environmentally friendly actions aimed at promoting species diversity, restoring dwindling populations of significant countryside species and enhancing/maintaining natural resources (Carvell et al. 2006; Hardman et al. 2016a).

Assessing the effectiveness of AES is difficult because of the complex interactions between biotic environmental components, landscape heterogeneity and differing land management practices among study sites (Scheper et al. 2013; Holland et al. 2015). Since the introduction of such schemes, a number of reviews have attempted to quantify the effectiveness of the scheme. The results are mixed but generally suggest an average increase in biodiversity in response (Whittingham, 2011; Batary et al. 2015). Batary et al. (2015) identify that scheme activities based on field-margin habitats, specifically including hedgerows, are considerably more effective than those concentrated on agricultural production areas and conclude that efforts should be focused on the creation and maintenance of current non-crop habitats. Existing research highlights the benefits of agri-environment schemes to farmland birds (Kleijn et al. 2011; Westbury et al. 2017), plants (Carvell et al. 2006; van Klink et al. 2017), mammals (Boughey et al. 2011; Broughton et al. 2014) and some invertebrate groups (Fuentes-Montemayor et al. 2011; Hof & Bright, 2010). The benefits of AES accrued to general invertebrate populations has been well recorded, but primarily with reference to invertebrates as food sources for vertebrates, birds, and mammals being the focal point of the conservation efforts (Holland et al. 2015).

With pollination becoming prominent in conservation efforts in agriculture in recent years (Larson et al. 2017; Wilson, Forister & Carril, 2017), specific actions have been introduced within the AES which benefit pollinating insects directly and indirectly. Set-aside of uncultivated land is a common action known to produce significant benefits to insect pollinators (bees, hoverflies, and butterflies: Raymond et al. 2014; Hardman et al. 2016b), promoting the abundance and diversity of perennial plants and increasing flower densities (Stoate et al. 2009). Setting aside land should not be

confused with abandonment, because they differ in that set-aside has direct management to increase biodiversity (Firbank et al. 2003). Additional pollinator-specific actions include flower mixes of nectar-rich flower species, the creation of low-input grasslands for nesting resources (Scheper et al. 2013), enhanced grassland buffer strips, non-rotational grassland strips along field margins, the creation and/or preservation of species-rich grasslands and rotational pollen and nectar mixes (Wood et al. 2015; Hardman et al. 2016a). These actions clearly highlight the need for landscape heterogeneity and a variable habitat matrix to provide seasonal support for pollinators (Stoate et al. 2009; Breeze et al. 2014). The schemes are designed to increase pollinator-specific forage available in agricultural landscapes (Wood et al. 2015).

The pollination services provided by insect pollinators are invaluable in agricultural landscapes, providing an estimated £603 million to the UK economy alone, through the pollination of entomophilous crops (Downing & Sutherland, 2017). In addition to crop pollination, bees and other pollinators contribute to the stability of terrestrial ecosystems through the pollination of wild plants and associated services (Potts et al. 2010). As human resource-demands increase with the growth of the global human population, so does rural demand for domesticated bees for pollination (Power, 2010). However, current crop pollination demands surpass the ability of domesticated *Apis mellifera* and *Bombus terrestris* to supply, thus the pollination efforts of wild bees have become increasingly important (Breeze et al. 2014; Hardman et al. 2016a).

Apis mellifera and a number of common *Bombus* species are well known and studied, but these only make up a small percentage of the total British bee fauna: with the majority of bees are solitary rather than colonial, and are relatively unknown (Wood, Holland & Goulson, 2017). While *Apis mellifera* and *Bombus* spp. develop colonies, solitary bees generally nest alone, with some nesting in aggregations (Potts & Willmer, 1997). Unlike *Apis mellifera*, bumblebees and solitary bees do not store pollen and nectar for extended periods of time, and thus can suffer greatly from gaps in resources over time. Management options which reduce such gaps are a positive aspect of AES (Rundlof et al. 2008; Wood et al. 2015). A number of bee genera and sub-genera (*Nomada*, *Sphecodes* and *Bombus (Psithyrus))* are kleptoparasites of the nests of other bees, where they lay their eggs (Lhomme & Hines, 2018). As brood parasites, the presence of kleptoparasites within the nest can ultimately reduce the likelihood of successful reproduction, by diverting brood care away from the host's true offspring and loss of resources by utilising the pollen stores (Lhomme & Hines, 2018).

For wild bees, the abundance and diversity of floral resources and any associated temporal gaps are significant factors limiting their densities (Scheper et al. 2013; Hardman et al. 2016a). Studies suggest that AES options that promote flower-rich habitats that can supply the resources needed

throughout the year increase the populations of bumblebees (Pywell et al. 2006; Wood et al. 2015). However, these increases could be caused by redistribution from elsewhere within the agricultural landscape (Holland et al. 2015; Wood et al. 2015). Many species-specific traits and individual niches of solitary bees are little understood, but there are marked differences among species in foraging range, length of the active season, nesting position and tongue length (Goulson & Darvill, 2004; Wood et al. 2015). Agriculturally managed landscapes lack many of the flowers that contribute towards food and nesting resources, primarily because of agrochemical application (Hardman et al. 2016a), detrimental cultivation techniques (Preston et al. 2012) and intensive livestock grazing (O'Huallachain et al. 2013).

This study investigates the effectiveness and viability of agri-environment schemes in terms of pollinator conservation and resource provisioning, based in South Shropshire, United Kingdom. The following hypotheses are tested; i) AES-compliant farms have significantly higher bee abundance and support a greater number of bee species. ii) AES-compliant farms supply significantly greater flowering plant diversity to act as forage resources. The focus is on bee and flower communities found in and alongside field margin habitats within agricultural landscapes, highlighting favoured floral resources and any resource gaps. The study compares *Apis*, *Bombus* and solitary-bee species between Conventional farms and the two levels of AES, identifying any specific actions within the AES levels that provide significant benefits to local bee communities and making a final judgement on the overall benefits of AES to bee conservation.

Methodology

Study sites

18 farms were surveyed between April and September 2018 in Shropshire, England. All were based within or on the boundaries of the Shropshire Hills Area of Outstanding Natural Beauty (AONB), designated based on natural and cultural heritage features (see Fig. 1). All farms were chosen to fit one of three treatment categories for comparison of their land management systems; Conventional (C: seven farms selected), Entry-Level Stewardship (ELS: five farms selected) and Higher-Level Stewardship scheme (HLS: six farms selected). All management techniques implemented on farms enrolled in AES adhered to DEFRA guidelines and complied with Natural England environmental regulations.

Farms within treatment groups were separated into two approximately equal sets to be surveyed on alternate weeks. Due to significant differences in landscape heterogeneity and

phenological differences, it was not possible to match farms into triplets, one of each treatment. Instead, farms were selected to represent the land-management composition within the region to try to represent the farming practices and the habitats across the AONB. Four farm types were included; arable, livestock-arable mixed, livestock-based and dairy. However, farms were not specifically selected based on type resulting in slight differences in between treatment groupings. Livestock-based and livestock-arable mixed were the most frequent farm types, with six livestock-based farms (four conventional, two HLS), and seven livestock-arable mixed farms (two conventional, four ELS and one HLS). There were three arable farms (one ELS, two HLS), and two dairy farms (one conventional, one HLS) (see Table 1).

A questionnaire was supplied to all landowners and tenants to collect information about the management and environment of each farm. Questions included how long farms have been enrolled in AES, the specific options adhered to within the AES, any agrochemicals applied and general information about the farm (for full answers see Table 1).

Bee surveys

All bumblebees (*Bombus* spp.), honeybees (*Apis mellifera*) and solitary bees were surveyed utilising a transect method adapted from the standard survey methodology used for butterflies (Pollard, 1977). A combined total of one kilometre of belt transects was established along the typical field-margin habitats (hedgerow, stream or ditch) of two or three fields on each farm. The start points were selected along the appropriate field-margin habitats, under the condition that the margins must be internal to the farm, not along roadsides, and must exclude the first 10 metres from the field entrance. Transects were approximately two metres wide, including the field-margin habitats (estimated to be one metre) and one metre of uncultivated field margins (or cultivated land where there were no margins in place). Observations/captures were made up to a height of two metres. Surveying was carried out between 10.00 and 17.00 on days with acceptable weather conditions (local air temperatures above 13°C, minimum 60% clear sky and no rainfall) (Pywell et al. 2006). Each farm within the three treatment groups was selected at random to be surveyed within specific time slots, rotating between morning (10:00-12:00), early-afternoon (12.30-14:30) and late-afternoon (15:00-17:00) to reduce the effect of any potential fluctuations in bee abundance over the day.

Two sampling techniques were implemented to assess the abundance and species diversity of bee communities. Visual encounter surveying was carried out while traversing the set field-margin transects. Transects were travelled at a constant steady pace, each taking approximately 60 minutes to complete. All bees were recorded, though no separation was made between queens, workers or males. To minimise multiple recordings of a single specimen, bees that could be identified to species

on sight were monitored until they left the transect. Bees that could not be immediately identified were either caught in a net, identified and released (these bees left the transect as a result), or caught and retained for identification at the end of the survey. Following the transect survey, a sweep net survey was conducted along the same belt transect, specifically to target solitary bee species. The net was moved both horizontally across the ground of the field margins and vertically along the vegetation face of the margin habitat itself. Specimens were identified at the end of the survey using the keys in Falk (2015) and verified using the local atlas (Jones & Cheeseborough, 2014). The bee names follow Falk (2015), except *Bombus terrestris* and *Bombus lucorum* agg., which were recorded collectively as *B. terrestris/lucorum* agg. because reliable identification of workers in the field is not possible. When any bee was seen feeding or foraging on any flowering vegetation, the flower species was recorded to genus or species level where possible (using Fletcher, 2010).

Data analysis

The summary data were the counts of the number of individuals of each bee species summed for each farm and for each treatment group, together with some summaries at generic level (*Andrena, Bombus, Lasioglossum*, and *Nomada*). The flower species seen utilised by bees as forage resources were recorded, together with the numbers of each bee species seen foraging on them.

To test the effect of the AES schemes on bee abundance and species diversity, for each survey the total abundance of all bees, and the three standard indices of diversity (Hill numbers: Chao et al. 2014) were calculated: H0 (species richness) emphasizes rare species, H1 puts more weight on common species, and H2 is an index of the number of superabundant species. These then formed the response variables in generalised linear mixed models, due to the use of repeated measures (random factors of individual farm and survey date) so as to be able to see the influence of the AES treatments on bee abundance and species diversity. Residuals were checked and the default normal errors were appropriate for all the analyses. All models included random factors of farm and date, and the fixed predictors of *AES* group, farm *type* and the *AES* x *type* interaction, tested by ANOVA. *A priori* contrasts were applied within each ANOVA, predicting that Conventional farms would have lower bee abundance and species diversity than farms managed under either AES (C < ELS + HLS) and that ELS farms would have a lower bee abundance and species diversity than HLS farms (ELS < HLS). In addition, data for bumblebee species were analysed separately. All the data analyses were conducted using R version 3.5.1 (R Core Team, 2018) using the package *lme4*.

Data for the genus *Bombus* were analysed separately due to the large amount of information collected on the genus, including the subgenus *Psithyrus*. Not only are a number of species from this genus present on all farms being surveyed, but the genus includes a mixture of both common and

more scarce species, as well as generalist and more specialised species, giving it an ability to showcase general trends and changes between bee communities based on a relatively small number of species. Now that *Bombus* species are actively being utilised and manipulated as commercial crop pollinators (e.g. *B. terrestris*), gaining a greater insight into the effect of farm management on their populations can allow for better future monitoring and conservation.

Floral diversity was estimated by counting the flowers utilised by foraging bees; means were used to allow for differences in sample sizes among treatment groups. Summing over all transects, the flower x bee matrix of total numbers of visits was formed, and the interactions plotted as community network diagrams using the *bipartite* package in R (Dormann, Gruber & Fruend, 2008). The time-course of the most-used flowers across the survey season highlighted any temporal gaps in forage.

Results

Bee abundance and diversity

A total of 4234 individual bee sightings were recorded over the entire study period (674 *Apis mellifera*, 2130 *Bombus* spp. and 1430 solitary bees). 1055 bee sightings occurred on Conventional farms, 1407 sightings on ELS and 1772 sightings on HLS (Fig. 2a). 65 species of 12 genera were identified, with a combined total of 44 species identified on Conventional farms, 47 on ELS and 50 on HLS (Fig. 2b; Appendix Table A1). The records included species locally scarce to Shropshire, such as *Melecta albifrons* and *Lasioglossum malachurum*. Overall species richness differed between farm treatments; Conventional farms ranged from 16 to 24 species between farms, ELS farms between 26 and 33, and HLS farms between 19 and 35.

The 15 most common species (Fig. 3) include seven *Andrena* spp., six *Bombus* spp., *Apis mellifera*, and *Halictus rubicundus*. In terms of total sightings, the most species-rich genera were *Andrena* (16 species), *Lasioglossum* (14 species), *Bombus* (11 species) and *Nomada* (11 species). The genera with the greatest abundances were *Bombus* (2130 sightings), *Andrena* (933) and *Apis* (674). The most abundant *Andrena* were *A. nigroaenea*, *A. haemorrhoa,* and *A. chrysosceles*; for *Lasioglossum* they were *L. calceatum* and *L. leucopus*; for *Bombus*, *B. terrestris/lucorum* agg., *B. lapidarius* and *B. pascuorum*; and for *Nomada*, *N. goodeniana* and *N. lathburiana*. The three most common species overall (See Fig. 3 and Fig. 4) were *Apis mellifera* (674 sightings), *B. terrestris/lucorum* agg. (632 sightings), and *B. lapidarius* (606 sightings). A total of 11 *Bombus* species out of the 18 recorded in Shropshire (Jones & Cheeseborough, 2014) were identified across all the study farms. Five

species were present of every farm; *Bombus terrestris/lucorum agg*., *B. lapidarius*, *B. pascuorum*, *Apis mellifera,* and *Andrena haemorrhoa*.

Bee phenology varied amongst species, with differing genera appearing throughout the season. *Bombus* spp. and *Apis mellifera* were present throughout the entire study period, appearing in every week of surveying in varying abundances (Fig. 4a, b, c). *Bombus* (*Psithyrus*) spp. were present only on farms where the associated host was also present, appearing in low abundances in two waves, during April – May and throughout August. *Andrena* spp. appeared early on in relatively high numbers (Fig. 4d), but these started to drop in late July, with no sightings into August. *Nomada* spp., kleptoparasites of *Andrena*, also appeared early on alongside their host species, with sightings occurring from April until June (Fig. 4f). *Halictus* and *Lasioglossum* were present sporadically until July when their abundances increased until the end of the survey period. Numbers of *H. rubicundus* increased during August (Fig. 4e), after appearing in low abundance throughout the survey period. The numbers of *Sphecodes* spp. fluctuated in association with their hosts (*Andrena, Halictus,* and *Lasioglossum*), appearing when their various host abundances peaked. An individual *Melecta albifrons* was identified, but its host, *Anthophora plumipes*, was not recorded at any point during the study period, although common in gardens throughout the local area.

Differences among AES treatments

Bee abundance and diversity per survey were found to be significantly related to land management under AES (Fig. 5; Appendix Table A2). Using either AES treatments had a significant positive influence compared to Conventional farms on the number of bees and all the measures of diversity, H0, H1, and H2. The first contrast (C < ELS+HLS) was always highly significant ($p << 0.001$: see Table A2). Compliance with either agri-environment scheme showed the greatest influence on abundance (Fig. 5a) and species richness (Fig. 5b), indicating that the largest effect was on rare species of bee. The smallest effect was found on H1 (Fig. 5c), which emphasizes common species. The second contrast (ELS < HLS) was not in the predicted direction for any of the Hill numbers (and hence not significant), but there was a small increase in overall bee abundance for HLS (Fig. 5; Table A2). Farm type showed no significant effects on any of the response variables (Table A2). However, there were significant or near-significant interactions between the interaction of AES and farm type for all response variables ($p = 0.011 - 0.019$: see Table A2; Fig. A1). Species richness (H0) shows the most significant response to the AES x farm type interaction (Fig. A1), where the difference between Conventional and HLS farms is smaller in Livestock-based farms than in other types of farm.

For just the bumblebees, the AES treatment had significant effects on abundance and H0 (species richness), but not H1 or H2, both of which place emphasis on common species (Table A3). For

abundance and H0, again there was a highly significant first contrast (C < ELS+HLS; $p << 0.001$), but no effect for the second contrast (ELS < HLS). Farm type and the interaction between AES and farm type showed no significant influence on the bumblebee community.

Community use of floral resources

Bees were recorded utilising 62 flowering plant species across all study sites throughout the season, with 36 used on Conventional, 40 on ELS and 39 on HLS farms. Mean counts showed species diversity remained highest in ELS-compliant farms, followed by HLS-compliant farms (see Fig. 6). Species counts on conventional farms ranged from five to 16 species, from 14 to 18 on ELS-compliant farms, and 10 to 18 on HLS-compliant farms. The most dominant flowers being used included *Crataegus monogyna, Taraxacum* spp., *Heracleum sphondylium, Trifolium pratense, Trifolium repens, Rubus fruticosus* and *Cirsium* spp (Fig. 7). *Impatiens glandulifera* (Himalayan Balsam, an aggressive invader which dominates banks of waterways) occurred on two farms where it acted as a significant late-season nectar source (Fig. A2), attracting many foraging *Bombus* spp. and *Apis mellifera*.

Discussion

Both Entry-level and Higher-level stewardship agri-environment schemes were found to influence significantly the abundance and species diversity of bees on farms, with higher numbers of bees and greater diversity of bees seen on farms associated with AES, in comparison to conventionally managed farms. This difference in bee abundance and diversity cannot solely be attributed to AES due to the magnitude of differences between farming landscapes, such as farm type, although general inferences can be made from the results. These results suggest that farms managed in accordance with AES provide an environment that supports an increased number of bees from a greater number of species. For all bees and for bumblebees separately, the influence of the AES is strongest on abundance and species richness, suggesting that compliance to an AES significantly affects the abundance and presence of rare species. Conventional and AES-compliant farms alike produce the environmental conditions to support common species, such as the six common generalist bumblebees (including *B.terrestris, B. lapidarius* and *B. pascuorum*) and *Apis mellifera* (Hanley & Wilkins, 2015).

The treatment group that produced the most variable results was HLS, with species diversity ranging from 19 to 35 species across the treatment group. This larger variation in species diversity among HLS sites could be due to the fact that management actions on these farms varied greatly, from field-level conservation actions to conservation focusing on specific areas of the farm. Conventional farms consistently showed the lowest abundances and lowest species diversity, of both rare and

common species alike. This highlights the significant lack of appropriate habitats for feeding and nesting resources. Likewise, AES-compliant farms supported more flowering plant species which were recorded being utilised, providing bees with a greater variety of forage resources than conventionally managed farms, and suggesting greater habitat diversity within the wider agricultural landscape.

Agri-environment schemes and landscape context

HLS farms can often focus their actions on specific areas of interest, such as woodland, in conjunction with some field-level actions, such as set-aside. In comparison, one of the most common ELS actions is land set-aside as non-crop field margins (see Table 1), with the majority of actions making small changes across a larger area. Since ELS farms supported the most diverse bee communities, this suggests that this level is more likely to establish the beneficial environments that increase and preserve local bee communities. This highlights the fact that actions spread across the landscape at field-level could be more beneficial than focusing on specific areas of interest. The slightly greater overall bee abundance on HLS-compliant farms suggests that these can support the level of resources needed to allow bee populations to be sustained at high levels. Pollinator abundance and diversity can decrease with increasing distance from semi-natural habitat (Gill et al. 2016), emphasizing that the spatial structure and configuration of AES actions across the landscape is essential for bee conservation and efficient pollination services (Holland et al. 2015).

Field margins provide nesting/foraging resources and refuge habitats at field-level, increasing connectivity between semi-natural, non-cultivated habitats throughout the local landscape (Holzschuh et al. 2006). This habitat connectivity within the agricultural landscape specifically benefits bumblebees and solitary bees through access to seasonally variable forage. In addition to habitat corridors, hedgerows can act as environmental buffers, reducing the spread of agrochemicals (Carvell et al. 2007; Hanley and Wilkins 2015). The positive influences derived from the management of non-crop field margins are likely due to the increase in the availability of flowering plant species (Pywell et al. 2006).

Conventional farms had lower bee abundances and species diversity of both bees and flowering plants, but a small community of common bees were still consistently present, showing that this approach to farming does not entirely remove the resources and environmental conditions needed to support basic bee communities. However, the landscape of such farms ultimately receives reduced pollination services, which may affect the long-term stability of the flowering plant community. A lack of habitat for flowering species limits diversity within the conventionally farmed landscapes. This significant reduction in landscape heterogeneity is a known cause of declining diversity of species associated with agricultural landscapes (Holzschuh et al. 2006; Landis 2017).

Pollinator-targeted actions

Farms that supported the greatest abundance and species diversity of bees adhered to a number of similar AES actions, such as sowing and management of nectar and pollen-rich flower mixes on several ELS and HLS-compliant farms (see Table 1). These mixes generally include a number of legume species and species of tussock grasses, providing both forage and nesting resources (Carvell et al. 2007). However, these mixes tend to flower after June (see Fig. A2), and hence fail to supply resources early in the season when bumblebee colonies begin development. The creation of a six-metre set-aside field margin is another action known to be effective at providing resources that support bee communities (Garibaldi et al. 2014). Although naturally regenerating, these areas are not devoid of management as most often they are mown annually, after the initial two years of establishment, which prevents domination by particular species. The success of this option can be dependent on the margin's age, with the appearance of *Cirsium* spp. increasing the abundance of several *Bombus* spp. (Carvell et al. 2007).

Late cutting of hay meadows is a commitment followed by a number of the HLS study sites, which allows flowering plants to set seed (Johansen et al. 2017), and the subsequent scattering of green hay can result in high floral diversity (Edwards et al. 2007). This management option can produce semi-natural hay meadows, providing diversity in nesting habitats and flowering plants, and supporting a greater range of foraging niches (Johansen et al. 2017). Previous research has shown the immediate effects of leaving uncut refuge habitats and late hay-meadow mowing on wild bees, highlighting the ease with which this low-input option could be assimilated into all levels of AES (Buri et al. 2014).

The option of hedgerow creation and restoration was taken up on several HLS-compliant farms. Although not an option offered specifically to benefit pollinators, hedgerow and tree-line restoration and the creation of dense, species diverse hedgerows has been linked to a marked increase in biological diversity (Staley et al. 2015). Hedgerows are valuable habitats for pollinators within agricultural landscapes, and their creation and optimal management can increase pollination services, benefiting crop production and pollination of wild flowering plants (Garrett et al. 2017). Hedgerows and tree lines provide shelter and forage resources for bees because they host a number of woody plants and flowers adapted to woodland-edge conditions not found in grassland habitats and on cultivated land (Wratten et al. 2012). Management practice is a significant limiting factor to the success of hedgerows in increasing biodiversity because they need to be long enough and to have structural integrity: both over-trimming and overall neglect in management reduce biodiversity (Staley et al. 2015).

Forage provisioning

The diversity of flowering plant species varied amongst the farms, with those managed in compliance with ELS having the highest species diversity, followed by HLS farms. The majority of field margins managed in ELS are low-input, self-regenerating margins, with the dominant flowering plant species being *Cirsium arvense, Cirsium vulgare, Heracleum sphondylium* and *Rubus fruticosus.* These species are rapid colonisers (Pywell et al. 2006) and occurred on farms of all treatment groups. Research suggests that forage provision acts as a significant limiting factor on local bee populations and that loss of floral diversity in conventionally managed agricultural landscapes is a prominent driver in bee declines (Dicks et al. 2015). Conventional farms range greatly in floral species diversity, with some locations supporting a very low diversity of flowering plants used by bees, thus limiting bee abundance and diversity.

From the data, the intentional sowing of field margins appeared to be successful in increasing the abundance and diversity of bees. Specific species sown on ELS and HLS farms include *Sinapis arvensis*, *Phacelia tanacetifolia*, *Trifolium repens,* and *Melilotus officinalis*, all known to attract bees, especially *Apis mellifera*. Game cover, used for the rearing of bird for the recreational shooting is often sown with pollinator-beneficial flowers, to enable the land to be enrolled in AES (Firbank et al. 2003). The addition of *Helianthus* spp. to game cover habitat provides a boost to forage resources late in the season, favoured particularly by *Bombus pascuorum* and *B. terrestris/lucorum* agg (see Fig. A2; Henderson, Vickery & Carter, 2004) as well as, an economic incentive to farmers through AES payments.

The time-course of foragers at flowers (Fig. A2) highlights a decline in mid-May, whilst the abundances of the commonly seen species (Fig. 4) do not reflect this decline in sightings. This suggests that there is a temporal gap in the diversity of flowering plants used for foraging at this time. *Crataegus monogyna* and *Taraxacum* spp. were the dominant flowering plants initially utilised at the beginning of the season. Resources at this time in the season are essential for emerging solitary bees and *Bombus* queens to begin nesting, laying and rearing brood (Devoto et al., 2013). Alterations to land management methods can help to alleviate this resource gap via less-intense cutting or not cutting selected areas of hedgerows where *C. monogyna* is dominant in the previous autumn/winter. *Impatiens glandulifera* was identified as an important late-season nectar source, providing resources when many flowering plant species have gone to seed. This invasive foreign plant may have displaced native flowers, thus actually reducing the diversity of nectar and pollen sources through the entire season (Flugel, 2017).

Implications for agri-environment schemes

This study confirms that the implementation of AES, both at entry and higher level, has the ability to mitigate the influences of modern intensive farming to allow a larger and more complex bee community to be supported. However, there are improvements that can be made to particular scheme actions to optimise farmer enrolment. Active management and sowing of set-aside field margins specifically for pollinator conservation do produce effective results, but the low-input method of leaving these margins to regenerate naturally also shows increases in bee abundance and diversity, and flowering plant diversity (Carvell et al. 2007). Encouraging the uptake of such low-input but effective options could increase more widespread adoption of AES. Research into conservation efforts such as AES often suggest them to be most effective in simple, homogeneous landscapes, and therefore efforts in areas of intensive agriculture have a high potential for success (Garratt et al. 2017). However, Dicks et al. (2010) suggest there is potential for such habitats to redistribute bee populations, rather than to increase their abundance.

Hardman et al. (2016a) stipulate that the future of agricultural management requires trade-offs between agriculturally viable land and the preservation of ecosystem services such as pollination, biocontrol, and nutrient cycling. Taking agricultural land out of production does not appear economically advantageous at first, but the additional pollination services can both increase crop pollination and wildflower communities in the surrounding landscape (Cole et al. 2017). With bans and changes of policy limiting the use of insecticides detrimental to pollinators, a second threat is from herbicides. While some can prove toxic to invertebrates, their main effect on bees is through reductions in flowers currently considered agricultural weeds (such as *Heracleum sphondylium, Rubus fruticosus,* and *Cirsium* spp.) (Gabriel & Tscharntke 2007; Bretagnolle & Gaba 2015). Understanding crop economic thresholds for weed tolerance could allow these pollinator-friendly species to be incorporated into seed mixes without negatively affecting crop yield.

Conclusion

The current broad agri-environment schemes do have the ability to produce environmental conditions that supply the resources needed to promote abundant and diverse bee communities within agricultural landscapes. Bee abundance and species diversity were positively influenced by AES options, such as the creation of non-crop field margins, hedgerow restoration, late-cut meadows and the sowing of nectar-rich flower mixes. The most widely used level of agri-environment scheme, ELS, has the ability to increase significantly the abundance and diversity of bee species with relatively low input from farmers. This study identifies the importance of flowers currently considered agricultural weeds to foraging bees through the year and highlights the need for a shift in opinion about and actions against these plants for the benefit of bee communities.

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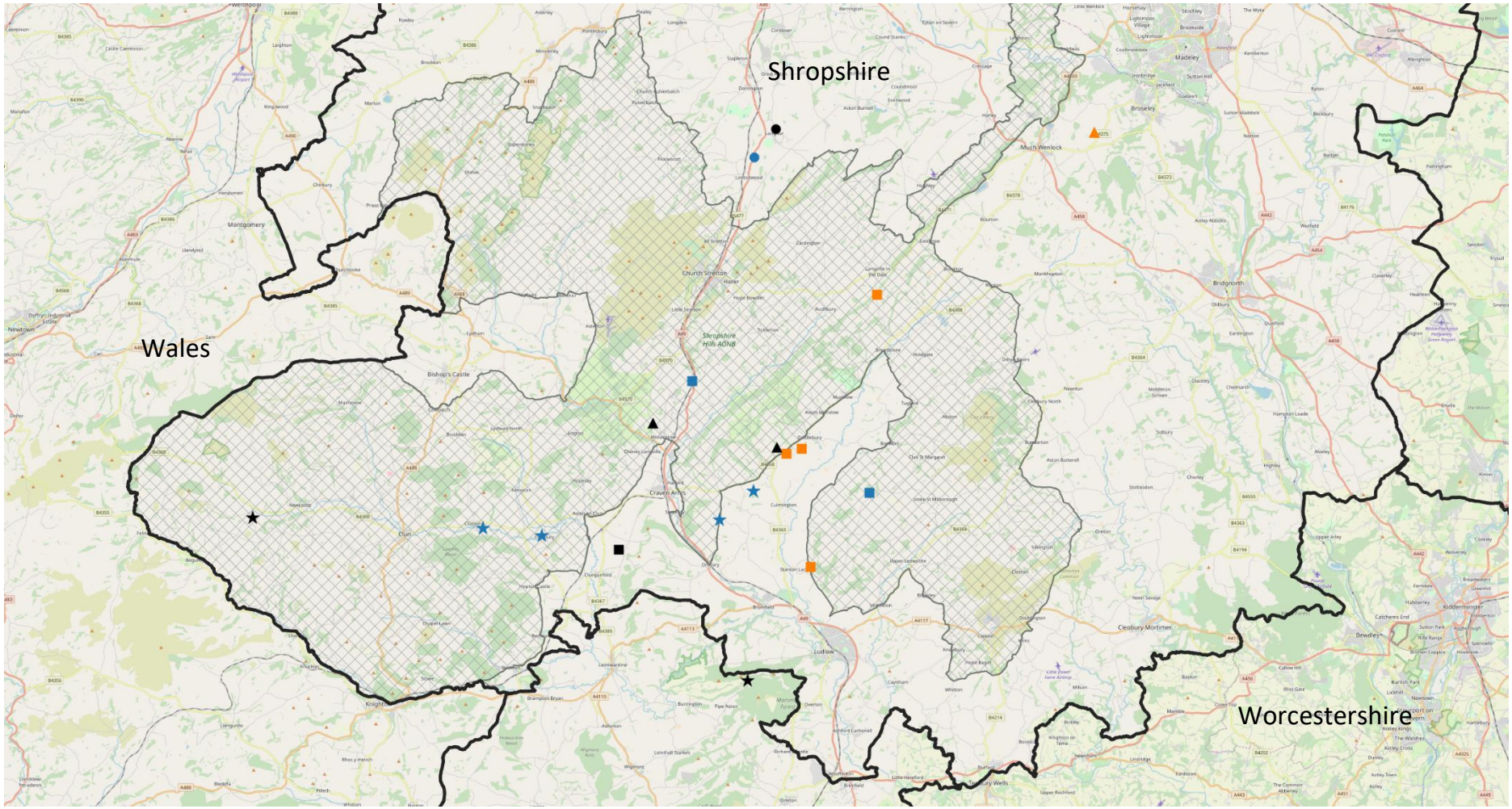


Fig. 1. Map of the locations of all study farms. Black lines indicate county boundaries and grey hatching shows the area designated as the Area of Outstanding Natural Beauty. Colours indicate individual farms; blue=Conventional farms, orange=ELS farms, black=HLS farm. Shapes represent farm types; circle=Dairy, triangle=Arable, star= Livestock-based, square=Livestock-arable mixed. The map was created using QGIS 3.0.3, using data sourced from MAGIC and Ordinance Survey.

Table 1. Key land management activities and agrochemical applications over the previous year on the study farms. Treatment groupings; conventional (C), Entry-level stewardship (ELS), higher-level stewardship (HLS). Farm type groupings; Dairy (D), Livestock based (L), Livestock-arable mix (LA), Arable (A).

Farm	Treatment	Years in treatment	Farm type	Farm size (acres)	Main AES commitments	Pollinator specific actions	Fertilisers	Pesticides (active ingredients)
1	C	-	D	55	-	-	24:0:16 and 24:0:0 and 26:13:0 (N, P, K)	no
2	C	-	LA	150	-	-	Nitrogen 34.5%	Pyrethroid - flea beetle insecticide
3	C	-	LA	90	-	-	Nitrogen 34.5%	Glyphosate
4	C	-	L	55	-	-	Not available	Not available
5	C	-	L	70	-	-	Not available	Not available
6	C	-	L	16	-	-	No	Dock spray (fluroxypyr & triclopyr)
7	C	-	L	30	-	-	Agricultural lime	No
8	ELS	12	LA	165	Hedgerow restoration, 6m set-aside field margins, over winter stubble, nectar and pollen mix	Nectar and pollen mix	Nitrogen 34.5%, 0:20:30 (N, P, K)	Laidir 10 CS (lambda-cyhalothrin)
9	ELS	6	A	280	Hedgerow restoration, 6m set-aside field margins, over winter stubble, spring cropping(blackgrass), woodland management	No	Nitram (Nitrogen) 34.5%	Atlantis (Mesosulfuron-methyl and Iodosulfuron-methyl sodium), Elatus (Benzovindiflupyr and prothioconazole)
10	ELS	2	LA	180	Hedgerow restoration, low input, set-aside field margins	No	Nitrogen 34.5%, 0:20:30 (N, NS & NPK), polysulphate	Pyrethroid - flea beetle insecticide

11	ELS	8	LA	120	Permanent pasture, over winter stubble, 6m watercourse margin, bird nesting ground set-aside	No	Poultry manure, Sulphan29, Nitrogen 34.5%	Laidir 10 CS (lambda-cyhalothrin)
12	ELS	10	LA	170	6m set-aside field margins, low input grasslands	Nectar mix	Nitrogen 34.5%, polysulphate, 0:20:30 and 0:24:24 (N, P, K)	CleanCrop Argent
13	HLS	18	D	750	6m set-aside margins, low input grasslands, nectar and pollen mix, hedgerow restoration	Nectar and pollen mix (mainly *Trifolium repens*) no agrochemical application	Manure, BetterGrass, VITA-grass	No
14	HLS	12	L	49	Hedgerow restoration, enhanced wild bird seed mix, semi-improved species-rich pasture	Semi-improved species-rich pasture (Fritillary butterfly)	No	Glyphosate, Grazon (triclopyr and clopyralid)
15	HLS	12	A	500	6m set-aside field margins, enhanced wild bird seed mix, nectar mix, over winter stubble	Nectar mix	Poultry manure, Nitrogen 34.5%	Glyphosate
16	HLS	8	A	370	6m set-aside field margins, enhanced wild bird seed mix, nectar mix, over winter stubble	Nectar mix	Poultry manure, Sulphan29, Nitrogen 34.5%	Laidir 10 CS (lambda-cyhalothrin)
17	HLS	5 + 30 in previous schemes	L	55	Permanent pasture, 6m set-aside field margins, late cut hay	Species-rich herbal mix, late cut species-rich hay meadows, no	No	No

					meadows, hedgerow restoration, clover strips	agrochemical application, clover strips		
18	HLS	20+	LA	320	6m set-aside field margins, nectar mix, enhanced wild bird seed mix	Nectar mix	Ammonium nitrate	Sparviero (pyrethroid), SHERPA (imidacloprid and imidazolidinimine)

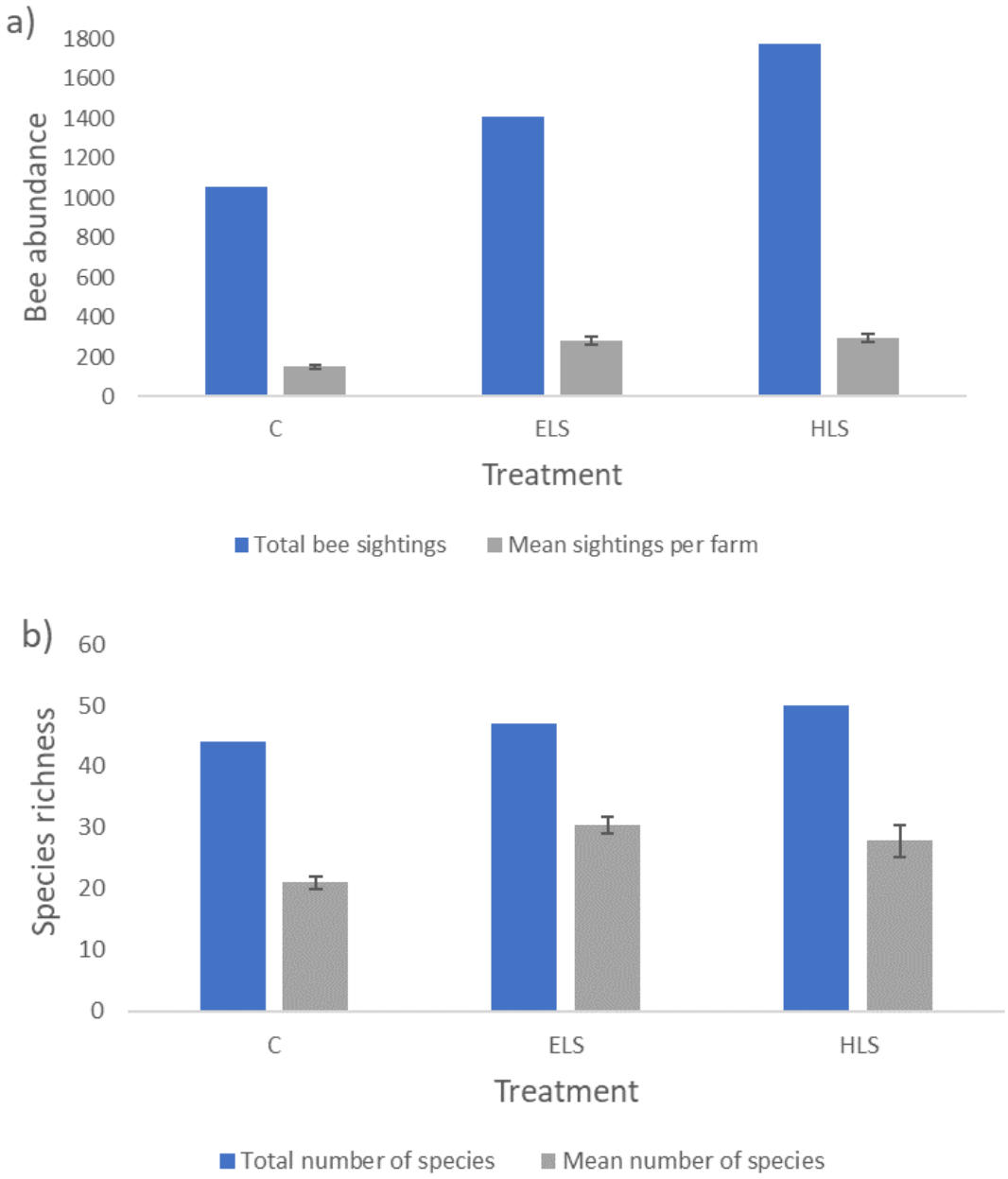


Fig. 2. Overall totals (blue) and means per survey (grey) of (a) bee abundance, and (b) species richness (H0) across the three treatment groups. Error bars represent Standard Errors. Farm treatments; C = Conventional (n=7), ELS = Entry-level stewardship (n=5), HLS = Higher-level stewardship (n=6).

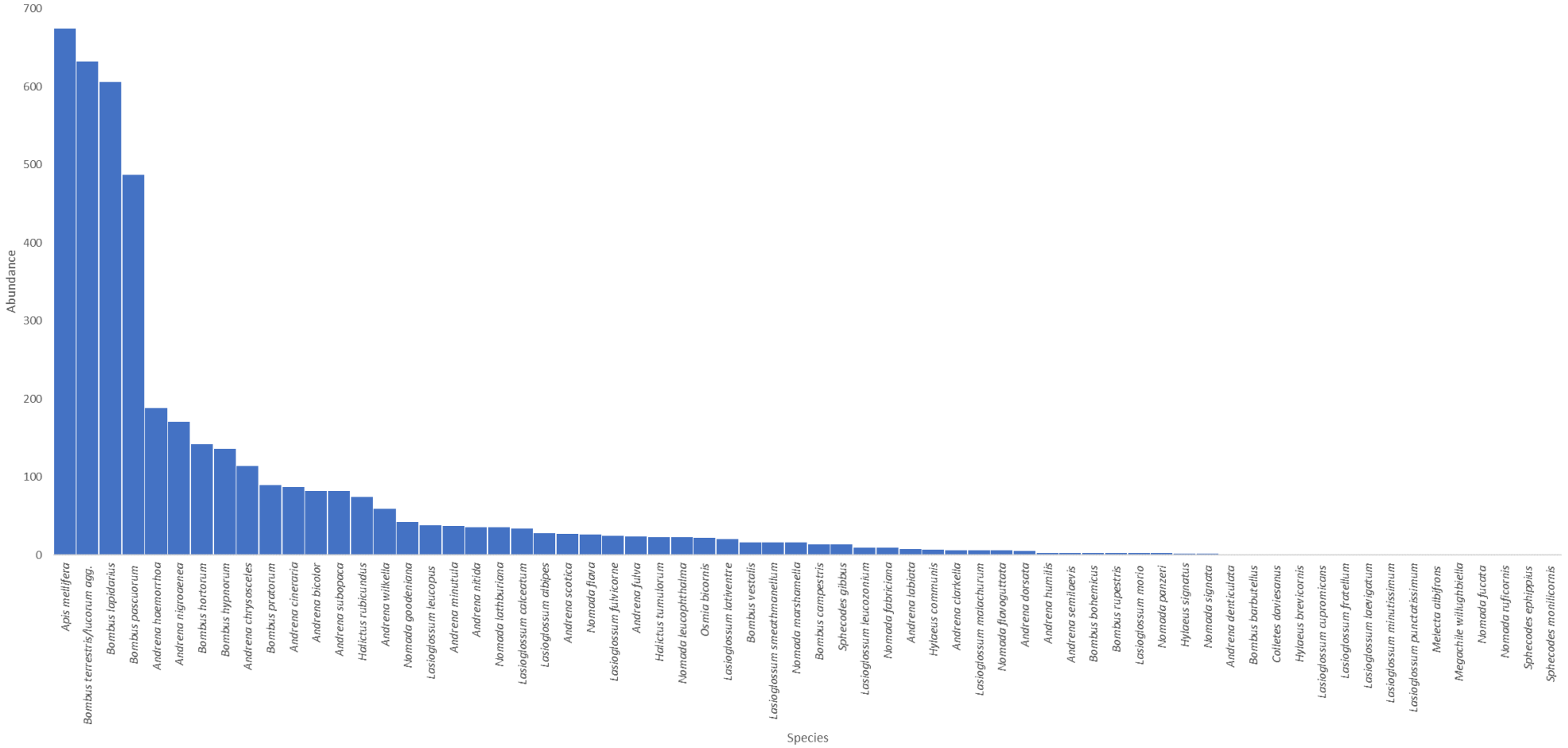


Fig. 3. Total abundance of all species identified throughout the entire study period.

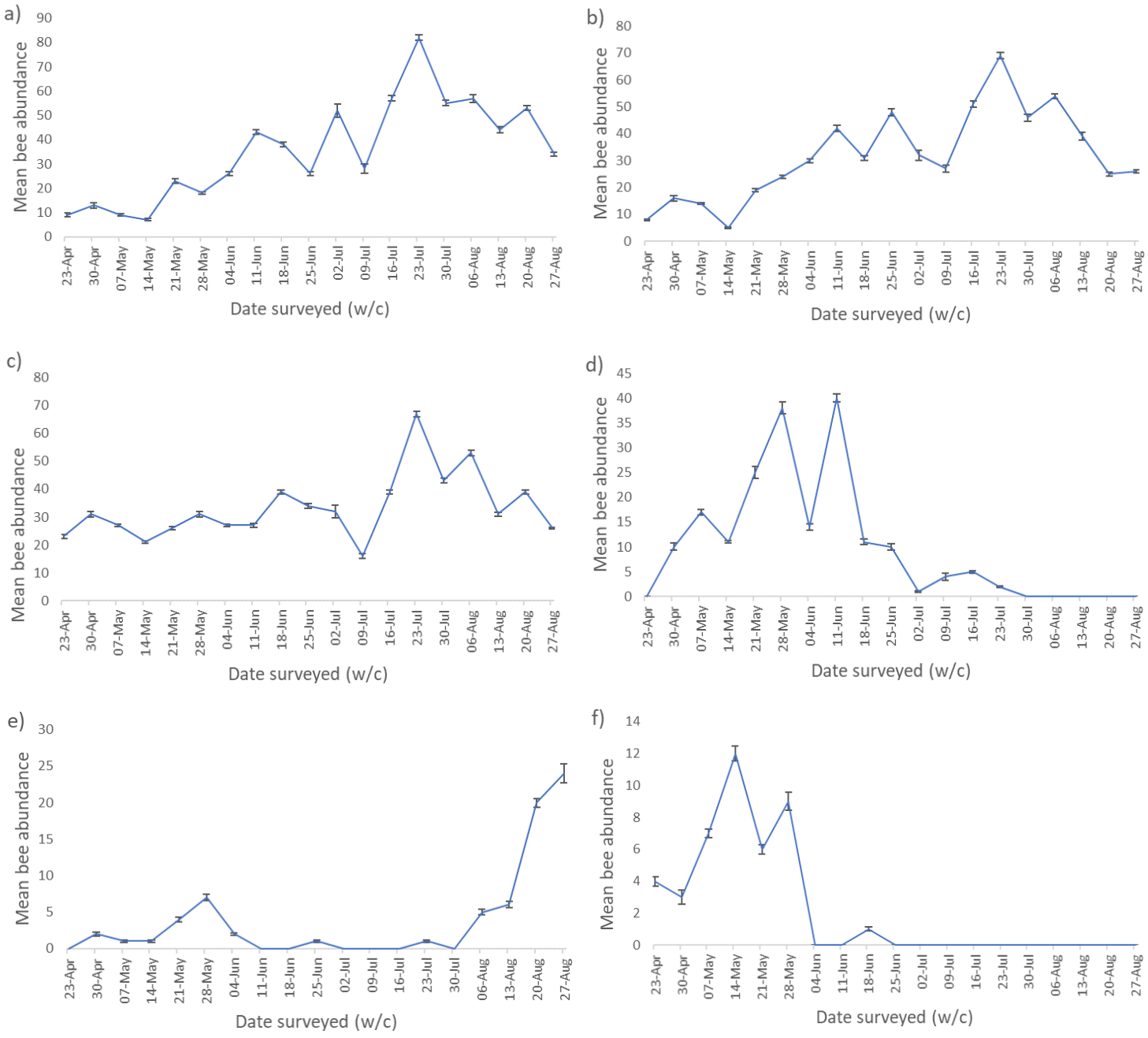


Fig. 4. Total number of sightings across all farms of a collection of common species. a) *Apis mellifera*, b) *Bombus lapidarius*, c) *Bombus terrestris/lucorum* agg., d) *Andrena heamorrhoa*, e) *Halictus rubicundus*, f) *Nomada goodeniana*. Error bars represent Standard errors.

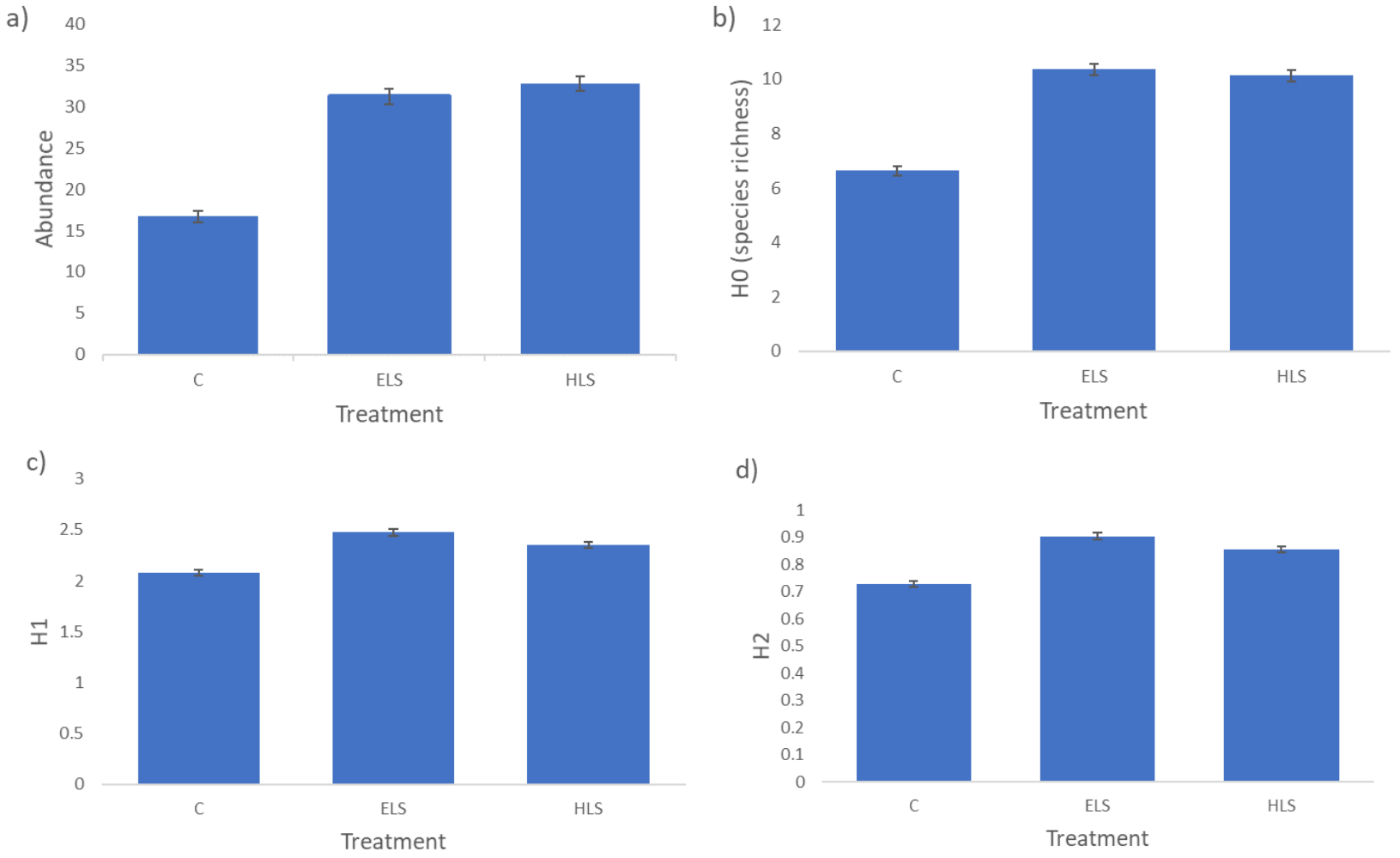


Fig. 5. Marginal means per survey for each treatment group. a) bee abundance, b) H0 (species richness), c) H1, d) H2. Error bars represent Standard Error. Farm treatments; C = Conventional (n=7), ELS = Entry-level stewardship (n=5), HLS = higher-level stewardship (n=6).

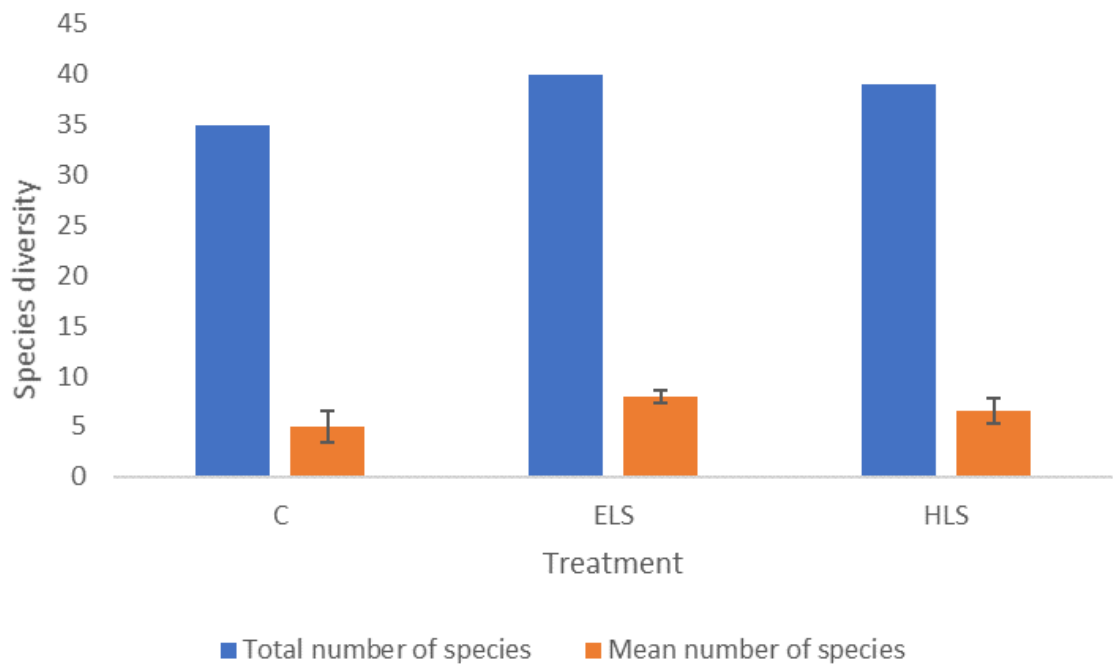


Fig. 6. Overall totals (blue) and means per survey (orange) of floral species diversity across the three treatment groups. Error bars represent Standard Errors. Farm treatments; C = Conventional (n=7), ELS = Entry-level stewardship (n=5), HLS = Higher-level stewardship (n=6).

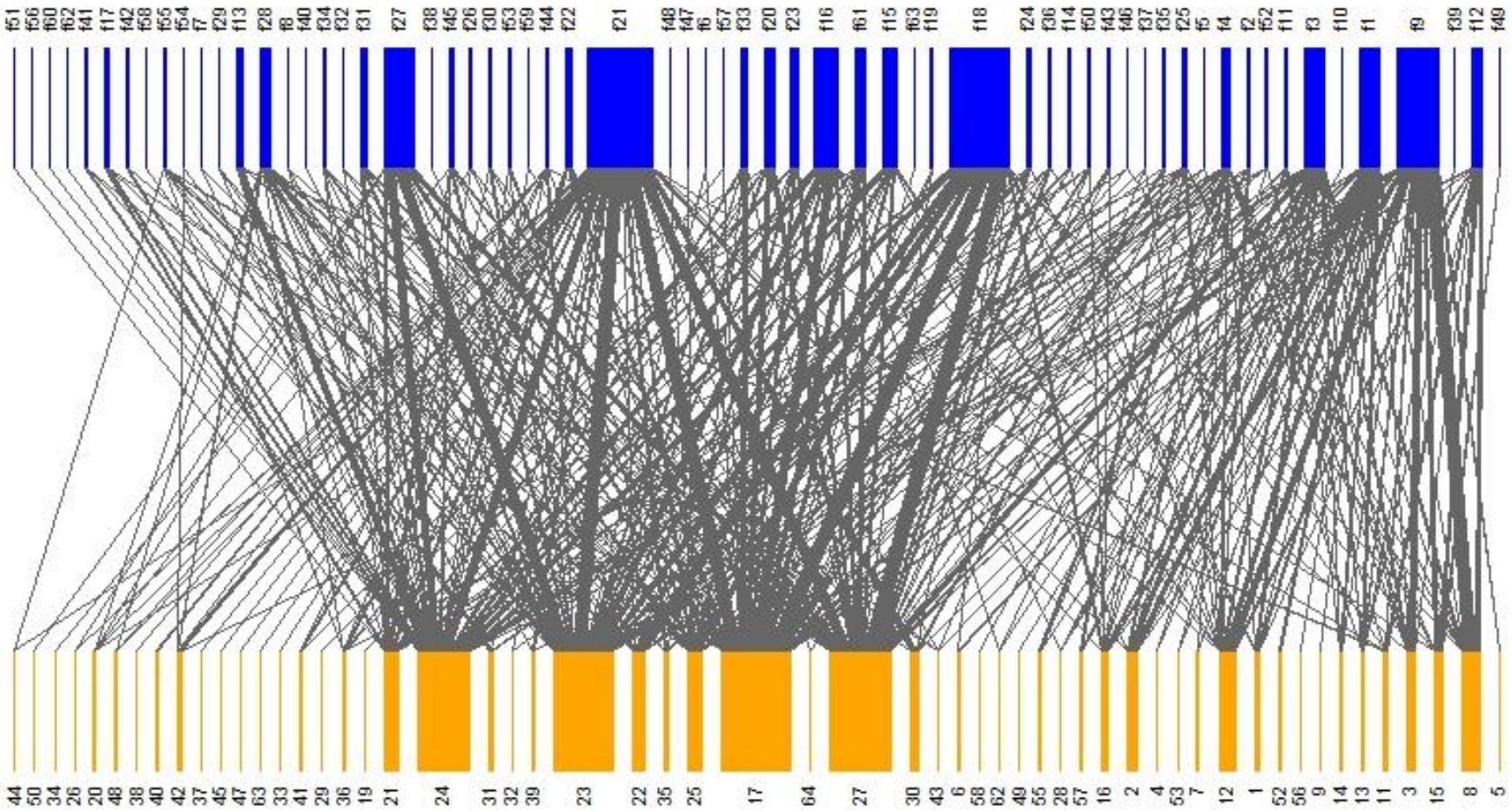


Fig. 7. Interactions between bee species and flowering plant species across the entire survey period, over all survey sites. Orange indicates bees, with numbers referring to species listed in Appendix Table A1. Blue indicates flowering plant species, with numbers referring to species listed in Appendix Table A4. The width of orange and blue nodes represents the number of bees observed and the grey lines represents the numbers of observed interactions between bee and flowering plant.

Appendix

Table A1. Total species present and abundance counts for each farm, summed for the entire study period. Farm type groupings; Dairy (D), Livestock based (L), Livestock-arable mix (LA), Arable (B). Nomenclature follows Falk (2015)**.**

	Treatment	**Conventional**								**Entry-Level stewardship**						**High-Level stewardship**						
	Number	1	2	3	4	5	6	7	**Total**	8	9	10	11	12	**Total**	13	14	15	16	17	18	**Total**
	Farm type	D	LA	LA	L	L	L	L		LA	A	LA	LA	LA		D	L	A	A	L	LA	
	Species	**Abundance**								**Abundance**						**Abundance**						
1	*Andrena bicolor*	3	0	4	1	3	5	5	**21**	0	8	2	3	7	**20**	7	7	10	8	1	8	**41**
2	*Andrena chrysosceles*	6	16	2	1	7	0	2	**34**	9	13	3	3	12	**40**	2	11	10	10	0	6	**39**
3	*Andrena cineraria*	0	3	2	9	0	8	5	**27**	7	0	8	8	4	**27**	4	0	9	11	3	6	**33**
4	*Andrena clarkella*	0	2	0	0	0	0	0	**2**	0	0	0	0	0	**0**	0	0	3	0	0	1	**4**
5	*Andrena denticulata*	0	0	0	0	0	0	0	**0**	0	1	0	0	0	**1**	0	0	0	0	0	0	**0**
6	*Andrena dorsata*	0	0	0	0	0	0	0	**0**	0	4	0	0	0	**4**	0	0	0	0	0	0	**0**
7	*Andrena fulva*	0	3	0	2	0	3	5	**13**	0	1	1	0	1	**3**	1	1	4	2	0	0	**8**
8	*Andrena haemorrhoa*	1	1	11	6	12	10	12	**53**	5	2	20	20	12	**59**	11	2	21	6	15	21	**76**
9	*Andrena humilis*	0	0	0	0	0	0	0	**0**	0	0	0	0	0	**0**	3	0	0	0	0	0	**3**
10	*Andrena labiata*	0	0	0	2	0	0	0	**2**	0	0	5	0	0	**5**	0	0	0	0	0	1	**1**
11	*Andrena minutula*	0	0	0	0	3	9	0	**12**	4	11	6	0	0	**21**	0	4	0	0	0	0	**4**
12	*Andrena nigroaenea*	0	2	0	19	6	12	3	**42**	17	11	16	19	15	**78**	6	5	12	13	4	11	**51**
13	*Andrena nitida*	1	5	2	1	2	2	1	**14**	7	3	6	1	0	**17**	1	0	2	0	1	1	**5**
14	*Andrena scotica*	0	4	4	2	0	0	1	**11**	1	1	1	0	3	**6**	0	0	0	2	4	4	**10**
15	*Andrena subopaca*	8	4	0	2	0	0	0	**14**	0	10	7	3	0	**20**	20	8	8	7	1	10	**46**
16	*Andrena wilkella*	0	0	0	0	0	0	3	**3**	2	1	2	5	1	**11**	10	27	11	3	3	9	**44**
17	*Apis mellifera*	61	25	25	23	7	26	34	**201**	48	42	47	56	35	**228**	43	0	62	52	30	34	**248**
18	*Bombus barbutellus*	0	0	0	0	0	0	0	**0**	1	0	0	0	0	**1**	0	0	0	0	0	0	**0**
19	*Bombus bohemicus*	0	0	0	0	0	0	0	**0**	0	1	1	0	0	**2**	0	0	0	1	0	0	**1**
20	*Bombus campestris*	1	0	0	0	0	0	0	**1**	3	2	2	2	0	**9**	0	2	1	0	2	1	**6**
21	*Bombus hortorum*	3	1	9	0	0	6	8	**27**	12	16	9	6	5	**48**	8	11	11	25	7	6	**68**
22	*Bombus hypnorum*	4	3	5	14	9	0	5	**40**	8	8	13	3	5	**37**	22	7	3	6	6	14	**58**
23	*Bombus lapidarius*	10	15	21	23	7	17	15	**108**	50	35	40	45	31	**201**	38	52	52	64	54	41	**301**
24	*Bombus pascuorum*	19	13	13	26	17	14	19	**121**	40	32	24	27	24	**147**	31	38	36	39	43	37	**224**
25	*Bombus pratorum*	2	0	0	4	0	0	5	**11**	4	17	8	11	0	**45**	7	01	5	7	5	9	**34**
26	*Bombus rupestris*	0	0	1	0	0	0	0	**1**	2	1	0	0	41	**3**	0	0	0	0	0	0	**0**
27	*Bombus terrestris/ lucorum* agg.	22	31	29	37	24	15	13	**171**	49	60	38	34	2	**222**	42	37	47	39	35	45	**245**
28	*Bombus vestalis*	0	1	2	0	0	0	0	**3**	0	2	2	1	0	**7**	2	0	0	1	0	3	**6**

29	*Colletes daviesanus*	0	9	0	0	0	0	0	**0**	0	0	0	0	0	**0**	0	0	1	0	0	0	**1**
30	*Halictus rubicundus*	0	0	5	7	4	2	3	**21**	5	3	6	3	0	**17**	7	0	8	13	5	4	**37**
31	*Halictus tumulorum*	2	0	2	0	0	4	0	**8**	3	4	3	0	0	**10**	0	0	0	2	2	2	**6**
32	*Hylaeus communis*	0	0	0	0	0	0	0	**0**	0	0	2	2	0	**4**	0	0	0	3	0	0	**3**
33	*Hylaeus brevicornis*	0	0	0	0	0	0	0	**0**	0	0	0	1	0	**1**	0	0	0	0	0	0	**0**
34	*Hylaeus signatus*	0	0	0	0	0	0	0	**0**	2	1	0	0	0	**3**	0	0	0	0	0	0	**0**
35	*Lasioglossum albipes*	0	0	3	0	0	3	0	**6**	0	1	1	0	0	**2**	0	2	2	14	2	0	**20**
36	*Lasioglossum calceatum*	1	1	1	2	0	3	1	**9**	0	3	5	2	2	**12**	3	3	2	0	3	2	**13**
37	*Lasioglossum cupromicans*	0	0	0	0	0	0	0	**0**	0	0	0	0	0	**0**	0	0	1	0	0	0	**1**
38	*Lasioglossum fratellum*	0	0	0	0	0	0	0	**0**	0	0	0	0	0	**0**	0	1	0	0	0	0	**1**
39	*Lasioglossum fulvicorne*	2	0	0	2	3	0	0	**7**	8	4	2	0	1	**15**	2	0	0	2	1	0	**5**
40	*Lasioglossum laevigatum*	0	0	0	0	0	0	1	**1**	0	0	0	0	0	**0**	0	0	0	0	0	0	**0**
41	*Lasioglossum lativentre*	0	1	8	0	0	0	0	**9**	0	1	0	0	0	**1**	0	3	6	0	0	1	**10**
42	*Lasioglossum leucopus*	0	1	1	0	0	0	0	**2**	2	0	2	1	2	**7**	3	17	0	5	4	0	**29**
43	*Lasioglossum leucozonium*	0	0	0	0	0	2	0	**1**	0	0	0	0	0	**0**	0	6	0	0	0	2	**8**
44	*Lasioglossum malachurum*	0	0	0	0	0	5	1	**6**	0	0	0	0	0	**0**	0	0	0	0	0	0	**0**
45	*Lasioglossum minutissimum*	0	0	0	0	0	0	0	**0**	0	0	0	0	0	**0**	0	0	1	0	0	0	**1**
46	*Lasioglossum morio*	0	0	0	0	0	0	0	**0**	0	0	0	0	0	**0**	3	0	0	0	0	0	**3**
47	*Lasioglossum punctatissimum*	0	0	0	0	0	0	0	**0**	0	0	0	0	0	**0**	0	0	0	0	0	1	**1**
48	*Lasioglossum smeathmanellum*	0	0	0	0	0	0	0	**0**	2	0	2	1	3	**8**	0	0	0	2	2	4	**8**
49	*Megachile willughbiella*	0	0	0	0	0	0	0	**0**	0	0	0	0	0	**0**	0	0	0	1	0	0	**1**
50	*Melecta albifrons*	0	0	0	0	0	0	0	**0**	0	1	0	0	0	**1**	0	0	0	0	0	0	**0**
51	*Nomada fabriciana*	0	0	0	0	0	1	1	**2**	0	0	2	0	0	**2**	0	0	0	0	0	2	**2**
52	*Nomada flava*	0	2	0	2	0	2	0	**6**	0	0	8	0	1	**9**	6	0	1	2	0	1	**10**
53	*Nomada flavoguttata*	1	0	0	2	0	2	0	**5**	0	0	0	0	1	**1**	0	0	0	0	0	0	**0**
54	*Nomada fucata*	0	0	0	0	0	0	0	**0**	0	0	0	0	0	**0**	0	0	0	0	0	1	**1**
55	*Nomada goodeniana*	1	0	0	3	0	6	0	**10**	3	1	3	3	3	**13**	2	3	5	7	0	2	**19**
56	*Nomada lathburiana*	0	0	0	4	3	1	0	**8**	0	4	4	8	2	**18**	4	1	0	1	0	4	**10**
57	*Nomada leucophthalma*	2	1	0	0	6	0	0	**9**	0	1	5	2	0	**8**	3	0	1	1	0	1	**6**
58	*Nomada marshamella*	0	0	0	0	0	0	1	**1**	1	0	0	2	1	**4**	2	4	2	0	0	3	**11**
59	*Nomada panzeri*	0	1	0	0	0	0	0	**1**	1	0	0	0	0	**1**	0	0	0	1	0	0	**1**
60	*Nomada ruficornis*	0	0	0	0	0	0	0	**0**	0	0	0	0	0	**0**	0	0	1	0	0	0	**1**
61	*Nomada signata*	0	0	0	0	0	2	0	**2**	0	0	0	0	0	**0**	0	0	0	0	0	0	**0**
62	*Osmia bicornis*	0	1	0	0	0	0	0	**1**	4	10	0	5	2	**21**	0	0	0	0	0	0	**0**
63	*Sphecodes ephippius*	0	0	1	0	0	0	0	**1**	0	0	0	0	0	**0**	0	0	0	0	0	0	**0**
64	*Sphecodes gibbus*	0	0	0	0	2	0	0	**2**	3	1	3	1	0	**7**	0	0	0	2	0	3	**5**
65	*Sphecodes monilicornis*	0	0	0	0	0	0	0	**0**	1	0	0	0	0	**1**	0	0	0	0	0	0	**0**

Table A2. Results of generalised linear mixed models with Normal errors describing the effect of agri-environment scheme (AES), farm type (type), and the AES x type interaction on bee abundance and the three Hill's numbers for diversity, H0 (species richness), H1 and H2. Farm identity and survey day were treated as random factors. In each case the same two *a priori* contrasts were tested among the AES of Conventional (C), Entry-level (ELS) and Higher-level (HLS) schemes. n.s = non-significant; probabilities between 0.1 and 0.05 have been retained. Deviances are distributed as χ^2. The 'null model' contains the random factors of farm identity and survey day.

Predictor	df	Deviance	P
Response = abundance			
AES	2	29.10	<< 0.001
C < (ELS +HLS)	1	t=5.17	<< 0.001
ELS < HLS	1	t=1.34	n.s.
type	3	7.37	0.061
AES x type	3	3.99	n.s.
null model	139	1255.80	
Response = species richness (H0)			
AES	2	20.76	<< 0.001
C < (ELS +HLS)	1	t=5.77	<< 0.001
ELS < HLS	1	t=-0.29	n.s.
type	3	1.68	n.s.
AES x type	3	11.13	0.011
null model	139	830.78	
Response = H1			
AES	2	10.30	< 0.01
C < (ELS +HLS)	1	t=3.33	< 0.001
ELS < HLS	1	t=-0.98	n.s.
type	3	1.05	n.s.
AES x type	3	9.99	0.019
null model	139	247.98	
Response = H2			
AES	2	11.98	< 0.01
C < (ELS +HLS)	1	t=3.73	< 0.001
ELS < HLS	1	t=-0.92	n.s.
type	3	0.91	n.s.
AES x type	3	11.04	0.012
null model	139	71.042	

Table A3. Results of generalised linear mixed models on *Bombus* data, with Normal errors describing the effect of agri-environment scheme (AES), farm type (type), and the AES x type interaction on bee abundance and the three Hill's numbers for diversity, H0 (species richness), H1 and H2. Farm identity and survey day were treated as random factors. In each case, the same two *a priori* contrasts were tested among the AES of Conventional (C), Entry-level (ELS) and Higher-level (HLS) schemes. n.s = non-significant; probabilities between 0.1 and 0.05 have been retained. Deviances are distributed as χ^2. The 'null model' contains the random factors of farm identity and survey day.

Predictor	df	Deviance	P
Response = abundance			
AES	2	30.608	<< 0.001
C < (ELS +HLS)	1	t=4.003	<< 0.001
ELS < HLS	1	t=0.494	n.s.
type	3	2.68	n.s.
AES x type	3	0.1549	n.s.
null model	139	1074.8	
Response = species richness			
AES	2	20.48	<< 0.001
C < (ELS +HLS)	1	t=3.692	<< 0.001
ELS < HLS	1	t=-0.109	n.s.
type	3	0.4075	n.s.
AES x type	3	2.8162	n.s.
null model	139	526.57	
Response = H1			
AES	2	3.5299	0.172
C < (ELS +HLS)	1	t=0.750	n.s.
ELS < HLS	1	t=-0.643	n.s.
type	3	3.1258	n.s.
AES x type	3	1.5888	n.s.
null model	139	-446.88	
Response = H2			
AES	2	3.2843	0.194
C < (ELS +HLS)	1	t=0.720	n.s.
ELS < HLS	1	t=-0.634	n.s.
type	3	3.1079	n.s.
AES x type	3	1.5691	n.s.
null model	139	-393.56	

Table A4. Full species list of flowering plants identified as foraging resources for bees

Code	Scientific name
f1	*Crataegus monogyna*
f2	*Veronica chamaedrys*
f3	*Taraxacum* spp.
f4	*Ranunclus* spp.
f5	*Cerastium fontanum*
f6	*Trifolium campestre*
f7	*Lamium galeobdolon*
f8	*Hyacinthoides non-scripta*
f9	*Heracleum sphondylium*
f10	*Ilex aquifolium*
f11	*Prunus spinosa*
f12	*Anthriscus sylvestris*
f13	*Vicia sativa*
f14	*hypochaeris radicata*
f15	*Trifolium pratense*
f16	*Trifolium repens*
f17	*Stachys sylvatica*
f18	*Rubus fruticosus*
f19	*Rosa canina*
f20	*Silene dioica*
f21	*Cirsium arvense*
f22	*Phacalia tanacetifolia*
f23	*Melilotus officinalis*
f24	*Digitalis* spp.
f25	*Tripleurospermum inodorum*
f26	*Rhinanthus minor*
f27	*Cirsium vulgare*
f28	*Cirsium palustre*
f29	*Prunella vulgaris*
f30	*Centaurea nigra*
f31	*Arctium lappa*
f32	*Sisymbrium officinale*
f33	*Chamaenerion angustifolium*
f34	*Symphytum officinale*
f35	*Ulex* spp.
f36	*Lonicera* spp.
f37	*Hypericum perforatum*
f38	*Glechoma hederacea*
f39	*Ranunculus ficaria*
f40	*Geranium pratense*
f41	*Lathyrus pratensis*
f42	*Lamium purpureum*
f43	*Filipendula ulmaria*
f44	*Scorzoneroides autumnalis*

f45	*Sinapis arvensis*
f46	*Lamium album*
f47	*Chelidonium majus*
f48	*Alliaria petiolata*
f49	*Aegopodium podagraria*
f50	*Calystegia sepium*
f51	*Ballota nigra*
f52	*Senecio jacobaea*
f53	*Solanum dulcamara*
f54	*Sonchus arvensis*
f55	*Solidago canadensis*
f56	*Lotus corniculatus*
f57	*Mentha aquatica*
f58	*Geranium robertianum*
f59	*Galeopsis tetrahit*
f60	*Lythrum salicaria*
f61	*Impatiens glandulifera*
f62	*Helianthus* spp.
f63	*Persicaria maculosa*

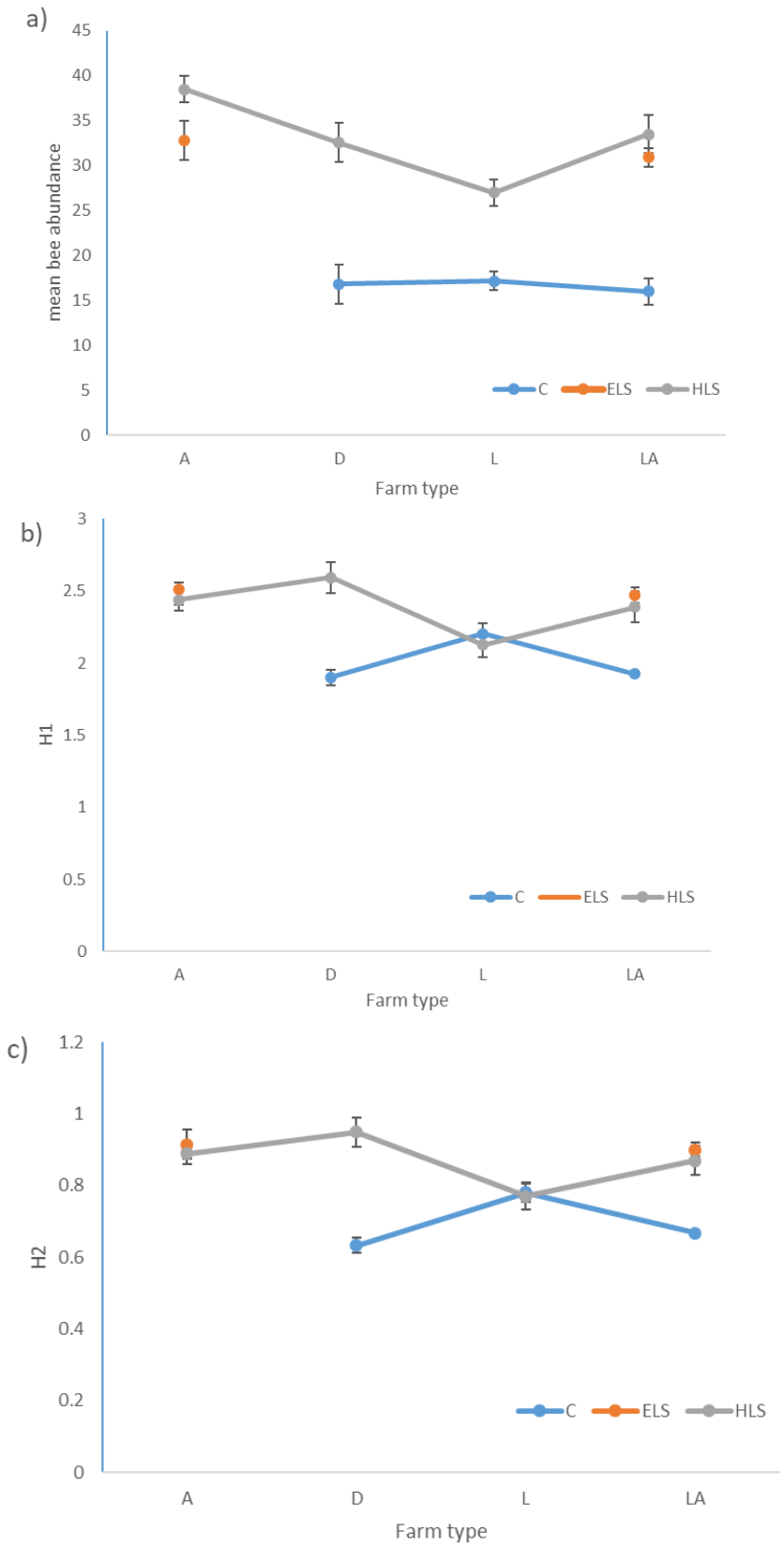


Fig. A1. Means per survey for the interaction between AES treatment grouping and farm type, for response variables; a) abundance, b) H1, c) H2. Error bars are 95% confidence limits of the mean. Farm type groupings; Dairy (D), Livestock based (L), Livestock-arable mix (LA), Arable (B). Treatment groupings; Conventional (C), Entry-Level Stewardship (ELS), Higher-Level Stewardship (HLS).

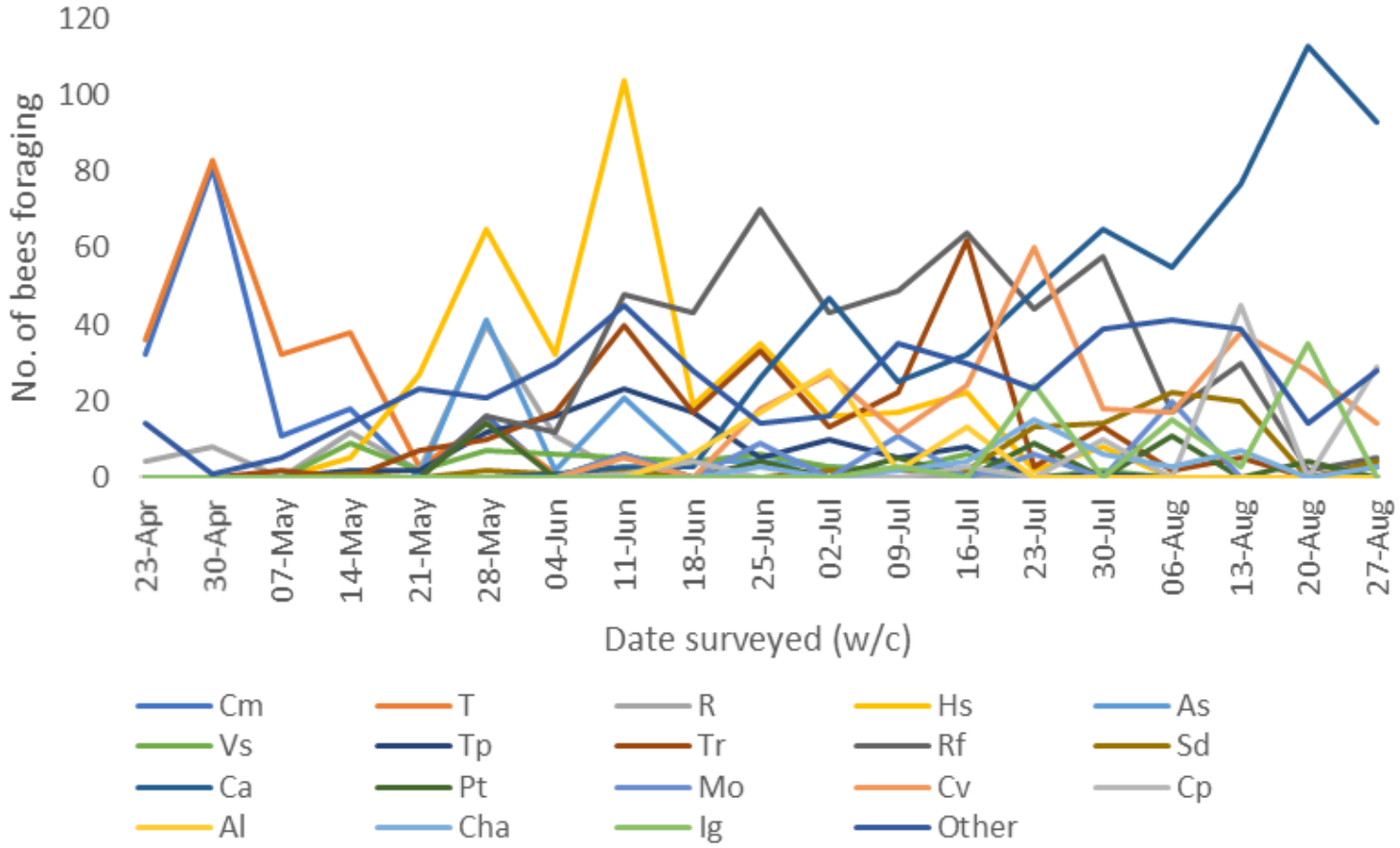


Fig. A2. The dominant flowering plants used as forage resources during the season. No. of bees foraging indicates the number of times bees were seen foraging on the flower species. Cm=*Crataegus monogyna,* T=*Taraxacum* spp., R=*Ranunclus* spp., Hs=*Heracleum sphondylium,* As=*Anthriscus sylvestris*, Vs=*Vicia sativa*, Tp=*Trifolium pratense*, Tr=*Trifolium repens*, Rf=*Rubus fruticosus*, Sd=*Silene dioica*, Ca=*Cirsium arvense*, Pt=*Phacalia tanacetifolia*, Mo=*Melilotus officinalis*, Cv=*Cirsium vulgare*, Cp=*Cirsium palustre*, Al=*Arctium lappa*, Cha=*Chamaenerion angustifolium*, Ig= *Impatiens glandulifera*.

Chapter 2.

The effect of agri-environment schemes on bumble bee colony success

Abstract

As with other species linked to agricultural environments, bumblebees are exhibiting significant population declines. The key drivers of this decline are habitat loss and fragmentation and application of agrochemicals, both resulting in a lack of foraging resources. With *Apis mellifera* unable to fulfil the current demand for crop pollination services, the services provided by domesticated and wild bumblebees are gaining importance. This study assesses the ability of *Bombus terrestris audax* (a species used for commercial crop pollination) colonies to be successful in agricultural ecosystems and compares whether current agri-environment schemes can increase colony success. Artificial nest boxes, containing *B. terrestris audax* colonies were places out in farmland, either conventionally managed or compliant with Entry-Level Stewardship (ELS) or Higher-Level Stewardship (HLS) agri-environment schemes (AES). Monitoring of colony growth rates through total nest box weight showed that colonies on AES-compliant farms gained significantly more weight than those on conventional farms, with nest boxes on conventional farms showing weight loss. Nests located on conventional farms were also more likely to become infested by the parasite *Aphomia sociella*, followed by ELS-compliant farms. The results of this study suggest that current AES have the potential to increase the likelihood of *B. terrestris audax* colony success, through the production of larger colonies, with greater ability to combat parasites infestations. Land management under AES generated ecosystems with greater floral diversity, more mid-succession habitats, and connectivity between these habitats, significantly benefiting bumblebee colony success.

Introduction

Bumblebees (*Bombus* spp.) are well known as important wild pollinators for both agricultural entomophilous crops and wild plants in the landscape, a service essential for entire ecosystem functioning (Carvell et al. 2007). Despite this ecological importance, bumblebees have suffered significantly during the intensification of agriculture, with modern practices having a detrimental effect on population abundance and almost all *Bombus* species exhibiting population declines. Bumblebees are highly susceptible to the adverse influences of agricultural management and are specifically affected by reductions in flowering plants (Carvell et al. 2011; Bretagnolle & Gaba, 2015), destruction and fragmentation of semi-natural habitats (Hardman et al. 2016), and the application of agrochemicals (Rundlof et al. 2008). The introduction of agrochemicals into the local landscape has

also been linked to susceptibility to diseases and parasites (Whitehorn et al. 2010; Hanley and Wilkins 2015). Sanchez-Bayo et al (2016) highlight that herbicides are responsible for the reduction in food resources, while pesticides increase susceptibility to parasites and disease through immune response suppression and direct fatality, leading to stress-induced colony loss.

In terms of declines in ecosystem services, bumblebees are of particular concern due to their ability to tolerate harsh climate conditions, appearing earlier in the year than other genera and remaining active in colder temperatures (Hanley & Wilkins 2015). With current crop pollination demand exceeding the ability of domesticated *Apis mellifera* to supply, pollination services provided by bumblebees, specifically *Bombus terrestris*, have become crucial to generate crop yield (Breeze et al. 2014; Hardman et al. 2016).

There are currently 25 *Bombus* species considered native to the United Kingdom. Three are considered extinct: *B. subterraneus* (recently reintroduced), *B. cullumanus* and *B. pomorum*. Seven species are highlighted in the UK Biodiversity Action Plan: *B.distinguendus, B. humilis, B. muscorum, B. ruderarius, B. ruderatus, B. subterraneus* and *B. sylvarum* (JNCC, 2016). *B. hypnorum* became established in the UK in 2001, and now occupies a previously 'vacant niche', preferring to nest above ground and favouring wooded habitats; it is now one of the most common bumble bee species in the UK (Crowther et al. 2014).

As eusocial species, bumblebees live in colonies which require sufficient pollen and nectar resources within normal foraging distances. Bumblebees cannot store these resources over the long term, and thus require constant access to semi-natural habitats supporting a variety of flowering plants (Carvell et al. 2008). Conventional agricultural management has been linked to the significant decline of floral diversity in the local landscapes, critically reducing the availability of forage resources for bumblebees across the season (Potts et al. 2016). The move to increase field size through boundary destruction has significantly reduced the areas available for nest sites. Bumblebees typically utilise abandoned burrows and tussock grasslands for nesting, habitats previously found along the hedgerow bases and ditches that have declined due to the intensification of land management (Kells & Goulson 2003).

Existing research also highlights the detrimental effects of parasite and predator pressure on bumblebee colony success, with a link to land management methods and pest presence. As with many bee genera, bumblebees have associated brood parasites, in their case in the closely related subgenus *Psithyrus* (Erler & Latterorff, 2010). *Bombus terrestris* is parasitized by the cuckoo bee *B.(P.) vestalis*, which invades existing *B. terrestris* colonies to produce their own brood, infesting approximately 42% of all *B. terrestris* nests (Erler & Latterorff, 2010). This process results in increased mortality rates of

B. terrestris workers and queens, decreasing the chance of the colonies reproductive success (Carvell et al. 2008). Another significant pest that poses a threat to colony reproductive success is *Aphomia sociella*, a small moth which seeks out bumblebee nests to reproduce (Goulson et al. 2002), and whose larvae develop within the nest, damaging the wax comb inside and causing its collapse (Westphal et al. 2009). Finally, bumblebees experience predation pressure from a number of predators, especially mammals, with the most common culprits being badgers *Meles meles* and foxes *Vulpes vulpes*, both known to contribute to the destruction of nests (Goulson et al. 2017).

Agri-environment schemes (AES) have been implemented in the UK to aid in rectifying the negative influence of modern agriculture on the biodiversity and ecosystem services of the British countryside (Carvell et al. 2007). Currently there are two main tiers of the environmental stewardship scheme open to farmers: Entry-level stewardship (ELS) is the basic, flexible level of the scheme, open to all farmers and with a large number of options (this level is currently changing and will be called Mid-tier); and Higher-level stewardship (HLS), a more selective scheme focusing on areas of high ecological value, with greater economic incentives received for actions requiring high commitment (Wood et al. 2015; Hardman et al. 2016). For pollinators especially, the schemes try to increase the extent and types of semi-natural habitats for nesting through the setting-aside of field margins. Established by sowing select flower mixtures, these field margins then naturally regenerate, and the result is an increase in the diversity of nectar-rich flowering plants available for foraging (Pywell et al. 2006; Wood et al. 2015). Appropriate flower mixtures can include plants for both foraging and nesting, including tussock grasses specifically for carder bee species such as *Bombus pascuorum* and *B. muscorum*, and particularly desirable flowers such as *Cirsium* spp. and *Heracleum sphondylium* usually labelled as pernicious agricultural weeds (Pywell et al. 2006).

This study compares the ability of ELS and HLS agri-environment schemes to support successful *Bombus terrestris audax* colonies when compared against conventionally managed farms. The success of each colony's foraging efforts was measured by the seasonal changes in colony weight. Additionally, the presence or absence of pest species within the artificial nest boxes will be used as an indication to the general health and robustness of the colonies, through maintaining a resistance to pest colonisation.

Methodology

Study sites

The study was conducted across a total of 14 farms within or on the boundary of the Shropshire Hills Area of Outstanding Natural Beauty (AONB) in the United Kingdom. Farms were selected based on their compliance with one of three treatment groups: i) Conventionally managed farms, with little to no input into "wildlife-friendly" actions; ii) Entry-level stewardship (ELS), or iii) Higher-level stewardship (HLS). The study sites included a variety of different farm types (arable, livestock-based, livestock-arable and dairy), selected to be representative of the local agricultural landscape (see Table 1 for farm details). Farms enrolled in AES were managed in accordance with the guidelines supplied by the Department for Environment, Food & Rural Affairs (DEFRA) and Natural England. Five conventional, five ELS and four HLS farms were selected as study sites. To try to use colonies that foraged within the boundary of each farm, nest boxes were situated as close to the central point of the farm as possible.

B. terrestris audax colonies

A total of 14 *B. terrestris audax* colonies were purchased from Agralan Ltd, Wiltshire, United Kingdom. *B. terrestris audax* was selected because this sub-species is native to the United Kingdom. The colonies supplied were relatively small and even aged, made up of a founding queen and a few worker bees. Most, but not all, bumblebee species favour nesting underground, yet *B. terrestris audax* is adaptable and will support a reproductively successful colony in artificial nest boxes (Westphal et al. 2009). The nest boxes supplied with the bees were made up of an interior ventilated plastic box for the colony nest, and a "nectar" source contained within a cardboard exterior. Each box was then placed inside a plywood outer case to protect the colony from damage by external threats, and a roofing-felt cover placed on top to increase insulation and protect the box from the rain. Nest boxes were positioned in a field on the top of two house bricks to prevent contact with the ground, reducing the possibility of intrusion of surface water. Bumblebees were able to enter and exit the nest box through a small valve that could be opened and closed manually to control worker movements when required.

Before the experiment began, all boxes were weighed. The weights included the internal and exterior boxes, nectar solution, wax comb, and its content and the bees. These weights varied slightly at the beginning of the experiment. Boxes were randomly assigned to study sites. On each farm, the box was situated at the base of hedgerow boundary habitat, in the corner of fields where two hedgerows met. The boxes were subsequently weighed five, eight and ten weeks after the beginning

of the experiment. Boxes were weighed in-situ during the daytime, and hence the measured weights may be slight underestimates due to the absence of foraging workers.

On the eighth and tenth week, all nests were examined for the presence of *Aphomia sociella* larvae, which were recorded simply as present or absent. Nest boxes were retrieved on the twelfth week: by this time the colonies had produced the new generation of queens and collapsed. The collected nests were checked for the extent of the damage that *A. sociella larvae* had caused to the wax comb, and a decision was made on whether the comb was destroyed or not.

Data analysis

The weights of the nest boxes were analysed using a generalised linear mixed model due to the repeated-measures design (the weighing of the same box over time), with three predictors: AES (with three levels: conventional, ELS, HLS), farm (the repeated-measure random factor) and the week surveyed (a random factor). Two *a priori* directional contrasts were used, with the prediction that conventional farms will produce smaller/lighter colonies when compared to AES-compliance locations (C < ELS + HLS) and Entry-Level Stewardship farms will produce smaller/lighter colonies than Higher-Level Stewardship (ELS < HLS).

The occurrences of *Aphomia sociella* inside bumblebee nest boxes were analysed using a simple binomial generalised linear model, with AES level as the predictor. Surveying of *A. sociella* occurrence in bumblebee nest boxes produced a small data set, too small for analysis with the *a priori* contrasts applied. However, the data collected has been compiled into a plot, highlighting the differences in presence of the parasitic moth species between farm treatment groupings; conventional, ELS and HLS.

Results

Weight change

At the beginning of the experiment, the average total weight of nest boxes and all internal biomass was 5980 ± 110g (mean ± SE). Weights of nest boxes situated on AES-compliant farms increased rapidly in the first five weeks, followed by a lower, but constant increase through the experiment (see Fig. 1). Boxes situated on HLS-compliant farms showed continuous weight gain for the entirety of the experiment, with the rate of increase decreasing at week eight, only to increase again through to week ten. Nest boxes on ELS-compliant farms showed a similar steep initial increase, with the rate of increase decreasing after week five. Nest boxes on AES-compliant farms showed only two instances

of weight loss, both on ELS farms (see Table A1). In contrast, nest boxes on the conventional farms showed a decrease in weight amongst the majority of next boxes, decreasing steadily throughout the experiment.

Analysis of the bumblebee nest box changes in weight over the survey period highlighted the significant influence that AES compliance had on colony success, through an increase in weight (see Table 2). Of the two *a priori* contrasts, only C < (ELS + HLS) was significant ($P << 0.001$). Farm type had no significant influence, and there was no evidence of any AES x farm-type interaction (Table 2).

Parasite presence

In week 8, there were four cases of the macroparasite *Aphomia sociella*, two on conventional and two on HLS-compliant farms, but no nest boxes on ELS-compliant farms. In week 10, all the remaining nest boxes on conventional farms were infested, while three of the five nest boxes on ELS-compliant farms were also infested. No new infestations occurred among the HLS treatment group, remaining at the same two of the four nest boxes. The numbers are too small for statistical analysis.

During the final inspection and collection of nest boxes, a decision was made on whether the wax comb within the nest boxes had been extensively damaged by the presence of *A. sociella* larvae or remained stable. None of the nest boxes situated on HLS-compliant farms appeared to show highly damaged wax comb as a result of moth infestations. Nest boxes on ELS-compliant farms showed less than half the comb was extensively damaged, while on Conventional farms all but a single nest box held highly damaged and collapsed wax comb (see Fig. 3).

Discussion

The results demonstrate that farm management under the conditions of an agri-environment scheme had a positive influence on the success of *Bombus terrestris audax* colonies, in terms of colony growth and (possibly) parasite infestation avoidance. The higher rate of weight gain seen in colonies positioned on AES-compliant farms suggest that the conditions produced under this more “wildlife-friendly” management style benefit bumblebees, presumably because they contain the floral resources needed to support colony growth and resistance. Conventionally managed farms, with little to no actions taken to conserve or promote local biodiversity and long-term ecosystem health, appeared to be unable to support adequate colony growth, and probably had an increased likelihood of *Aphomia sociella* infestation in comparison to farms adhering to AES.

The lower overall weight and noted weight loss of nest boxes situated on conventional farms could be considered a decline in reproductive success, with smaller colonies linked to lower production of sexuals (Goulson et al. 2002; Westphal et al. 2009). Bumblebees depend upon a diverse forage community to supply a continuous nectar and pollen source in sufficient amounts for colony survival and reproductive success (Westphal et al. 2009). The decline in the weight of nest boxes situated on conventional farms is most likely due to a lack of floral resources, and possibly a lower immunity to disease: both may be a consequence of agrochemical application (Goulson et al. 2015). Chronic exposure to agrochemicals, specifically neonicotinoids and pyrethoids, has been shown to decrease colony queen production (Gills et al., 2012) and reduce worker foraging performance (Bryden et al. 2013). Management under AES does not eliminate the usage of agrochemicals, but it does change the type of chemical used, and the set-aside field margins also act as buffers to agrochemicals sprayed on crops (Carvell et al. 2007; Hanley & Wilkins 2015).

Goulson et al (2002) suggest that bumblebees favour mid-successional floral communities. These habitat conditions are readily produced on AES-compliant farms through actions such as late mowing of set-aside field margins, cutting of hedgerows every two/three years and crop rotations (Marja et al, 2018). The availability of forage, whether through semi-natural habitats or mass flowering crops, acts as a limiting factor for bumblebee colonies (Williams et al., 2012). Its lack on conventional farms restricts colony growth and reproductive success through the production of fewer and smaller worker bees, increases in the time taken for larval development and a lower number of sexuals (Carter & Dill, 1991; Pelletier & McNeil, 2003). Through AES options such as field margins of uncultivated land and hedgerow restoration, connectivity between semi-natural and uncultivated land can be increased, allowing wildlife to use such areas as corridors through agricultural landscapes (Donald & Evans, 2006; Garrett et al. 2017). For bumblebees, that need constant access to sufficient foraging resources through the season, connectivity through the local landscape is a significant benefit.

The results of this study suggest that smaller colonies that weigh less may have reduced overall health and immunity than larger, heavier colonies (Figs 2 & 3). The overall rate of parasite infestation across this experiment may not accurately represent natural proportions, because artificial nest boxes may be more easily detectable (Goulson et al. 2002). However, the results should mirror the differences in infestation rates between the two AES levels and conventional farms and thus enable an approximate comparison, although sample-size limitations prevented statistical significance. Goulson et al. (2002) suggest that populations of *A. sociella* are higher in areas with a greater, denser population of host nests. However, the findings here suggest that these larger, stronger colonies are better able to combat infestations, resulting in a lower proportion in nests on AES-compliant farms being infested.

As a generalist species, *Bombus terrestris* probably shows the most positive effects of agricultural improvements on colony health and growth. This species can forage on a large variety of flowering plants, over a wider geographical range, than many other species, and hence these results cannot be considered representative of putative effects of AES on many of the less abundant, more specialised bumblebees (Goulson et al, 2002; Lye et al, 2012). Further research into the effect of AES on bumblebees, surveying of specialist or scarce species, such as *B. muscorum, B. ruderarius* and *B. sylvarum,* would allow for a more overarching synthesis on the potential benefits of AES. Additionally, analysis of agrochemical residues found within the organic matter of experimental nest boxes might give some insights into the toxicity of environments around bumblebee nests.

AES-compliance improves the growth and possibly the resistance of *Bombus terrestris audax* colonies, but there is no evidence of any extra benefit of the HLS versus ELS level of compliance. Uptake of such conservation options should be encouraged to preserve bumblebee populations and secure pollination services.

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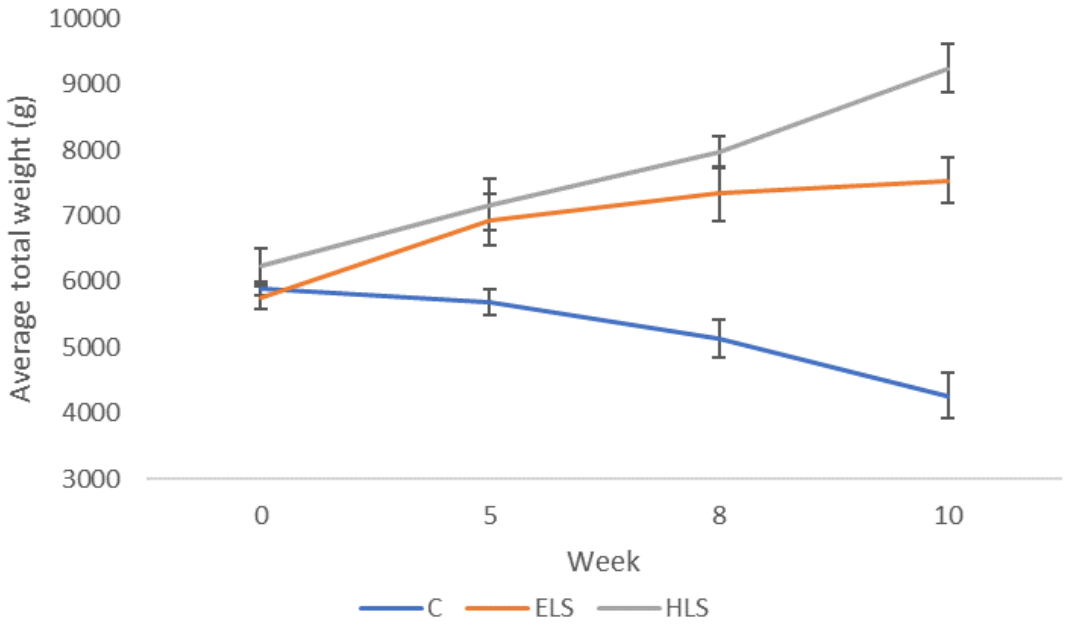


Fig. 1. Average total weight of nest boxes of each treatment group in grams. Error bars represent Standard Error. Farm treatment groupings; C = Conventional, ELS = Entry-Level Stewardship, HLS = Higher-Level Stewardship.

Table 1. Key land management activities and agrochemical applications over the previous year on the study farms. Treatment groupings; conventional (C), Entry-level stewardship (ELS), higher-level stewardship (HLS). Farm type groupings; Dairy (D), Livestock based (L), Livestock-arable mix (LA), Arable

Farm	Treatment	Years in treatment	Farm type	Farm size (acres)	Main AES commitments	Pollinator specific actions	Fertilisers	Pesticides (active ingredients)
1	C	-	D	55	-	-	24:0:16 and 24:0:0 and 26:13:0 (N, P, K)	no
2	C	-	LA	150	-	-	Nitrogen 34.5%	Pyrethroid - flea beetle insecticide
3	C	-	LA	90	-	-	Nitrogen 34.5%	Glyphosate
4	C	-	L	55	-	-	Not available	Not available
5	C	-	L	70	-	-	Not available	Not available
6	ELS	12	LA	165	Hedgerow restoration, 6m set-aside field margins, over winter stubble, nectar and pollen mix	Nectar and pollen mix	Nitrogen 34.5%, 0:20:30 (N, P, K)	Laidir 10 CS (lambda-cyhalothrin)
7	ELS	6	A	280	Hedgerow restoration, 6m set-aside field margins, over winter stubble, spring cropping(blackgrass), woodland management	No	Nitram (Nitrogen) 34.5%	Atlantis (Mesosulfuron-methyl and Iodosulfuron-methyl sodium), Elatus (Benzovindiflupyr and prothioconazole)
8	ELS	2	LA	180	Hedgerow restoration, low input, set-aside field margins	No	Nitrogen 34.5%, 0:20:30 (N, NS & NPK), polysulphate	Pyrethroid - flea beetle insecticide
9	ELS	8	LA	120	Permanent pasture, over winter stubble, 6m watercourse	No	Poultry manure, Sulphan29, Nitrogen 34.5%	Laidir 10 CS (lambda-cyhalothrin)

					margin, bird nesting ground set-aside			
10	ELS	10	LA	170	6m set-aside field margins, low input grasslands	Nectar mix	Nitrogen 34.5%, polysulphate, 0:20:30 and 0:24:24 (N, P, K)	CleanCrop Argent
11	HLS	18	D	750	6m set-aside margins, low input grasslands, nectar and pollen mix, hedgerow restoration	Nectar and pollen mix (mainly *Trifolium repens*) no agrochemical application	Manure, BetterGrass, VITA-grass	No
12	HLS	12	A	500	6m set-aside field margins, enhanced wild bird seed mix, nectar mix, over winter stubble	Nectar mix	Poultry manure, Nitrogen 34.5%	Glyphosate
13	HLS	8	A	370	6m set-aside field margins, enhanced wild bird seed mix, nectar mix, over winter stubble	Nectar mix	Poultry manure, Sulphan29, Nitrogen 34.5%	Laidir 10 CS (lambda-cyhalothrin)
14	HLS	20+	LA	320	6m set-aside field margins, nectar mix, enhanced wild bird seed mix	Nectar mix	Ammonium nitrate	Sparviero (pyrethroid), SHERPA (imidacloprid and imidazolidinimine)

Table 2. Results of generalised linear mixed models with Normal errors describing the effect of agri-environment scheme (AES), farm type (type), and the AES x type interaction the weight of bumble bee nest boxes. Farm identity and survey day were treated as random factors. Two *a priori* contrasts were tested among the AES of Conventional (C), Entry-level (ELS) and Higher-level (HLS) schemes. n.s = non-significant; probabilities between 0.1 and 0.05 have been retained. Deviances are distributed as χ^2. The 'null model' contains the random factors of farm identity and survey day.

Predictor	**df**	**Deviance**	**P**
Response = weight			
AES	2	17.345	<< 0.001
C vs (ELS + HLS)	1	t=4.429	<< 0.001
ELS vs HLS	1	t=0.929	n.s.
Type	3	2.3271	n.s.
AES x type	3	1.7349	n.s.
Null model	59	199.43	

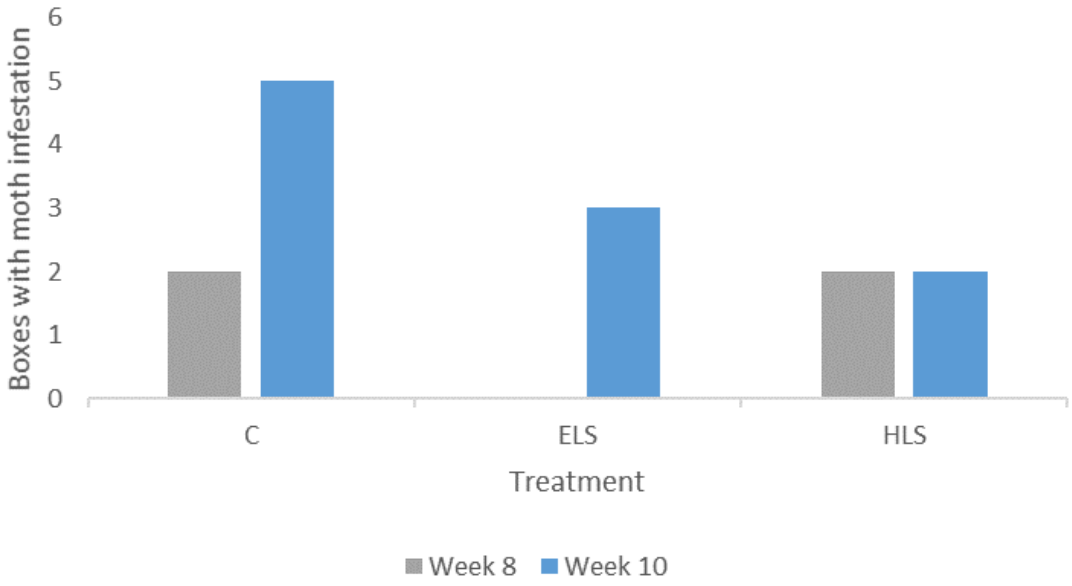


Fig. 2. Number of nest boxes infested with *Aphomia sociella* during weeks eight and ten of the experiment. Treatment grouping; Conventional (C) n=5, Entry-Level Stewardship (ELS) n=5, Higher-Level Stewardship (HLS) n=4.

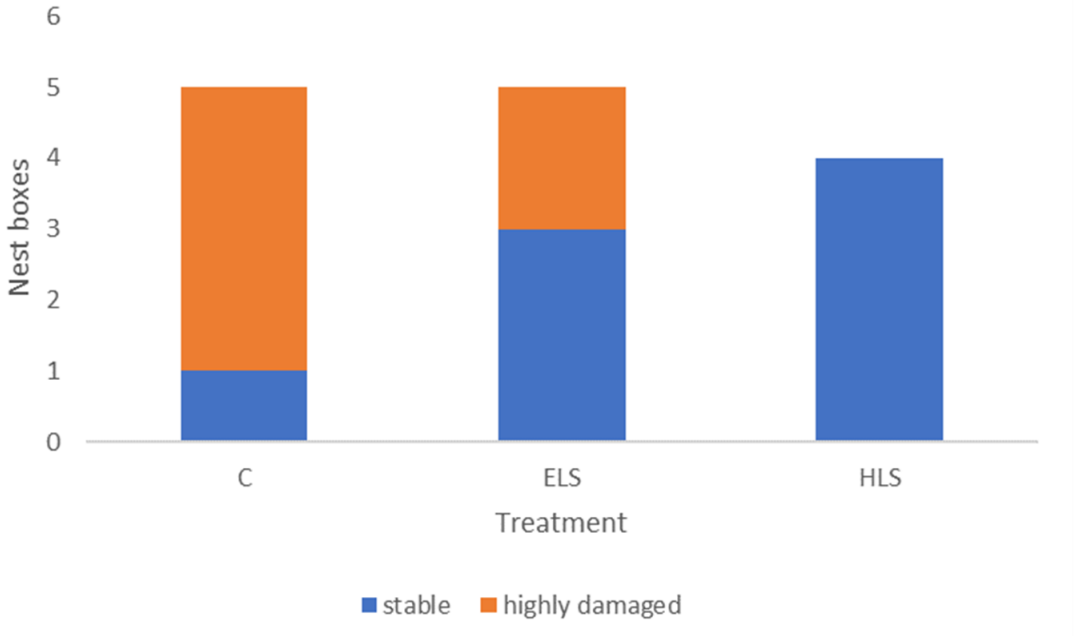


Fig. 3. Proportions of bumble bee nest boxes that showed structural stable wax comb in comparison to highly damaged wax comb as a result of *Aphomia sociella* infestation. Treatment grouping; Conventional (C), Entry-Level Stewardship (ELS), Higher-Level Stewardship (HLS).

Appendix

Table A1. Total weight measurements of bumble bee nest boxes over the entire experiment, measurements taken in at the beginning of the experiment (week 0) and five, eight and ten weeks into the study. Treatment groups; C = Conventional, ELS = Entry-Level Stewardship and HLS = Higher-Level Stewardship.

		Weight (g) for week			
Box number	**Treatment**	0	5	8	10
1	HLS	6900	8100	8600	9000
2	HLS	5600	6200	7500	9100
3	C	5500	5200	5600	3400
4	C	6000	5600	5700	5500
5	HLS	6200	7300	7700	10300
6	ELS	5400	6500	8100	8700
7	ELS	5500	6200	7800	7800
8	ELS	5900	6200	6200	6600
9	ELS	6400	8000	8100	7100
10	HLS	6300	7100	8100	8600
11	C	6100	5600	5000	4400
12	C	6000	6400	5300	4000
13	ELS	5600	7800	6500	7500
14	C	5900	5600	4100	4000