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Supporting beneficial insects with wildflowers in gardens and vineyards

by

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STATEMENT

I, Janine Griffiths-Lee, hereby declare that the thesis entitled 'Supporting beneficial insects with wildflowers in gardens and vineyards' and the work presented within it is my own.

Parts of this work have been published/submitted as:

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I hereby declare that this thesis has not been and will not be, submitted in whole or in part to another University for the award of any other degree.

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ABSTRACT

Land-use change and habitat destruction have reduced biodiversity to the extent that 60% of ecosystem services are considered degraded. Ecological habitat management aims to regulate ecological functions, including ecosystem services such as pest control and pollination. My research has focused on the planting of wildflowers as habitat management for beneficial insects in allotments, gardens and vineyards, as intensively-managed, lesser-studied landscapes. The estimated 400,000 ha of UK gardens provide considerable potential pollinator habitat, although a commonly perceived barrier to wildlife gardening is lack of space. Using citizen science, I investigated the effectiveness of a small 4 m^2 wildflower patch in recruiting beneficial insects, allocating participants to one of three treatment groups (two wildflower mixes and control) who sampled insects in their private gardens and allotments. Small wildflower patches provided resource-rich habitats, with different treatments attracting different taxa. To assess the ability of a wildflower to attract pollinators to a crop and increase pollination services, I introduced bee-friendly borage as a companion plant co-located with a strawberry plant. In this citizen science project, I found that strawberries companion planted with borage produced significantly more fruit, and fruit of higher aesthetic quality. Verification of the results of both citizen science projects allowed the analysis of effective sampling methods and possible bias in projects conducted in private urban spaces. UK agri-environmental schemes have yet to make vineyard-specific recommendations to support biodiversity in viticulture, despite it being one of the fastest-growing sectors of English agriculture. By conducting insect and floral surveys in a British vineyard, I tested five inter-row treatments (three wildflower mixes, natural regeneration, and mown grass) on their potential in supporting beneficial insects. Sown and spontaneous wildflowers significantly increased insect abundance and richness, with no loss of space for grapevines. I engaged directly with British viticulturists through a survey to understand current management practices and barriers to adopting wildlife-friendly approaches. The majority of respondents reported reliance on synthetic pesticides, having grass-only inter-row cover and frequent summer mowing. Based on the findings in my thesis, I encourage the establishment, management and restoration of floral plantings in vineyards, gardens and allotments. Wildflowers can attract beneficial insects in these environments, enhancing biodiversity, benefiting ecosystem services and contributing to a sustainable future of viticulture and urban agriculture.

CONTENTS

CHAPTER 1

1. General introduction

1.1. Global biodiversity loss

Land-use change and habitat destruction have reduced biodiversity and degraded ecosystems across all landscapes (Chase et al 2020; Díaz et al 2019; Newbold et al 2016) to the extent that only 13% of the ocean and 23% of land is still classed as 'wilderness' (Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services (IPBES) 2019). Despite the huge variation in human land-uses across the regions of the world, all obtain natural resources to sustain human economic and social benefits to the detriment of the environment. Further biodiversity loss threatens any remaining potential for sustainable development (Newbold et al 2016).

Parties to the Convention on Biological Diversity (CBD) define biodiversity as "the variability among living organisms from all sources including, inter alia, terrestrial, marine and other aquatic ecosystems and the ecological complexes of which they are part; this includes diversity within species, between species and of ecosystems" (UN Convention on Biological Diversity, 1992). Biodiversity health is integral for the health of ecosystem function and ecosystem services on which we all depend. Ecosystem services are the benefits people obtain from ecosystems, and the Millennium Ecosystem Assessment (MEA) framework uses four categories to describe these services: provisioning services, regulating services (including pollination services and pest control), cultural services and supporting services (MEA 2005). Sixty per cent of ecosystem services are now considered degraded (MEA 2005). Animal species that provide pollination, pest control and cultural values as ecosystem services have witnessed significant declines (Oliver et al 2015).

Although declining species richness and biodiversity are the common focus of conserving ecosystem services and function, also of importance is the decline in bioabundance. The abundance of common species is attributed to driving ecosystem service delivery (Gaston et al 2018, Winfree et al 2015) and so conservation action should try and maintain their 'commonness' whilst also trying to preserve rarer species (Gaston 2011).

1.2. Pollinator declines and threats

In 2016 the IPBES published its global assessment of pollinators and pollination services and confirmed large-scale declines in wild pollinators in Europe and North America (IPBES 2016). Declines in pollinators have been documented in many countries (Biesmeijer 2006; Cardoso and Gonçalves 2018; Potts et al 2010; Powney et al 2019) accompanied by declines in insect-pollinated wild plants (Biesmeijer 2006). The European Red List indicates that 9% of bee species are threatened or near threatened with extinction, though this figure is likely to be much higher considering that 57% of European species are considered data deficient (Nieto et al 2014). In the UK, 23 flower-visiting bee and wasp species are now considered extinct (Ollerton et al 2014).

It is widely accepted that the most important drivers of global pollinator decline are land cover changes and land management (Dicks et al 2021; IPBES 2016; Potts et al 2016). Lack of floral resources (Goulson et al 2015), metal contamination (Meindl and Ashman 2013), transfer of viruses from managed to wild bees (Murray et al 2019), climate change affecting plant-pollinator interactions (Dicks et al 2016), and pesticide use (Woodcock et al 2016b), are all driving the decline of bees. However, many of the drivers of pollinator decline also interact, either additively or synergistically, leading to higher population losses. For example, bees are more susceptible to parasites due to reduced immune response provoked by exposure to pesticides and lack of floral resources (Goulson et al 2015).

The economic and societal importance of pollination services cannot be understated. Loss of wild pollinator diversity will directly impact human well-being, degrading ecosystem services, creating crop yield instability and reducing the resilience of food systems (Dainese et al 2019; Dicks et al 2021; IPBES 2016). The global percentage of flowering plants requiring pollination by animals is 87.5% (Ollerton et al 2011), and animal pollination directly affects the quality and yield of 75% of the world's leading food crops (Klein et al 2007). The global value of animal pollination for agriculture is estimated to be $235-577 billion US dollars (IPBES 2016), although pollination services of wild plants is invaluable. Despite the importance of this essential ecosystem

service, pollinator populations decline while global demand for the service soars. In the last five decades, global agriculture has become twice as dependent on pollinators (Potts et al 2016), yet pollination services are themselves at risk from intensive agricultural practices (Kremen et al 2002). Such declines in wild pollinators have led to the growth in commercially managed pollinators, such as honeybees, bumblebees (Goulson 2010), solitary bees (such as *Osmia*) (Bosch et al 2021), and even hoverflies (as larvae, e.g. 'Polyfly' polyfly.es/en/).

1.3. Loss of wildflower resources

A drive for self-sufficiency in Britain in the wake of the second world war led to the intensification of agricultural practices and loss of grasslands, meadows and marshland (Goulson et al 2008). Consequently, in England and Wales, 97% of lowland wildflower meadows were lost between 1930 and 1984 (Fuller 1987). By 2010 an estimated 5,000-10,000 ha of these highly localised, fragmented meadows still existed (Joint Nature Conservation Committee (JNCC) 2011). Such habitat loss decreases the range and quality of foraging habitat, reducing the availability of pollen and nectar on which many beneficial insects rely. Indeed, visitors to wildflowers are highly diverse (Grass et al 2016) and wildflowers are beneficial for many taxa, including butterflies (Kolkman et al 2021), moths (Peter et al 2021), bumblebees (Carvell et al 2004; Korpela et al 2013), parasitoids (Hoffmann et al 2018) and natural predators of pests (Tschumi et al 2016). Wildflowers also aid the reproductive success of many species of solitary bee, by providing increased nesting sites and reduced foraging time for provisioning young (Carvell et al 2022; Ganser et al 2020).

Plant-pollinator interactions are susceptible to anthropogenically-driven changes. For example, climate change and the shifting phenologies of plants and bees create interaction mismatches and a decline in pollination services (Burkle et al 2013). Major changes in the plant-pollinator networks have been witnessed over the past 120 years, with rarer species, specialised foragers and cavity nesters those bee species most at risk (Burkle et al 2013). Changes in plant-pollinator interactions are more vulnerable in those regions more susceptible to climate change such as northern regions of North America, Europe and Asia (Byers and Chang 2017). Furthermore, urbanisation homogenises the environment, promotes invasive plant species, causes changes in phenological events, restricts plant growth and reduces plant richness (Ruas et al 2022).

The decline in pollinators mirrors the decline in insect-pollinated wild flowering plants in agricultural and urban landscapes (Biesmeijer 2006; Theodorou et al 2020). Further, bumblebee foraging plants in the UK have declined at a greater rate than other native plants (Carvell et al 2006). Certain species of bumblebee remain widespread and common, such as generalist foragers that utilise non-native plants and mass flowering crops (Goulson et al 2002). Conversely, rare species with more restricted diets are commonly associated with Fabaceae grasslands that are in decline (Goulson et al 2005).

1.4. Beneficial insects for pollination and pest control services

Beneficial insects provide ecosystem services integral to human survival, including pollination, decomposition and biological control. Hymenoptera is an order including wasps, bees and ants, and is species-rich with around 153,000 known extant species (Aguiar et al 2013). There are over 19,800 extant species of bee in seven families (Aguiar et al 2013), and in the UK, there are 25 species of bumblebee, one species of honeybee and around 240 species of solitary bee (Falk 2015).

Honeybees are important in terms of improving the yield of many crops, yet higher densities of managed honeybees can spread disease (Colla et al 2006; Geldmann and Gonzalez-Varo 2018; Graystock et al 2013; Schmid-Hempel et al 2014), compete with wild bees for floral resources and nesting sites (Goulson 2003; Ings et al 2006; Inoue et al 2008) and negatively impact wild bee conservation and pollination services (Angelella et al 2021). Wild bees have a significant role in crop pollination that cannot be replaced by managed honeybees (Mallinger et al 2015; Blitzer et al 2015; Lowenstein et al 2015). For example, wild bees are more effective pollinators of fruit crops in multiple crop systems worldwide (Garibaldi et al 2013; Eeraerts et al 2019; MacInnis and Forrest 2019) and the pollination of the most important pollinator-dependent British food crops, such as the field bean, oilseed rape, strawberry and apple, is mostly executed by wild bees (Hutchinson et al 2021a). Indeed, managed honeybees supplement, rather than substitute, pollination by wild bees (Garibaldi et al 2013).

Generally, ‘non-bee’ flower visitors are not as effective at pollination, yet they may provide similar pollination services to bees due to the frequency of visits (Rader et al 2016). Hoverflies (Diptera:Syrphidae) are an abundant and diverse group, with around 6,000 known species (Doyle et al 2020). Subfamilies Syrphinae and Eristalinae rely on

foraging flowers in adulthood (Doyle et al 2020) and feed on honeydew, or pollen and nectar (Rotheray and Gilbert 2011). Although hoverflies are well-known pollinators of numerous wild plants and cultivated crops (Larson et al 2001; Orford et al 2015; Ssymank et al 2008) they do vary in specialisation (Klecka et al 2018) and more recent evidence suggests a limited range of suitable forage plants than previously thought (van Rijn and Wackers 2016). Hoverflies are not only beneficial to pollination services, as many species of hoverfly have zoophagus larvae, they also have an important role in biological pest control (Doyle et al 2020).

Non-syrphid Diptera 'other flies' are commonly neglected from pollination studies and Agri-environmental schemes (AES) schemes, although non-syrphid Diptera are as effective as hoverflies as pollen vectors (Orford et al 2015). Foraging, behavioural and physical differences mean that non-syrphid Diptera are not as efficient pollinators as bees for most crops, but due to their sheer abundance they have an important role in pollination services. Some important commercial crops are primarily pollinated by small flies, for example, *Theobroma cacao* (cacao) which is pollinated by *Forcipomyia midges* (Glendinning 1972). In a UK context, non-syrphid flies are highly abundant pollinators of crops in farmland (Orford et al 2015) and are known pollinators of oil seed rape (Phillips et al 2018). In this thesis, I have included non-syrphid Diptera (referred to as 'other flies') in my analyses, as understanding the effects of habitat management, and their role in pollination is essential, especially considering bee population declines (Orford et al 2015; Rader et al 2016).

There are around 103,000 known extant species of wasp, 70% of which are parasitoid wasps wasps and the remainder being aculeate wasps (Aguiar et al 2013; Brock et al 2021). Parasitoids are important natural enemies of pests (Goulet and Huber 1993) and therefore have an important role in integrated pest management (IPM) in agricultural systems. Parasitoid wasps depend on flowering plants for pollen, nectar, nesting and overwintering sites during their life cycle (Tscharntke et al 1998). Aculeate wasps are a diverse group spanning 22 families, and 'Aculeata' refers to the defining feature of the group: having an ovipositor modified into a stinger (although many species do not sting) (Aguiar et al 2013). Aculeate wasps are globally widespread, relatively understudied and therefore potentially undervalued, although they support a suite of ecosystem services, including pest control, pollination and decomposition (Brock et al

2021). Nine hundred and sixty plant species are associated with aculeate wasps as pollinators, including 164 species with obligate pollination (Brock et al 2021).

As the majority of aculeate wasps (~97%) are solitary (Brock et al 2021) I have grouped aculeate wasps and parasitoid wasps together as counts of 'solitary wasp' within the chapters of this thesis. Counts of social wasps include the 'yellowjackets' of the genera *Vespula* (including the widespread *Vespula vulgaris*), *Dolichovespula* and *Vespa* (although no hornets were collected in these projects).

Moths and butterflies belong to the group Lepidoptera, comprising 180,000 species (Hamm and Wittmann 2009) and flowers provide an important resource to this group (Kolkman et al 2021; Peter et al 2021). Around 90% of Lepidoptera are moths (Shields 1989), although empirical studies on the pollination services provided by moths are limited (Hahn and Brühl 2016). Nocturnal moths complement the work of diurnal pollinators and contribute to the pollination of key wild plant families (Macgregor et al 2015; Walton et al 2020) and some commercial crops (Macgregor et al 2015). Further research and consideration of the role of nocturnal moths and agricultural habitat management are needed. Although butterflies and moths are important pollinators, these were rarely captured in the sampling methods contained in the projects.

1.5. Habitat management for pollination and pest control services

Ecological habitat management aims to regulate ecological functions, including ecosystem services such as pest control and pollination services. AES provide funding incentives to land managers and farmers to include habitat management practices that support biodiversity and ecosystem services, and such management can support crop production (Pywell et al 2015). Indeed, in a recent study on the impacts of long-term AES interventions, Redhead et al (2022) found that taking the least productive land out of crop production and converting it into wildlife habitat boosted biodiversity whilst improving the yield of some crops. Many AES across Europe include strategies such as sowing flower-rich margins to provide habitat and forage for insects (e.g. DEFRA 2020). Wildflower strips for AES in agricultural landscapes provide essential resources for pollinators, aiding pollinator conservation and promoting pollination services in managed landscapes (Albrecht et al 2020; Blaauw and Isaacs 2014a; Carreck and Williams 2002; Carvell et al 2006; Carvell et al 2007; Korpela et al 2013; Pywell et al

2015). Therefore, pollinator visits are higher in crops with adjacent floral plantings compared to those without (Albrecht et al 2020; Feltham et al 2015; Carvell et al 2022) and floral planting next to fruit crops can increase pollination services resulting in increased fruit set and yield (Blaauw and Isaacs 2014a; Eeraerts et al 2019).

Current agri-environment habitat management focusing on pollinators may provide floral resources for a limited range of bee species (Nichols et al 2019; Wood et al 2017). For example, the commonly sown 'pollen and nectar mix' which includes legumes creates good foraging habitat for bumblebees (Pywell et al 2006). However, solitary bee species are important crop pollinators (Woodcock et al 2013), and species-rich insect communities with diverse functional traits promote effective and resilient pollination (Dainese et al 2019; Woodcock et al 2019) and improve crop yield (Hoehn et al 2008). Therefore current AES schemes need to support a higher diversity of species, especially solitary bees, by changing the composition of wildflower mixes (Hutchinson et al 2021a; Nichols et al 2019; Wood et al 2017). Floral species considered 'weeds' are more attractive to pollinators than many AES-recommended wildflower mix species (Balfour and Ratnieks 2022). Generally, diverse plant species in wildflower mixes are considered to support the highest diversity of beneficial insects (Albrecht et al 2020; Tscharntke et al 2005), although the inclusion of particular key plant species is effective in increasing pollinator abundance (Nichols et al 2019; Warzecha et al 2018).

As well as pollination, biological pest control is a vitally important ecosystem service supported by insects. Biological control has been defined as: "The action of parasites, predators or pathogens in maintaining another organism's population density at a lower average than would occur in their absence" (De Bach 1964). Natural biological pest control is negatively impacted by intensive farming and insecticide use (Jonsson et al 2012). Support for pest control can be achieved through habitat management in agri-environments (Tschumi et al 2015), by providing essential resources for natural enemies (Landis et al 2000). Wildflower plantings next to crops, therefore, support predaceous arthropods, such as hoverflies (Hatt et al 2017), ladybirds (Blaauw and Isaacs 2015), lacewings (Tschumi et al 2016) and parasitoid wasps (Hoffmann et al 2018), and such species-rich insect communities promote effective pest control services (Dainese et al 2019). Indeed, wildflower strips adjacent to crops have been found to enhance pest control services by 16% (Albrecht et al 2020) and are documented to reduce pest

damage (Tschumi et al 2015). For example, wildflowers support aphidophagus hoverflies thereby reducing the abundance of aphid pests (Hatt et al 2017; Tschumi et al 2016). Further, pest control by parasitoid wasps can be enhanced with floral habitat management (Ellis et al 2005). Therefore, as part of IPM, the use of wildflowers is an effective alternative to pesticide use (Wilson and Danne 2017). Including IPM, such as wildflower margins, in agriculture can be very beneficial under 'land sharing' initiatives (Phalan et al 2011; Redhead et al 2022). Furthermore, a recent study in the US concluded that IPM can reduce insecticide use by 95% (Pecenka et al 2021).

1.6. Urbanisation and the potential of urban gardens

By 2030, the global human population is estimated to reach 8.5 billion (United Nations, 2022) and 60% of the global population will live in urban areas (UK Government Office for Science, 2021). Global urbanisation drives habitat and biodiversity loss (Seto et al 2012) with projected future growth predicted to cause the extinction of hundreds of species in just the next 20 years (Simkin et al 2022). Urbanisation is one of the most homogenizing of all human activities as cities are fundamentally built to support one species, and these changes are long-term and intensify over time (Marzluff and Ewing 2001; McKinney 2006).

Loss of natural habitats is often irreversible in urban landscapes, but some urban green spaces can still have high numbers of bee species (Baldock et al 2015; Theodorou et al 2020) and compared to intensively managed agricultural landscapes, cities can be considered a 'refuge' for some insects (Hall et al 2017). Pollinators have different responses to urbanisation, especially bees and hoverflies (Bates et al 2011; Persson et al 2020; Verboven et al 2014). The value of urban landscapes for pollinators may also depend on many factors, such as surrounding landscape, foraging preferences and morphological traits of the insect (Bennett and Lovell 2019; McKinney 2006; Theodorou et al 2016; Theodorou et al 2020; Williams et al 2010; Wilson and Jamieson 2019). Nevertheless, urbanisation reduces species richness for the majority of taxa, affects community composition, and can reduce biodiversity at a regional and global level (Grimm et al 2008). Indeed, the majority of studies conclude that an increase in urbanisation results in a decrease in the diversity of pollinators (Ahrne et al 2009; Bates et al 2011; Banaszak-Cibicka and Dylewski 2021; Harrison et al 2017) and parasitoid

wasps (Bennett and Gratton 2012).

Although 84% of the population lives in urban areas in the UK (The World Bank 2018), there is also considerable potential habitat for pollinators in urban centres, including gardens, allotments, cemeteries, nature reserves, road verges and recreational parks (Baldock et al 2019). UK gardens cover an area of 400,000 ha (The Wildlife Trust 2021) and 24-36% of the area of UK cities (Baldock et al 2019), and this considerable area, along with the diversity of plants provided by allotments, make gardens and allotments the most valuable green spaces in urban areas (Baldock et al 2019).

Globally, lawns cover up to 70-75% of urban green areas (Ignatieva 2010; Ignatieva et al 2015). Historically for many countries in the developed world, the ideal garden lawn is regarded as monoculture grass, cut frequently short (Smith and Fellowes 2013) and although there is growing momentum towards less intense management in urban landscapes, change is slow (Bryne 2005). Additionally, chemical pesticides are readily available in DIY stores and garden centres, with herbicides, molluscicides and insecticides most commonly used (Health and Safety Executive (HSE) 2019). Low-intensity, unmanaged urban areas have a higher diversity of floral resources (Lerman et al 2018; Wastian et al 2016) and urban floral availability positively impacts the abundance and diversity of bees (Burdine and McCluney 2019; Del Toro and Ribbons 2020; Theodorou et al 2016; Wilson and Jamieson 2019) and parasitoid wasps (Bennett and Gratton 2012). Yet, a common obstacle to wildflower habitat management, or wildlife gardening, is the perceived lack of space in gardens (Goddard et al 2013). Further studies are needed to inform on effective habitat management practices in urban spaces, such as successful wildflower mixes, impacts on beneficial insect abundance and the space commitment required.

Globally, 800 million people practice urban agriculture (FAO 2019) and account for 6% of global food production (Thebo et al 2014). Urban and under-used green spaces in the UK are overlooked yet have considerable potential for urban agriculture, if these areas were used this would account for 38% of the UK's fresh vegetable and fruit consumption (Walsh et al 2022). Therefore, protecting biodiversity in these landscapes is essential for provisioning of ecosystem services, such as pest control, decomposition and pollination services. Indeed, urban fruit and vegetable production is enhanced by more diverse bee communities (Lowenstein et al 2015) and parasitoid wasps (Arnold

2022). Companion planting is a common traditional gardening technique used to improve fruit set, seed set, crop yield or aesthetics, by enhancing pest control or pollination services. However, empirical studies on the use of companion planting to increase pollination services within domestic gardens and allotments are limited. Further studies on the use of wildflowers in enhancing crop yield in urban production systems are needed.

1.7. The potential of vineyards for habitat management

Globally, around 7.4 million hectares of land are currently cultivated for wine or table grapes (*Vitis* spp.) (OIV 2019). Cultivated grapes do not have an obligate relationship with insect pollinators, although it has been previously documented that pollination may increase the size and quality of the grape (McGregor 1976). Nevertheless, increasing the abundance of pollinators is beneficial for biodiversity of the wider landscape, especially as traditional viticulture is intensively managed monoculture with high pesticide use (Pertot et al 2017; Urruty et al 2016). Indeed, floral plantings in vineyards in Europe, California, and South Africa benefit pollinators (Kratschmer et al 2019; Kratschmer et al 2021; Kehinde and Samways 2014; Wilson et al 2018). In addition to benefits to biodiversity, wildflowers in vineyards support the natural enemies of pests (Danne et al 2010; Judt et al 2019; Möller et al 2020; Pétremand et al 2017; Tschumi et al 2016) and can increase pest predation (Thomson and Hoffmann 2010). Furthermore, the use of floral cover crops in vineyards increases soil organic carbon, improves water filtration, reduces greenhouse gas emissions and enhances microbial and fungal networks (Abad et al 2021a). Although there is increasing movement toward environmentally-friendly viticulture practices around the world, the need for adequate control of pests threatens future sustainability (Daane et al 2018b). The British viticulture sector is still in its relative infancy, yet with a changing climate it is witnessing considerable growth (South Downs National Park Authority (SDNPA) 2021), and UK AES schemes do not currently include vineyard-specific recommendations. Knowledge of effective habitat management options for beneficial insects, including current UK land use and pest control preferences is lacking.

1.8. Citizen science as a monitoring tool

The need for regular assessments of the status and trends of biodiversity is realised by

many international treaties and organisations, such as CBD and IPBES. Two important knowledge gaps on biodiversity are the lack of indigenous and local knowledge, and the status and trends of certain taxa, including insects (IPBES 2019). It follows that mobilising local volunteers to gather and submit data on nature has great potential.

In the 1990s, Irwin coined the phrase 'citizen science', translated as "science which assists the needs and concerns of citizens" and "a form of science developed and enacted by the citizens themselves" (Irwin 2018). Citizen science is not a new concept and can be traced back as far as ancient China, where locals have tracked locust outbreaks for 2,000 years (Irwin 2018). Citizen science, (also known as c-science, community science, or crowdsourcing (citizenscience.org)) has witnessed dramatic growth in the last two decades due to technological advances for effective data collection, accessibility of projects and effectiveness for education and outreach (Dickinson et al 2010; Silvertown 2009). Indeed, an estimated 70,000 people participate annually in UK citizen science projects (Pocock et al 2015). Personal values, engagement with nature, and the desire to learn or share knowledge are the most common motivations for citizen science participation (Agnello et al 2022). As public interest in pollinators and their decline has grown rapidly (Domroese and Johnson 2016), in the last decade many pollinator-focused research projects utilising citizen science have been successfully developed (e.g. Appenfeller et al 2020; Birkin and Goulson 2015; Lye et al 2012; Maher et al 2019; Mason and Arathi 2019).

Given the scale and complexity of the suite of environmental problems and the challenges of gathering data to inform conservation action, citizen science can be an efficient means of gathering data on a variety of spatiotemporal scales. When properly designed and analysed, citizen science can generate high-quality data sets to inform policymaking and conservation action (Chandler et al 2017; McKinley et al 2017; Theobald et al 2015). However, there are limitations to this approach, in terms of taxonomic, geographic, socio-political and -economic biases in data collection and participants (Chandler et al 2017; Cooper et al 2007; Merenlender et al 2016). Further limitations typically focus on possible inaccuracies and inconsistencies (Aceves-Bueno et al 2017; Burgess et al 2017; Gardiner et al 2012; Law et al 2017), and misidentification of insects (Austen et al 2016; Kremen et al 2011; Falk et al 2019; Maher et al 2019; Roy et al 2016). Exploring different sampling methods and directly

comparing the samples collected by citizen scientists and researchers will help inform on the effectiveness, bias, and limitations of large-scale hypothesis-driven citizen science projects.

1.9. Thesis aims and data chapters

The overarching aim of this thesis is to investigate habitat management treatments in vineyards, gardens and allotments as lesser-studied landscapes with considerable potential for providing beneficial insect habitat. The benefits of AES for beneficial insect populations is well documented in agri-environments, although further research is needed to support pollinators in other landscapes (Powney et al 2019). For example, urban ecology is a relatively new discipline, as urban areas were largely ignored by ecologists for most of the 20th century (Grimm et al 2008). As urban societies offer a large and capable resource to aid the monitoring of beneficial insects on private land, I used citizen science in two projects in this thesis (**chapters 2 and 3**).

This thesis aims to address the following questions:

1) Do wildflower companion plants attract pollinators to a crop, enhancing pollination services and ultimately increasing crop yield and fruit quality?

2) Can a small mini-meadow positively impact beneficial insect abundance and richness in domestic gardens and allotments?

3) Can sown or spontaneous wildflowers growing on inter-row ground cover in a vineyard encourage beneficial insects?

4) Can wildflower mixes or different treatments in vineyards, gardens and allotments be taxon-specific in attractiveness?

5) What are the common vineyard pests, pest control methods and land-use practices in British viticulture and is there potential for a sustainable future in this emerging agricultural sector?

6) How comparable are the results between citizen scientists and researchers in pollinator-focused hypothesis-driven experimental projects?

To understand if the use of pollinator-friendly co-flowering plants in gardens and allotments distracts or attracts pollinators from a crop, in **chapter 2** I discuss the results of a UK-wide experimental citizen science project (Super Strawberries). This chapter considers the role of companion planting borage with strawberry, as a potential method to increase pollination services, yield and quality of the fruit. This chapter used a dual approach to data collection, combining citizen science with experimental replicates at the campus of the University of Sussex.

Considering that lack of space is a perceived obstacle in wildlife gardening (Goddard et al 2013) and the general size of gardens in cities and urban areas, the Sow Wild! project in **chapter 3** considers the effectiveness of a small 4 m^2 sown mini-meadow in domestic gardens and allotments at recruiting beneficial insects. Sow Wild! was a UK-wide, two-year experimental citizen science project, which asked citizen scientists to collect data, with samples returned to the University of Sussex for verification. Using the researcher-verified data obtained through the results of the Sow Wild! project, in **chapter 4** the limitations and potential bias in a hypothesis-driven experimental citizen science project are discussed, as well as effective insect sampling methods for citizen scientists.

UK agri-environmental schemes have yet to make vineyard-specific recommendations to support biodiversity in viticulture, despite it being one of the fastest-growing sectors of English agriculture (SDNPA 2021). In **chapter 5** I discuss the results of field trials conducted over two years, at an experimental plot in a vineyard in East Sussex, England. I consider the role of sown and spontaneous wildflowers and regularly mown grass as ground cover in vine inter-row alleys in increasing the abundance and richness of beneficial insects. Understanding the current use of synthetic chemicals, land management preferences and barriers to habitat management is important considering the growth of the viticulture sector in the UK. In **chapter 6** I analyse responses to a questionnaire circulated to UK-based viticulturists to highlight the most common pests, pest control methods, land management practices and the potential for future sustainable practices in British viticulture.

This is a papers-style thesis, and all chapters have been accepted or are currently in peer review with journals. The title of the paper, current publication status and the contribution of the authors preludes each chapter.

CHAPTER 2

2. Companion planting to attract pollinators increases the yield and quality of strawberry fruit in gardens and allotments

This chapter has been published as:

Griffiths-Lee, J., Nicholls, E., & Goulson, D. (2020). Companion planting to attract pollinators increases the yield and quality of strawberry fruit in gardens and allotments. *Ecological Entomology*, 45(5), 1025–1034. https://doi.org/10.1111/een.12880

JGL, EN and DG conceived the ideas and designed methodology; JGL collected and analysed the data, and led the writing of the manuscript. All authors commented on draft versions of the manuscript, and a slightly amended version of the published paper is presented here.

2.1. Abstract

Global pollinator declines have led to concern that crop yields might fall as a result of a pollination deficit. Companion planting is a traditional practice thought to increase yield of insect-pollinated crops by planting a co-flowering species next to the crop. Using a combination of conventional researcher-led experiments and observational citizen scientist data, we tested the effectiveness of bee-friendly borage (*Borago officinalis*) as a companion plant to strawberry (*Fragaria* x *ananassa*). Insect visitors to the 'test' (strawberry + borage) versus 'control' (strawberry only) plants were observed, and strawberry fruit collected. Strawberries collected during the researcher-led experiment were also subject to fruit measurements and assessments of market quality. Companion plants were found to significantly increase both yield and market quality of strawberries, suggesting an increase in insect pollination per plant. Test strawberries companion planted with borage produced an average of 35% more fruits, and 32% increased yield by weight. Test strawberry plants produced significantly more fruit of higher aesthetic quality when assessed by Marketing Standards for Strawberries. Although there was no significant difference in the overall insect visits, when broken down by broad insect group there were significantly more flies visiting the test strawberries than controls. These results could have implications for both gardeners and commercial growers. As consumers prefer a cosmetically perfect fruit, the production of fruit with increased aesthetics aids food waste reduction.

2.2. Introduction

Animal pollination directly affects the quality and yield of 75% of the world's leading food crops (Klein et al 2007). Yet this vital ecosystem service is threatened by a suite of anthropogenic factors, including habitat loss, pesticide use, disease, climate change and invasive species (Goulson et al 2015; Potts et al 2010; Powney et al 2019; Vanbergen 2013).

Pollinator declines have led to a growth in the trade of managed honeybees, bumblebees and some solitary bees, which are redistributed around the world to enhance crop pollination (Goulson 2003). An estimated 15,000 bumblebee nests are purchased for use in soft fruit farms per annum in the UK (Goulson 2010). However, this commercialisation poses risks for wild bee populations, including the transmission of

pathogens and parasites (Colla et al 2006; Graystock et al 2013; Schmid-Hempel et al 2014) and competition for floral resources and nesting sites (Ings et al 2006; Inoue et al 2008).

An alternative to introducing managed bees to aid pollination is to support the existing wild pollinator population through the planting of additional floral resources. Much research is currently focused on encouraging a diverse array of pollinators to agricultural environments using wildflowers (Blaauw and Isaacs 2014a; Carreck and Williams 2002; Carvell et al 2006; Pywell et al 2015; Woodcock et al 2014). Considering strawberry plants, pollinator visits have been estimated to be 25% higher when adjacent to wildflower strips (Feltham et al 2015). Enhancement of existing ecosystem services through 'ecological intensification' can also improve the yields of small-scale farmers (Garibaldi et al 2016). With urban agriculture frequently occurring in community gardens and allotments (Mougeot 1999) such 'ecological intensification' (Garibaldi et al 2016) could also be beneficial in improving the yields of crop plants grown in urban community gardens and allotments. This is of considerable significance given that globally, 800 million people practise urban agriculture (FAO 2019).

Companion planting is a traditional gardening practice whereby a second flowering plant species is deliberately planted alongside a crop with the ultimate aim of improving yield (Franck 1983). Companion planting of 'banker' plants is well researched in the context of encouraging natural predators of crop pests (Balzan 2017; Frank 2010; Sigsgaard et al 2013). Planting of co-flowering species can also improve pollination services through pollination facilitation (Feldman et al 2004; Ghazoul 2006; Laverty 1992). However, a recent study on intercropping strawberries in a commercial setting concluded limited evidence of enhanced pollination services (Hodgkiss et al 2019). Some studies have shown more attractive plant species can distract pollinators from a particular focal plant (Chittka and Shürkens 2001; Diekötter et al 2010; Foulis and Goulson 2014; Nicholson et al 2019).

The cultivated strawberry (*Fragaria x ananassa* Duch.) is a member of the family Rosaceae. Strawberries are a popular commercial fruit, with UK production in 2017 over 127,600 tonnes (FAOSTAT) and they are also widely grown in allotments and gardens all over the UK. The achenes of the strawberry are the true fruits, each containing an ovule that when fertilized produces the hormone auxin (Nitsch 1950).

Auxin stimulates the growth of the receptacle, so for a perfectly-shaped fleshy strawberry most of the ovules must be fertilised, if too few are fertilised an irregular-shaped 'nubbin' will result (McGregor 1976). Self-pollination of strawberry flowers is possible, although as the stigmas of the strawberry flower are receptive before the anthers dehisce and pollen is available, cross-pollination is more effective (McGregor 1976).

Cross pollination in strawberries can result in increased yield and market quality (e.g. Bartomeus et al 2014; Klatt et al 2014a). Early studies concluded that insects are more effective pollinators than wind in the pollination of strawberry flowers (Hughes 1961; Kronenberg et al 1959). Furthermore, Connor and Martin (1973) estimated that self-pollination can account for the development of 53% of the achenes, with wind motion increasing this to 67%, and insect pollination increasing it further to 91%. Recent estimates of UK strawberry yield attribute 45% to pollinators (Smith 2011), while Wietzke et al (2018) report a 92% increase in the commercial value of marketable strawberry fruits in the presence of insect pollinators. Other studies have reported decreased malformations in strawberry fruit pollinated by insects (Abrol et al 2019; Herrmann et al 2019; Klatt et al 2014b).

In this study, we examined the potential benefits of companion planting strawberry with borage (*Borago officinalis*). Borage is an annual herb from the family Boraginaceae. A common garden plant, borage is very attractive to pollinators (Carreck and Williams 2002; Garbuzov and Ratnieks 2014; Rollings and Goulson 2019), and frequently features in gardening lists of bee-friendly plants (e.g. The Wildlife Trusts 2019). This study was conducted in two parts: by professional scientists on the campus of the University of Sussex, UK and by volunteer 'citizen scientists' at various locations across the UK. Citizen science has been used for a range of disciplines and monitoring at a range of levels - from species to ecosystems (Dickenson et al 2012). Citizen science projects have become popular, gathering data that would otherwise require massive resources while engaging the public in scientific research, and they are increasingly supported by new technologies (Pocock et al 2015). Many citizen science projects have focused on pollinators (Birkin and Goulson 2015; Deguines et al 2012; Lye et al 2012; Oberhauser and LeBuhn 2012; Phillips 2008; Roy et al 2016) contributing valuable scientific data to the field.

The aims of the experiment were fourfold: to test whether the presence of a companion plant a) increases insect visitations to a crop b) increases the yield of a crop c) increases the quality of the fruit, and also, d) to compare the experimental results found by volunteers when compared to professional scientists. Aim d) serves to gauge the feasibility and reliability of such experimental pollinator experiments being conducted by citizen scientists.

2.3. Methods

2.3.1. Study plants

Everbearing strawberry plants (*Fragaria* x *ananassa*) 'Albion' variety (Ken Muir Ltd, Essex, UK) produce flowers from April to August, thus were selected to maximise the likelihood of overlap in flowering between borage and strawberry plants over a geographically large area (Appendix A for locations of citizen scientists around the UK). Albion variety are disease-resistant, hardy plants, ideal for growing in containers (Ashbridge Nurseries 2018) and readily available to purchase in garden centres. Although the seed-like achenes are the true fruits, in this paper we will refer to the entire fleshy receptacle of the strawberry as an individual 'fruit'. Borage blue (*Borago officinalis*) (Sarah Raven's Kitchen and Garden Ltd, Marlborough, UK) was selected as the companion plant. It is an annual with a long flowering period, that is highly attractive to pollinators, hardy, easy to germinate from seed and suitable for growing in containers.

2.3.2. Researcher experiment

Researcher-led experiments took place on the University of Sussex campus, Brighton, UK, between March and August 2018. Strawberry runners were planted individually in 6 litre 'Hadopot™' containers (Hadopots Ltd, Malvern, UK; hereafter 'pot') with organic compost, and kept in an unheated greenhouse from March 2018. Any strawberry new runners or flowers were removed to conserve the plants' energy until the experiment started. Three borage seeds were planted in a 13.5 litre pot and kept in the greenhouse, initially under UV light for two weeks. After initial growth plants were thinned to the two strongest borage seedlings per pot.

Once the strawberry plants and borage were flowering simultaneously, they were placed in 26 different sites around the campus, a minimum of 30 metre apart. One pot containing a single strawberry plant ('test') was placed directly next to a borage plant and one pot containing a single strawberry plant ('control') was placed three metres away from the test strawberry plant and borage in a paired design. Both test and control plants were kept at least three metres from all other flowering plants. This distance was constrained by the fact that citizen scientists would be conducting the experiment in their gardens and allotments and therefore would be limited in space. All three plant pots (control, test, borage) were placed in the same aspect and labelled with a unique ID.

2.3.3. Pollinator observations

Over four weeks during June and July 2018, diurnal insect visits to the flowering strawberry and borage plants were observed weekly. Insects were categorised as one of the following broad taxonomic groups: beetle, hoverfly, 'other fly', butterfly or moth, bumblebee, honeybee, solitary bee, wasp, and 'other' insects. Visits were recorded for five minutes per plant (control strawberry, test strawberry and borage), between 10 am-4 pm in adjacent time-slots, on sunny, low-wind days when temperatures were above 13 ˚C. If the strawberry plant did not have any flowers, visits were not recorded. If the test strawberry did not have flowers, visits to the borage plant were also not recorded. The number of open flowers on the strawberry plants was recorded during the weekly insect visits; as the flowers last less than three days (pers.obs.), it was assumed that flowers were not counted twice.

2.3.4. Strawberry fruit harvest

After the end of the four-week pollination period, 52 strawberry plants were brought back into the greenhouse so the strawberry fruit could ripen in conditions with a reduced threat of pests, and to facilitate fruit harvesting. At this point, a permanent marker (Sharpie, Sanford L.P, US) was used to make a red mark on the stems of all flowers, nubbins, unripe and ripe fruit. From this point onwards, any newly opening flowers or fruit developing from unmarked stems were removed and disposed of, ensuring that only fruit resulting from flowers pollinated in the field were harvested. Strawberries were harvested when deep red in colour.

2.3.5. Strawberry quality and fruit measurements

Strawberry fruit diameter and length in millimetres were first recorded using digital callipers. Fresh weight was then recorded to the nearest hundredth of a gram (Precisa 125A, Precisa Gravimetrics AG, Switzerland). The quality of individual strawberries was assessed according to the Marketing Standards for Strawberries (Rural Payments Agency 2011). The assessment standards were as follows: EXTRA class = bright red, defect free, 25mm+ diameter; Class I = white patch of <10%, slight defects, 18mm +, slight pressure marks; Class II = white patch <20%, defects, 18mm +, slight bruising; N/A = damaged, not intact, deteriorating, foreign matter, pests, damage, external moisture or foreign smell/taste. The assessment was conducted blind to the experimental treatment, to eliminate any bias.

A refractometer (0-50%) was used to measure the sugar content of strawberry juice (Degrees Brix, % sugar content of aqueous solution). Half of each strawberry was placed in an oven at 40 ˚C for seven days to fully dehydrate the fruit and calculate the water content (dry weight subtracted from wet weight multiplied by two). The second half of the fruit was macerated using a kitchen hand blender, along with 200 ml of water, following the protocol detailed in Hodgkiss et al (2018). The mixture was allowed to settle for 20 minutes, and then sunken fertilised achenes and floating unfertilised achenes were counted.

2.3.6. Citizen scientist project packs and methodology

One hundred and ten volunteers were recruited at various locations around the UK (Appendix A). Volunteer citizen scientists who had previously taken part in similar projects run by The University of Sussex were invited to participate in the Super Strawberries project, which was also advertised via Twitter. Volunteers were sent a pack including two dormant ‘Albion’ variety strawberry runners, one pack of borage seeds, two 6 litre pots, one 13.5 litre pot and a workbook (see Appendix B, C, D for workbook, instructions and ID guide). A full list of pack contents is available in Appendix C. The protocol followed by the volunteers was the same as the researcher experiment over the same summer in 2018, except for the laboratory-based strawberry measurements. Instead, volunteers were asked to count and weigh the harvested red fruits weekly.

2.3.7. Data analysis

All data submitted by citizen scientists on insect visits and harvest were used in analysis, although the data differed in terms of completion. Fruit quality and measurement data were available for the researcher experiment only. Data analysis was carried out in R version 3.5 (R Core Team 2018). A Shapiro-Wilk normality test was conducted to test the data were suitable for parametric analysis. Generalised Linear Mixed Models (GLMMs) were built using *lme4* package, zero-inflated models were built using *glmmTMB* package. Models of best fit were chosen based on diagnostic residual plots and AIC values. ANOVAs were performed by comparing full and reduced models and reported as chi-square values.

Pollinator observations. To test for differences in insect visitation and to test for differences in the number of flowers produced by test strawberry plants or control strawberry plants, zero-inflated GLMM's with Poisson distribution were used with the same structure, with plant treatment (test vs. control) as a predictor variable, experimental week as a random variable and site (unique identifier for garden/allotment/university replicate) and individual plant ID as nested random variables. Total insect visits were analysed both separately for the citizen scientist and researcher data set, and also in combination. For analysis of the insect visitations by separate taxonomic groups (beetle, hoverfly, 'other fly', butterfly/moth, bumblebee, honeybee, solitary bee, wasp, and 'other' insects), the combined data set was used with zero-inflated GLMMs with Poisson distribution, as the counts of insects for certain groups were too low for the data to be split by experiment. Benjamini Hochberg corrections are used to adjust p values to control for the occurrence of Type I errors (Benjamini and Hochberg 1995). However, p-adjusted corrections are conservative and raise the likelihood of Type II errors, so we conducted Benjamini Hochberg corrections alongside non-adjusted p values.

Fruit harvest. To compare yields by fruit number between strawberry plants that were paired (test) or not (control) with the companion plant, a GLMM with Poisson distribution was used to test for differences in the number of strawberry fruits produced per plant. Plant treatment (test/control) was a predictor variable and site was a random variable. The citizen scientist and researcher data sets were analysed separately and in

combination. To compare the yield by fruit weight between strawberry plants that were paired (test) or not (control) with the companion plant, a Linear Mixed Model (LMM) was used to test differences between the total fruit fresh weight produced per plant. Plant treatment (test/control) was a predictor variable and site was a random variable. The citizen scientist and researcher data sets were analysed separately and in combination, although any obvious erroneous strawberry weight entries from citizen scientists were omitted from analysis.

Fruit quality and measurements. LMMs were used to compare fruit measurements: fruit diameter, length, fresh weight, Brix, water content and proportion of fertilised achenes. For all fruit measurements plant treatment (test/control) was a predictor variable, with site and plant ID as nested random variables. The proportion of fruit in each market class was compared between treatment groups using a chi-square test.

2.4. Results

2.4.1. Pollinator observations

Considering the combined data set that includes both the researcher and citizen science experiments, the number of flowers did not differ significantly between the test and control plants n=334 (X^2 = 0.456, df = 1, P = 0.499) (test, mean ± SE: 7.36 ± 0.297 and control, mean ± SE: 7.0 ± 0.349), so the number of flowers was not included in further analysis of insect visitation. There was no significant difference between the mean number of total insect visitors between treatments (test, mean ± SE: 1.60 ± 0.161 and control, mean ± SE: 1.35 ± 0.138) (Fig 2.1; X^2 = 0.409, df =1, P = 0.523).

The citizen scientist and researcher experiments were then analysed individually in terms of differences in total insect visitations between strawberry treatments. Firstly for the researcher experiment, the mean number of insect visitors did not significantly differ between the test strawberry plant paired with borage and the control plant (X^2 = 0.152, df =1, P = 0.697) (test, mean ± SE: 1.22 ± 0.215 and control, mean ± SE: 1.31 ± 0.18). There was also no statistically significant difference in the mean number of insect visitors between the test and control plants for the citizen scientist experiment (X^2 = 1.547, df =1, P = 0.214) (test, mean ± SE: 2.03 ± 0.234 and control, mean ± SE: 1.39 ± 0.211).

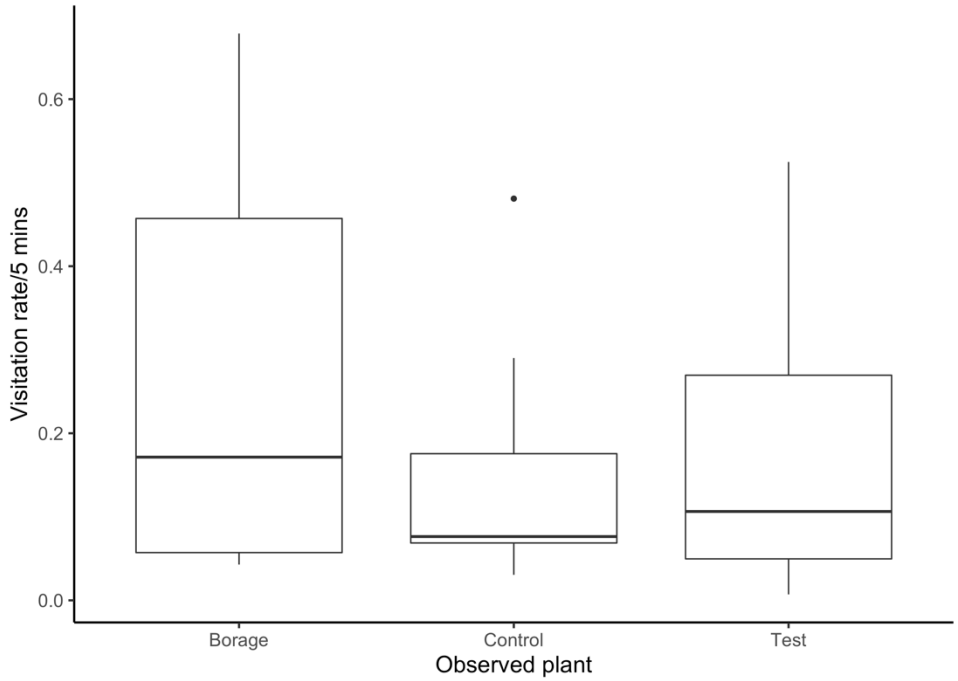

Figure 2.1. *Overall insect visits (by visitation rate - mean per five-minute observations), to test strawberry, control strawberry and borage plants. Showing the median (central horizontal lines). As the number of five-minute observations for each treatment differed, an overall mean visitation rate per plant was calculated (by dividing the insect group total count by the total number of five-minute observations for each plant treatment (borage n = 140, control n = 131, test n = 141)).*

When insect visits were compared by taxonomic group (Fig 2.2), significantly more 'other flies' (excluding hoverflies) visited test strawberry plants paired with borage, compared to the unpaired control plant (Table 2.1; test, mean ± SE: 0.369 ± 0.124 and control, mean ± SE: 0.176 ± 0.102), with strawberry plants next to borage receiving more than twice as many visits as plants that were three metres away. Visits to the test and control plants did not differ significantly for other taxonomic groups (Table 2.1). Although not quite statistically significant, there were also more than twice as many bumblebee visits to strawberry plants adjacent to the companion plant (Table 2.1; test, mean ± SE: 0.156 ± 0.096) compared to those placed three metres away (control, mean ± SE: 0.069 ± 0.111).

Insect Group	X^2	df	P =	P adjust	Control Mean (±SE)	Test Mean (±SE)
Bumblebee	3.612	1	0.057	0.256	0.069 ± 0.111	0.156 ± 0.096
Beetle	0.222	1	0.638	0.256	0.481 ± 0.169	0.525 ± 0.185
Butterfly/Moth	0.076	1	0.783	0.411	0.069 ± 0.094	0.078 ± 0.102
Other fly*	4.005	1	*0.045	0.477	0.176 ± 0.102	0.369 ± 0.124
Honeybee	0.001	1	0.97	0.97	0.076 ± 0.093	0.106 ± 0.130
Hoverfly	0.007	1	0.932	0.97	0.290 ± 0.118	0.27 ± 0.101
Other insect	1.555	1	0.212	0.97	0.122 ± 0.135	0.043 ± 0.096
Solitary bee	0.028	1	0.867	0.97	0.038 ± 0.086	0.050 ± 0.094
Wasp	2.212	1	0.137	0.97	0.031 ± 0.086	0.007 ± 0.084

Table 2.1. *Effect of strawberry plant proximity to the companion plant borage (test = paired, control = 3 metres away) on insect visitation, by broad taxonomic group. Presented with X^2, df, P value, and p-adjust with Benjamini Hochberg corrections. *statistical significance at $P < 0.05$.*

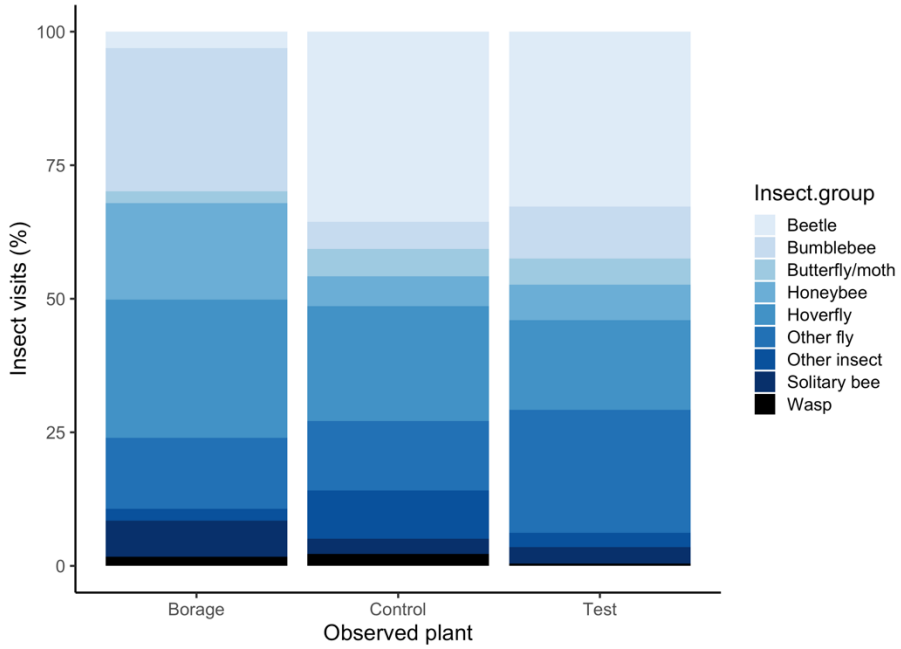

Figure 2.2. *Percentage insect visits by broad taxonomic group to test strawberry, control strawberry and borage.*

2.4.2. Strawberry fruit harvest

Analysis of harvest by number of fruits using the combined data set indicates that the test strawberry plants placed adjacent to the companion plant produced significantly more fruits than control plants (X^2 = 15.009, df = 1, P = 0.0001) (test, mean ± SE: 11.3 ± 0.384 and control, mean ± SE: 8.36 ± 0.332), with 35% more fruit produced on average, by test plants. This pattern is consistent when the citizen scientist and researcher experiments were considered individually (Fig 2.3). For the citizen scientist experiment, the test plant produced significantly more fruit than the control plant (X^2 = 5.55, df = 1, P = 0.018) (test, mean ± SE: 9 ± 0.734 and control, mean ± SE: 6.38 ± 0.573), equating to a 41% increase in the average number of fruit produced. Considering the researcher experiment, the test plant produced significantly more fruit than the control plant (X^2 = 8.859, df = 1, P = 0.003) (test, mean ± SE: 13 ± 0.408 and control, mean ± SE: 10.2 ± 0.373), a 28% increase in the average number of fruit produced.

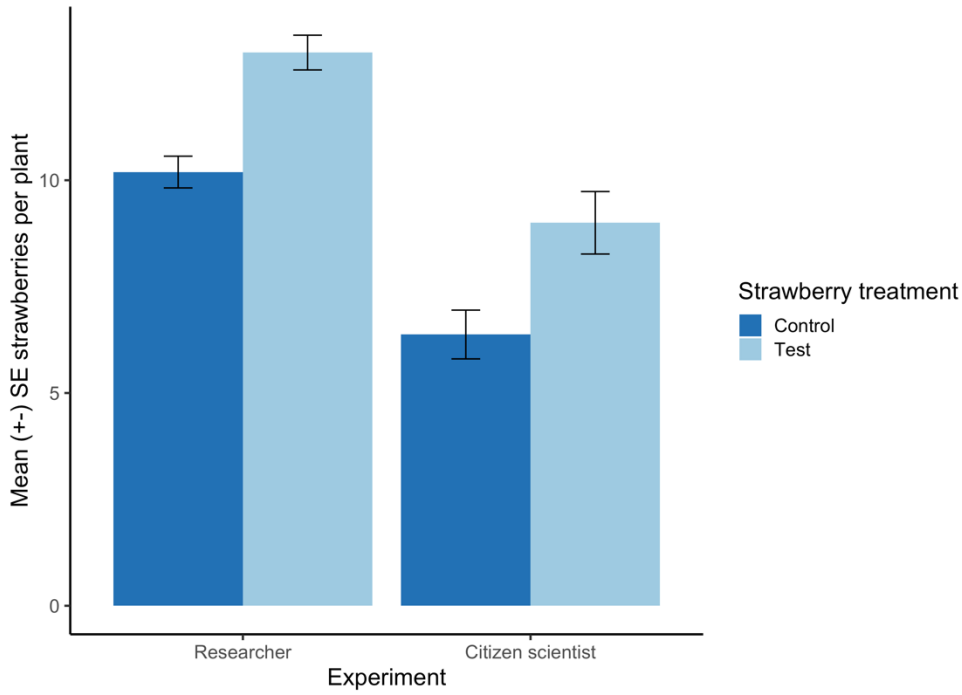

Figure 2.3. *Mean (±SE) number of strawberries produced by test strawberry plants paired with borage compared with unpaired control, for both the citizen science and researcher-led experiments.*

Analysis of harvest by total weight of fruits using the combined data set indicates that the test strawberry plants placed adjacent to the companion plant produced a significantly higher yield by weight than the control plant, Fig 2.4 (X^2 = 5.590, df =1, P = 0.0181) (test, mean ± SE: 81.688 ± 9.711 and control, mean ± SE: 61.91 ± 7.483), with 32% more strawberry yield by weight produced on average, by test plants. Considering only the researcher experiment, the average yield by weight produced by the test plants was 26% higher than the control plants. However, the difference in the total average weight of fruit produced by test plants compared to control plants was not quite statistically significant (X^2 = 3.630, df = 1, P = 0.057) (test, mean ± SE: 85.065 ± 10.627 and control mean ± SE: 67.719 ± 8.340). Considering the citizen scientist experiment the average yield by weight produced by the test plants was 40% higher than the control plants. However the difference in the total average weight of fruit produced by test plants compared to control plants was also not statistically significant (X^2 = 2.029, df =1, P = 0.154), (test, mean ± SE:77.067 ± 18.146 and control, mean ± SE: 55.045 ± 13.094).

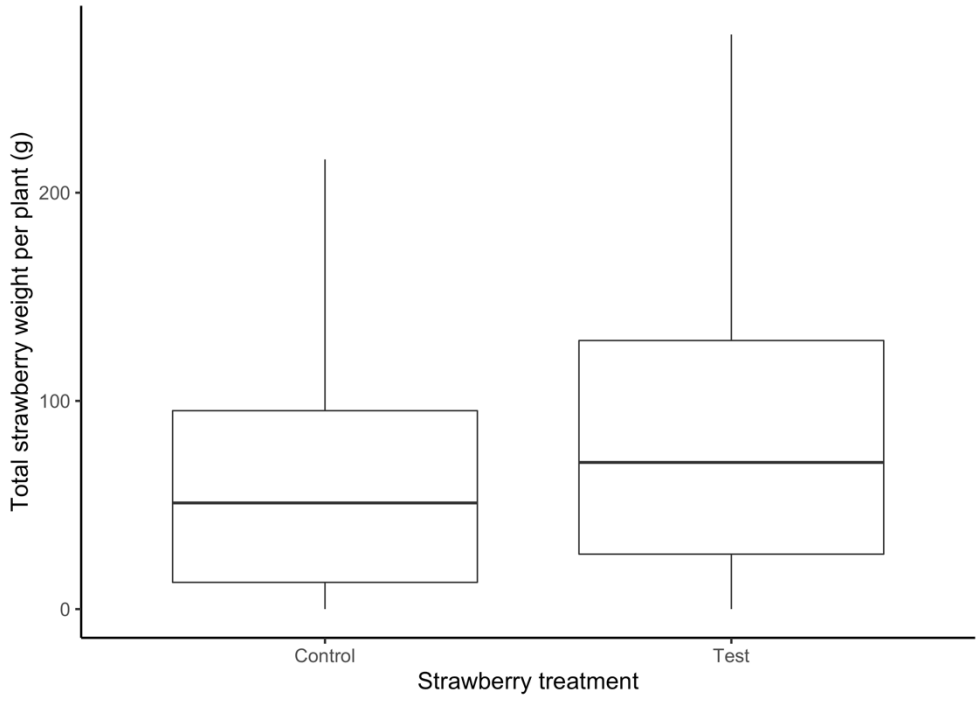

Figure 2.4. *Total strawberry yield by weight produced per plant, for test plants paired with borage, compared to unpaired control. Showing the median (central horizontal lines).*

2.4.3. Strawberry quality and fruit measurements

The categories of market class fruit differed significantly between the test strawberry plants and the control (X^2 = 16.5, P = 0.001), with more EXTRA class and Class I fruit produced by test strawberry plants than controls (EXTRA test mean ± SE: 0.885 ± 0.325 fruits, control mean ± SE: 0.115 ± 0.188 fruits; Class I test mean ± SE: 5.27 ± 0.39 fruits, control mean ± SE: 3.58 ± 0.323 fruits), (Fig 2.5) Comparing fruits harvested from test and control plants, on average there was no significant difference in the fruit measurements (Table 2.2).

				Control		**Test**	
Measurement	X^2	**df**	P =	**Mean**	**SE (±)**	**Mean**	**SE (±)**
Diameter (mm)	5e - 04	1	0.983	23.1	0.073	23.1	0.064
Length (mm)	0.324	1	0.569	24.7	0.071	24.4	0.065
Fresh weight (g)	0.104	1	0.747	6.64	0.097	6.54	0.087
Brix (°Bx)	0.954	1	0.329	8.33	0.054	7.91	0.054
Fertilised achenes (prop)	0.457	1	0.499	0.67	0.016	0.69	0.134
Water content (g)	0.072	1	0.788	6.43	0.094	6.33	0.084

Table 2.2. *Fruit measurements of strawberry fruit produced by test strawberry plants paired with borage, compared with unpaired control*

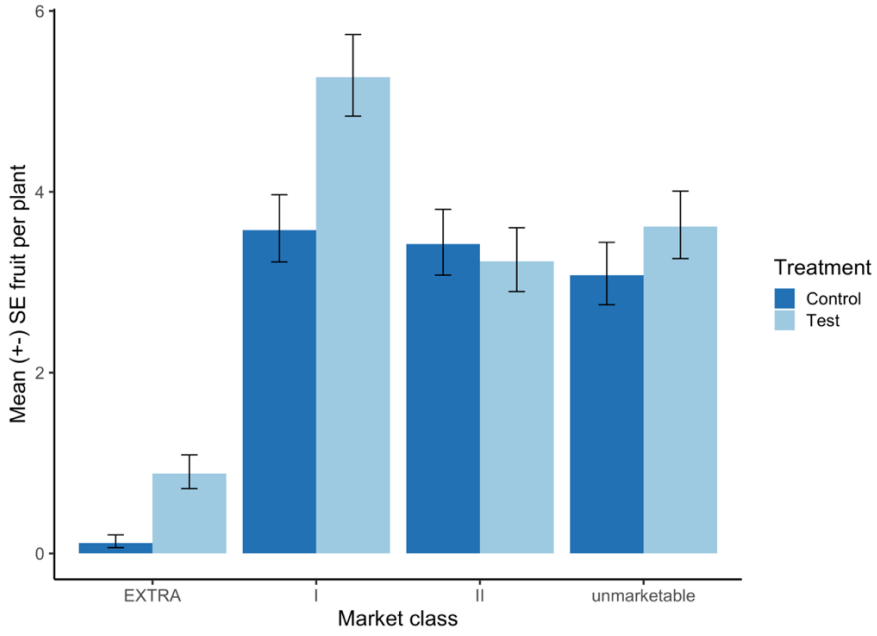

Figure 2.5. *Mean (±SE) number of strawberries classified by Market Class (EXTRA class, Class I, Class II and unmarketable fruit) produced by test strawberry plants paired with borage, compared with unpaired control.*

2.4.4. Citizen scientists

One hundred and ten citizen scientists were recruited for the project. Forty-two volunteers (38%) signed up using their allotment, and 68 (62%) used their garden. Sixty volunteers (55%) remained engaged throughout the project (including those that told us when and why they dropped out), with 30 volunteers (27%) submitting data forms. Of those volunteers who dropped out yet were still engaged, 11 (37%) cited personal reasons and 19 (63%) cited failure of the experiment (usually due to plants dying, or a mistiming of the flowering period between the strawberry and borage plant).

2.5. Discussion

Companion planting is a traditional gardening practice, designed to improve crop yield by attracting pollinators and other beneficial insects. After developing a simple citizen science methodology to investigate this practice, we have shown that companion planting strawberry plants with pollinator-friendly borage increases the crop yield and the market quality of strawberry fruits.

2.5.1. Insect visitations

We found that the overall number of insect visitations between the test and control strawberry plants was not significantly different. However, when individual insect groups were considered, the number of visits by 'other flies' and bumblebees were more than twice as high to the test plants compared to controls, although the latter was not quite statistically significant. Borage is known to be attractive to honeybees (Garbuzov and Ratnieks 2014; Rollings and Goulson 2019) and bumblebees (Carreck and Williams 2002). Here we found borage to attract a range of insects, especially bumblebees, honeybees, 'other flies' and hoverflies. This could have a positive impact on fruit set, as insect communities with diverse functional traits promote effective pollination (Woodcock et al 2019). We conclude that, at least for 'other flies' and perhaps for bumblebees, this results in spillover to the adjacent strawberry plant. Similarly, Feltham et al (2015) found that planting wildflower mixes adjacent to commercial strawberry crops increased insect visitation to the crop by 25%, the majority of visits being by bumblebees.

'Other flies' were frequent visitors to strawberry (similar to Ellis et al 2017), as well as beetles and hoverflies. Bees and flies have different foraging behaviours; bees forage and transport pollen and nectar back to their nests, whereas other insects generally forage only for their own needs (Ssymank et al 2008). These behavioural differences, together with the lack of dense hair on a fly's body, mean they aren't as effective as bees in pollinating some plant species but due to their abundance, their role in crop pollination shouldn't be undervalued. Although flies are commonly neglected in pollination studies, they are known to pollinate over 100 cultivated crops (Ssymank et al 2008) and are considered important contributors to global crop pollination, especially considering declines in bee populations (Orford et al 2015; Rader et al 2016). Previous studies have concluded that, in terms of strawberry crop pollination, flies provide a unique contribution, in that they visit flowers during periods of inclement weather when other pollinators were absent (Ellis et al 2017), and hoverflies are efficient pollinators of strawberry (Hodgkiss et al 2018). Indeed, studies conclude that it is abundance and functional trait, more than pollinator type, which contributes most to pollination efficiency in strawberries (Connelly et al 2015; Ellis et al 2017). In both the citizen science and researcher experiments, beetles were also frequent visitors to strawberry plants. However, we noted in the researcher-led experiment that this was due to a high number of small pollen beetles covering the emerging strawberry flower and remaining

for long periods. Previous studies suggest that Coleoptera have limited potential as pollinators of strawberry and are primarily pollen consumers (Albano et al 2009).

2.5.2. Strawberry yield and quality

Strawberry plants placed directly adjacent to borage plants produced on average 35% more fruits and 32% increased yield by weight, when compared to plants placed a distance of three metres away, suggesting the control strawberries experienced a pollination deficit in the absence of the borage plant. In addition to increasing yield, we found that companion planting with borage also improved the aesthetic quality of the fruit, with more 'EXTRA' and 'Class I' strawberries produced by the test plants. This increase in quality suggests that, due to the presence of a companion plant, more complete pollination of the achenes has resulted in aesthetically better fruit. Considering this result it is perhaps surprising that the proportion of fertilised achenes was not significantly different between the test and control strawberry; aesthetically-improved fruit may instead be a result of the even distribution of pollen. Indeed, Wietzke et al (2018) state that an even distribution of pollen over the stigmas of the strawberry flower is important for fruit development, combined with a minimal threshold of pollen needed per stigma and, importantly, malformation may occur when these criteria are not met. It is widely agreed that bees are efficient pollinators of strawberry (Abrol et al 2019; Bigey et al 2005; Feltham et al 2015; Foulis and Goulson 2014; Klatt et al 2013; Klatt et al 2014a; Wietzke et al 2018; Yanagi et al 2017) often walking around the flower distributing pollen. Additionally, strawberries pollinated by bumblebees have been found to produce more marketable and better-shaped fruit (Dimou et al 2008).

2.5.3. Future research

Consumers prefer a cosmetically perfect fruit, with recent estimates suggesting over a third of total farm production is lost due to aesthetics (Porter et al 2018). Many commercial soft fruit farms buy bumblebee nests or rent honeybee hives for pollination, although the planting of strips of borage could provide an alternative, perhaps cheaper, means of boosting yields and reducing food waste. However, this experiment was limited to individual pots in gardens and allotments, investigating whether this could work on a commercial scale under real agronomic conditions is an essential next step. It may be that any benefits accrued from improved pollination may not offset the cost,

time and space required for the companion plants. Planting pollinator-friendly wildflower mixes adjacent to commercial strawberries has been found to increase crop visitation by bumblebees (Feltham et al 2015), while Hodgkiss et al (2019) concluded that intercropping strawberries with coriander, field forget-me-not and corn mint in a commercial setting had limited benefits, with no difference in the number of marketable fruits produced.

Strawberry and borage plants in this experiment were grown in separate pots, removing any competition or interaction between the roots of the plants. In the UK, strawberries are grown in either open ground or raised bed systems (DAERA 2020). The current approach is therefore analogous for raised bed systems as pots containing borage could be placed alongside raised beds. However, considerations would be necessary to adjust this experiment for open ground systems, accounting for root interactions and considering space taken up by borage plants. Additionally, the seeds of borage self-sow (Sarah Raven 2018) which would require management in open ground systems.

In our experiments, test and control plants were just three metres apart, suggesting that the companion plant effect may be localised. The number of strawberry flowers in a commercial setting would be greater than those seen during this experiment. Therefore the optimal arrangement and ratio of pollinator-friendly borage to strawberry plants would need consideration in a commercial setting, due to complex interactions between the density and spatial arrangement of conspicuous flowering species and pollinator response (Seifan et al 2014).

2.5.4. Citizen scientists

We have successfully developed a method to assess the effectiveness of companion planting, with valuable contributions from volunteer citizen scientists across the UK. Results and patterns were consistent across data collected by researchers and those collected by citizen scientists. The engagement rate of the citizen scientists in this experimental project was good, with 27% submitting data forms and 55% continued engagement, compared to a report stating an average of 27% of participants return to a project for a second time (Sauermann and Franzoni 2015). Therefore this experimental citizen science method could be adapted for other companion plant combinations, all the while engaging the public in wildlife gardening. Future pollination-based experiments

should incorporate sessions of remote training to increase the accuracy of insect identification (Ratnieks et al 2016).

CHAPTER 3

3. Sown mini-meadows increase pollinator diversity in gardens

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JGL and DG conceived the ideas and methodology; JGL collected and analysed the data, and led the writing of the manuscript. All authors commented on draft versions of the manuscript, and a slightly amended version of the published paper is presented here.

3.1. Abstract

Habitat loss and fragmentation are considered the foremost threats to pollinator decline, and in England and Wales, 97% of wildflower meadows were lost by 1984. The value of creating flower-rich margins in agricultural environments is established, yet there is growing potential to support pollinator populations in urban landscapes. We used citizen science to investigate the effectiveness of small 4 m^2 sown wildflower 'mini-meadows' in UK gardens and allotments in recruiting beneficial insects. Participants were allocated one of three treatment groups: mix 1 (commercially available 'meadow mix'); mix 2 (formulated based on existing literature on pollinator foraging preferences); or control (no additional wildflowers). All participants conducted insect sampling over two years using standardised pan and sticky trap methods from May to August. Samples were returned for identification by trained specialists. Mini-meadows provided resource-rich habitats, increasing wild bee richness and supporting on average 111% more bumblebees, 87% more solitary bees and 85% more solitary wasps in the year following seed-sowing, compared to control plots. The wildflower mixes were also taxon-specific in their attractiveness. Mix 1 attracted more solitary bees and bumblebees, whereas mix 2 attracted more solitary wasps. There was no significant difference in the abundance of hoverflies between treatments. Higher abundance of solitary wasps and bees caught amongst the mini-meadow was perhaps due to shorter foraging ranges. Domestic gardens and allotments provide huge potential habitat for pollinators, and small-scale floral enhancements can attract more beneficial insects in fragmented urban landscapes, supporting urban biodiversity, pollination services and biological control.

3.2. Introduction

Expanding urbanisation is a significant driver of habitat loss and fragmentation, with 55% of the global human population now living in urban environments (Vié 2009; UN 2019). Habitat loss and fragmentation are considered one of the foremost threats to the decline of pollinators, reducing the availability of essential pollen, nectar and refuge (Goulson et al 2015). In England and Wales, 97% of lowland wildflower meadows were lost between 1930 and 1984 (Fuller 1987).

The availability of floral resources directly influences bee abundance (Roulston and

Goodell 2011), and so most agri-environment schemes (AES) implemented across Europe include strategies to boost the number of flowers, such as sowing flower-rich margins to provide habitat and forage for pollinators in agricultural landscapes (DEFRA 2020). There is evidence that such schemes do increase both pollinator abundance (e.g. Carreck and Williams 2002; Carvell et al 2007) and the abundance of some natural predators of pests (Tschumi et al 2015). Like wild bees, solitary wasps depend on plants for pollen, nectar, nesting and overwintering sites during their life cycle (Tscharntke et al 1998). Sown wildflowers can attract parasitoid wasps in agricultural landscapes, thereby enhancing natural pest control (Hoffmann et al 2018). Recent studies emphasise considering bee and non-bee species when designing floral mixes (Howlett et al 2021).

Compared to agricultural landscapes, fewer studies have been conducted in gardens on the link between additional floral resources and pollinator abundance, yet they contribute considerable green space to urban areas. Gardens comprise an estimated 24 - 36% of the area of UK cities (Baldock et al 2019) covering an area of 400,000 ha (The Wildlife Trust 2021). Similarly, gardens account for 36% of urban space in a New Zealand city (Mathieu et al 2007), although this can vary greatly, with gardens accounting for just 16% of urban space in Stockholm, Sweden (Colding et al 2006). Likewise, in developing countries, gardens also contribute essential green space to cities. Private garden patios in León, Nicaragua for example, account for 86% of the city's green space (Gonzalez-Garcia and Sal 2008). Gardens differ considerably from rural farmland landscapes, with high numbers of non-native plants, and often substantial areas of impervious surfaces (Matteson and Langellotto 2011) and have less area available for sowing of wildflower patches. Given the considerable area of potential habitat for pollinators represented by gardens collectively in Europe and beyond, more research is needed to understand the value and effects of enhancing floral resources in these settings.

Although urbanisation is often regarded as having negative impacts on biodiversity in general, a considerable diversity of bees can be found in cities and urban areas (Fortel et al 2014; Lanner et al 2019), particularly in gardens and allotments (Baldock et al 2019). For pollinators to thrive in urban green spaces there must be sufficient nesting/breeding opportunities and an adequate supply of foraging plants (Goulson et al 2015; Splitt et al 2021). The planting of additional floral resources is considered to positively impact

pollinator abundance and richness in gardens (Garbuzov and Ratnieks, 2014; Pawelek et al 2009; Salisbury et al 2015), although there are exceptions (e.g. Matteson and Langellotto 2011).

In agricultural landscapes, providing particular plant species rather than increasing overall plant richness is most effective in increasing pollinator abundance (Warzecha et al 2018). Similarly, in a study of flowering species specifically grown in discrete patches, 18 out of 40 bee-friendly wildflowers provided forage for 100% of observed bee species (Nichols et al 2019), and garden flowers can vary approximately 100-fold in their attractiveness to insects (Garbuzov and Ratnieks 2014), suggesting selectivity over plant species is key to increasing pollinator abundance (Nichols et al 2019). Different types of plants are attractive to different pollinator groups, for example, bumblebees are commonly attracted to long-corolla flowers and parasitoid wasps and hoverflies to short-corolla flowers (Campbell et al 2012). Additionally, native flowers are considered to have positive effects on bee richness and abundance in gardens (Pardee and Philpott 2014; Rollings and Goulson 2019). Strategies to support pollinators recommend planting pollen- and nectar-rich plants in green spaces (e.g. Royal Horticultural Society 2021 'Plants For Pollinators'). Ready-to-sow wildflower mixes targeting pollinators are readily available, although, to the best of our knowledge, there are no previous published studies on how successful these mixes are at increasing the abundance of insects and richness of bee species in domestic gardens or allotments.

Citizen science (also known as 'community science') is used in multiple disciplines and the potential for monitoring is recognised by the United Nations Sustainable Development Goals (Fraisl et al 2020). Citizen science projects focusing on bees have contributed valuable data (e.g. Birkin and Goulson 2015) gaining data on a temporal and spatial scale that would otherwise be difficult to achieve. However, bee-based citizen science is biased toward social species, with fewer projects on solitary bees (Koffler et al 2021). In our study, we used citizen science as a novel and pragmatic approach to access private gardens to survey insects.

The Sow Wild! project focused on the effectiveness of sown mini-meadows in UK domestic gardens and allotments, addressing the following questions: i) Does the creation of a mini-meadow increase the abundance of 'beneficial insects' (pollinators and natural enemies of pests) and richness of bee species; ii) Do wildflower mixes differ

in their success in recruiting different groups of beneficial insects; iii) Does a mini-meadow have a positive 'spillover' effect on pollinator abundance throughout the garden or allotment.

3.3. Methods

3.3.1. Citizen scientist recruitment for 'Sow Wild!'

Participants were recruited in 2015 through social media, via allotment societies and members of 'The Buzz Club' (a citizen science charity based at the University of Sussex https://www.thebuzzclub.uk/). Expression of interest was obtained via an online survey, with the basic requirements being that participants had a garden or allotment (hereafter 'site') of at least 20 m^2 and space of 2x2 m to establish a 'mini-meadow' wildflower patch. Participants meeting these requirements then completed a second survey asking detailed information on their site management. A private Facebook group was created to encourage engagement.

One hundred and fifty participants were randomly split into three groups of 50 participants, receiving mix 1 seeds, mix 2 seeds, or control. The control group did not receive any seed mixes but still conducted insect sampling in their garden. Experiments were conducted in 2016 (year 1) and 2017 (year 2).

3.3.2. Wildflower mixes

Mix 1 (Table 3.1) is based on a mix recommended under the UK's Countryside Stewardship Scheme for the establishment of flower-rich plots under its AES, a general-purpose 'meadow mix' (Emorsgate EM3 (2016 composition), Emorsgate Seeds, UK). We also added *Papaver rhoeas* and *Centaurea cyanus* to the mix, to provide additional floral cover in the first year, and reduce weed competition. Mix 2 (Table 3.1) was formulated based on existing literature and personal communications with Brown, R, and Wood, T.J, identifying flowers to attract a range of pollinator species and providing flowering cover across the season. Mix 2 was formed mostly of perennials as they produce more pollen and nectar than annual flowers (Hicks et al 2016), create more overwinter nesting capacity for insects (Ganser et al 2019) and last multiple seasons. Species commonly included in commercial mixes include *Centaurea cyanus*, *Leucanthemum vulgare*, *Centaurea nigra*, *Daucus carota*, *Lotus corniculatus*, *Silene*

dioica, and *Trifolium pratense* (Hicks et al 2016 and references therein) and these were included in both mixes.

Mix 1 and Mix 2 Common Flowering Plants			
Centaurea cyanus (a)			
Centaurea nigra (p)			
Centaurea scabiosa (p)**			
Daucus carota (b)			
Leontodon hispidus (p)			
Leucanthemum vulgare (p)			
Lotus corniculatus (p)			
Papaver rhoeas (a)			
Ranunculus acris (p)			
Additional Flowering Plants		**Grasses**	
Mix 1	**Mix 2**	**Mix 1**	**Mix 2**
Achillea millefolium (p)	*Alliaria petiolata* (b)	*Agrostis capillaris*	*Cynosurus cristatus*
Betonica officinalis (p)	*Barbarea vulgaris* (b/p)	*Cynosurus cristatus*	*Festuca rubra ssp commutata*
Filipendula ulmaria (p)*	*Campanula glomerata* (p)**	*Festuca rubra*	*Festuca rubra ssp juncea*
Galium album (p)	*Echium vulgare* (b)	*Phleum bertolonii*	*Poa pratensis*
Galium verum (p)	*Hypochaeris radicata* (p)		
Origanum vulgare (p)	*Knautia arvensis* (p)**		
Plantago media (p)	*Matricaria chamomilla* (a)		
Primula veris (p)	*Onobrychis viciifolia* (p)**		
Prunella vulgaris (p)	*Reseda lutea* (b/p)		
Rhinanthus minor (a)	*Scabiosa columbaria* (p)**		
Rumex acetosa (p)	*Scorzoneroides autumnalis* (p)**		
Sanguisorba minor (p)			
Silene dioica (p)			
Lychnis flos-cuculi (p)			
Trifolium pratense (p)			
Vicia cracca (p)			

Table 3.1. *Mix 1 and mix 2 flowering plant and grass composition. Species labelled * (mix 1 or ** (mix 2) did not flower in any site during the study. Letters refer to whether species are annual (a), biennial (b) or perennial (p).*

3.3.3. Year 1 materials and methodology

Participants received a project pack, including: 16 g wildflower seeds (according to group allocation), specimen jars (Medline 200ml Polypropylene Container, Rapid

Electronics, UK), pan traps, printed instructions, data collection workbook (Appendix E) and ID guides (Appendix F). Pan traps were spray painted by hand, and a set consisted of three 750ml takeaway-style plastic food containers (Go Packaging Products, UK), one white, one pink (Rust-Oleum spray paint Direct to Plastic White and Rust-Oleum Painters Touch Berry Pink Gloss, Rust-Oleum Corporation, US), and one blue (PlastiKote Pacific Blue Gloss: PlastiKote, Valspar, US).

In April, mix 1 and mix 2 group participants were instructed to sow their wildflower seeds at 4 g/m^2 to create a mini-meadow. Insect sampling using pan traps took place during the first week of the months May-August, over a dry and sunny 48-hour period. Mix 1 and mix 2 were instructed to place one set of pan traps side by side in the middle of the mini-meadow, and a second set in a designated area 10 metres away from the mini-meadow and not amongst garden flowers. Control group participants were instructed to place a single set of pan traps in their site, away from existing garden flowers. Pan traps were ¾ filled with water and a squeeze of lightly fragranced washing-up liquid ('Ecover' was recommended: Ecover, Malle, Belgium), and left undisturbed for 48 hours. Specimens were collected in labelled jars of clear distilled household vinegar.

Each month, all participants were instructed to complete the workbook, identifying diurnal insects collected to group: bumblebee, honeybee, solitary bee, wasp, hoverfly, butterfly, moth, other fly, other insects. Mix 1 and mix 2 groups listed the flowering species appearing in the mini-meadow. Participants in all groups were instructed to list and estimate other plants species flowering in the rest of their garden or allotment using the following scale: 1-10, 11-25, 26-100, 101-200, 201-1000, 1001-5000, 5000+ plants (Carvell et al 2007). Participants took photos each month of the mini-meadow and/or site.

3.3.4. Year 2 materials and methodology

Sampling commenced as in year 1, with some adaptations based on participant feedback designed to improve the insect sampling methods. Yellow sticky insect traps (Gardening Naturally, UK) were co-located with pan traps, attached to a bamboo cane elevated ½ metre *in situ* for 2 weeks, then labelled and covered in clingfilm. A fourth yellow pan trap (Rust-Oleum Painters Touch Sun Yellow Gloss: Rust-Oleum

Corporation, US) was also added to the set. A large asterisk was drawn in thick permanent black marker pen (Sharpie, Sanford L.P, US) on the inside of all pan traps to act as a ‘nectar guide’. Participants were explicitly asked to remove slugs, snails, butterflies and moths from samples as in year 1 these were found to partially dissolve in vinegar and made insect identification difficult.

3.3.5. Identification of samples

Insect sample pots, sticky traps and workbook recording sheets were returned via post, and photographs returned digitally. Pan trap and sticky trap insects were sorted by researchers in the laboratory to broad insect group, with all pan trap bees and hoverflies identified to species level. Hereafter, we refer to 'solitary bees' to include non-corbiculate bees that are solitary or eusocial, and those that do not fall under the bumblebee (*Bombus*) or honeybee (*Apis*) groups. ‘Wild bees’ refers to both solitary bees and bumblebees (i.e. all bees except honeybees).

3.3.6. Data analysis

Data analysis was conducted in R (R core team 2020). A Shapiro-Wilk normality test was conducted to test for parametric data. Generalised Linear Mixed Models (GLMMs) were built using *lme4* package, zero-inflated models were built using *glmmTMB* package. Pan trap data for year 1 and year 2 were analysed separately due to changes in sampling methods and participant drop-out in year 2. Models of best fit were chosen based on diagnostic residual plots and AIC values. ANOVAs were performed by comparing full and reduced models and reported as chi-square values. Tukey's Honest Significant Difference test was used to compare mix 1 and mix 2.

A Shannon Diversity Index of other garden flowers present in the rest of the site was calculated per site per month, using richness and abundance data (mid-point of flowering plant count scale) provided by participants. ‘Total insect abundance’ includes solitary bees, bumblebees, honeybees, hoverflies, social wasps, solitary wasps and ‘other’ flies. Analysis of ‘bee richness’ includes species of solitary bees, bumblebees and honeybee. Hoverfly richness could not be analysed, as too few hoverflies were sampled over the two years.

To test whether the creation of mini-meadows increases the abundance of beneficial

insects, ‘Total insect abundance’ was used as a response variable. The total insect abundance counts from pan traps set inside the mini-meadows (mix 1 and mix 2 data combined) was compared to counts from pan traps in control sites, irrespective of mix. Trap placement (inside mini-meadow *vs.* control), month and Shannon Diversity Index of other garden flowers were predictor variables. Site ID was allocated as a unique identifier and used as a random variable. GLMM with negative binomial family was fitted for year 2 pan trap data, whereas a GLMM with Poisson family was fitted for year 1 pan trap and year 2 yellow sticky trap data. To test the effects of the mini-meadow on the abundance of specific insect groups, these were considered separately (bumblebees, solitary bees, hoverflies and solitary wasps), as was bee species richness (all with GLMMs with zero-inflated negative binomial distribution).

Secondly, we wanted to test if the wildflower mixes affected the response variable ‘Total insect abundance’. A GLMM (Poisson) was used with treatment (mix 1, mix 2, control), month, and Shannon Diversity Index of other garden flowers as predictor variables, and site ID as a random variable. Insect group abundance was considered separately, as was bee species richness (GLMMs with zero-inflated negative binomial distribution).

To investigate how localised the effect of the mini-meadows were on pollinator abundance, ‘Total insect abundance’ was compared between pan traps placed directly within the mini-meadow, with those placed 10 metres away. Data from mix 1 and mix 2 were combined for this analysis. A GLMM (negative binomial) was modelled with trap placement (inside mini-meadow *vs.* 10 m away), month, and Shannon Diversity Index of other garden flowers were included as predictor variables, and site ID as a random variable. Again, insect group abundance was also analysed separately, as was bee species richness (GLMMs with zero-inflated negative binomial distribution).

Lastly, we used rarefaction analysis to explore the diversity of bee species of mix 1, mix 2 and control sites, allowing comparison of unequal sample sizes (Hsieh et al 2016). Rarefaction and extrapolation curves were created using three diversity orders of Hill numbers: species richness ($q = 0$), Shannon diversity ($q = 1$) and Simpson diversity ($q = 2$) with 95% confidence intervals, all computed in the iNEXT package (Hsieh et al 2016). Diversity measures differ significantly at $p \leq 0.05$ if the 95% confidence intervals (CI) do not overlap (Colwell et al 2012).

3.4. Results

3.4.1. Mini-meadow establishment

Sown wildflower species richness increased annually from year 1 to year 2, when considering all the floral data collected across the four sampling months and both mixes (Mean ± SE: 1 ± 0.11, to 2.43 ± 0.11 respectively) as was expected with the establishment and flowering of more biennial and perennial species in the second year. Mix 1 saw a greater annual increase in sown richness (number of sown flowering species) on average (Mean ± SE: 0.88 ± 0.14 to 2.71 ± 0.16 respectively) compared to mix 2 (Mean ± SE: 1.14 ± 0.17 to 2.04 ± 0.15 respectively). Mix 2 patches had a higher richness of unsown flowers (species not included in the seed mix) in both years of study, on average (Mean ± SE: year 1: 1 ± 0.19, year 2: 0.98 ± 0.26) compared to mix 1 (Mean ± SE: year 1: 0.31 ± 0.13, year 2: 0.44 ± 0.13). In mix 1, 24 (96%) of the wildflower species contained in the mix flowered during the study in at least one site, compared to 19 (68%) for mix 2 (Table 3.1). Seasonal changes are seen within both mixes, with flower richness peaking in July in year 2 for both mixes (Fig 3.1).

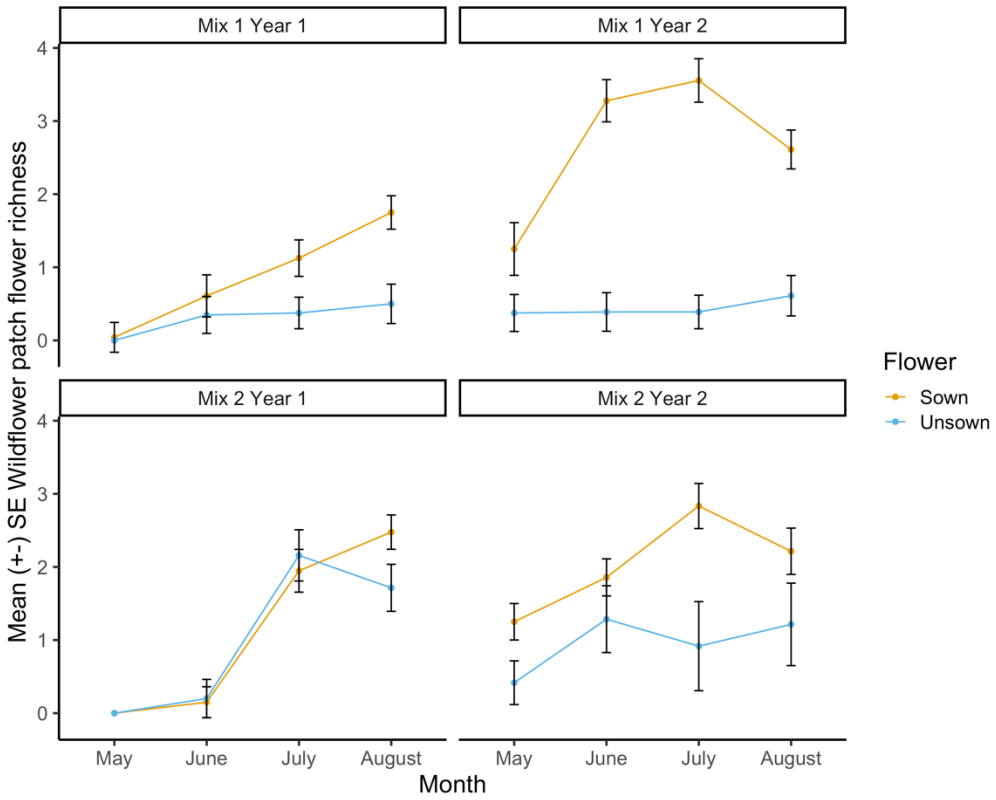

Figure 3.1. *Mean (± SE) Richness of sown and unsown wildflower in mix 1 and mix 2 in year 1 and year 2.*

3.4.2. Insect abundance in gardens and allotments

Over two years, a total of 454 bumblebees, 218 hoverflies, 877 solitary bees, 176 honeybees, 4,443 solitary wasps and 28,270 'other' flies were sampled. Sixty-six species of wild bee were identified to species level from pan trap samples, spanning 14 genera and including ten species of bumblebee. The most abundant wild bee species are listed in Table 3.2. Twenty-two species of hoverfly were identified over 16 genera: the most abundant *Helophilus pendulus*, accounted for 38% of hoverflies identified to species, followed by *Episyrphus balteatus* at 11%. (Full species list for bees and hoverflies available in Appendix G).

Wild Bee Species	Count
Bombus terrestris agg.	169
Lasioglossum leucopus	101
Lasioglossum smeathmanellum	79
Lasioglossum morio	74
Bombus pascuorum	56
Bombus pratorum	43
Bombus hortorum	33
Halictus tumulorum	31
Lasioglossum calceatum	26
Hylaeus hyalinatus	25
Lasioglossum albipes	24
Lasioglossum minutissimum	23
Bombus lapidarius	22
Osmia bicornis	22
Bombus hypnorum	20
Lasioglossum pauxillum	18
Andrena haemorrhoa	17
Lasioglossum cupromicans	13
Megachile centuncularis	12
Andrena bicolor	10
Anthidium manicatum	10

Table 3.2. *Most observed wild bee species in UK domestic gardens and allotments captured using pan traps, combining year 1 and 2 data.*

3.4.3. Citizen scientist participation

Out of the initial 150 participants, 68 (45%) returned samples in year 1. In year 2, 48 (32%) returned pan trap samples and 46 (31%) returned sticky trap samples (deployed in year 2 only). Participants that submitted data in both years of the study were evenly distributed across treatment groups (Table 3.3), meaning drop-out rates were likely not affected by the treatment group a participant was assigned to. The average size of the site was 236 m^2 in year 1 and 249 m^2 in year 2 (Table 3.3). The majority of sites were in urban locations (Table 3.3; based on Rural Urban Classification (DEFRA 2021)).

Treatment	Year 1 participants	Year 2 participants	Urban sites year 1/year 2	Site size (Avg.) year 1/ year 2
Mix 1	37% (N=25)	38% (N=18)	92 / 94%	217 / 238m^2
Mix 2	34% (N=23)	31% (N=15)	96 / 100%	263 / 276m^2
Control	29% (N=20)	31% (N=15)	85 / 87%	228 / 235m^2

Table 3.3. *Distribution of treatment group participants in year 1 and 2. Percentage of sites located in urban locations (versus rural) and average size of sites in each treatment for years 1 and 2.*

Of the participants returning samples, 43 (63%) participants submitted photographs of the mini-meadow and/or site in year 1, dropping to 23 (48%) in year 2 (Fig 3.2). However, photographs were non-standardised, and therefore abundance of individual flower species could not be discerned, especially smaller species. Photographs showed that in year 1, when present, *Centaurea cyanus* appeared to dominate the flower patches, followed by *Papaver rhoeas*, *Silene dioica* and *Leucanthemum vulgare*. In year 2, *Leucanthemum vulgare*, *Daucus carota*, *Ranunculus acris*, *Silene dioica*, the knapweeds (*Centaurea* spp.) and the dandelion-like flowers (e.g. hawkbits) dominated when present.

Figure 3.2. *Example of the mini-meadow photographs submitted by participants. Clockwise from top left: year 1 mix 1; year 1 mix 2; year 2 mix 2; year 2 mix 1 (photos courtesy of Amanda James, Anne Macarthur, name withheld and Judith Gray, respectively).*

3.4.4. Do mini-meadows increase the abundance of beneficial insects?

When the insect abundance data from mix 1 and 2 were combined and compared against the control (with no mini-meadow), there was no significant difference in total insect abundance (all solitary bees, bumblebees, honeybees, hoverflies, social wasps, solitary wasps and 'other' flies) in either year 1 or year 2 pan traps or year 2 sticky traps (Table 3.4). However, in year 2, when flowering plant species richness was highest, significantly more bumblebees were caught in pan traps, and significantly more solitary bees and solitary wasps were caught using sticky traps, in sites with a mini-meadow compared to sites without (Fig 3.3; Table 3.4). There was no significant difference in the abundance of hoverflies between sites with or without a mini-meadow for any year or sampling method used (Table 3.4). Bee richness did not differ between sites with a mini-meadow compared to control in year 1. In year 2 however, sites with a mini-meadow had significantly more bee species than control (Table 3.4).

We considered the difference between the mean observed counts of bumblebees,

solitary bees and solitary wasps, comparing those captured at sites with a mini-meadow compared to control, across all months and locations. In year 1, sites with a mini-meadow had 109% more bumblebees, 24% more solitary bees, and 126% more solitary wasps compared to sites without. In year 2 sites with a mini-meadow supported 111% more bumblebees, 87% more solitary bees and 85% more solitary wasps than control.

		(i) by treatment							(ii) by mini-meadow				
Abundance	**Method**	X^2	**df**	P =	**Sign.**	**Control**	**Mix 1**	**Mix 2**	X^2	**df**	P =	**Sign.**	**All mix**
Total insect	PT Y1	6.63	2	0.04	*	47.2 ± 0.72 **(ab)**	48.2 ± 0.64 **(b)**	29.4 ± 0.43 **(a)**	0.99	1	0.32	NS	39.2 ± 0.42
Solitary wasp	PT Y1	2.76	2	0.25	NS	2.52 ± 0.21	2.79 ± 0.21	1.96 ± 0.16	0.22	1	0.64	NS	2.39 ± 0.14
Solitary bee	PT Y1	9.89	2	0.01	*	0.71 ± 0.24 **(ab)**	1.59 ± 0.29 **(b)**	0.38 ± 0.16 **(a)**	0.60	1	0.44	NS	1.03 ± 0.2
Bumblebee	PT Y1	3.22	2	0.20	NS	0.25 ± 0.15	0.52 ± 0.14	0.44 ± 0.19	2.01	1	0.16	NS	0.48 ± 0.12
Hoverfly	PT Y1	4.00	2	0.14	NS	0.1 ± 0.13	0.24 ± 0.13	0.12 ± 0.14	1.30	1	0.25	NS	0.18 ± 0.09
Total insect	PT Y2	1.06	2	0.59	NS	31.4 ± 0.56	32.9 ± 0.49	30.6 ± 0.71	<0.01	1	0.95	NS	31.9 ± 0.41
Solitary wasp	PT Y2	4.91	2	0.09	NS	1.56 ± 0.22	2.58 ± 0.22	4.75 ± 0.63	3.13	1	0.08	NS	3.52 ± 0.34
Solitary bee	PT Y2	9.53	2	<0.01	**	0.83 ± 0.32 **(ab)**	1.61 ± 0.26 **(b)**	0.28 ± 0.14 **(a)**	1.77	1	0.18	NS	1.03 ± 0.2
Bumblebee	PT Y2	6.54	2	0.04	*	0.27 ± 0.21 **(b)**	0.58 ± 0.16 **(a)**	0.55 ± 0.27 **(ab)**	6.29	1	0.01	*	0.57 ± 0.15
Hoverfly	PT Y2	1.29	2	0.53	NS	0.24 ± 0.35	0.26 ± 0.17	0.27 ± 0.18	1.91	1	0.17	NS	0.26 ± 0.12
Total insect	YT Y2	3.72	2	0.16	NS	20.2 ± 0.4	22.9 ± 0.34	28.1 ± 0.48	1.38	1	0.24	NS	25 ± 0.29
Solitary wasp	YT Y2	8.44	2	0.02	*	6.32 ± 0.27 **(a)**	9.7 ± 0.28 **(ab)**	13.2 ± 0.61 **(b)**	7.12	1	<0.01	**	11.1 ± 0.31
Solitary bee	YT Y2	13.63	2	<0.01	**	0.23 ± 0.13 **(b)**	1.04 ± 0.16 **(a)**	0.89 ± 0.18 **(a)**	12.78	1	<0.001	***	0.98 ± 0.12
Bumblebee	YT Y2	2.21	2	0.33	NS	0.16 ± 0.17	0.37 ± 0.17	0.3 ± 0.18	2.21	1	0.14	NS	0.35 ± 0.13
Hoverfly	YT Y2	0.07	2	0.97	NS	0.46 ± 0.53	0.21 ± 0.17	0.24 ± 0.23	2e - 04	1	0.99	NS	0.22 ± 0.14
Richness (iii)													
Bee richness	PT Y1	12.37	2	<0.01	**	0.73 ± 0.15 **(a)**	1.34 ± 0.16 **(b)**	0.71 ± 0.18 **(a)**	1.31	1	0.25	NS	1.01 ± 0.12
Bee richness	PT Y2	12.38	2	<0.01	**	0.7 ± 0.2 **(a)**	1.54 ± 0.14 **(b)**	0.6 ± 0.16 **(a)**	4.07	1	0.04	*	1.19 ± 0.11

Table 3.4. *Insect abundance and bee richness of pan traps in year 1 (PT Y1) and year 2 (PT Y2) and yellow sticky traps year 2 (YT Y2). GLMM ANOVA results for effects of (i) Treatment (mix 1, mix 2 and control) on the abundance of all insects, solitary wasps, solitary bees and bumblebees, (ii) mini-meadow (all mixes) versus control and iii) effects of treatment on bee richness (solitary bees, bumblebees, honeybees). Presented with mean ± standard error, chi-square X^2, degrees freedom df, significance (NS, not significant; *, $p < 0.05$; **, $p < 0.01$; ***, $p < 0.001$) and Tukey's Honest Significant Difference test for comparisons where relevant (designated by letters in bold).*

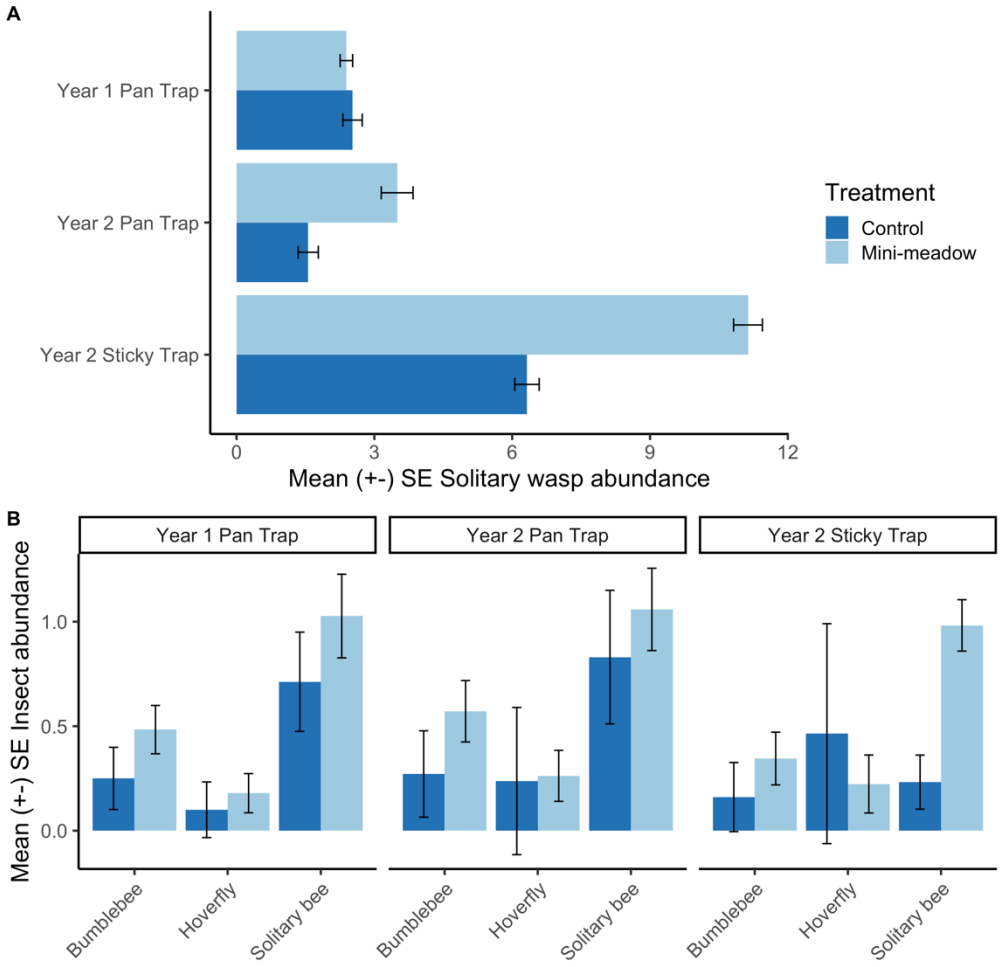

Figure 3.3. *Mean (± SE) abundance of (A) solitary wasps and (B) wild bees and hoverflies found in sites with a mini-meadow (mix 1 and 2 combined) and those without (control) in year 1 (pan traps only) and year 2 (pan traps and sticky traps).*

3.4.5. Do different mixes recruit different beneficial insect groups?

In year 1, in total there were significantly more insects caught in the mix 1 mini-meadows compared to mix 2 (Table 3.4). This is largely driven by the high number of flies caught in both mix 1 mini-meadows (mean ± SE: 43.2 ± 0.65) and control sites (43.3 ± 0.74), compared to mix 2 mini-meadows (28 ± 0.43). In year 2 there was no significant difference in overall insect abundance between the three treatments (mix 1, mix 2, control), for either pan trap or sticky trap caught insects. (Table 3.4).

In both year 1 and year 2, there were significantly more pan trap-captured solitary bees in mix 1 compared to mix 2. Furthermore, in year 2, sticky traps caught more solitary

bees in both mix 1 and mix 2, compared to control (Table 3.4; Fig 3.4). In year 2 pan traps, mix 1 caught significantly more bumblebees than control (Table 3.4; Fig 3.4). There was no difference in bumblebee abundance between the three treatments in year 1, or sticky traps in year 2.

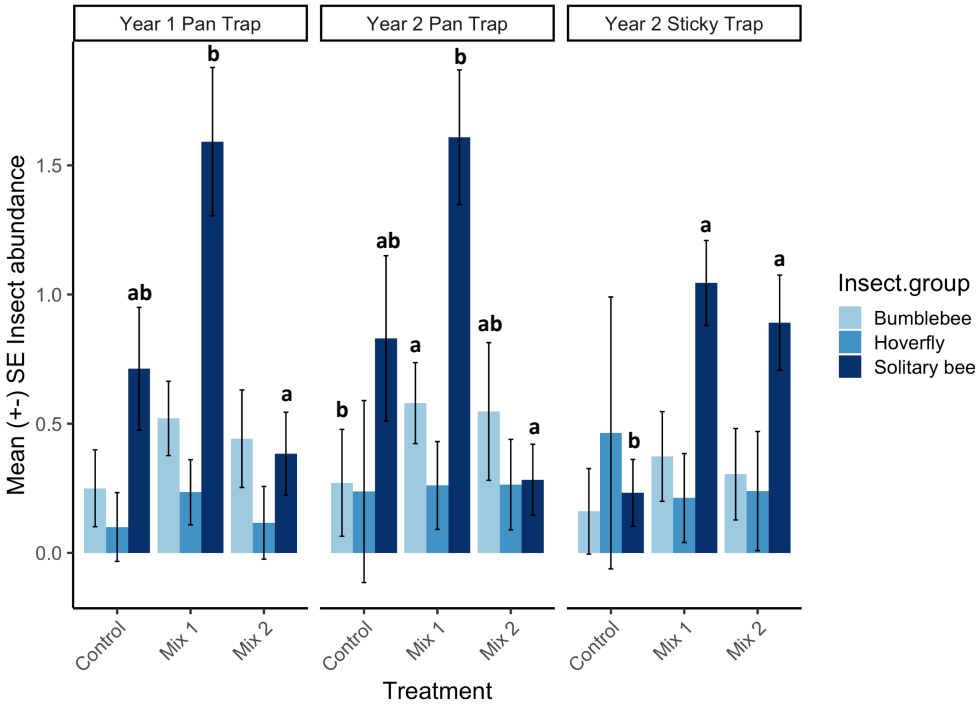

Figure 3.4. *Mean (± SE) abundance of bumblebees, solitary bees and hoverflies sampled in year 2 (pan traps and sticky traps) and year 1 (pan traps only) comparing mix 1, mix 2 and control. Letters indicate significant differences in abundances between treatments (Tukey's Honest Significant Difference).*

There was a significant difference between treatments in the abundance of solitary wasps caught using sticky traps, with post hoc tests indicating that there were significantly more solitary wasps captured in mix 2 mini-meadows than control (Table 3.4; Fig 3.5). There was no significant difference in the abundance of solitary wasps in pan traps between the different mixes in year 1 or year 2. There was no significant difference in the abundance of hoverflies for either year or sampling method.

In both year 1 and 2, mix 1 mini-meadows had significantly higher bee species richness than both mix 2 or control (Fig 3.6).

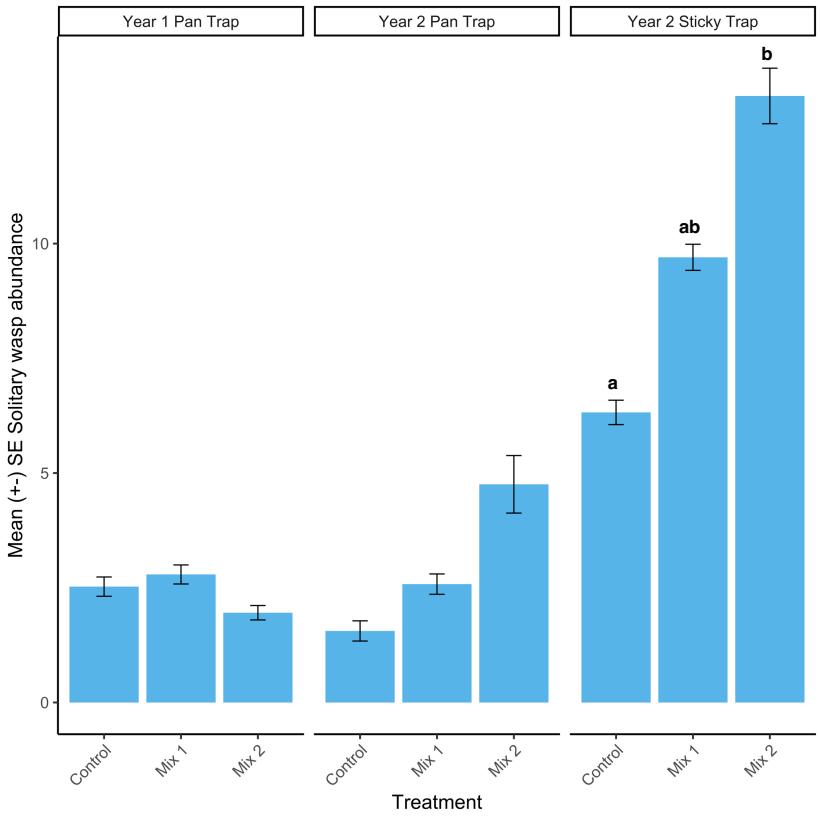

Figure 3.5. *Mean (±SE) abundance of solitary wasps sampled in year 2 (pan traps and sticky traps) and year 1 (pan traps only) comparing mix 1, mix 2 and control. Letters indicate significant differences in abundances between treatments (Tukey's Honest Significant Difference).*

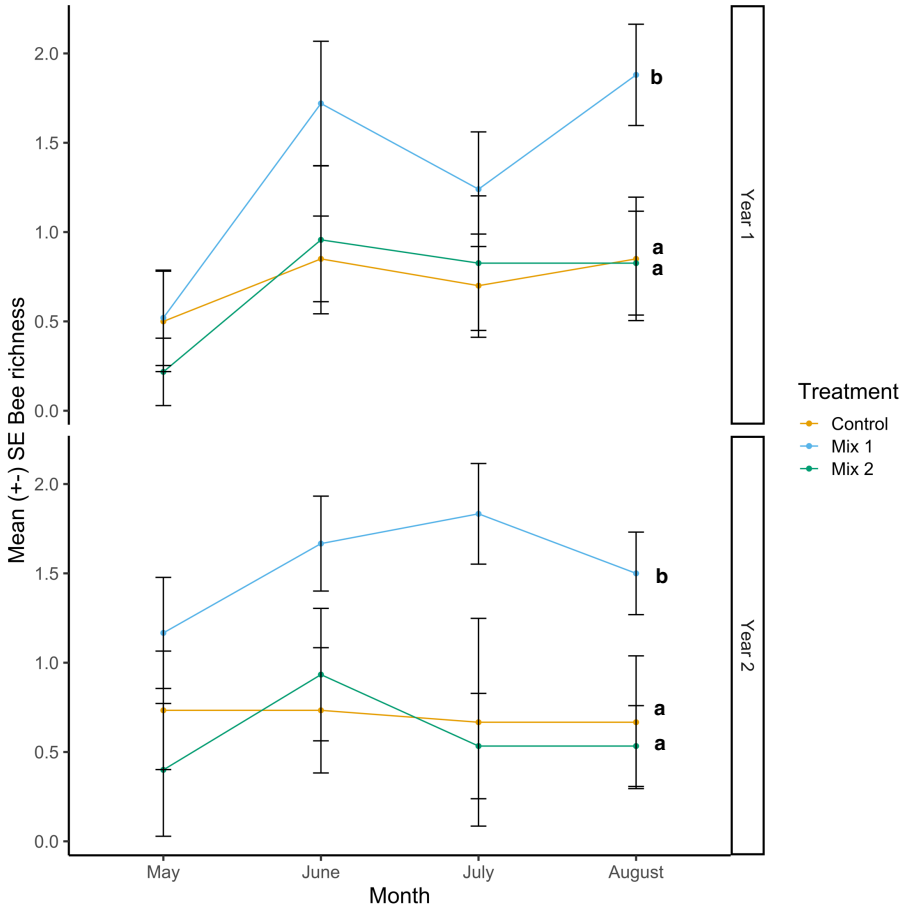

Figure 3.6. *Mean (±SE) bee species richness (bumblebees, solitary bees and honeybee data combined) in year 1 and 2, comparing mix 1, mix 2 and control. Letters indicate significant differences in richness between treatments (Tukey's Honest Significant Difference).*

In year 1, rarefaction analysis across the three diversity measures (species richness, Shannon diversity, Simpson diversity) showed little difference in the bee species composition of the sites according to treatment, with 95% CI overlapping (Fig 3.7A). In year 2, however, rarefaction analysis across the three diversity measures indicated bee species diversity differed according to treatment (Fig 3.7B), with the highest dissimilarity (and species turnover) in species composition in mix 1 sites. Considering Shannon diversity and Simpson diversity (middle and right panel, Fig 3.7B), the species diversity composition of mix 1 differed significantly from both mix 2 and control sites, as the 95% CI are not overlapping.

Analysis was conducted on the effects of the diversity of garden flowers on the abundance of insects and richness of bees (Appendix H). Only bumblebee abundance in

year 2 with sticky traps was predicted by garden flower diversity. Since this is not a primary focus of our study we do not discuss this further.

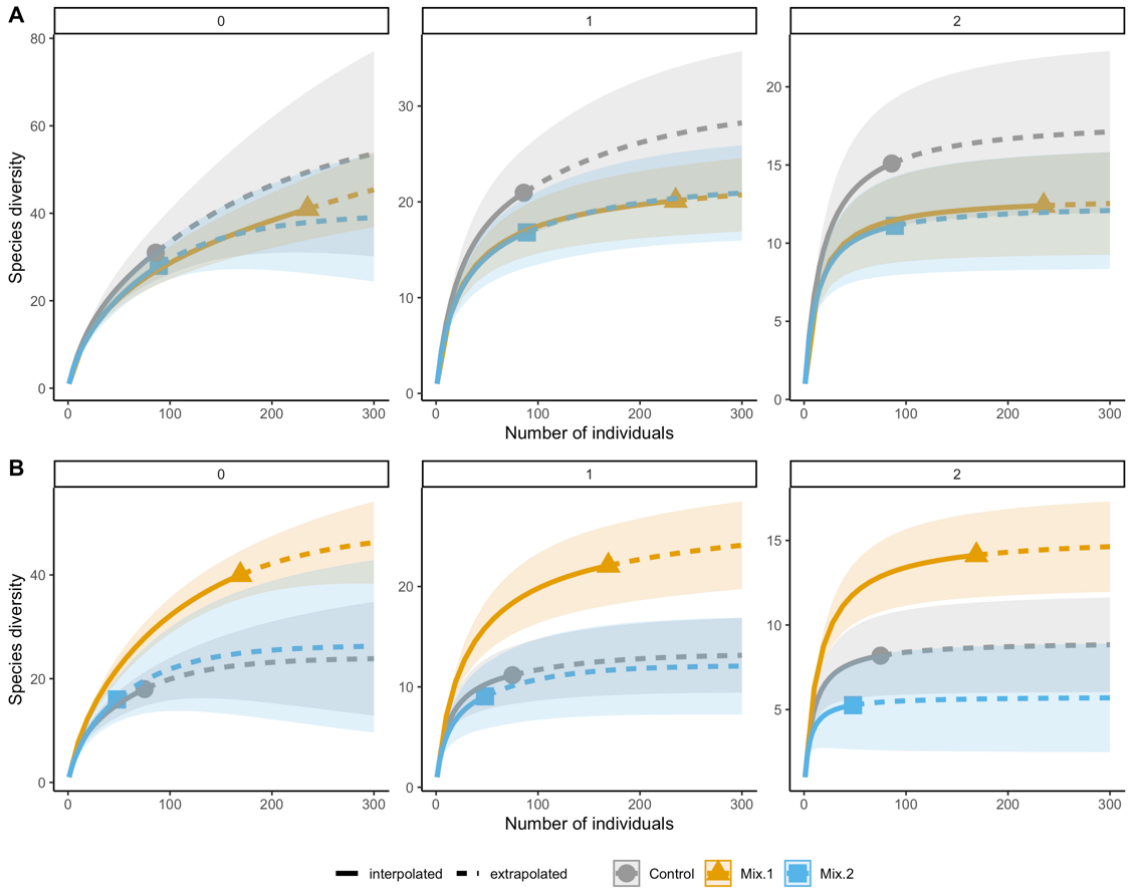

Figure 3.7. *(A) Year 1 and (B) year 2 rarefaction curves, showing the expected number of bee species as a function of sampling effort (number of individuals) in the three treatments (mix 1, mix 2, control). Separated by diversity order: q = 0 (species richness, left panel), q = 1 (Shannon diversity, middle panel) and q = 2 (Simpson diversity, right panel). Solid lines show empirical (interpolated) results, dashed lines show extrapolation. Shaded areas show 95% confidence intervals.*

3.4.6. How localised is the impact of the mini-meadow?

Abundance and diversity of insects were compared within sites between samples collected from pan traps and sticky traps placed directly inside the mini-meadows (combined data from mix 1 and 2) and samples collected from pan and sticky traps that were placed 10 metres away from the meadow. There was no significant difference in the total abundance of insects caught inside the meadows compared to 10 m away for

any year or sampling method (Table 3.5).

However, when comparing the abundance of specific insect groups, in pan trap samples from year 2, there were significantly more solitary bees and solitary wasps inside the meadows compared to 10 m away, although this pattern wasn't detected in year 2 sticky traps. Solitary wasp abundance was also significantly higher inside meadows in year 1 pan trap captures. There was no significant difference in bumblebee or hoverfly abundance inside meadows compared to 10 m away (Table 3.5). Bee species richness also did not differ inside or 10 m away from the meadow in either year (Table 3.5).

Abundance	**Method**	X^2	**df**	P =	**Sign.**	**Mini-meadow**	**10 m away**
Total insect	PT Y1	0.05	1	0.83	NS	39.2 ± 0.42	39.3 ± 0.43
Solitary wasp	PT Y1	5.15	1	0.02	*	2.39 ± 0.14	1.94 ± 0.14
Solitary bee	PT Y1	0.14	1	0.71	NS	1.03 ± 0.2	0.81 ± 0.12
Bumblebee	PT Y1	0.22	1	0.64	NS	0.48 ± 0.12	0.54 ± 0.14
Hoverfly	PT Y1	1.4	1	0.24	NS	0.18 ± 0.09	0.15 ± 0.12
Total insect	PT Y2	0.002	1	0.97	NS	31.9 ± 0.41	31 ± 0.39
Solitary wasp	PT Y2	4.29	1	0.04	*	3.52 ± 0.34	2.44 ± 0.21
Solitary bee	PT Y2	5.78	1	0.02	*	1.03 ± 0.2	0.65 ± 0.14
Bumblebee	PT Y2	0.54	1	0.46	NS	0.57 ± 0.14	0.48 ± 0.14
Hoverfly	PT Y2	2.52	1	0.11	NS	0.26 ± 0.12	0.12 ± 0.1
Total insect	YT Y2	2.38	1	0.12	NS	25 ± 0.29	22.3 ± 0.26
Solitary wasp	YT Y2	1.98	1	0.16	NS	11.1 ± 0.31	8.89 ± 0.19
Solitary bee	YT Y2	0.37	1	0.54	NS	0.98 ± 0.12	0.95 ± 0.2
Bumblebee	YT Y2	0.25	1	0.62	NS	0.35 ± 0.13	0.5 ± 0.17
Hoverfly	YT Y2	0.09	1	0.77	NS	0.22 ± 0.14	0.35 ± 0.24
Richness							
Bee richness	PT Y1	0.01	1	0.99	NS	1.01 ± 0.12	0.94 ± 0.11
Bee richness	PT Y2	3.29	1	0.07	NS	1.19 ± 0.11	0.89 ± 0.11

Table 3.5. *Insect abundance and bee richness in pan traps in year 1 (PT Y1) and year 2 (PT Y2) and yellow sticky traps year 2 (YT Y2). GLMM ANOVA results for comparisons within the mini-meadows (mix 1 and 2 combined) and 10 metres away for abundance of all insects, solitary wasps, solitary bees and bumblebees, and also bee richness (solitary bees, bumblebees, honeybee). Presented with mean ± standard error, chi-square* X^2*, degrees freedom df, significance (NS, not significant; *, p < 0.05; **, p < 0.01; ***, p < 0.001)*

3.5. Discussion

We have demonstrated that sown mini-meadows in domestic gardens and allotments can provide resource-rich habitats for pollinators and solitary wasps, increasing both abundance and richness of wild bee species compared to gardens and allotments without mini-meadows. Although this study was conducted in the UK, the methodology can be easily replicated in any urban landscape. Significant patterns of abundance of insect groups and bee richness differed between years and sampling methods. This was predominantly due to wildflowers becoming more established in year 2, and sampling methods differing in their sensitivity of detecting different insect groups. For example, yellow sticky traps were more sensitive to solitary wasp abundance. To obtain more information on wild bee species populations, a combination of sampling techniques are recommended (Templ et al 2019).

Our results correspond with previous research that found that planting flowers in gardens increases bee richness (Pawelek et al 2009; Salisbury et al 2015). Though Matteson and Langellotto (2011) concluded that floral additions in New York community gardens do not increase pollinator richness, our sites were notably smaller on average (year 1 236 m^2/year 2 249 m^2, compared to 909 m^2), and as the authors suggest, additional floral resources placed in a location with a higher baseline abundance of flowers might see negligible impact on pollinator increases. Therefore, there is potentially a 'saturation point', only up to which any floral additions will benefit pollinator numbers (Simao et al 2018). While garden size can be regarded as a barrier to wildlife gardening (Goddard et al 2013) we have found that planting a mini-meadow of just 4 m^2 can enhance resources for beneficial insects, with only a small loss of garden space. In fact, more numerous and smaller mini-meadows throughout landscapes may be more beneficial for the recruitment of bees than larger meadows because of such 'saturation' effects (Simao et al 2018).

Our study also recorded the quick recruitment of beneficial insects. Sites with mini-meadows supported 109% more bumblebees, 24% more solitary bees, 126% more solitary wasps in year 1, and 111% more bumblebees, 87% more solitary bees and 85% more solitary wasps in year 2 when compared to control sites. Sown wildflowers are known to be utilised by bees relatively quickly, with a previous study stating a quarter

of species known from the Munich region were recruited to wildflower strips within one year of sowing (Hofmann and Renner 2020).

Our mini-meadows also supported less well-studied beneficial insects. Non-syrphid flies were the most abundant insect group sampled and are increasingly being recognised as key pollinators of food crops (Orford 2015). Though previous studies have found that wildflower patches in urban grasslands increase the abundance of hoverflies (Blackmore and Goulson 2014), surprisingly there was no difference in the hoverfly abundance recorded between sites with and without mini-meadow. The number of hoverflies collected over the entire study was lower than anticipated at a total of 218 insects, so the sampling technique and small sample size may instead be responsible for this result, and also meant that effects on hoverfly species richness could not be investigated further in this study.

Solitary wasps are a hugely diverse and difficult group of insects to identify, so it was outside the scope of this study to identify this group to species level. However, parasitoid wasps were seemingly numerous in the pan traps (pers. obs.) and identification to species would be an interesting next step. Floral additions provide essential resources to the natural enemies of pest insects as a natural biological control (Araj and Wratten 2015) and sown wildflowers strips are beneficial to ecosystem services by promoting parasitoid wasps in agricultural landscapes (Hoffmann et al 2018). Here we show that solitary wasps can also be promoted in domestic gardens and allotments by providing additional floral resources, similar to Bennett and Gratton (2012) who found a positive relationship between parasitoid abundance and floral diversity.

The composition of flowers in the mini-meadows led to recruitment of different taxa. In years 1 and 2, mix 1 consistently attracted significantly more individual solitary bees and more species. In year 2, when the wildflowers were more diverse and established, mix 1 also attracted significantly more bumblebees, whereas mix 2 attracted more solitary wasps. Wildflower mixes in agricultural landscapes can be taxon-specific in their attractiveness depending on key plant species in the mix (Warzecha et al 2018) and we have shown this can also be achieved in domestic gardens and allotments. Identification of such mixes can facilitate conservation efforts (Warzecha et al 2018).

Certain localised effects on insect abundance were observed in the mini-meadow compared to samples collected 10 metres away; both solitary wasps and solitary bees were more abundant inside the meadow. Insects from both these groups tend to be smaller in size leading to a more limited foraging range compared to highly-mobile bumblebees which have a foraging range of 1.5 km or more (Osborne et al 2008). The higher abundance of solitary bees and wasps may also indicate that the wildflowers provide refuge in addition to pollen and nectar. Richness of wild bee species was greater in the gardens which had a mini-meadow compared to those without. This was observed over both years of study and with no localised effects, suggesting the planting of a mini-meadow will increase the overall diversity of wild bees in gardens and allotments through a positive 'spillover' effect.

Flowers of mix 1 established more successfully, and seasonal flowers appeared over the course of the year, providing a range of different flowering plants for wild bees. Participants did not observe insects directly on flowers, but as the abundance and richness of solitary bees are consistently higher for mix 1, we expect key species for solitary bees to be present in this mix. Warzecha et al (2018) identified four plant species that provided resources to 81% of recorded pollinators. Likewise, Nichols et al (2019) found that 14 flower species accounted for 99.7% of bee visitations. Using direct observation to record such plant-pollinator interactions would be the next step for this study. It would be interesting to determine which sown/unsown species was responsible for the increase in solitary wasp abundance detected in mix 2, considering the high number of unsown flowers that appeared. Indeed, flowers considered 'weeds' can contribute valuable foraging resources; dandelions (*Taraxacum* agg.) produce high quantities of pollen and nectar (Hicks et al 2016) and enhance biocontrol efficacy by increasing parasitoid longevity and egg load (Araj and Wratten 2015). Studies on biocontrol of pests by enhancing floral resources to enhance natural enemies have often focused on providing just one or a small number of flowering plants; it would be worth investigating a larger range, and the benefits of providing a more diverse flower community (Fiedler et al 2008).

In this study, citizen scientists made an invaluable contribution, planting and managing wildflowers and completing sampling techniques. However, drop-outs year-on-year may have been non-random. Participants with poorly established wildflowers, or those

that caught fewer insects may have left the project, leaving more pollinator-friendly gardens continuing into year 2. This could potentially bias the increases of insect abundance in year 2 when compared to control gardens.

Horticultural and conservation organisations advise the public on the potential of their gardens to encourage biodiversity, but also of importance is planning policy for new urban developments. A modelling approach by Baldock et al (2019) found that increasing the area of allotments in cities, and increasing floral abundance in urban green spaces is beneficial for plant-pollinator interactions and should be considered in urban planning. We support the notion that gardens and allotments could effectively be included in conservation planning, considering domestic gardens as interconnected habitats and not individual units (Hofmann and Renner 2020). Attracting diverse beneficial insects to gardens and allotments through floral additions has multiple benefits, in addition to enhancing biodiversity. Diverse bee communities enhance urban fruit and vegetable production (Lowenstein et al 2015) can benefit ecosystem services such as natural pest control and soil protection (Wratten et al 2012) and enriching a garden has positive impacts on human wellbeing (Fuller et al 2007).

CHAPTER 4

4. Sow Wild! Effective methods and identification bias in pollinator-focused experimental citizen science

This paper is currently in peer review:

Griffiths-Lee, J., Nicholls, E., & Goulson, D. Sow Wild! Effective methods and identification bias in pollinator-focused experimental citizen science.

JGL and DG conceived the ideas and methodology; JGL collected and analysed the data, and led the writing of the manuscript. All authors commented on draft versions of the manuscript.

4.1. Abstract

A common debate on the value of citizen science projects is the accuracy of data collected and the validity of conclusions drawn. Sow Wild! was a hypothesis-driven citizen science project which investigated the benefits of sowing a 4 m^2 mini-meadow in private gardens and allotments to attract beneficial insects. The use of researcher-verified specimen-based collection methods (pan traps, yellow sticky traps) and observational methods (insect watches) allowed investigation of potential bias in identification skills and sampling methods conducted by citizen scientists. For bumblebees and honeybees, identification of pan trap insect specimens was similar between researchers and citizen scientists, but solitary bees were often misidentified as social wasps or hoverflies. Key results of the Sow Wild! project differed between specimen-based and observation-only data sets, probably due to unconscious bias, such that incorrect conclusions would have been drawn if we had relied solely on observations made by citizen scientists. Comparing the efficiency of sampling methods, insect watches produced the most insect observations overall, but solitary bees were under-recorded. Yellow sticky traps collected more solitary wasps, social wasps, hoverflies and honeybees than pan traps. There was also variation in the abundance of insects caught according to the four pan trap colours. While all of these sampling methods can be successfully incorporated into citizen science projects to monitor a range of flying insects in urban landscapes, we recommend that verification of data by taxonomic experts is a vital component of hypothesis-led citizen science projects, and increased training is required if target taxa include less conspicuous insect groups.

4.2. Introduction

Animal pollination directly affects the quality and yield of 75% of the world's leading food crops (Klein et al 2007) and 87.5% of flowering plants benefit from pollination by animals (Ollerton et al 2011). As pollinators provide an essential ecosystem service, monitoring their status and trends on a local and global level is of economic and cultural importance and necessary for effective conservation policy. Through monitoring, recent global pollinator assessments have recorded large-scale declines in Europe and North America (IPBES 2016).

Citizen science is defined as "scientific work undertaken by members of the general

public, often in collaboration with or under the direction of professional scientists and scientific institutions" (OED 2014). A network of volunteer participants of variable backgrounds and experience are engaged to gather and contribute to large data sets on broad temporal or spatial scales, using methodology developed by (or alongside) trained experts and researchers. Citizen science contributes knowledge towards indicators in the UN Sustainable Development Goals, and with increased partnerships and investment has the potential to contribute toward many more indicators on nature and the environment (Fraisl et al 2020). Citizen science projects most commonly fall in the areas of conservation, ecology and biology (Kullenberg and Kasperowski 2016) and ecological projects cover a broad range of taxa from a local to global level (Dickinson et al 2012). Such data collected by citizen scientists form the basis of many successful international monitoring schemes. For example, multi-taxa recordings through iNaturalist (inaturalist.org) and global bird sightings through eBird (The Cornell Lab of Ornithology, ebird.org) have collected data that has contributed to conservation action. Currently, bias exists in the geographic location and taxonomic groups, with many citizen science programmes based in North America and Europe, and with a general focus on animals (Chandler et al 2017), reflecting similar biases with conventional scientific projects (Theobald et al 2015).

Citizen science has proved valuable in monitoring wild bee populations and determining the effectiveness of interventions to conserve pollinators. Such projects have contributed knowledge on pollination services ('Bees 'n Beans': Birkin and Goulson 2015), management practices ('Squash Bee Survey': Appenfeller et al 2020), abundance in urban landscapes ('Native Bee Watch': Mason and Arathi 2019), effects of urban wildflower patches ('Sow Wild!': Griffiths-Lee et al 2022), nesting ecology ('The solitary bee project': Maher et al 2019: 'BeeWatch', Lye et al 2012) and pollinator populations (UK Pollinator Monitoring Scheme: ukpoms.org.uk). Citizen scientists are also collecting valuable data on other flying foraging insects, such as social wasps (bigwaspsurvey.org) and hoverflies (hoverflylagoons.co.uk).

There are many benefits of utilising citizen science in ecological monitoring, including the potential increased spatial and temporal scale of data collection and the possibility of accessing private locations to conduct sampling (Bonney et al 2009). Engagement in a citizen science project not only provides benefits for the experts collecting the data.

Such projects can facilitate behavioural changes in conservation and environmental issues and create educational opportunities (Bonney et al 2016; Merenlender et al 2016). The desire to learn about pollinators and contribute to science drives participation in pollinator-focused projects (Domroese and Johnson 2016) and this active engagement can create an emotional connection and lifelong commitment to nature (Schuttler et al 2018).

Perceived limitations of data collected by citizen scientists typically focus on accuracy and inconsistencies in data collected by non-experts (Aceves-Bueno et al 2017; Burgess et al 2017; Gardiner et al 2012; Law et al 2017). For example, smaller and less conspicuous bees may be misclassified or go unnoticed, with bias toward species or groups that can be identified (Kremen et al 2011; Maher et al 2019). Even the identification of more conspicuous, larger taxa such as bumblebees can be prone to errors at the species level (Austen et al 2016; Falk et al 2019; Roy et al 2016). However, several insect-based studies comparing observations of citizen scientists to experts have found the results to be similar (Dennis et al 2017; Griffiths-Lee et al 2020; Kremen et al 2011; Maher et al 2019; Mason and Arathi 2019). Effective training of citizen scientists is important for data accuracy (Kremen et al 2011; Roy et al 2016) and success may depend on methods and taxa collected. Unverified data records submitted by citizen scientists risk incorrect conclusions (Falk et al 2019), and biases and potential errors are poorly understood, it has been argued that citizen science data should be seen as complementary to researcher-led data, rather than an alternative (Dickinson et al 2010).

There are a variety of sampling methods available to monitor insect groups, each with its advantages, limitations, and potential bias towards certain taxa (McCravy 2018). Pan traps (or Moericke traps) are bowls of soapy water, painted in different colours to attract a range of foraging insects. They are considered the “most efficient, unbiased, and cost-effective method for sampling bee diversity” (Westphal et al 2008). Although smaller species of bees are more commonly captured by pan traps, they do typically capture a broad range of genera (Droege et al 2010). Different colour pan traps are considered attractive to different bee taxa (Geroff et al 2014; Leong and Thorp 1999) and a recent meta-analysis found that yellow pan traps most efficiently sampled smaller solitary bees, while blue was best for bumblebees (Hutchinson et al 2021b). Pan traps are also effective at monitoring aculeate and parasitoid wasps (Bakowski et al 2013; Heneberg

and Bogusch 2014). A set of different coloured traps is better for overall monitoring of bees to capture common and uncommon species (Buffington et al 2020; Toler et al 2005) and the addition of 'nectar guides' increases the number of specimens collected (Wilson et al 2016). Yellow sticky traps are elevated, bright yellow, flat traps covered in non-drying sticky glue, often with a black grid to aid insect counts. Yellow sticky traps have been effectively used to sample parasitoid wasps (Hall et al 2019; Griffiths-Lee et al 2022; Wallis and Shaw 2008) and hoverflies (Burgio and Sommaggio 2007).

Larger insects such as bumblebees are most effectively monitored by visual identification on transect walks (Hutchinson et al 2021b). Visual observation and counts of pollinating insects can be successfully conducted in citizen science projects, such as 'Polli:Nation' (Cruickshanks et al 2018) and the UK Pollinator Monitoring Scheme. However, visual identification of insects by untrained professionals can be prone to errors, although this is mostly documented when trying to identify them to a finer taxonomic level (Kremen et al 2011; Maher et al 2019).

Multiple sampling methods are recommended for a more complete data set, which is particularly important when studying species richness (McCravy 2018). As pan traps and yellow sticky traps can be set and collected without entomological training, and as a timed insect watch is an enjoyable and accessible approach to obtaining abundance information, these sampling methods were deemed suitable for use in the Sow Wild! project. Sow Wild! was a hypothesis-driven citizen science project which investigated the effectiveness of creating a wildflower mini-meadow in attracting beneficial insects in private gardens and allotments (Griffiths-Lee et al 2022). Citizen scientists sowed and maintained the mini-meadow, and then successfully collected data over two years. Using these data we aimed to determine: 1) the accuracy of identification of insect samples by citizen scientists; 2) if non-destructive observation-only sampling techniques were consistent with the data collected with specimen-based methods; 3) which sampling methods were more or less effective at collecting data on specific taxa, and suitable for citizen science projects.

4.3. Methods

4.3.1. Citizen scientist recruitment and retention

Sow Wild! project volunteer recruitment took place in December 2015, through 'The Buzz Club' (a citizen science charity based at the University of Sussex https://www.thebuzzclub.uk/) and social media. At least three allotment societies in every UK county were also sent an invitation along with a poster and QR code linking to the project page. Expression of interest was via an online survey (surveymonkey.com) with a closing date of February 2016. This survey covered the basic requirements of the project: having a garden or allotment (thereafter 'site') of at least 20 m^2, space of 4 m^2 to establish a wildflower patch, and a willingness to partake in destructive insect sampling methods and long-term availability to complete the project. All volunteers meeting the basic requirements were invited to complete the second online survey which asked for more detailed information on the management and details of their site. One hundred and fifty participants were randomly split into three groups: two groups that would create mini-meadows (using wildflower seed mixes, mix 1 or mix 2) and one group allocated control, with no mini-meadow.

A private Facebook group was created for participants to communicate with each other. Participants were regularly contacted via email with project updates, reminders, FAQs and an identification quiz. Guidance on seasonal and long-term management of the wildflowers was provided. Questions and comments via email and Facebook were encouraged and responded to within 24 hours. Participants were sent paper and electronic copies of the wildflowers mix flower guides, and insect guides (aiding identification to broad insect group) (Appendix F). At the end of the project, participants were sent a species list of the bees and hoverflies found in their sites, and a copy of the published paper (Griffiths-Lee et al 2022).

4.3.2. Methodology

Sow Wild! experiments were conducted in 2016 (year 1) and 2017 (year 2). Those groups that received wildflower seeds sowed their 4 m^2 mini-meadows in April 2016. In this paper, we focus on the data collected in year 2 of the project (May to August 2017) as this was the year the full suite of sampling methods was conducted (pan traps, yellow sticky traps, insect watches), and the mini-meadows were fully established.

Pan traps were spray painted by hand, and a set consisted of four 750ml takeaway-style plastic food containers (Go Packaging Products, UK), one white, pink, yellow (Rust-

Oleum spray paint Direct to Plastic White; Rust-Oleum Painters Touch Berry Pink Gloss; Rust-Oleum Painters Touch Sun Yellow Gloss. Rust-Oleum Corporation, US), and one blue (PlastiKote Pacific Blue Gloss: PlastiKote, Valspar, US). A large asterisk was drawn in thick permanent black marker pen (Sharpie, Sanford L.P, US) on the inside of all pan traps to act as a 'nectar guide'.

Pan trapping took place during the first week of each month from May to August, over a dry and sunny 24-hour period. Those participants with sown mini-meadows were instructed to place one set of pan traps side-by-side and elevated to flower height in the middle of the mini-meadow, and a second set in a designated area 10 metres away from the mini-meadow and not amongst garden flowers. Control group participants were instructed to place a single set of pan traps on their site, not amongst any existing garden flowers. Pan traps were ¾ filled with water and a squeeze of lightly fragranced washing-up liquid ('Ecover' was recommended: Ecover, Malle, Belgium), and left undisturbed for 24 hours. Specimens were collected in labelled jars of clear distilled household vinegar. Each month, all participants were instructed to complete the workbook, identifying insects collected in the pan traps to one of the following groups: bumblebee, honeybee, solitary bee, social wasp, hoverfly, butterfly, moth, other fly, other insect. Participants were explicitly asked to remove slugs, snails, butterflies and moths from samples as these were found to partially dissolve in vinegar which made insect identification difficult. Participants were not asked to count solitary wasps as this was deemed too difficult.

Yellow sticky insect traps (sized 7 cm x 3 cm) (Gardening Naturally, UK) were co-located with pan traps (amongst mini-meadows and 10m away, or control) and attached to a bamboo cane elevated ½ metre *in situ* for 2 weeks, then labelled and covered in clingfilm.

Volunteers were also asked to conduct an observational insect watch in real-time on a clear sunny day at the beginning of each month May to August, between the times of 10:00-16:00. For those participants with a mini-meadow, the insect watch was conducted by recording any insects spotted to broad insect group (as above) in the 4 m^2 mini-meadow for 10 minutes, then repeating this in a 4 m^2 area 10 metres away from the wildflower patch. The control group conducted their insect watch in a 4 m^2 area where the pan traps are usually set.

Those participants with sown mini-meadows listed the flowering species appearing in the mini-meadow each month and all groups were instructed to list and estimate the abundance of other plant species flowering in the rest of their site using a supplied scale. Participants took photos each month of the mini-meadow and/or site. At the end of summer, volunteers returned the pan trap samples, yellow sticky traps and workbook recording sheets via the post. Photographs of the site and wildflower patch were returned digitally.

Once returned to the university, pan trap insects were sorted and recorded to broad insect group (bumblebee, honeybee, solitary bee, solitary wasp, social wasp, hoverfly, other fly, other insects), with all bees and hoverflies pinned and identified to species level. Insects attached to the yellow sticky trap were counted to broad insect group, as identification to species level was not possible. In this paper, we refer to 'solitary bees' which include non-corbiculate bees that are solitary or eusocial, and those that do not fall under the bumblebee (*Bombus*) or honeybee (*Apis*) groups.

4.3.3. Data analysis

All data analysis was conducted in R (R core team 2020). A Shapiro-Wilk normality test was conducted to test for parametric data. Generalised Linear Mixed Models (GLMMs) were built using *lme4* package, zero-inflated models were built using *glmmTMB* package, graphs were created using *ggplot2*. Models of best fit were chosen based on diagnostic residual plots and AIC values. ANOVAs were performed by comparing full and reduced models and reported as chi-square and p values. Where appropriate, Tukey's Honest Significant Difference test was performed post-hoc to determine where significance lay.

To test how accurate the citizen scientists were at identifying insect groups from the pan traps (bumblebee, honeybee, hoverfly, solitary bee, social wasp) we compared citizen scientist counts to researcher counts at site level. Chi-square goodness of fit test was conducted to compare if the citizen scientists tended to overestimate or underestimate counts of insects (by group) in the pan traps.

To test the effect of capture method (yellow pan trap, pink pan trap, blue pan trap, white pan trap, yellow sticky trap, insect watch) on the abundance of the broad insect group

(bumblebee, honeybee, hoverfly, solitary bee, solitary wasp, social wasp) we used a zero-inflated GLMM with negative binomial family. Method of capture and participant group allocation (wildflower mix 1, mix 2 or control) were used as explanatory variables, and site number as a random variable. We also tested the colour of pan trap and its effects on bee species richness using a zero-inflated GLMM with negative binomial family, with pan trap colour and participant group allocation as explanatory variables, and site number as a random variable.

4.4. Results

4.4.1. Insect collection

Using pan trap and yellow sticky trap data collected by researchers, and insect watch data collected by citizen scientists, the study recorded 647 bumblebees (402 insect watch; 143 pan trap; 102 yellow sticky traps), 302 honeybees (164 insect watch; 79 pan trap; 59 yellow sticky traps), 395 hoverflies (245 insect watch; 61 pan trap; 89 yellow sticky trap), 616 solitary bees (134 insect watch; 254 pan trap; 228 yellow sticky trap), 231 social wasps (46 insect watch; 16 pan trap; 169 yellow sticky trap) and 3,410 solitary wasps (820 pan trap; 2,590 yellow sticky trap).

4.4.2. Citizen scientist participation

Of the initial 150 participants, 48 (32%) returned pan trap samples, 46 (31%) returned yellow sticky trap samples, 34 (23%) participated in the insect watch at least once and 23 (15%) returned photos of their plots or sites. According to group allocation, the percentage of participants in mix 1, mix 2 and control was 38%, 31% and 31%, respectively.

4.4.3. Insect identification by citizen scientists

Results of pan trap sample identification data collected by citizen scientist participants and professional researchers were compared, to determine whether citizen scientists tended to overestimate or underestimate the abundance of certain insect groups. Counts of bumblebee and honeybees were comparable ($X^2 = 0.47$, $P = 0.49$ and $X^2 = 0.05$, $P = 0.82$ respectively, Fig 4.1). However, numbers of solitary bees were underestimated ($X^2 = 6.26$, $P = 0.01$, Fig 4.1) and social wasps were overestimated by citizen scientists (X^2

= 19.17, $P = 0.00001$, Fig 4.1). Hoverfly counts did not significantly differ between citizen scientists and researchers, although counts of hoverflies were notably higher for citizen scientists ($X^2 = 1.09$, $P = 0.3$, Fig 4.1).

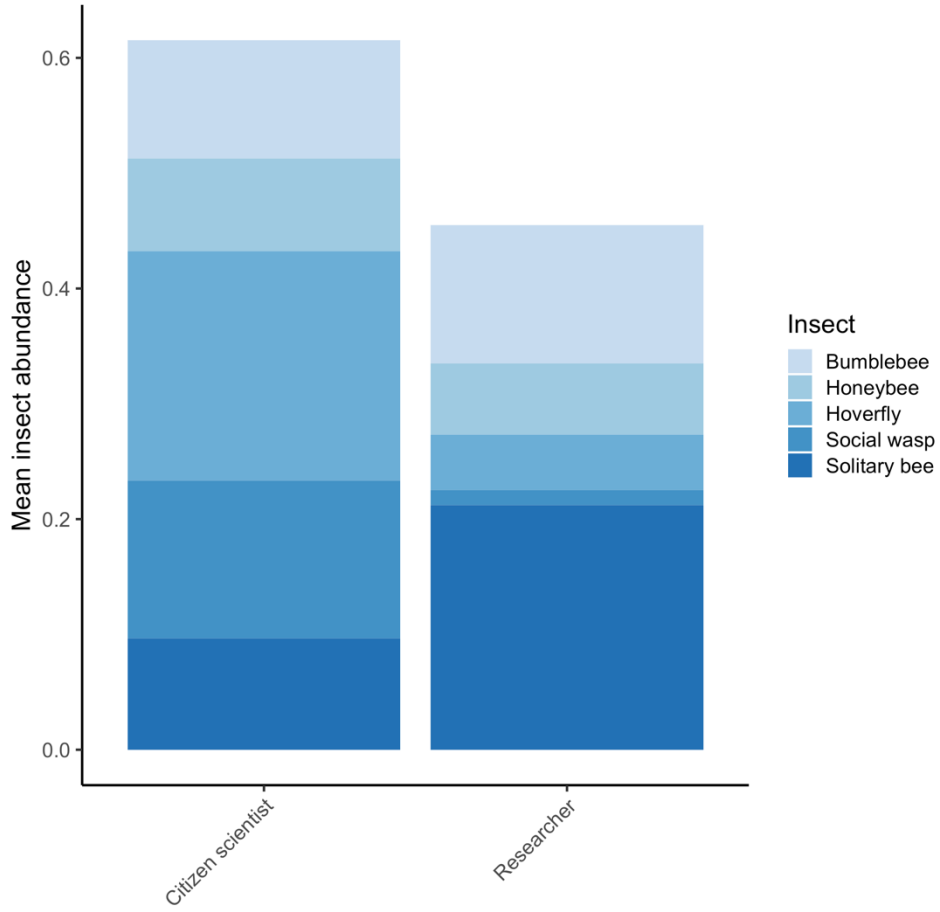

Figure 4.1. *Mean abundance of broad insect groups, as identified by citizen scientists from pan trap samples, compared to professional researchers' identification of the same samples.*

4.4.4. Sampling methods and Sow Wild! project results

We compared the mean abundance of broad insect groups considering the Sow Wild! project treatments (mini-meadow, 10 m away, control sites) and the three different sampling methods (the set of four coloured pan traps and yellow sticky traps using researcher data, and insect watch using citizen science data) (Fig 4.2). Treatment patterns between pan traps and yellow sticky traps are similar, with mini-meadows having the highest insect abundance and control having the least (Fig 4.2), although

overall sticky yellow traps collected more solitary wasps. However, patterns of insect abundance recorded during the insect watch differ from pan trap and yellow sticky trap methods, with control sites having the highest insect abundance and mini-meadows the least (Fig 4.2). Insect watch also recorded a higher abundance of the more conspicuous groups: bumblebees, honeybees and hoverflies. Citizen scientists were not asked to count solitary wasps.

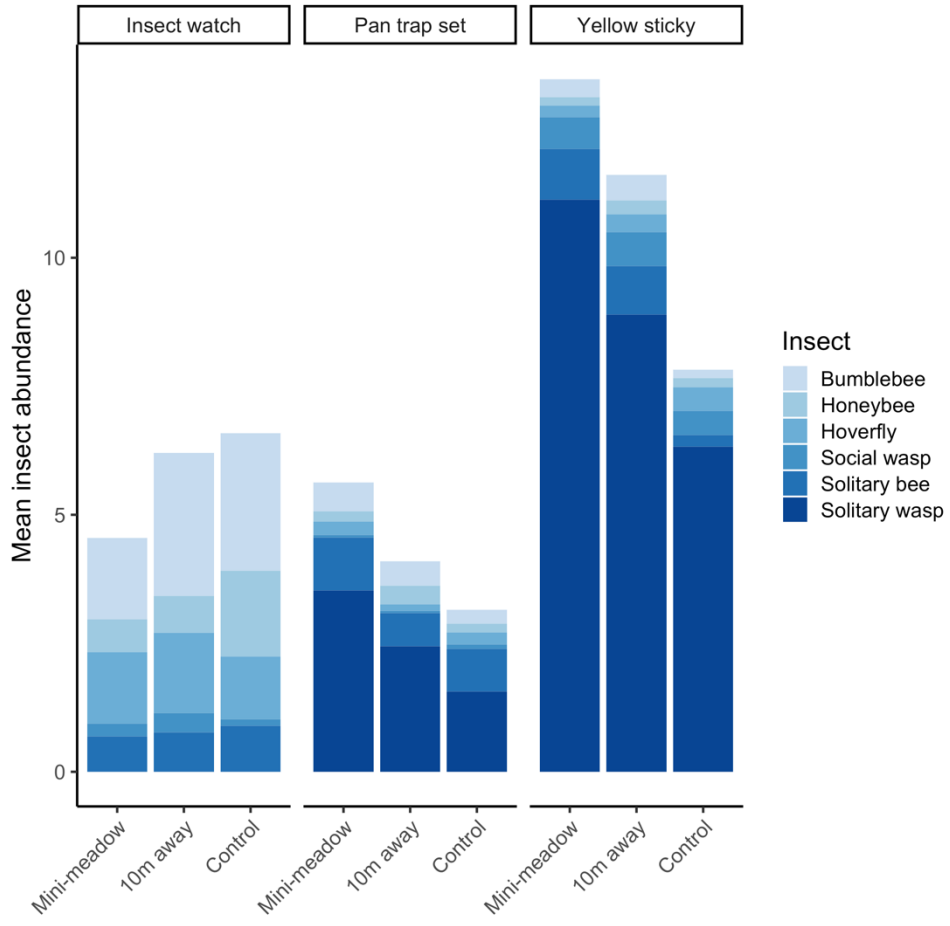

Figure 4.2. *Mean abundance of bumblebees, honeybees, hoverflies, solitary bees, social wasps and solitary wasps recorded over the three sampling methods used in the Sow Wild! project (insect watch, pan trap set and yellow sticky traps) and each of the project treatments (sampling mini-meadow, 10 m away from mini-meadow, and control sites). Solitary wasps were not recorded by citizen scientists in the insect watch. Pan trap and yellow sticky trap data collected by researchers, insect watch data collected by citizen scientists.*

4.4.5. Sampling methods for insect sampling

The method of sampling had significant effects on the capture rate (abundance) of all broad insect groups considered (bumblebees, honeybees, hoverflies, solitary bees, social wasps, solitary wasps) (Fig 4.3a,b,c; Table 4.1). Insect watches produced the most observations for all groups except for social wasps (citizen scientists were not asked to record solitary wasps). Yellow sticky traps were the most effective at collecting social and solitary wasps (Fig 4.3a,c). Of the pan traps, white pan traps were the most effective pan traps at capturing pollinators overall, especially bumblebees and solitary bees (Table 4.1). Blue and pink pan traps consistently collected similar data for each of the insect groups, and this was far less than the white and yellow pan traps.

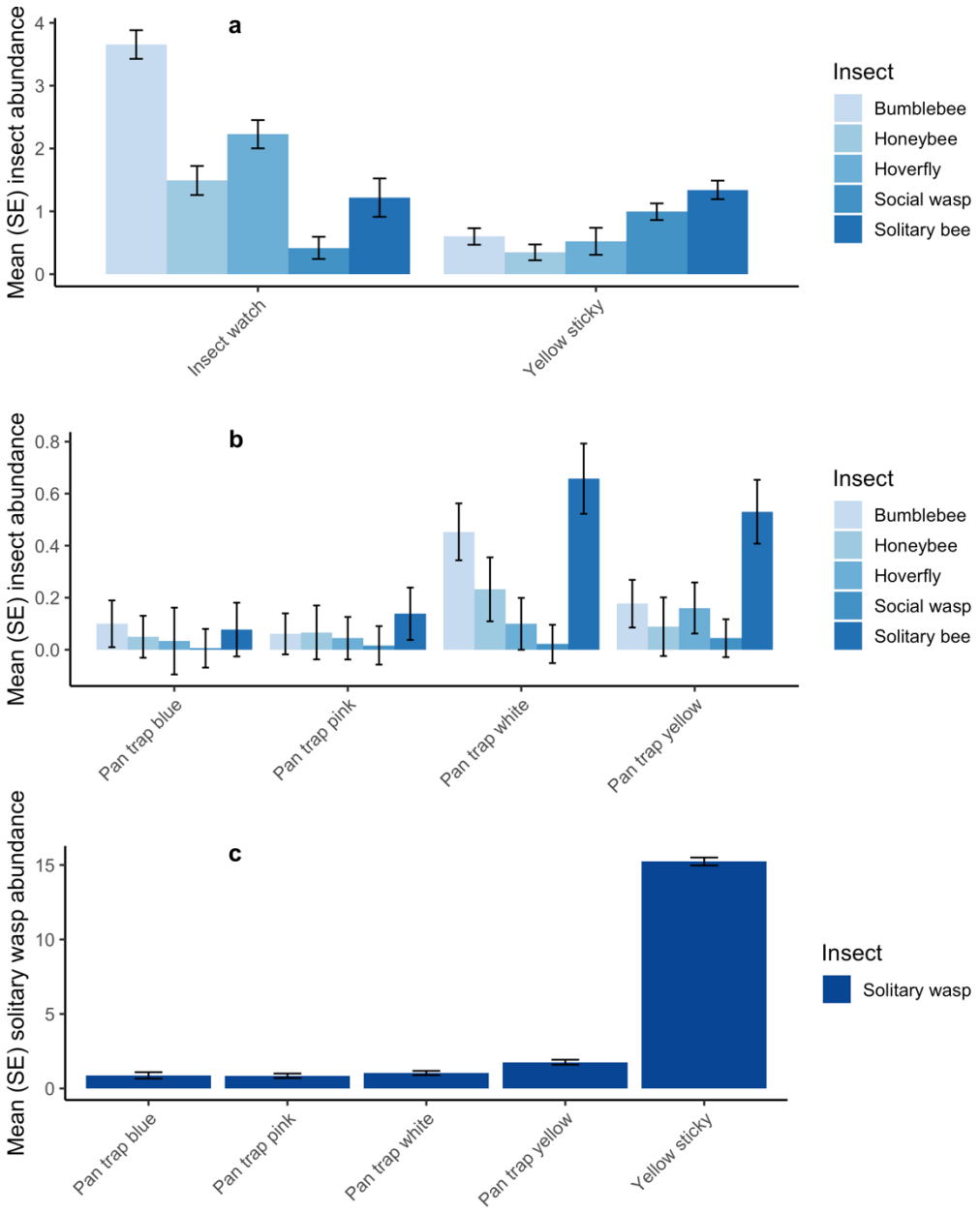

Figure 4.3 *Mean abundance of bumblebees, honeybees, hoverflies, social wasps, and solitary bees collected, comparing the different sampling methods: a) insect watch and yellow sticky traps, b) pan traps by colour (blue, pink, white, yellow), c) solitary wasp abundance collected by pan traps colour (blue, pink, white, yellow) and yellow sticky traps. Pan trap and yellow sticky trap data collected by researchers, insect watch data collected by citizen scientists.*

Abundance	X^2	**df**	P =	**Insect watch**	**Pan trap (blue)**	**Pan trap (pink)**	**Pan trap (white)**	**Pan trap (yellow)**	**Yellow sticky trap**
Bumblebee	323.72	5	< 2.2e-16	**(c)** 3.65 ± 0.23	**(a)** 0.1 ± 0.09	**(a)** 0.06 ± 0.08	**(b)** 0.45 ± 0.1	**(a)** 0.18 ± 0.09	**(b)** 0.6 ± 0.13
Honeybee	133.1	5	< 2.2e-16	**(d)** 1.49 ± 0.23	**(a)** 0.05 ± 0.08	**(a)** 0.07 ± 0.1	**(bc)** 0.2 ± 0.1	**(ab)** 0.09 ± 0.1	**(c)** 0.35 ± 0.13
Hoverfly	194.4	5	< 2.2e-16	**(d)** 2.23 ± 0.23	**(a)** 0.03 ± 0.13	**(ab)** 0.04 ± 0.08	**(ab)** 0.1 ± 0.1	**(b)** 0.16 ± 0.09	**(c)** 0.52 ± 0.22
Solitary bee	175.57	5	< 2.2e-16	**(cd)** 1.22 ± 0.31	**(a)** 0.08 ± 0.1	**(a)** 0.14 ± 0.1	**(bc)** 0.66 ± 0.14	**(b)** 0.53 ± 0.12	**(d)** 1.34 ± 0.15
Social wasp	214.04	5	< 2.2e-16	**(b)** 0.42 ± 0.18	**(a)** 0.01 ± 0.07	**(a)** 0.02 ± 0.07	**(a)** 0.02 ± 0.07	**(a)** 0.04 ± 0.07	**(c)** 0.99 ± 0.13
Solitary wasp	627.63	4	< 2.2e-16	NA	**(a)** 0.88 ± 0.21	**(a)** 0.85 ± 0.15	**(a)** 1.04 ± 0.14	**(b)** 1.76 ± 0.17	**(c)** 15.2 ± 0.26
Richness									
All bee	131.9	3	< 2.2e-16	NA	**(a)** 0.11 ± 0.06	**(a)** 0.13 ± 0.06	**(c)** 0.61 ± 0.07	**(b)** 0.38 ± 0.07	NA

Table 4.1. *GLMM ANOVA results for effects of sampling method on the abundance of insect group and bee species richness. Abundance of broad insect groups (bumblebees, honeybees, hoverflies, solitary bees, solitary wasps) recorded in each of the sampling methods used (insect watch, blue pan traps, pink pan traps, white pan traps, yellow pan traps, yellow sticky traps) and richness of bee species (including solitary bees, bumblebees and honeybee) collected in pan traps only. Presented with mean ± standard error, chi-square X^2, degrees freedom df, significance (NS, not significant; *, p < 0.05; **, p < 0.01; ***, p < 0.001) and Tukey's Honest Significant Difference test for comparisons (designated by letters in bold).*

Yellow sticky traps had the highest proportion of social wasps and the four colour pan traps were relatively equal in the proportion of insect groups collected (Fig 4.4). Insect watch collected the highest proportion of bumblebees, and also collected the lowest proportion of solitary bees, noticeably less than the other sampling methods (Fig 4.4).

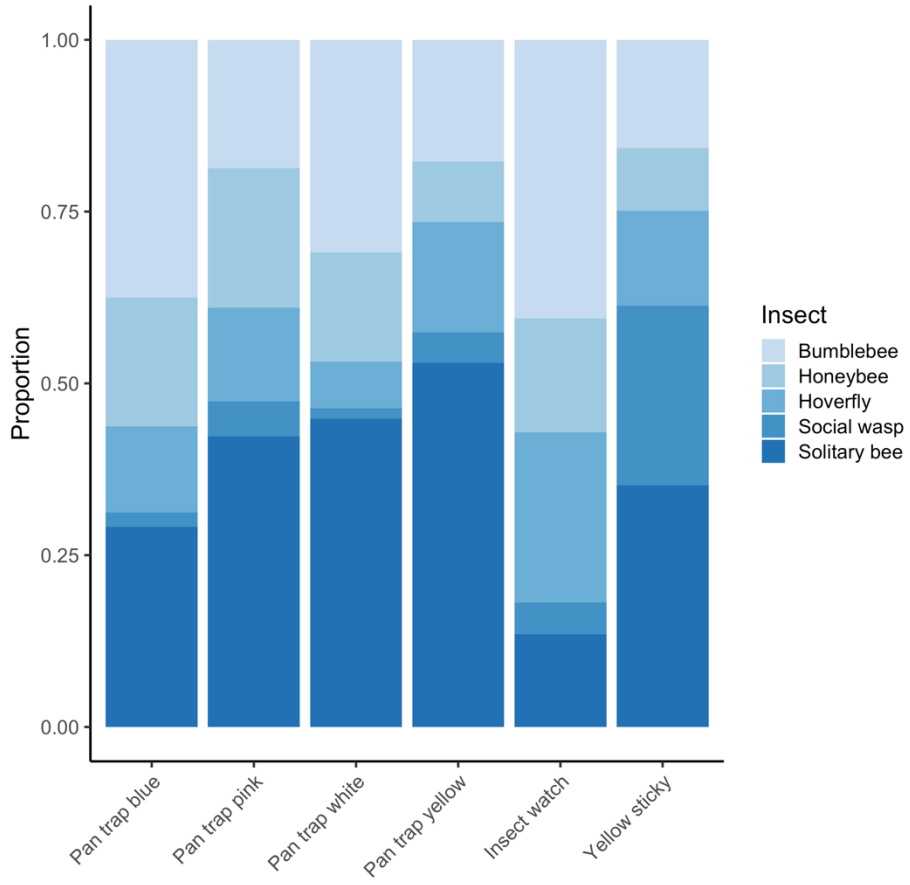

Figure 4.4. *Proportion of insect groups (bumblebees, honeybees, hoverflies, social wasps, and solitary bees) collected by sampling method (blue, pink, white and yellow pan trap, insect watch, yellow sticky traps). Pan trap and yellow sticky trap data collected by researchers, insect watch data collected by citizen scientists.*

White and yellow pan traps were equally effective at capturing the most common bee species despite white pan traps capturing more of these insects overall. Pink and blue pan traps were also equally effective at capturing common bee species (Fig 4.5).

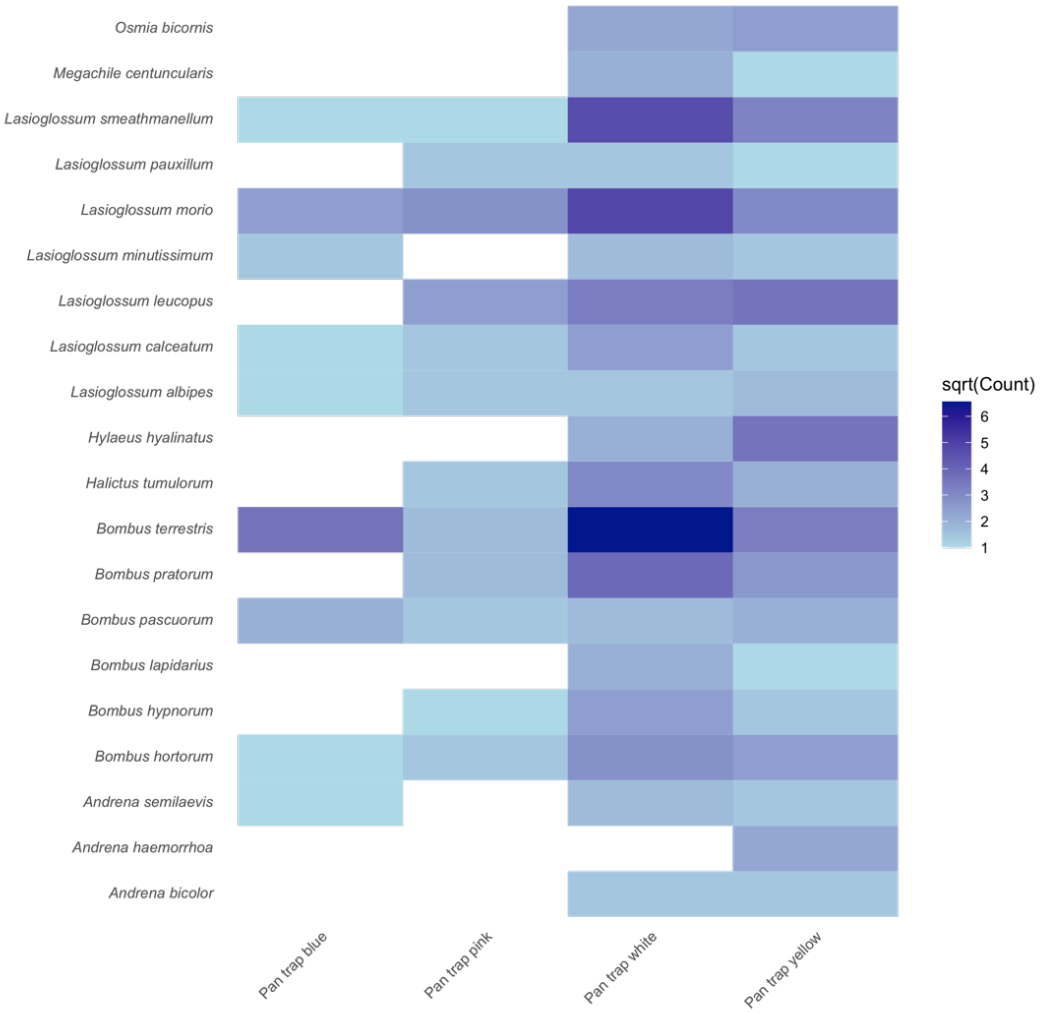

Figure 4.5. *Abundance heatmap of twenty most abundant wild bee species. Based on count of bees sampled by pan trap colour (blue, pink, white, yellow). Square root transformed for visualisation purposes.*

The colour of pan trap also had a significant effect on the species richness of bees collected, with white pan traps collecting the highest richness, followed by yellow pan traps and blue and pink traps catching the lowest bee species richness (Table 4.1).

4.5. Discussion

Using researcher-verified data collected by citizen scientists in the Sow Wild! project, we were able to compare insect identification by citizen scientists and researchers. We found that counts of the more ‘conspicuous’ (that is, larger and more well-known) bumblebees and honeybees were similar between citizen scientists and researchers.

However, numbers of solitary bees in pan trap samples were underestimated by citizen scientists. Furthermore, when comparing data collected during the observational insect watch and the specimen-based sampling methods, the proportions of solitary bees were again lower than expected and probably also under-recorded during the insect watch. This is similar to previous studies which have concluded that less conspicuous groups tend to be under-recorded by citizen scientists (Kremen et al 2011) especially the smaller solitary bees (Maher et al 2019). We also found that social wasps were overestimated by citizen scientists, and although hoverfly counts did not significantly differ between researcher and citizen scientists, the overall counts of hoverflies were much higher from citizen scientists. Therefore, although we were not able to verify exactly which specimens were misidentified, it is highly probable that solitary bees may have been mistaken for social wasps and hoverflies.

In the first year of the study, when faced with numerous small flies in the pan trap samples, we found that citizen scientists were discouraged from sorting through and recording the groups present. Similarly, Kleinke et al (2018) discussed how volunteers found the task of counting numerous seeds too onerous. In year 2, we told citizen scientists that exact fly counts were unnecessary and we also did not ask citizen scientists to count solitary wasps as this would have been too difficult. However, we found that when high numbers of flies *were* recorded by citizen scientists, parasitoid wasps were numerous and commonly misidentified as small flies (pers.obs.).

Results of the Sow Wild! project on the effectiveness of mini-meadows differed between researcher verified, specimen-based data and citizen scientist observation-only data sets, such that incorrect conclusions would have been drawn if we had relied solely on observations made by citizen scientists. When comparing the abundance of insect groups recorded in the different project treatments (that is data collected in the mini-meadows, 10 m away and the control sites) insect watch patterns are markedly different to those of the pan traps and yellow sticky traps. This is an unexpected result and, although the vegetation in the wildflower patch may have made it more challenging to spot insects compared to a control area, it could also be explained by participant bias. Although advised to measure out 2x2 m, few participants reported doing so. Those participants in the control group may not be able to visualise a 2x2 m area in 3D space without measuring out this transect, compared to the groups actively working with a

mini-meadow of clearly defined size. Without pre-measured transects, it would be easy to report insects outside the transect unintentionally, or perhaps underestimate the importance of reporting zeros. Our results are in contrast with Kremen et al (2011) who found that observational data followed patterns in specimen-based data, and such differences between our projects could be due to the level of training. Kremen et al (2011) were able to offer in-person training with fewer participants (n = 13), compared to our project with an initial larger pool of citizen scientists (n = 150).

We have also found that different sampling methods vary in their effectiveness at collecting different insect groups, all of which can be easily and successfully incorporated into citizen science projects. Such knowledge is useful when selecting the method to monitor specific taxa and could avoid excessive lethal sampling. The insect watch collected the highest insect counts out of all the methods. However, higher counts of insects in the insect watch could have been in part due to repeated counting of a re-visiting insect, which would have only been counted once in the specimen-based sampling. We found white traps were the most effective pan trap colour overall, collecting the highest bee species richness, and collecting around a third more beneficial insects than yellow traps, which were the second most effective colour. The efficiency of pan trap colours differs according to bee species (Toler et al 2005), body size (Hutchinson et al 2021b; Krahner et al 2021; Wilson et al 2008), sex (Leong and Thorp 1999) surrounding landscape and habitat (Nielson et al 2011; McCravy 2018; Saunders and Luck 2013) and neighbouring crops (Hutchinson et al 2021b). We found white pan traps collected more bumblebees and solitary bees, and yellow pan traps collected more social wasps and solitary wasps, highlighting effective pan trap colours in sampling beneficial insects in UK urban environments. Furthermore, we found that yellow sticky traps were more effective than pan traps at sampling solitary wasps, solitary bees, social wasps, hoverflies and honeybees. These results agree with previous studies that conclude yellow sticky traps are useful in sampling parasitoid wasps (Hall et al 2017; Wallis and Shaw 2008) and hoverflies (Burgio and Sommaggio 2007). However, the smaller species were difficult to remove from yellow sticky traps, and hence identification to species would be difficult for some taxa.

Generally, it is assumed that citizen science projects with a simple protocol will retain more volunteers (Birkin and Goulson 2015). However, we found volunteers were not

discouraged despite a slightly complicated experimental protocol, and the commitment required to set up the initial meadow plots. Forty-eight of the initial participants continued through to year 2 of the project, which produced high-quality data and significant findings on effective pollinator habitat management in gardens (Griffiths-Lee et al 2022). The majority of those who left the project reported changes in personal circumstances, health reasons, or that the mini-meadow did not establish sufficiently to continue with the project, and many participants remained engaged and interested even after dropping out. Participant drop-out may have been non-random, with poorly established mini-meadows or those that caught fewer insects perhaps leaving the more productive pollinator-friendly gardens continuing with the project. Yet drop-out rates were unlikely due to group allocation, as similar proportions of participants remained in each group (control, mix 1 and mix 2) throughout the project.

As a standardised hypothesis-driven project, Sow Wild! relied on fewer dedicated participants than unstructured, opportunistic projects. To retain participants we set up social media accounts to create a sense of community, interacted with participants regularly, and provided feedback during and at the end of the project. Such communication and interaction are acknowledged to enhance engagement rates (Birkin and Goulson 2015; Mason and Arathi 2019). For future projects, we would further recommend a survey at the beginning and end of the project to give a better understanding of motivations and how these align with the protocol to ultimately retain more participants (Domroese and Johnson 2016).

We asked the participants to identify insects to broad group with the aid of an ID guide and practice through an online insect identification quiz, when in reality direct training is more desirable to aid identification. A few sessions of remote training can be as effective as one session of direct training and even a slide show can increase identification accuracy (Ratnieks et al 2016), and hence could be used to improve accuracy in similar future projects with limited resources.

4.5.1. Conclusion

We recommend that verification of specimen identity by researchers is a vital component of a hypothesis-led citizen science project such as Sow Wild!, due to different patterns in data collected in verified specimen-based versus observation-only

data sets, and the under-recording of the less conspicuous taxa. We agree with Dickinson et al (2010), that citizen science should complement traditional researcher-led studies, and also Kremen et al (2011) who argue that invertebrate monitoring should include citizen scientists and professional experts. This could be achieved with expert verification of all data as we have done, or through a random sub-sample for larger projects. Submission of photographs for verification is also useful for observation projects (Falk et al 2019), and some studies suggest the collection of reference data will highlight inaccuracies (Aceves-Bueno et al 2017). Indeed, using unverified data risks drawing incorrect conclusions about rare or declining species (e.g. Gardiner et al 2012). We conclude that different sampling methods need to be considered when designing a citizen science project, depending on taxa and hypothesis. To monitor a range of beneficial insects a combination of the methods discussed in this study could be deployed as they are all attractive to different insect groups. To limit by-catch, sampling methods can be used selectively if there is a particular taxon of interest.

CHAPTER 5

5. Sown wildflowers between vines increase beneficial insect abundance and richness in a British vineyard

This chapter has been published as:

Griffiths-Lee, J., Davenport, B., Foster, B., Nicholls, E., & Goulson, D. Sown wildflowers between vines increase beneficial insect abundance and richness in a British vineyard. *Agricultural and Forest Entomology*.

JGL & DG conceived the methodology and site design; JGL & BD conducted fieldwork; BF identified wasp samples to family; JGL conducted data analysis and led the writing of the manuscript; JGL, DG and EN commented on draft versions of the manuscript.

5.1. Abstract

Traditional vineyards are generally intensive monocultures with high pesticide usage. Viticulture is one of the fastest-growing sectors of English agriculture, although there is currently limited research on habitat management practices. In a vineyard in East Sussex, England, we tested five inter-row ground cover treatments on their potential in supporting beneficial insects: two commercially available seed mixes (meadow mix and pollen and nectar mix), a wild bee seed mix (formulated based on pollinator foraging preferences), natural regeneration, and regularly mown grass. Over two years, from May to August, we conducted monthly floral surveys and insect surveys using transect walks and pan traps. The abundance and richness of flowers in the natural regeneration treatment were twice that of the regularly mown inter-row treatment. By year 2 the abundance of 'total insects' sampled was significantly higher in the wild bee mix compared to mown. Likewise, there was a significant effect of treatment type on pollinator richness, with higher mean richness found in wild bee mix. Solitary wasp family richness was highest in the natural regeneration treatment and lowest in the mown treatment. Given the rapid growth and lack of specific environmental recommendations for British viticulture, we demonstrate a simple and effective approach for supporting beneficial insects and ecosystem services. Promotion of perennial wildflowers through sowing or allowing natural regeneration in inter-row ground cover in vineyards has the potential to boost biodiversity in vineyards on a large scale if widely adopted.

5.2. Introduction

Land-use change due to intensive agricultural practices is a major driver of global biodiversity loss (Newbold et al 2016). Habitat conversion to vineyards currently threatens biodiversity in many of the world's top wine-growing regions, including South Africa (Fairbanks et al 2004), California (Merenlender 2000) and Chile (Armesto et al 2010). Globally, approximately 7.4 million hectares of land are under vine (OIV 2019) and these landscapes are generally intensively managed monocultures with high pesticide usage (Urruty et al 2016). In Great Britain, vineyard coverage has more than quadrupled since 2000 (WineGB 2021a), and currently there are 3,800 ha of land under vine. Ninety-eight per cent of British vineyards are in England (WineGB 2021a) and

viticulture is considered one of the fastest-growing sectors of English agriculture (South Downs National Park Authority (SDNPA) 2021).

European agri-environmental schemes (AES) include recommendations for the sowing of wildflowers to provide resources for pollinators (e.g. DEFRA 2020). Wildflower strips can provide important resources for pollinators in agricultural environments (Blaauw and Isaacs 2014a), aiding pollinator conservation and promoting pollination services (Korpela et al 2013). However, there are currently no vineyard-specific recommendations under the UK AES. Grapevines are not dependent on pollinators, yet the positive effects of wildflowers in vineyards for pollinators have received attention in many traditional wine-growing regions. For example, studies on inter-row floral plantings in vineyards in Europe, California, and South Africa conclude increased wild bee richness, abundance and functional traits (Kehinde and Samways 2014; Kratschmer et al 2019; Kratschmer et al 2021; Wilson et al 2018) regardless of organic or conventional practices (Kratschmer et al 2021).

Habitat management in agri-ecosystems also provides essential resources for natural enemies of pests (Landis et al 2000), increasing abundance of beneficial insects such as hoverflies, lacewings and ladybirds (Tschumi et al 2016) and reducing pest damage (e.g. Tschumi et al 2015). Such ecologically-based pest management as a part of integrated pest management is increasingly considered an alternative to pesticide use (Wilson and Danne 2017). Agro-ecological approaches to vineyard habitat management also promote natural pest control, with inter-row wildflower strips increasing the abundance of insect parasitoids (Judt et al 2019). Natural regeneration of floral communities in a vineyard has also been found to promote hoverfly diversity (Pétremand et al 2017). Adult hoverflies are effective pollinators (Doyle et al 2020), and zoophagous hoverflies have predatory larvae that are also pest control agents (Wotton et al 2019). However, some studies have found that although floral plantings attract natural enemies and increase parasitism, this doesn't necessarily translate into effective pest reduction (Berndt et al 2006; English-Loeb et al 2003; Pétremand et al 2017).

Reduced mowing regimes have a positive effect on insect abundance and diversity (Wastian et al 2016) and indeed on the abundance of parasitoid wasps in vineyards (Zanettin et al 2021). Due to high levels of disturbance, the abundance of natural enemies of pests can be low in agri-ecosystems (Landis et al 2000), and perennial

grasses may provide refuge for natural enemies during such disturbances (Daane et al 2018a). In an Australian vineyard, the abundance and diversity of parasitoids were higher in vines surrounded by perennial grasses, and predation of the pest *Epiphyas postvittana* was greater (Danne et al 2010). Likewise, in Mediterranean vineyards, the abundance and richness of parasitoid species were higher in the natural regeneration or 'managed weed' treatment areas (Möller et al 2020). In addition to supporting pollination and pest control services, there are numerous other ecosystem service benefits associated with sowing wildflowers. Wildflowers can provide soil protection, weed suppression, biodiversity enhancement and increased aesthetics (Fiedler et al 2008) and enhance soil fungal networks, leading to increased nutrient availability for grapevines and increasing tolerance to abiotic stress (Trouvelot et al 2015).

The viticulture industry in Great Britain is experiencing rapid growth (SDNPA 2021) with thus-far limited research into agro-ecological management. To the best of our knowledge, this is the first published study on the effects of wildflowers on biodiversity in a British vineyard. Here we focus on the intrinsic value of beneficial insects in supporting a healthy and biodiverse ecosystem, considering changing habitat in the South Downs National Park, England. There has been a 90% increase in the coverage of vines in the South Downs National Park since 2016 and an estimated further 40,000ha of the park is suitable for viticulture under climate change projections (SDNPA 2021). Considering these projections, appropriate environmental land and sustainability management of this sector is vital. By experimentally increasing floral plantings in inter-row spaces, we evaluate their potential to increase the abundance and richness of beneficial insects in a British vineyard. We aimed to determine: 1) if inter-row sowing of wildflower seed mixes increases insect, pollinator and solitary wasp abundance and richness; 2) which inter-row ground cover treatment interventions best encourage beneficial insects; 3) the effectiveness of natural regeneration in encouraging beneficial insects and floral establishment, compared to mowing inter-row spaces.

5.3. Methods

5.3.1. Study site and inter-row treatments

The study took place at a vineyard estate in East Sussex, UK (Lat/long 50.797, 0.125). The vineyard is located in the South Downs National park, on lime-rich chalk soil and

land previously used as conventionally managed arable farmland. The experimental site within the vineyard contains 37 rows of established vines, allowing 36 rows of inter-row ground cover treatments. Prior to the study, the treatment rows were regularly mown. Five different inter-row treatments were tested, including three different wildflower mixes, natural regeneration, and a control of mown grass. Appendix I lists the wildflower and grass mix compositions, indicating which of the flowering species germinated, and in which year of the study.

Treatment rows were 140 m in length and were paired, so two rows of the same treatment were placed together and the 18 pairs were then randomly allocated to one of five different inter-row ground cover treatments as replicates (Appendix J shows the arrangement of treatment rows). 'Meadow mix' treatment was based on a wildflower mix recommended under UK AES for the establishment of flower-rich margins and plots. Meadow mix contains both perennials and grasses ideal for chalky and limestone soils. It was sown on four replicates at a rate of 4 g/m^2. 'Wild bee mix' treatment was formulated based on existing literature and personal communications identifying biennial and perennial flowers that attract a range of wild pollinator species and provide flowering cover over the longest season. We chose to create mixes with mostly perennial species as they tend to produce more pollen and nectar than annual plants (Hicks et al 2016), and last multiple seasons. Wild bee mix was sown on four replicates at a rate of 4 g/m^2. 'Pollen and nectar mix' treatment was based on a mix recommended under the Countryside Stewardship Scheme for the planting of nectar-rich flowering species under its AES. The mix was grass seed-free and contained six nectar-rich flowering species. It was sown on four replicates at a rate of 1 g/m^2. The 'natural regeneration' treatment strips were permitted to regenerate naturally from flowering plant species already present at the vineyard site. Natural regeneration was allocated to three replicates. The 'mown' treatment strips were mown approximately every two weeks through spring and summer, in line with the management of the vineyard outside of the experimental site. The mown treatment was allocated to three replicates.

Except for the 'mown' and 'natural regeneration' treatments, grass was removed with a disc cutter, and wildflower mixes sown in May 2016 by mechanically broadcasting along the inter-rows. Seeds were supplied by Agrii (United Agri Products Ltd & Masstock Arable Ltd, Cheltenham, UK). Growth was cut back in August and cuttings

removed.

5.3.2. Insect surveys

Diurnal insect surveys consisted of transect walks and pan trapping. Surveys took place monthly from July to August 2016 and May to August 2017 between 10:00-16:00, on days with a minimum temperature of 13 °C, low wind and no precipitation.

One inter-row of every treatment pair was randomly chosen for a transect walk, walked at a pace of approximately 10 metres/minute. At approximately 30 metre intervals on the transect walk, a butterfly net was swept into the inter-row ground cover foliage for 20 seconds (collecting wild bees and hoverflies only) and a pooter to collect smaller species from the net. Insects were collected in jars containing ethyl acetate.

A pan trap set was placed on the ground under the vine in between each treatment pair, at the same halfway point of each row. A 24-hour period was chosen each month with a low chance of rain, and daytime temperatures above 13 °C. Pan traps were spray-painted by hand and a set consisted of four 750 ml plastic food containers (Go Packaging Products Ltd, UK), one sprayed white, one yellow, one pink (Rust Oleum spray paint Direct to Plastic White / Sun Yellow Gloss / Berry Pink Gloss), one blue (Plastikote Pacific Blue Gloss). An asterisk was drawn in permanent marker pen (Sharpie, Sanford L.P, US) on the inside of the pan traps as a ‘nectar guide’. Pan traps were ¾ filled with water and a squirt of natural fragranced washing-up liquid (Ecover, Malle, Belgium).

5.3.3. Identification of samples

Using pan trap samples, the abundance of bumblebees, solitary bees, honeybees, solitary wasps (including parasitoid wasps), social wasps, beetles, hoverflies and ‘other’ (non-syrphid) flies were counted. No butterflies or moths were caught. In this paper, our definition of 'solitary bees' includes non-corbiculate bees that are solitary or eusocial, and those that do not fall under the bumblebee (*Bombus*) or honeybee (*Apis*) groups. From net and pan trap samples, all hoverflies, bumblebees and solitary bees were identified to species level (10 specimens were only recorded to broad group as they were unidentifiable). Solitary wasps were recorded to family level for July 2016 and 2017 pan traps only (identification for this group is very time-consuming, so a month

with a high occurrence of wasps was chosen as a representative sample).

5.3.4. Floral surveys

During the transect walk, floral surveys were also conducted at the 30-metre intervals, using 1x1 m quadrats. All blooming inflorescences were identified to species and percentage coverage of flower heads estimated. Grasses and non-flowering plants were not identified. Using the percentage coverage of each species present in the 1x1 m quadrat, the average for each species was calculated over three quadrats per row and recorded as average species to the nearest integer +1 (this allowed us to account for the rarer flower species only occurring in one quadrat).

5.3.5. Data analysis

Data analysis was conducted in R (R core team 2020). Data from 2016 and 2017 (henceforth year 1 and year 2) were analysed separately due to differences in flower abundance and diversity that occurred between years, due to the establishment of perennial flowers. Data from the two sampling methods (pan trap and transect walk) was also analysed separately. 'Total insect abundance' included counts of solitary bee, bumblebee, honeybee, hoverfly, solitary wasp, social wasp, beetle, 'other' (non-syrphid) fly. 'Total insect abundance' was only available for pan trap methods as transect walks only recorded bees and hoverflies. Hoverfly and bee richness considered the number of species, and data from both insect groups were combined into a single measure of 'pollinator richness' for analysis. Solitary wasp (including parasitoid wasp) richness was analysed at the family level and for July in years 1 and 2. For flowering plants, Shannon's diversity index was calculated for each row for each month, and included both sown (i.e. included in the wildflower mix) and unsown flowers (spontaneous).

Effects of inter-row treatment on total insect abundance. A Shapiro-Wilk normality test was conducted to test for parametric data. Generalised Linear Mixed Models (GLMMs) were constructed using *lme4* package, zero-inflated models using *glmmTMB* and graphs were created using *ggplot2*. Models of best fit were chosen based on AIC values followed by diagnostic residual plots to ensure they conformed to underlying model assumptions. ANOVAs were then performed comparing full and reduced models and results reported as chi-square and p values. Tukey's Honest Significant Difference Test

was used post-hoc to compare inter-row treatments. To investigate the effects of inter-row treatment on total insect abundance, GLMM's with negative binomial family was constructed with treatment, month and diversity of flowers as predictor variables. Row number was included as a random variable (to account for repeated measures).

Effects of treatment on richness of hoverflies, bee and solitary wasps. To investigate the effects of inter-row treatment on richness of pollinators (number of species of bees and hoverflies), treatment, month and diversity of flowers were set as predictor variables and row number as a random variable. Year 1 transect walk and year 2 pan trap were both analysed using GLMM with Poisson distribution, whereas zero-inflated GLMM with Poisson distributions was constructed for year 1 pan trap and year 2 transect walk data. To test the effects of inter-row treatment on the richness of solitary wasps (number of families), a Kruskal-Wallis H test was conducted.

Community dissimilarity analysis. Community dissimilarity analysis was performed to assess the i) floral, ii) bee and hoverfly, and iii) solitary wasp communities of the inter-row treatments over the two years of study. Jaccard dissimilarity was performed on the floral community matrix, and Bray-Curtis was performed on the bee and hoverfly matrix, and also on the solitary wasp community matrix (Vegan package), followed by Non-metric Multidimensional Scaling (NMDS) using MASS package to create an NMDS matrix. Significance of key species/families was tested with 999 permutations and adjusted using Bonferroni corrections. To analyse 'Treatment' and 'Year', a Permutational Multivariate Analysis of Variance (PERMANOVA) was performed on the interaction between the two variables. A PERMANOVA tests differences in similarities, and a significant result suggests that groups differ in their location and/or relative dispersion (Assis et al 2013). When PERMANOVA results were significant, a Permutation Analysis of Multivariate Dispersion (PERMDISP) was performed on the community matrix (Jaccard/Bray-Curtis), determining if there was variability in dispersion, possibly accounting for significant results seen in the PERMANOVA.

5.4. Results

5.4.1. Wildflower establishment

Over two years, 50 species of flowering plants spanning 17 families were identified (Fig

5.1), of which 24 were sown species, and 26 were established via spontaneous natural colonisation. The floral diversity for each of the five treatments increased from year 1 to year 2 (Fig 5.2c), as did the abundance and richness of the sown flower species (Fig 5.2a,b), which would be expected with the establishment and flowering of perennials in the year following sowing. In year 2 the diversity of wildflowers was greatest in inter-rows sown with meadow mix, followed by wild bee mix and pollen and nectar mix (Fig 5.2c) and greatest sown species richness and abundance were seen in meadow mix and wild bee mix (Fig 5.2a,b).

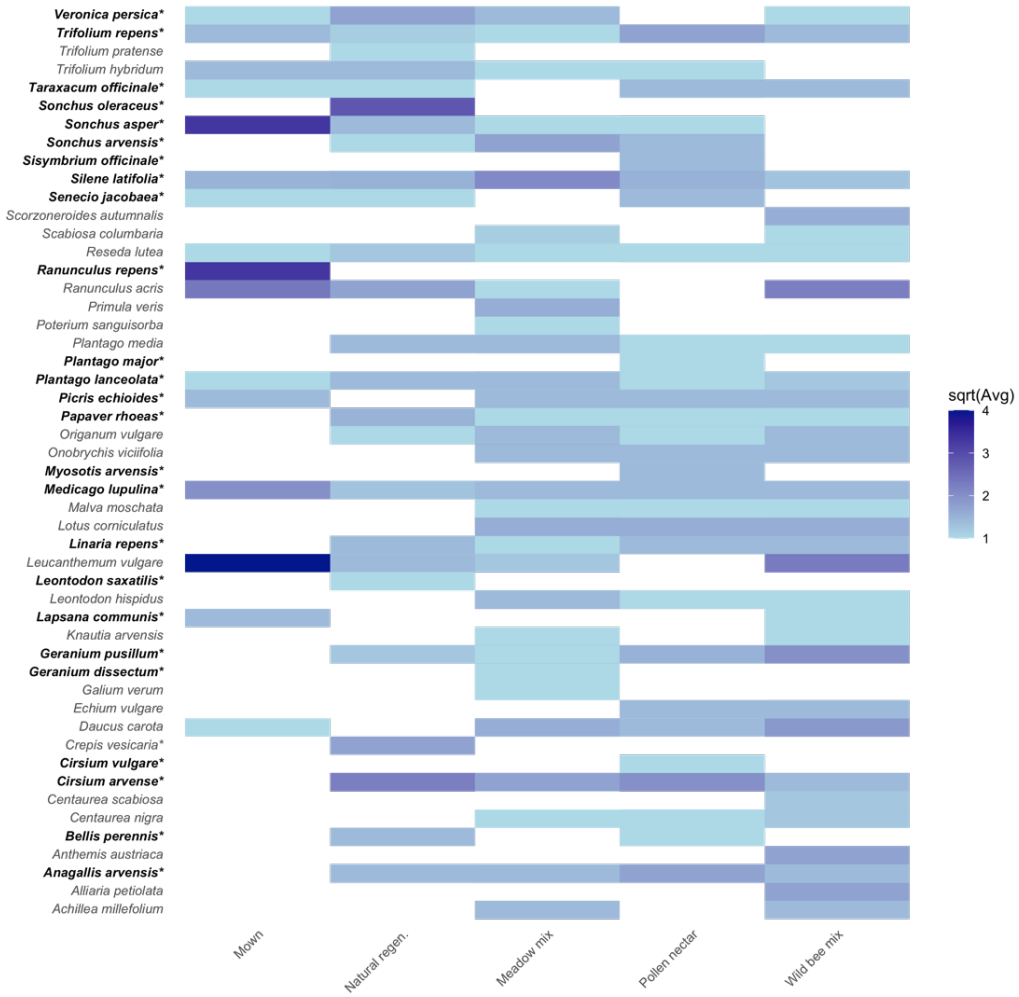

Figure 5.1. *Flowering plant species occurrence by treatment. Heatmap presenting all flowering plant species recorded at the study site within the five inter-row ground cover treatments, combining data from years 1 and 2. Those flowering species presented in bold with an asterisk are unsown and colonised naturally. Based on mean species abundance, square root transformed for visualisation purposes.*

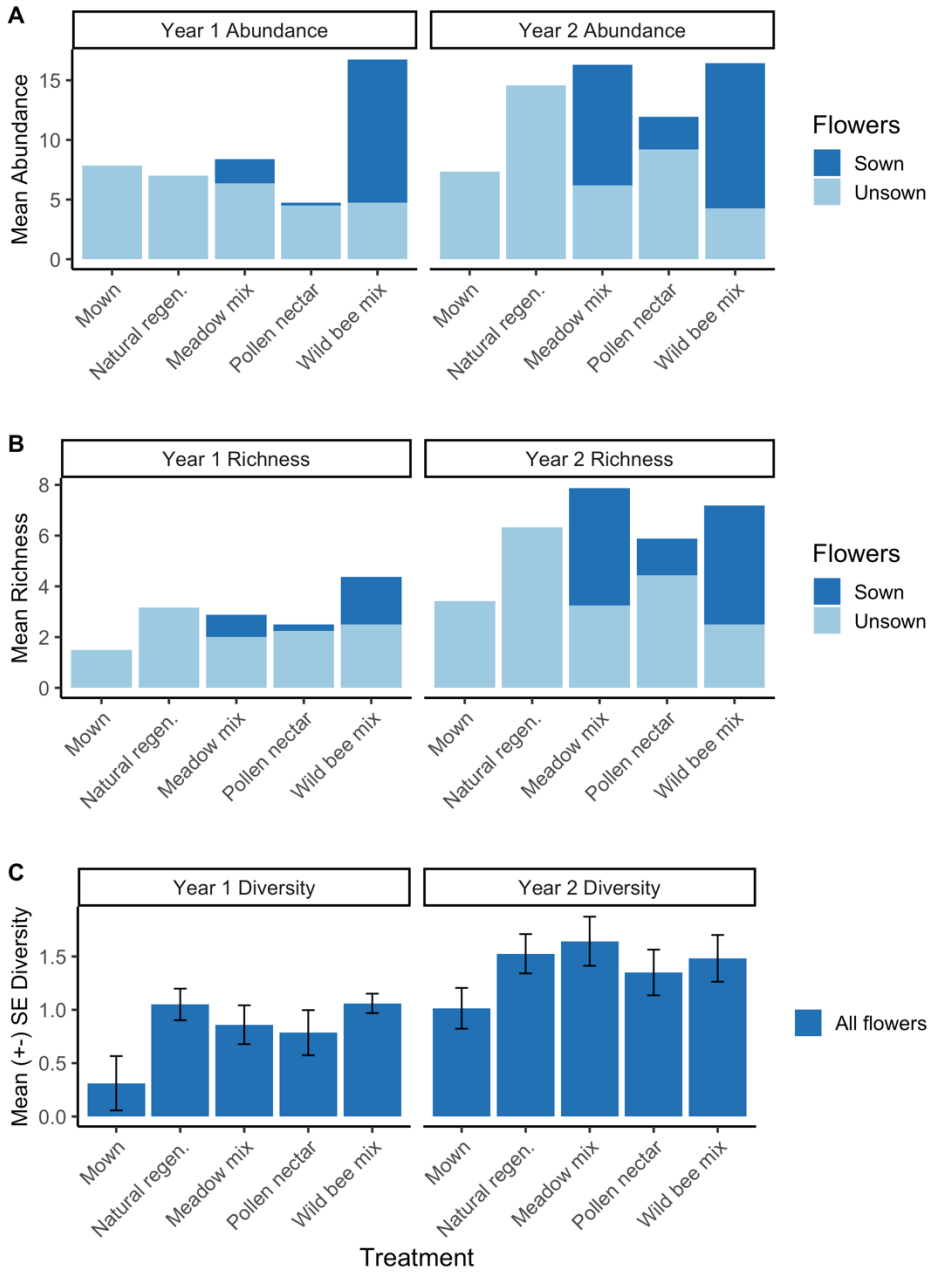

Figure 5.2. *Mean A) abundance B) richness and C) diversity of flowering plant species. Species mean abundance and species mean richness of sown and unsown flowering plant species. Diversity (Shannon's Diversity Index) of both unsown and sown flowers. Flowers were recorded in five inter-row ground cover treatments, in both year 1 and year 2 of the study.*

The floral diversity, richness and abundance of flowers in natural regeneration were greater than the mown treatment (Fig 5.2a,b,c). In year 1, the mean richness of the flowering species found in natural regeneration was 3.17 species (SE ± 0.27), compared to 1.50 species (SE ± 0.18) for mown. By year 2 species richness of natural regeneration

was mean 6.33 species (SE ± 0.43), compared to 3.42 species (SE ± 0.37) for mown (Fig 5.2b). Mean abundance of flowering species in year 1 was very similar between natural regeneration (mean 7.00 species SE ± 0.65) and mown (mean 7.83 species SE ± 1.45), but by year 2, species abundance had doubled to mean 14.58 species (SE ± 0.81) in natural regeneration, whereas mown strips remained roughly the same as in the first year of the study (mean 7.33 species SE ± 0.59) (Fig 5.2a). The diversity of flowering species in natural regeneration in year 1 was mean 1.05 species (SE ± 0.15) and year 2 was mean 1.52 species (SE ± 0.18; Fig 5.2c). This is compared to year 1 mown mean 0.31 species (SE ± 0.25) and year 2 mean 1.01 species (SE ± 0.19; Fig 5.2c).

NMDS analysis showed that inter-row ground cover treatment floral communities differ significantly, (Fig 5.3; PERMANOVA: $F_{4,76} = 4.84$, $P < 0.001$), and analysis of dispersion suggested that this was due to variation between treatments rather than within treatments (PERMDISP: $F_{4,81} = 2.065$, $P = 0.101$). All mixes showed high levels of overlap with other inter-row treatments in terms of floral composition (Fig 5.3). Likewise, NMDS analysis showed that year 1 and 2 floral communities differ significantly (PERMANOVA: $F_{1,76} = 9.24$, $P < 0.001$), and analysis of dispersion suggested that this was due to variation between year 1 and 2 rather than within years (PERMDISP: $F_{1,84} = 3.713$, $P = 0.061$). Nine flowering plant species showed significant presence within the ordination and were significantly associated with specific inter-row treatments and years of the study (Fig 5.3). Four of these nine were sown as part of the wildflower mixes: *Centaurea nigra*, *Leucanthemum vulgare*, *Daucus carota*, and *Lotus corniculatus,* the remaining five species were spontaneous.

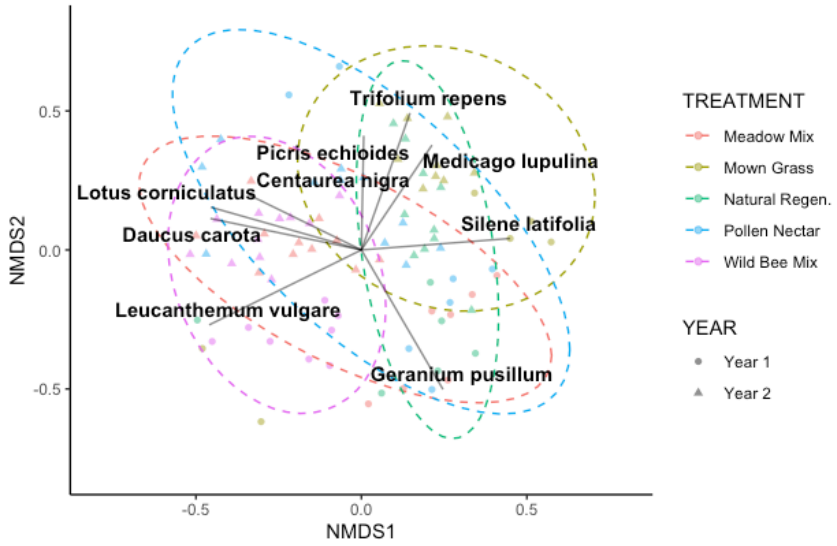

Figure 5.3. *NMDS plot using Jaccard dissimilarity distances of flowering plant species amongst different inter-row treatments. Nine of the flowering plant species identified at the vineyard showed significant presence associated with year/treatment after Bonferroni correction, with black lines representing the direction and strengths of their gradients within ordinate space. Ellipses show the 95% CI of multivariate t-distribution for each treatment.*

5.4.2. Beneficial insect abundance

Over two years, 77 bumblebees, 215 hoverflies, 20 honeybees, 844 solitary bees, and 920 solitary wasps were collected. Eighteen families of solitary wasps were identified (July year 1 and 2). The majority of the wasps identified were parasitoids, the only exceptions being the crabronid sample and some pompilids (Table 5.1). Thirty-six species of bee were identified, spanning 9 genera including *Apis mellifera* and five *Bombus* species. The most common wild bee was *Lasioglossum minutissimum*, a solitary mining bee that may benefit from the undisturbed soil in the vineyard for nesting. Thirteen species of hoverfly (including *Sphaerophoria* sp. which could not be

identified to species level) were identified spanning 9 genera. The most common hoverfly, *Eupeodes corollae,* is an aphidophagus hoverfly that could contribute to pest control of aphids in a vineyard landscape. The top 20 most abundant bees (solitary bees, honeybees and bumblebees) identified are listed in Table 5.1, also listed are all hoverfly species identified and all solitary wasp families. (Full species list of bees and hoverflies is available in Appendix K).

i) Bee species	**Count**	**ii) Hoverfly species**	**Count**	**iii) Wasp family**	**Count**
Lasioglossum minutissimum	397	*Eupeodes corollae*	102	Pteromalidae	54
Halictus tumulorum	114	*Sphaerophoria scripta*	42	Figitidae	32
Andrena flavipes	94	*Melanostoma mellinum*	29	Platygastridae	31
Lasioglossum calceatum	47	*Sphaerophoria taeniata*	10	Braconidae	27
Lasioglossum morio	44	*Episyrphus balteatus*	9	Ceraphronidae	22
Bombus lapidarius	39	*Syrphus ribesii*	8	Diapriidae	14
Bombus terrestris	29	*Eupeodes luniger*	3	Pompilidae	11
Lasioglossum malachurum	24	*Sphaerophoria* sp.	2	Ichneumonidae	10
Halictus rubicundus	21	*Platycheirus manicatus*	2	Eulophidae	9
Apis mellifera	20	*Melanostoma scalare*	2	Megaspilidae	7
Lasioglossum pauxillum	18	*Cheilosia vernalis*	1	Mymaridae	7
Andrena minutuloides	14	*Eristalis tenax*	1	Tetracampidae	2
Lasioglossum leucopus	13	*Syritta pipiens*	1	Proctotrupidae	1
Halictus eurygnathus	6			Aphelinidae	1
Lasioglossum parvulum	5			Torymidae	1
Lasioglossum leucozonium	5			Cynipidae	1
Lasioglossum lativentre	5			Crabronidae	1
Lasioglossum xanthopus	4			Encyrtidae	1
Osmia bicornis	4				
Bombus hypnorum	4				

Table 5.1. *i) Twenty most abundant bee species, ii) all hoverfly species and iii) all solitary wasp families sampled across two years in all five inter-row treatments. Bee and hoverfly data includes that sampled by transect walks and pan traps across all months of the study. Solitary wasps were captured by pan trap in July only year 1 and 2.*

There were no significant differences in the overall abundance of all insects between treatment groups in year 1 pan traps ($X^2 = 4.88$, df = 4, $P = 0.30$; Fig 5.4). In year 2 pan

traps, however, significant differences were detected in the overall abundance of all insects between treatment groups ($X^2 = 10.31$, df = 4, $P < 0.05$; Fig 5.4), with post-hoc Tukey tests indicating the abundance of 'all insects' was significantly higher in the wild bee mix compared to the mown inter-row treatment.

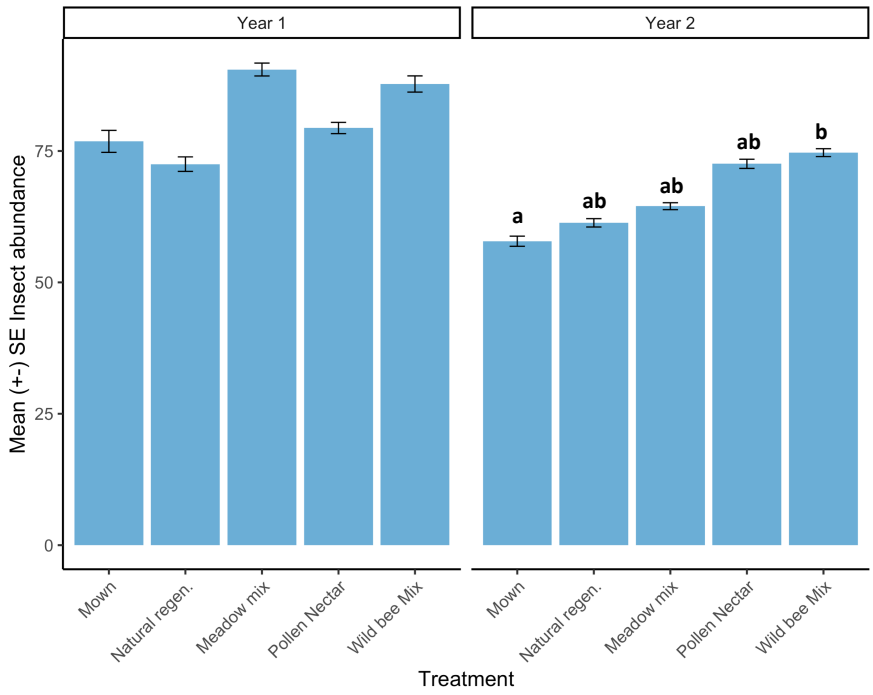

Figure 5.4. *Abundance of 'all insects' caught in pan traps by treatment. Mean (±SE) abundance of insects caught in five different inter-row ground cover treatments in year 1 and year 2. Letters indicate significant differences in abundances between treatments (Tukey's Honest Significant Difference).*

Generally, the most abundant bees were evenly distributed across inter-row treatments, although fewer bees were captured in the mown treatment (Fig 5.5a). The most abundant bees, *Lasioglossum minutissimum* and *Halictus tumulorum* were abundant across all inter-row treatments. Certain species, such *Bombus lapidarius* and *Bombus terrestris* were most abundant in the three wildflower mix treatments compared to the mown inter-row treatment or natural regeneration. Fewer hoverflies were captured in the mown inter-row treatment compared to the other four treatments (Fig 5.5b). The majority of hoverfly species were recorded in the pollen and nectar mix and wild bee mix. The most commonly sampled hoverfly *Eupeodes corollae* was abundant across all treatments. Solitary wasps were also evenly distributed between treatments (Fig 5.5c). The most abundantly observed wasp family, Pteromalidae, was abundant in all

treatments, although several families showed greater abundance in the natural regeneration treatment.

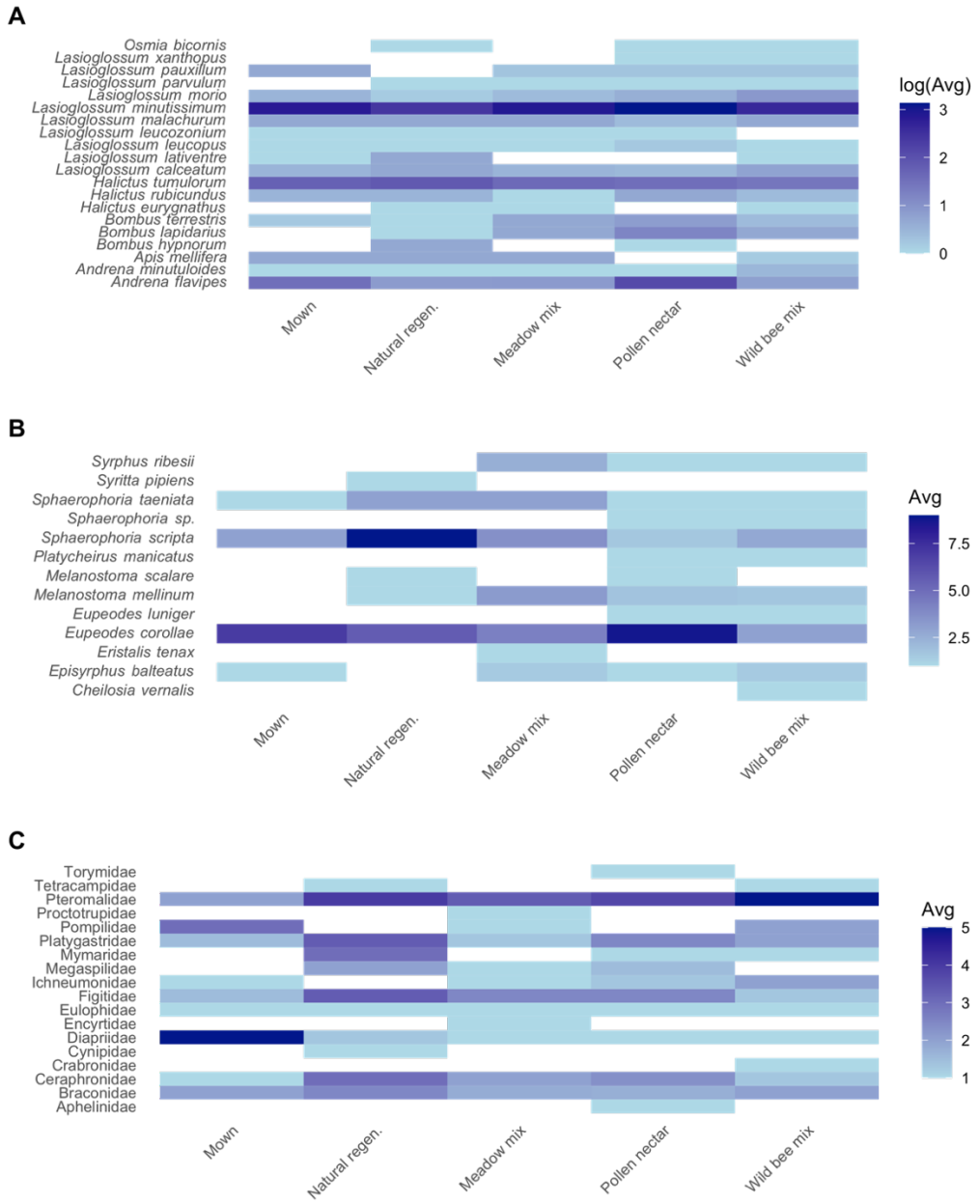

Figure 5.5. *Abundance heatmaps of A) twenty most abundant bee species B) all hoverfly species and C) all solitary wasp families. Based on average mean abundance of sampled insects by inter-row ground cover treatment combining year 1 and year 2 data. Bee heatmap (A) presents the 20 most abundant bee species sampled by pan trap and transect walk, log-transformed for visualisation purposes. Hoverfly heatmap (B) presents species sampled by pan trap and transect walk. Solitary wasp heatmap (C) presents family-level based on pan trap samples from July only.*

5.4.3. Pollinator (bee and hoverfly) and solitary wasp richness

In year 1, inter-row treatment did not have a significant effect on the richness of pollinator species for either pan trap ($X^2 = 2.53$, df = 4, $P = 0.64$; Fig 5.6) or transect walk ($X^2 = 5.8$, df = 4, $P = 0.21$; Fig 5.6) sampled insects. In year 2 however, analysis of transect walk data indicates a significant effect of treatment on pollinator richness ($X^2 = 9.87$, df = 4, $P < 0.05$; Fig 5.6), although post-hoc tests did not identify the driver of this effect. However, wild bee mix had the highest pollinator richness (mean ± SE: 2.38 ± 0.34) and mown treatment had the lowest (mean ± SE: 0.50 ± 0.32). In year 2, inter-row treatment did not have a significant effect on the richness of pollinator species for pan trap sampled insects ($X^2 = 4.92$, df = 4, $P = 0.30$; Fig 5.6).

The majority of the solitary wasps identified to family were parasitoid wasps (section 5.4.2). There were no differences between treatment in the richness of solitary wasp families in year 1 ($X^2 = 1.93$, df = 4, $P = 0.75$; Fig 5.6). There were also no differences between treatments in the richness of solitary wasp families in year 2 ($X^2 = 8.92$, df = 4, $P = 0.06$; Fig 5.6), however, this is a marginal result. Again, the average richness of wasp families sampled from mown was lower (mean ± SE: 5 ± 0.26) than all other inter-row treatments (Fig 5.6), most noticeably natural regeneration (mean ± SE: 8.67 ± 0.6).

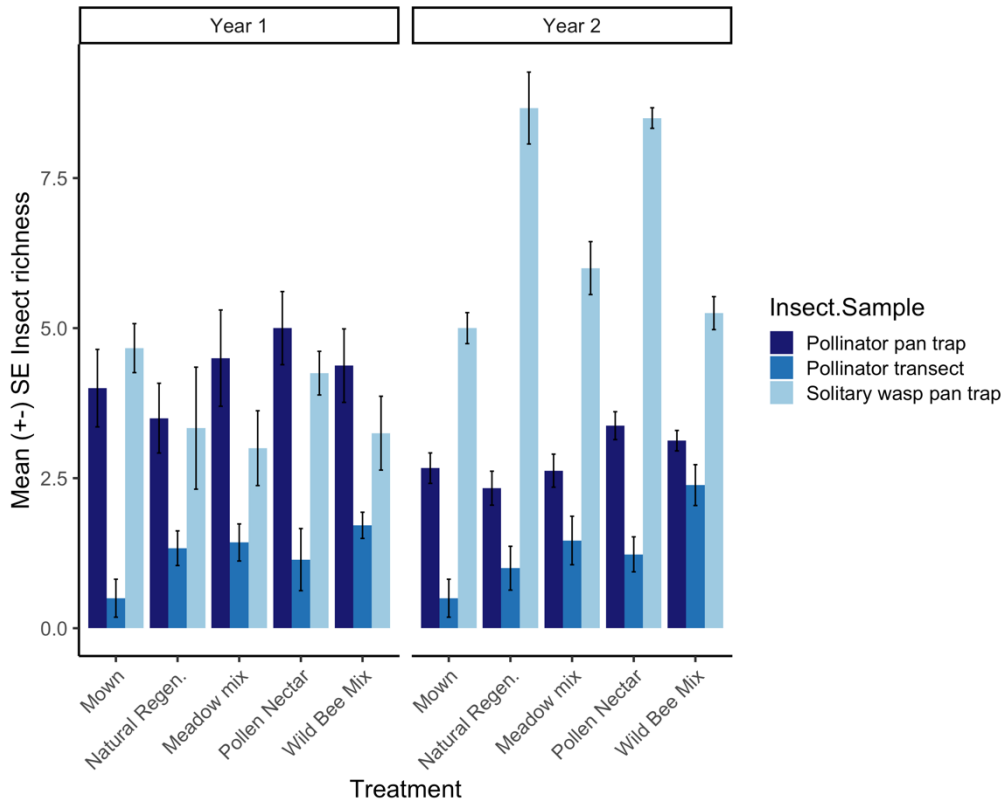

Figure 5.6. *Richness of pollinators (pan-trap and transect walk data) and solitary wasps (pan trap only) collected across five different inter-row ground cover treatments. Pollinator species (bees and hoverflies) are from monthly samples collected between May-August each year, and solitary wasps are from July only each year.*

NMDS analysis showed that pollinator communities (bee and hoverflies species) did not differ significantly between inter-row treatments (PERMANOVA: $F_{1,34} = 0.98$, $P = 0.51$). Solitary wasp family communities did also not differ significantly between inter-row treatments (PERMANOVA: $F_{1,34} = 0.77$, $P = 0.8$).

5.5. Discussion

In an experimental manipulation of vineyard inter-row ground cover management, we found that insect abundance, pollinator richness and solitary wasp richness respond positively to the sowing of wildflowers in a British vineyard. While this result is not unexpected, it is to the best of our knowledge the first published study on the role of wildflowers in increasing insect biodiversity in a British vineyard. It confirms that wildflowers have the potential to support biodiversity in these typically monocultured landscapes, boosting biodiversity and potentially enhancing pest control management.

Sowing wildflowers increased both floral abundance and diversity. By year 2, the diversity of the floral community had increased for all five treatments, which would be expected with the establishment of perennials in the year following sowing, and dispersal of seeds amongst rows in the experimental site. The diversity, richness and abundance of flowers were highest for the mixes that contained grasses (meadow mix and wild bee mix), followed by the pollen and nectar mix and natural regeneration. Unsurprisingly, the mown treatment had the lowest floral richness and abundance. By the second year of the study, floral diversity, richness and abundance of flowers in the natural regeneration treatment were twice that of the mown treatment. Two-thirds of British vineyard managers currently maintain frequently mown grass as inter-row ground cover (with mowing regime ranging from 10 days to monthly in the spring and summer). Of the remaining vineyards, 28% allow natural regeneration of the existing seed bank, and just 6% currently sow wildflower seeds between rows (chapter 6).

In year 2, a total of 23 species of flowering plants were recorded in natural regeneration inter-row treatment, 18 of which naturally colonised (not included in any of the sown mixes). A total of 13 flowering plants were recorded in the mown inter-row treatment, 10 of which naturally colonised. Certain flowers are traditionally considered ‘weeds’, yet contribute valuable food resources for pollinators with high nectar/pollen rewards. For example, dandelions (*Taraxacum* agg.) produce high quantities of pollen and nectar (Hicks et al 2016), and *Taraxacum officinale,* along with three species from the *Sonchus* genus, (commonly known as ‘sow thistles’ from the dandelion tribe) were present in the natural regeneration inter-rows (compared to just one of these *Sonchus* species being present in the mown inter-rows). Likewise, *Cirsium arvense* a top nectar producer, and *Papaver rhoeas*, a top pollen producer (Hicks et al 2016) germinated in the natural regeneration treatment but not the mown. Existing seed bank can provide a diverse range of flowers that are visited regularly by hoverflies and bees (Warzecha et al 2018). Therefore, natural colonisation and simply reducing mowing could enhance pest management and biodiversity without the agronomic, management and resource challenges of adding floral plantings. The site of the study vineyard was previously arable farmland and has a varied seed bank of perennial flowers that reappear readily after mowing, so even the mown inter-row treatment produced flowers during this study. Other vineyards may have a more limited seed bank, perhaps due to herbicide application or a more frequent mowing regime, and perhaps more significant

differences between wildflower mix and mown inter-row treatments would be seen in these vineyards.

Once wildflowers were more established in the second year of the study, the abundance of all insects was significantly higher in the wild bee mix treatment compared to the mown treatment. There was also a significant effect of inter-row treatment on pollinator richness in year 2, and although post-hoc comparisons could not determine where this significance lay, again the wild bee mix had the highest average richness of pollinators and mown inter-row strips had the lowest average richness. Certain plant species are more or less beneficial for increasing pollinator abundance (Warzecha et al 2018), and in our study, floral communities differed significantly between the treatments. This suggests that key species to benefit pollinators are found in the wild bee mix. Our findings are consistent with previous studies conducted in wine-growing regions throughout the world (Kehinde and Samways 2014; Kratschmer et al 2019; Kratschmer et al 2021; Wilson et al 2018), that inter-row floral plantings increase the richness of bee species and beneficial insect abundance. In our study, significant results were limited to year 2 when wildflowers were established, and differences in significance were also seen between the two sampling methods. Indeed, Templ et al (2019) recommend a combination of both sampling techniques to obtain more information on wild bee species populations.

The majority of the solitary wasps identified to family were hymenopteran parasitoid wasps, a group of insects with a very important role in pest control. The effect of inter-row treatment on the richness of wasps in the second year of the study was marginally significant, despite data being limited for this particular analysis. As was found for pollinator richness results, mown inter-rows had the lowest average wasp richness compared to all other treatments. However, in contrast to the results for pollinator species richness (which was highest in the wild bee mix treatment), wasp richness was highest in the rows permitted to naturally regenerate. Similarly, previous studies report that introduced floral resources are beneficial for parasitoid wasps in vineyards (Judt et al 2019; Nicholls et al 2000) as is natural regeneration (Möller et al 2020) and simply a reduced mowing regime (Zanettin et al 2021).

Previous research regarding habitat management to enhance natural pest control has been dominated by the cultivation of a limited number of plant species. Indeed, one or

more of the plant species *Phacelia tanacetifolia*, *Fagopyrum esculentum, Lobularia maritima* and *Coriandrum sativum* were used in 79% of studies included in a review of habitat management for natural predators by Fiedler et al 2008. The authors state as these particular species were effective in earlier studies they have become influential in later research. Interestingly, flowers considered 'weeds' were as effective in increasing parasitoid longevity and fecundity when compared to 'flowers' commonly used in parasitoid studies (Araj and Wratten 2015). It would be beneficial to investigate the potential of a more diverse range of flowers in providing dual resources for pollinators and parasitoid wasps, as we have shown in this research.

The presence of parasitoid wasps or hoverfly larvae has been associated with reduced pest population (Ramsden et al 2017) and limited pest damage (Tschumi et al 2015) although other studies question whether this increased abundance of natural enemies translates into effective pest reduction (Berndt et al 2006; English-Loeb et al 2003). An extension of the current study would explore pest - natural enemy interactions and quantify any pest reduction. Seventy-four per cent of British vineyard owners use synthetic chemical treatments for pest control (chapter 6), therefore, further research into effective natural biological control would contribute to the sustainability of this sector.

The spatial scale in the current study is the main limitation, which may have been too small to detect significant differences in certain analyses. A greater distance between inter-row wildflower strips and a block design, for example, would limit cross-over of flowers and insects between treatments. Future research should ideally be expanded to incorporate multiple vineyards on different soil types and over a longer temporal scale, and include landscape-scale factors, given this has been shown to affect wild bee diversity in various ways (e.g. Kratschmer et al 2018; Kratschmer et al 2019; Uzman et al 2020; Wilson et al 2017). Comparison of crop yield data of different inter-row ground cover treatments within the vineyards is also necessary before making definitive recommendations to landowners. The potential role of wildflowers on other taxa, such as soil-dwelling arthropods and birds, should also be explored in future studies.

One of the perceived obstacles in the creation of floral plantings in agri-ecosystems is the loss of space for crops (Landis et al 2000), however, the approach tested here utilises inter-row spaces with no loss of cropped land. Headlands around the vines are

commonly used for wildflower planting, with 80% of British vineyards utilising this space for sown or unsown flowers (chapter 6). However, headlands are generally much smaller than the swathes of land converted to ground under-vines. Additionally, inter-row plantings could act as corridors, encouraging natural enemies which would spill over onto the vines (Woodcock et al 2016a).

Research on inter-row floral plantings in cherry orchards found that active management in keeping floral cover height at 20cm increased floral abundance and provided pest regulation services comparable with floral plantings cut at the end of the summer season (Mateos-Fierro et al 2021). The authors suggest this management might encourage more landowners to plant floral resources as it reduced humidity for the crop and facilitates management activities. Difficulties in accessing the vines is a reason for resisting the planting of inter-row wildflowers in Californian vineyards (Wilson and Danne 2017). Indeed, alternating management of inter-row ground cover by having wildflowers every other row would benefit biodiversity whilst also facilitating movement around the vines. Additionally, patches of bare ground as part of a habitat mosaic could also benefit insectivorous birds (Schaub et al 2010).

5.5.1. Conclusions

Promotion of perennial wildflowers through sowing or allowing natural regeneration in inter-row ground cover in vineyards has the potential to boost biodiversity in vineyards on a large scale if widely adopted. Here we report that total insect abundance and pollinator richness benefited from increased floral resources, and the creation of more diverse insect communities results in more resilient pollination services (Woodcook et al 2019). We also found that a wild bee wildflower mix attracted more insects overall and specifically more pollinator species than any other inter-row treatment, probably due to key floral species present in the mix. We found that simply allowing the recolonisation of floral species by decreasing the mowing regime in the natural regeneration treatment increased the diversity of flowers. Furthermore, although significance was marginal, average solitary wasp family richness was greater in naturally regenerated inter-rows than that of the mown treatment. Therefore, natural regeneration of inter-row space could benefit biodiversity without requiring significant resources. UK agri-environmental schemes have yet to make specific recommendations to support biodiversity in viticulture. Here we demonstrate a simple, low cost and

effective approach for maximising beneficial insects and supporting key ecosystem services. Given the rapid growth of the vineyard industry and its potential impact on habitat change, further investigation of the potential for enhancing biodiversity in British vineyards is essential.

CHAPTER 6

6. Grape expectations: A survey of British vineyard land management practices from an environmental perspective

This chapter has been published as:

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JGL, EN and DG conceived the ideas and methodology; JGL collected and analysed the data, and led the writing of the manuscript. All authors commented on draft versions of the manuscript, and a slightly amended version of the published paper is presented here.

6.1. Abstract

Traditional vineyard landscapes are generally intensively managed with heavy reliance on synthetic pesticides. Viticulture is one of the fastest-growing sectors of English agriculture and information on land management is essential to secure a sustainable future. We surveyed viticulturists to ascertain vineyard pest presence, pest control, inter-row ground cover and wildflower use. The majority of viticulturists reported the presence of vineyard pests and relied heavily on pesticides, with 74% using synthetic pest control, 40% using herbicides and 40% using fungicides. Inter-row, 66% of vineyards have grass-only cover and frequent summer mowing, with only 6% sowing wildflowers. However, 60% use natural pest control, 80% reported the existence of wildflowers in headlands, and 29% mentioned reduced mowing. We discuss spontaneous and sown wildflowers and benefits for biodiversity, integrated pest management and the commonly perceived barriers to adaptation. We conclude there is huge variation in management styles and more evidence-based environmental advice for viticulturists is needed.

6.2. Introduction

Globally, around 7.4 million hectares of land are currently cultivated by wine or table grapes (*Vitis* spp.) (OIV 2019). Ongoing conversion of natural habitats to viticulture is to the detriment of biodiversity in many of the world's top wine-producing regions (Armesto et al 2010; Fairbanks et al 2004; Merenlender 2000), particularly since traditional vineyard landscapes are generally intensively managed with heavy reliance on synthetic chemical pesticides (Urruty et al 2016). Synthetic pesticides are of great concern to human health and the wider environment, and more sustainable and ecological methods in agricultural food production are urgently needed (Nicolopoulou-Stamati et al 2016).

Grapevines cannot benefit from crop rotation or changes to cropping systems practised in traditional agriculture, and this can increase pressure from pests. *Erysiphe necator* (powdery mildew), *Plasmopara viticola* (downy mildew) and *Botrytis cinerea* (botrytis, or grey mould) are among the most important pests, and the fungicides used to treat these diseases account for the majority of pesticide treatments in European vineyards (Pertot et al 2017). Insecticide use against arthropod grape pests is currently low in

European vineyards (Pertot et al 2017), although the emergence of new vineyard pests due to shifts in distributions under a changing climate is of concern (Reineke and Thiery 2016).

There are common approaches to integrated pest management (IPM) practised in European viticulture. These include the use of resistant varieties, semiochemicals, biopesticides, biological pest control, and pest monitoring combined with the use of epidemiological mathematical models to schedule and limit pesticide use (Pertot et al 2017). Biopesticides are not as widely used as synthetic pesticides due to cost, shelf-life and lower effectiveness, but potassium bicarbonate and seaweed extracts, for example, are common alternatives to chemical fungicides to treat downy mildew (Pertot et al 2017).

The planting scheme commonly practised in viticulture leaves a large portion of uncultivated and untilled soil between the vine rows. Diversity of soil-dwelling organisms and surface organic matter generally decreases with increasing tillage intensity in agriculture (Roger-Estrade et al 2010). Minimising tillage is also beneficial for bee diversity because of the encouragement of perennial flowers (McHugh et al 2022), and therefore vineyards have great potential to support biodiversity because they are not regularly tilled.

In agricultural environments, sown wildflower strips are often implemented to provide resources for pollinators (Blaauw and Isaacs 2014a) and although grapevines do not have an obligate relationship with pollinators, the establishment of wildflowers in these typically monocultured landscapes is beneficial for biodiversity. For example, studies on inter-row plantings of wildflowers in wine-growing regions conclude that they increase the richness and abundance of wild bees (Kehinde and Samways 2014; Kratschmer et al 2019; Kratschmer et al 2021; Wilson et al 2018).

Wildflower strips also provide essential resources for natural enemies of pests (Landis et al 2000). In vineyards, inter-row wildflowers are beneficial for insect parasitoids (Judt et al 2019) and other natural enemies (Abad et al 2021a). By reducing vine vegetative growth, cover crops in inter-row alleys also reduce the incidence of fungal diseases such as mildew (Abad et al 2021b) and are a traditional alternative to using herbicides to control inter-row vegetation in vineyards (Pertot et al 2017). In addition to

supporting biodiversity and pest control services, wildflowers in a vineyard enhance numerous other ecosystem services with positive effects on soil organic carbon, water infiltration, and soil erosion reduction (Abad et al 2021a).

There are also benefits to reducing mowing, thereby encouraging the spontaneous flowering plant species that grow in vineyard inter-rows. Low-intensity meadows with less frequent mowing have a higher diversity of plants, bees and butterflies (Weiner et al 2011). Reducing mowing frequency enhances insect diversity (Del Toro and Ribbons 2020; Wastian et al 2016) and in a vineyard setting has been found to benefit parasitic wasps (Zanettin et al 2021).

In Great Britain, vineyard coverage has quadrupled since 2000, with around 800 vineyards and approximately 3,300 ha of land under vine (WineGB 2021a). Ninety-eight per cent of these vineyards are based in England (WineGB 2021a). UK agri-environmental schemes have yet to make specific recommendations to support biodiversity in viticulture, despite it being one of the fastest-growing sectors of English agriculture (South Downs National Park Authority (SDNPA) 2021). Considering this growth, there is huge potential to establish sustainable, environmentally friendly land management practices while this production system is still in its relative infancy. We conducted a survey of vineyard owners and managers in Great Britain, to ascertain land management and pest control preferences, and to establish research priorities to support a sustainable future for this sector. We wanted to understand: 1) most frequent pests present; 2) synthetic and natural pest control methods employed; 3) use of inter-row ground cover; 4) use of wildflowers in the vineyard; 5) information resources used to support decisions.

6.3. Methods

A survey was created to evaluate the land management practices of vineyard owners or managers (viticulturists). The main themes of the survey were pest abundance, pest control methods, synthetic chemical use, mowing regime, utilisation of wildflowers and information sources used to make management decisions. The survey consisted of 15 questions and was a combination of multiple choice and free text (Appendix L lists the survey questions). The survey was circulated to British vineyards via ‘WineGB’ members and by direct contact. Available online (hosted on ‘Qualtrics’) and as a Word

document, the survey was open for four weeks during June-July 2021. Vineyards could choose to remain anonymous.

Thematic analysis was conducted on the free text options across all responses (Braun and Clarke 2006), identifying key themes and the frequency these were mentioned. If a vineyard mentioned the same theme across multiple answers, this was still classed as a single count. Due to the range of responses, only themes with a count of two or more are presented in this study. Graphs were produced in R (R core team 2020) using *ggplot2*.

6.4. Results

6.4.1. Responding vineyards

Viticulturists from 35 British vineyards responded to the survey with full responses that could be used in the analysis. The majority of vineyards were based in the South of England: 43% in the South West and 37% in the South East (Fig 6.1). The remaining vineyards were evenly distributed in the East Midlands, East of England, Wales, and the West Midlands. The size of the vineyards ranged from 0.1 ha to 94 ha, with a mean of 8.9 ha (median of 2.75 ha) and more recently established vineyards were generally smaller (Fig 6.2). The majority of vineyards had vines that had been established for 10-15 years (Fig 6.2); the oldest vines were planted in the 1980s.

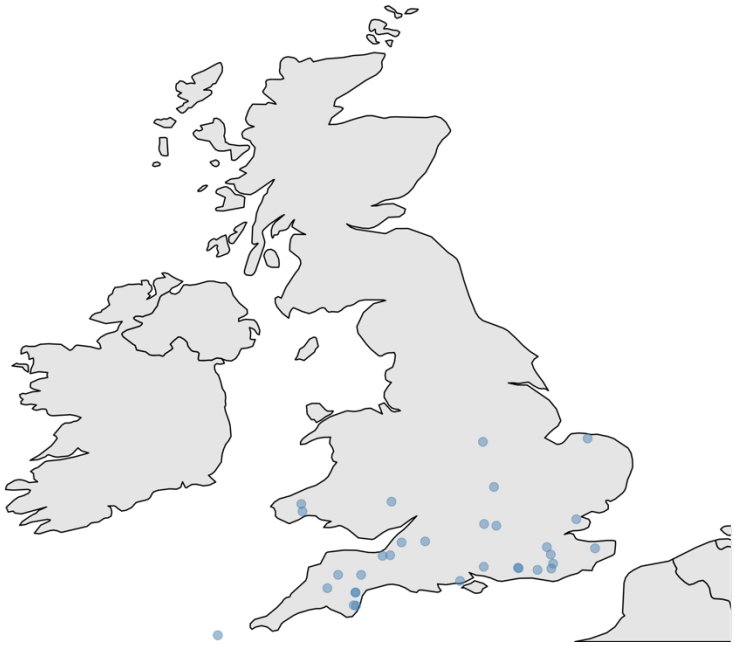

Figure 6.1. *Map of Great Britain showing the approximate locations (lat/long) of non-anonymised vineyards participating in the survey.*

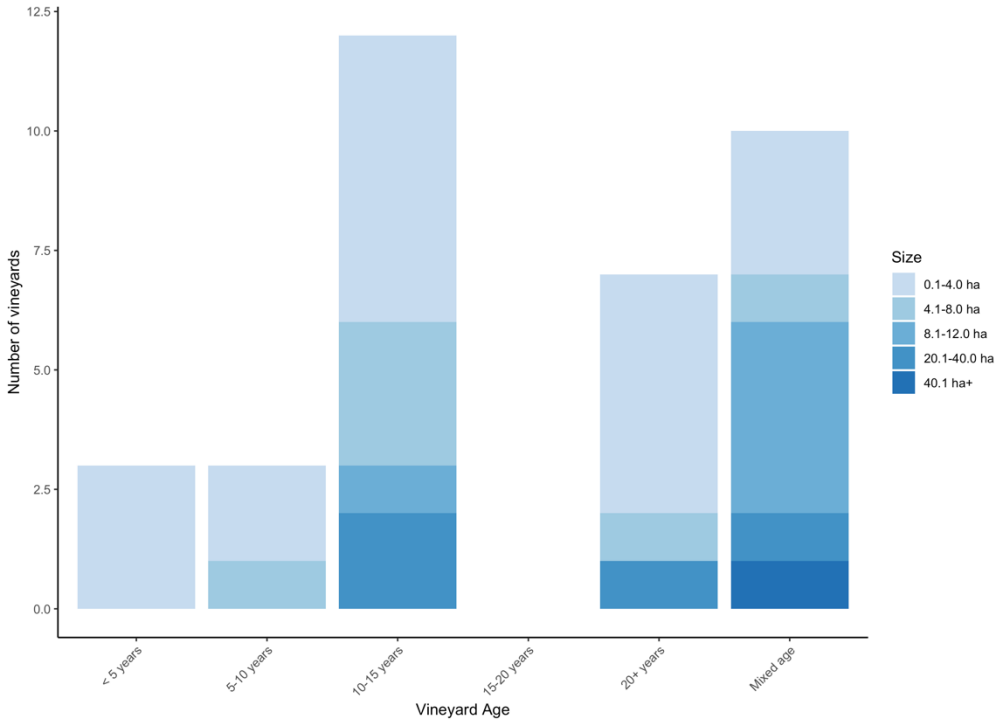

Figure 6.2 *Size in hectare (ha) of 35 participating vineyards, grouped by size (0.1-4.0 ha, 4.1-8.0 ha, 8.1-12.0 ha, 12.1-20.0 ha, 20.1-40.0 ha, 40.1 ha +) and time since establishment (<5 years, 5-10 years, 10-15 years, 20+ years, mixed age. No data for 15-20 years).*

6.4.2. Vineyard pests

In response to the question *'Could you please tell us about the pests that are a problem at your vineyard, including any you have eradicated, or are an ongoing problem?'*, pests were grouped into vertebrate pest, insect pest, and fungal pest (which also included oomycetes), and 74% reported the presence of pests in their vineyard (Fig 6.3) detailing current, seasonal or historic pests. The majority of viticulturists reported the presence of one distinct vineyard pest of any type, although the presence of up to seven distinct pests was reported (Fig 6.4). Over half of viticulturists reported the presence of at least one insect pest species (Fig 6.3) with the majority of those reporting just one insect pest species (Fig 6.5). Wasps were the most commonly reported pest, mentioned by 31% of viticulturists (Table 6.1). Although not explicitly stated, we assume these to be common social wasps, as they were described to feed on grapes. Birds were mentioned by 20% of viticulturists, mildew (both downy and powdery) by 17%, and botrytis by 11% of viticulturists (Table 6.1). Deer were mentioned by 11% of viticulturists and were perceived to cause damage by eating the younger vines.

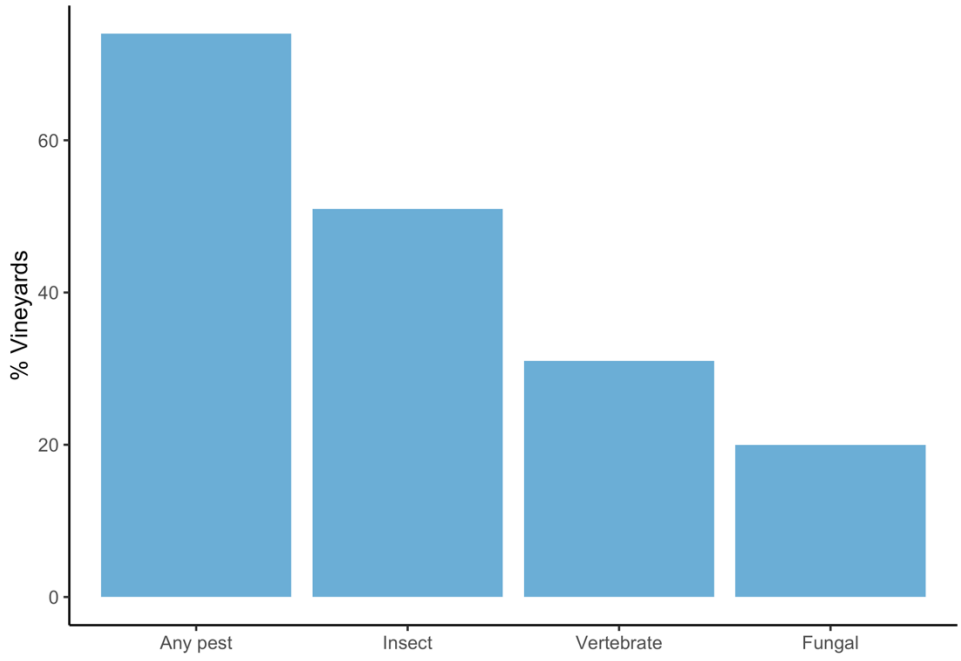

Figure 6.3. *Percentage presence/absence of pests in vineyard responding to the survey. Presented as any pest, insect pest, vertebrate pest, and fungal pest. Sample size n = 35 vineyards.*

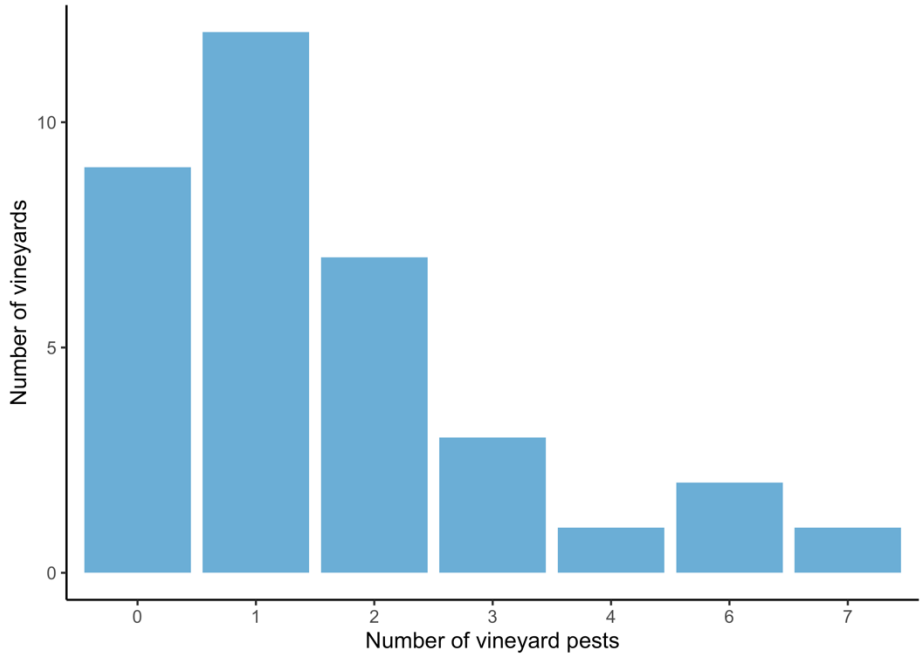

Figure 6.4. *Count of all distinct pests (combining insect, vertebrate, or fungal) recorded in vineyards. Response to question – 'Could you please tell us about the pests that are a problem at your vineyard, including any you have eradicated, or are an ongoing problem?' Sample size n = 35 vineyards.*

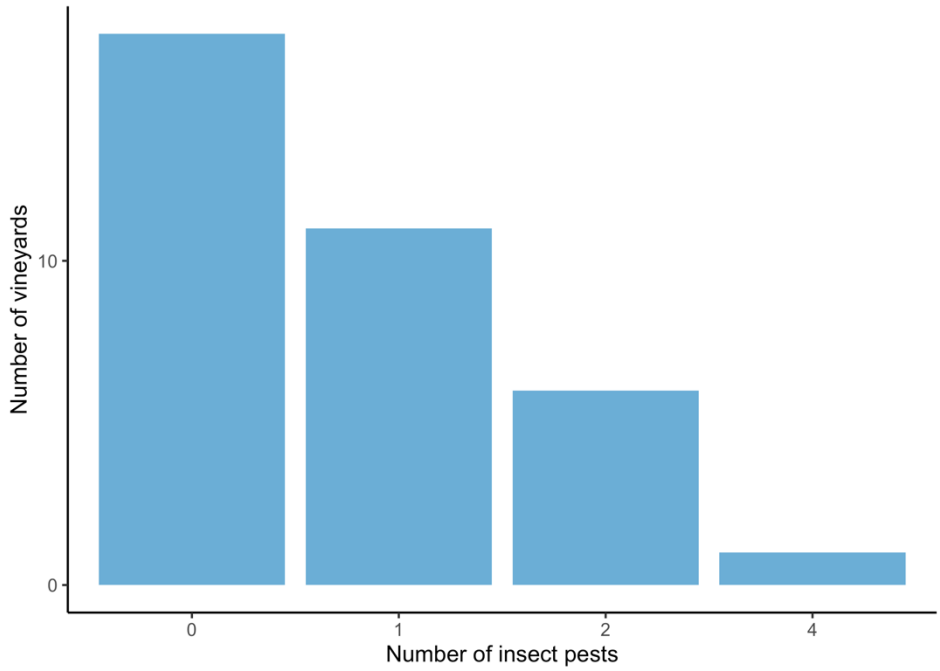

Figure 6.5. *Counts of distinct insect pests recorded in vineyards. Sample size n = 35 vineyards.*

Theme	Vineyard	Theme	Vineyard
Pest		**Flowers in headlands**	
Spotted wing drosophila	11%	Bird's foot trefoil	17%
Wasps	31%	Chicory	6%
Badgers	11%	Vetch	11%
Botrytis	11%	Clover	20%
Mildew (powdery and downy)	17%	Wild marjoram	6%
Birds	20%	Teasel	6%
Little brown apple moths	6%	Scarlet pimpernel	6%
Thrips	11%	Cowslip	6%
Deer	11%	Dandelion	6%
Mites	6%	**Barriers to using sown wildflowers**	
Natural pest control		Natural regeneration sufficient	20%
Seaweed extract	11%	Under consideration	11%
Exclusion netting / fencing	6%	Cost and/or logistics	17%
Potassium bicarbonate	11%	**Other**	
Nettle extract	6%	Hedgerows	9%
Wasp and *Drosophila* traps	20%	Reduced mowing	29%
Wildflowers	9%	Natural regeneration establishment	11%
Pest and land management advice			
Online, book, published research	43%		
Other vineyards	11%		
Agronomist/ecologist	26%		
Consultants	14%		
No advice needed	9%		
WineGB	14%		

Table 6.1. *Thematic analysis and % of viticulturists that mention themes, across all survey free-text responses.*

6.4.3. Synthetic chemical pest control

In response to the question *'Are you an organic vineyard?'*, 14% were certified organic (Fig 6.6) and a further 11% of vineyards reported practising organic methods but were not officially certified.

In response to the question *'Do you use any chemical treatments to eradicate insect pests or vine diseases at your vineyard?*' and if the answer was 'yes': *'If you are happy*

to tell us more about the chemical treatments used for insect pests or vine diseases, please do so here. Such as: Chemical treatment name, Applications per year, Target pest, % Effectiveness', we found synthetic chemical pest control to be widespread in those British vineyards responding to our survey (74%) (Fig 6.6). The majority of synthetic treatments reported were fungicides with 40% of viticulturists listing these treatments. Spraying regime varied greatly, with comments stating 'early in the season only', 'throughout the season', and 'every 10-14 days'. The number of products used also varied greatly from vineyard to vineyard, ranging from one to 13 fungicide products. Although not strictly classified as synthetic, we have included copper oxychloride fungicide here, which was mentioned by 6% of viticulturists, because of its effects on edaphic biodiversity and persistence in soils. Only 9% of viticulturists listed the use of chemical insecticides. Thematic analysis specifically on synthetic chemical use for pest control was not possible, due to the range of products, ingredients, and spraying regimes followed.

In response to the question '*Do you use weed killer or herbicide between vine rows?*' and if the answer was 'yes': *'If you are happy to do so, please tell us what weed killer or herbicide you use',* 40% of viticulturists reported using herbicide (Fig 6.6). Of those responding positively to this question, glyphosate was used by 85% with the remaining viticulturists failing to disclose which herbicide they used.

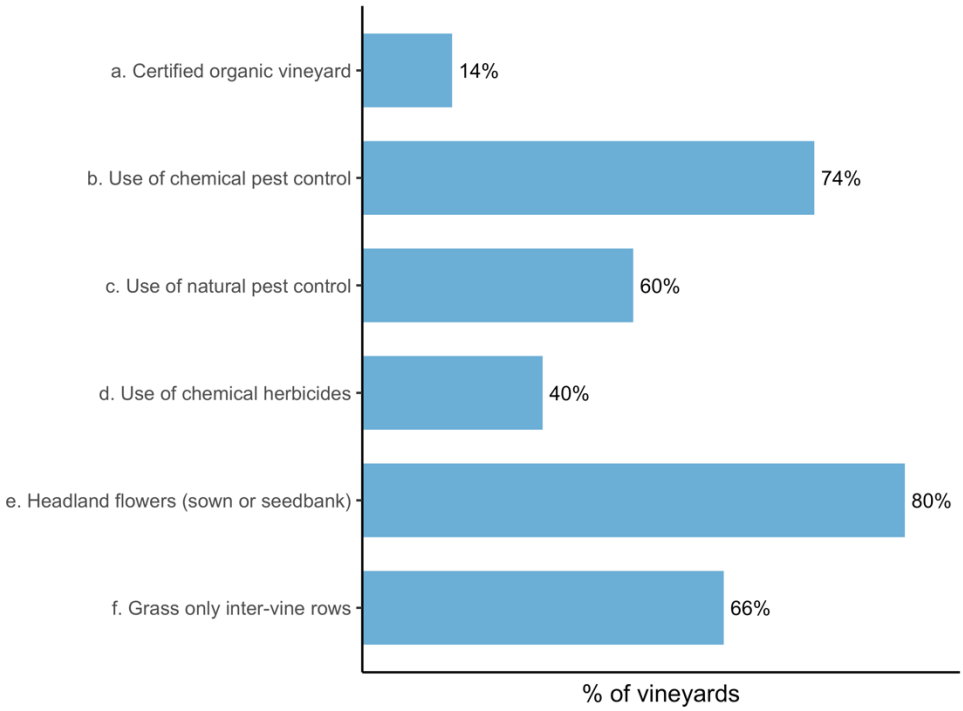

Figure 6.6. *Land management and pest control preferences. Percentage responding 'Yes' to a) 'Are you an organic vineyard? b) 'Do you use any chemical treatments to eradicate insect pests or vine diseases at your vineyard?' c) 'Do you use any natural methods to eradicate insect pests or vine diseases at your vineyard?' d) 'Do you use weed killer or herbicide between vine rows?' e) 'Do you have any sown wildflower margins, or areas of natural flower regeneration in the land surrounding the vines?' and responding 'grass only' to question f) 'What type of ground cover do you have in-between your vines?'. Sample size n = 35 vineyards.*

6.4.4. Natural pest control

In response to the question '*Do you use any natural methods to eradicate insect pests or vine diseases at your vineyard?*' and if 'yes': *'If you are happy to tell us more about the natural methods used for insect pest eradication or vine disease, please do so here. Such as: Natural method name, Applications per year, Target pest, % Effectiveness'*, 66% of viticulturists use natural (ie. non-synthetic chemical) methods of pest control (Fig 6.6), while 54% use both natural and synthetic pest control methods. The most commonly used natural pest control methods were traps (mostly for wasps, but also *Drosophila*), mentioned by 20% of viticulturists. Wildflowers in the context of pest control were mentioned by 9% of viticulturists. Seaweed extract and potassium

bicarbonate were both reported to be sprayed on vines for natural pest control in 11% of vineyards (Table 6.1).

6.4.5. Inter-row ground cover and headlands

In response to the question '*What type of ground cover do you have in-between your vines*?' 66% of viticulturists reported the growth of grass inter-row (Fig 6.6). This space was reported to be mowed often during the spring and summer months, with frequency of mowing ranging from every 10 days to once a month. Twenty-eight per cent reported or identified spontaneously-occurring wildflower species in the inter-row alleys. Six per cent of viticulturists sow wildflower seeds in inter-row alleys to supplement the naturally occurring flowering species (Fig 6.6).

In response to the question *'Do you have any sown wildflower margins, or areas of natural flower regeneration in the land surrounding the vines?'* and if the answer was 'yes', *'Please tell us more, such as which wildflowers you sow',* 80% reported flower margins or headlands around the vines (Fig 6.6). Forty per cent of viticulturists relied on natural regeneration of spontaneously occurring flowering species, while 20% mentioned wildflowers being supplemented with wildflower seeds in the margins and headlands. The most frequently mentioned flowering species were *Lotus corniculatus* (bird's foot trefoil) and *Trifolium* species (clovers), although we could not ascertain if these were sown or spontaneous (Table 6.1). The majority of wildflowers reported were native species.

Responding to the free text question *'If you don't use flowers in-between vine rows or in the margins around your vines, is this something you are thinking about doing? If not, could you tell us why?',* 20% of the viticulturists felt the natural regeneration of wildflowers was sufficient, although 11% said they would consider sowing wildflowers in the future (Table 6.1). Seventeen per cent of the viticulturists mentioned cost and/or logistics as a factor in sowing wildflowers at the vineyard. One viticulturist elaborated and told us that mown grass is easier to walk on for long hours compared to taller vegetation. Another perceived barrier was the potential for mildew resulting from the sowing of wildflowers inter-row, while another viticulturist stated it was a 'silly idea'.

The benefits of reduced or delayed mowing for pest control/wildlife were mentioned by

29% of viticulturists, and the benefits of hedgerows by 9% (Table 6.1). The time taken for natural regeneration to establish a diverse floral community was mentioned by 11%, with viticulturists stating it took at least 10 years.

6.4.6. Land management and pest control information sources

In response to the free text question *'Where do you get advice on pest treatments and land management?',* many of the viticulturists reported using multiple sources of information for decisions on pest treatment and land management. Forty-three per cent of viticulturists mentioned books or online resources for research, and 26% mentioned agronomists or ecologists (Table 6.1). Other sources of advice included consulting other vineyards (11%), use of consultants (14%) and contacting WineGB (14%). Nine per cent of viticulturists reported not needing advice on pests and land management.

6.5. Discussion

We surveyed 35 vineyard owners or managers to understand current land management practices in British viticulture, gathering key information on vineyard pest abundance, pest control methods, synthetic chemical use, mowing regimes and the utilisation of wildflowers in vineyard landscapes. We conclude there is considerable variation in management styles and the resources used to inform practices in British viticulture.

Nearly three-quarters of vineyards responding to our survey used some form of synthetic chemical pest control (excluding herbicides) and 14% of the vineyards were certified organic. Just 9% of vineyards reported using insecticides, which accords with their reported low use in European vineyards (Pertot et al 2017). Synthetic herbicide use was reported by 40% of viticulturists, with the majority of those (85%) using glyphosate. The most widely used herbicide across the agricultural sector (Baylis 2000), the safety of glyphosate is subject to ongoing debate, with numerous studies investigating its impacts on human health (see Nicolopoulou-Stamati et al 2016 and references therein) and negative impacts on bees (Motta et al 2018; Straw et al 2021).

Pests were present in the majority of British vineyards (including vertebrate, insect and fungal pests) and over half of vineyards had at least one insect pest. Wasps were the most common pest in the vineyards and were typically controlled using natural methods such as wasp traps. Downy and powdery mildew and botrytis were mentioned by a

smaller percentage of viticulturists (17% and 11% respectively) although fungicides used for controlling these diseases were the most reported synthetic chemical treatments used. There was also a large variation in spraying regimes reported between vineyards. Similarly, in European vineyards, fungicides to treat botrytis and mildew account for the majority of pesticide use (Pertot et al 2017). Given that fungicides have negative effects on non-target species, including sub-lethal and lethal effects on bees (Cullen et al 2019) there is potential to improve sustainability through the recommendation and further research of alternative methods to control fungal pests.

Wildflowers can provide a natural alternative to herbicides, fungicides and insecticides for certain pests. A systematic review on the effects of inter-row crop cover found a reduction in vine vegetative growth, and an associated reduction in the incidence of fungal disease in 67% of studies (Abad et al 2021b). These studies recorded reductions in the incidence of powdery mildew and botrytis, both frequently listed as pests by vineyards in our study. Additionally, a traditional and natural alternative to herbicide use in viticulture is cover cropping or shallow tillage (Pertot et al 2017). Furthermore, studies on inter-row plantings in traditional wine-growing regions to benefit biodiversity and natural pest control of insect pests are numerous (Abad et al 2021b and references therein; Judt et al 2019; Kehinde and Samways 2014; Kratschmer et al 2019; Kratschmer et al 2021; Wilson et al 2018).

Two-thirds of viticulturists reported the growth of grass only in inter-row alleys. We presume at least some of these vineyards had smaller flowering plant species spontaneously appear through natural regeneration in between the mowing regime, although these vineyards reported to frequently mow the grass in the spring and summer months. Encouragingly, the benefits of reduced or delayed mowing for pest control/wildlife were recognised by nearly one-third of vineyards. Only 6% of vineyards reported supplementing naturally-occurring flowering species with wildflower seeds inter-row, and only 9% of vineyards acknowledged wildflowers in the context of pest control. There is therefore considerable potential to raise awareness of the benefits of sown wildflowers for biodiversity, natural pest control and reducing reliance on synthetic chemicals.

We identified commonly perceived barriers to sowing wildflowers inter-row through our thematic analysis, such as flowers growing too tall, and this causing potential

problems accessing the vines and potentially increasing humidity, an issue also reported in Californian viticulture (Wilson and Danne 2017). However, actively managing floral cover at a maximum height of 20 cm in cherry orchards was found to provide favourable pest control services, limit humidity impacts on the crop and to facilitate access (Mateos-Fierro et al 2021). It would be valuable to research the impact of similar management in a vineyard landscape.

The majority of viticulturists reported the presence of flower margins in the vineyard headlands, and twice as many vineyards rely on natural regeneration rather than sowing wildflower seeds. However, headlands may not have as many benefits for providing natural pest control services when compared to allowing the natural regeneration or sowing of wildflowers in inter-row alleys. Inter-row plantings would act as corridors, encouraging natural enemies of pests to spill over into vines by increasing movement (Woodcock et al 2016a). Some vineyards considered the spontaneous natural regeneration of headland wildflowers to be sufficient, with no need to supplement this with seeds. Indeed, seed bank in agricultural landscapes has been shown to have high floral diversity of flowers favourable to pollinators (Warzecha et al 2018). Bird's foot trefoil and clovers received frequent mention by viticulturists and are well known to support pollinators (Cole et al 2022; Wood et al 2015), which is encouraging for the provision of food resources for pollinating insects in a vineyard landscape. Previous research has shown that targeted sowing of particular plant species rather than simply increasing overall plant richness is often more beneficial for pollinators (Warzecha et al 2018). Supplementing existing flowers with low-lying species such as dandelions (*Taraxacum* agg.) which are high in pollen and nectar (Hicks et al 2016) would provide valuable resources to support biodiversity.

A caveat of our study is that the use of pest control methods and the presence of pests are self-reported. More experienced viticulturists or those with an ecological background may be able to conduct a more systematic survey of pests or damage from pests, so there could potentially be biases in reporting. Further research into land management and pest control methods could incorporate vineyard surveys by trained experts, or more detailed interviews with viticulturists and consultants.

Overall, the use of synthetic pest control products and the spraying regimes varied greatly. The resources and information sources used by vineyards on land management

and pest control were also highly variable, and from the current survey we could not ascertain if these sources practised sustainable, organic or more traditional techniques. Established in 2019, the Sustainable Wines of Great Britain had 61 members as of 2021, accounting for 33% of the area of Britain under vine (WineGB 2021b), and has great potential to inform British vineyards of sustainable evidence-based practices as it grows in membership. Additionally, decision-support systems in IPM methods could reduce reliance on chemical pesticides (Pertot et al 2017).

The majority of vineyards responding to our survey were based in the South East and South West of England. These regions are experiencing rapid growth in the viticulture industry; In the South Downs National park, for example, there has been a 90% increase in the coverage of vines since 2016 (SDNPA 2021). We suggest that further research on natural pest control methods, evidence-based IPM and enhancing biodiversity in British vineyards are needed to improve the sustainability of this sector. The use of sown and spontaneous wildflowers in inter-row alleys as part of a suite of IPM methods may limit the reliance on synthetic chemicals, which are routinely used by British vineyards and beyond. As we have discussed, wildflowers can reduce the incidence of mildew and botrytis, are traditional alternatives to herbicide use, provide essential resources for the natural enemies of insect pests, benefit wider biodiversity and support multiple ecosystem services.

CHAPTER 7

7. General discussion

7.1. Research purpose

Habitat loss has had catastrophic effects on biodiversity. The global human population is estimated to reach 8.5 billion by 2030 (United Nations, 2022) and with this population growth comes an expansion of urban areas and agricultural systems, and increased pressure on ecosystem services. Beneficial insects provide ecosystem services integral to human survival, including pollination, decomposition and biological control. Within anthropogenically altered landscapes there is potential for habitat management to benefit biodiversity and ecosystem services, yet in general, the majority of work on habitat management utilising wildflower plantings has focused on arable farmlands. In this thesis, I have focused on provisioning wildflower resources in the potential space provided by gardens, allotments (chapters 2 and 3) and vineyards (chapter 5): anthropogenic habitats which have received significantly less attention in the scientific literature.

Firstly, as literature on companion planting in gardens and allotments is limited, I wanted to explore if introducing a pollinator-friendly wildflower companion plant can enhance pollination services to common garden crops, ultimately increasing yield ('Super Strawberries' chapter 2). I also wanted to investigate if small wildflower plots, which could be easily sown and managed by gardeners themselves, could boost insect abundance and richness ('Sow Wild!' chapter 3). To enable data collection for these two projects in private gardens and allotments I utilised the power of citizen science, allowing the collection of data at a spatiotemporal scale that would otherwise be difficult to achieve, whilst also engaging the public in experimental science. Verification of the results of both projects allowed analysis of effective sampling methods and possible bias in citizen science (chapters 2 and 4).

Under current climate change projections, potential land deemed suitable for viticulture in the UK is expanding, and we have a unique opportunity to influence the sustainably of this growing sector while it is still in its infancy. Just as with gardens, there appears to be an opportunity to incorporate more wildflowers within vineyards, boosting

biodiversity. To the best of my knowledge, I conducted the first field trials in the UK testing the effect of different inter-row ground cover treatments on beneficial insects in a vineyard (chapter 5). To understand current viticulture land management practices in the UK, and potential barriers to adopting such inter-row ground cover practices that are beneficial to pollinators, I also conducted a survey of UK-based viticulturists (chapter 6).

This thesis concludes that wildflowers can be introduced to gardens and vineyards, positively enhancing the abundance and richness of beneficial insects. A small 4 m^2 mini-meadow in gardens and allotments provided resource-rich habitats, supporting higher species richness of bees, and beneficial insect abundance compared to gardens without a mini-meadow (chapter 3). Furthermore, the addition of a wildflower as a companion plant in gardens and allotments can enhance pollination services to a commonly grown garden crop, increasing both crop yield and fruit aesthetics (chapter 2). Likewise, inter-row ground cover from sowing seeds or spontaneous wildflowers can have positive effects on beneficial insects in a vineyard, with no loss of land for grapevines (chapter 5). Furthermore, different wildflower mixes can be taxon-specific concerning the insects they attract in gardens and vineyards (chapters 3 and 5).

Currently, the UK viticulture industry is small in scale, but the use of synthetic chemical pesticides is similar to those reported by European counterparts (chapter 6) and I have explored the potential role of wildflowers in enhancing natural pest control in UK vineyards (chapter 5 and 6). Finally, I have examined the limitations, bias, and effective methods of citizen science conducted in private urban spaces (chapter 4). In this general discussion, I will consider the main themes and key outcomes which transcend the chapters.

7.2. The potential value of gardens, allotments and vineyards for habitat management

Sustainable intensification aims to increase yield without the adverse environmental impacts and loss of further land, with an awareness of the relationship between agricultural and non-agricultural landscape components (Pretty and Bharucha 2014). ‘Land sharing’ uses wildlife-friendly farming methods, whereas ‘land sparing’ separates natural habitat from intensive farming and is considered the most beneficial (Phalan et

al 2011). Indeed, a recent study found that taking the least productive cropland out of production and converting it into wildlife habitat boosted biodiversity whilst improving the yield of some crops (Redhead et al 2022). It is also important to consider the potential of vineyards and urban green spaces in the creation of wildlife friendly habitats and practices.

In the UK, 84% of the population live in urban areas (The World Bank 2018) and the number of households in England is estimated to increase by 7% between 2018 and 2028 (Office of National Statistics (ONS) 2021). However, the UK also has considerable potential habitat for pollinators in urban centres, including gardens, allotments, cemeteries, nature reserves, road verges and recreational parks (Baldock et al 2019). As gardens cover an area of 400,000 ha (The Wildlife Trust 2021) and comprise an estimated 24-36% of the area of UK cities, the sheer area covered makes them the most valuable urban green space in terms of habitat management for pollinators (Baldock et al 2019). Allotments, or community gardens, are also urban 'pollinator hotspots' providing valuable green space due to the diversity of pollinators and plants (Baldock et al 2019).

Historically, the ideal garden lawn was monoculture grass, cut short and frequently (Smith and Fellowes 2013), and this traditional 'perfect' lawn is still generally preferred by landowners (Bryne 2005). As recent as the year 2000, a New York Times article discussed the benefits of genetically modified grasses that could keep lawns free of 'weeds' (Barboza 2000). Furthermore, the global plastic artificial grass market is estimated to be worth $5.8bn by 2023 (Kaminski 2019), and in the UK context, 10% of homeowners have replaced natural lawn with artificial grass (AVIVA 2022). Despite this, there is increasing realisation that wild gardening benefits biodiversity (Goddard et al 2010) and growing momentum towards less intense management. For example, in the UK, Plantlife's 'no-mow May' (https://nomowmay.plantlife.org.uk) has received considerable coverage on the benefits of reducing mowing. Indeed, considerable positive effects on beneficial insects in gardens are achieved by simply mowing less (Del Toro and Ribbons 2020; Lerman et al 2018; Wastian et al 2016). In the UK, 12% of homeowners have a wildflower patch in their garden (AVIVA 2022). To increase awareness, we must challenge common expectations of what a garden should look like while educating on the benefits of wildlife gardening and rewilding.

Globally, approximately 7.4 million hectares of land are under vine (OIV 2019). In a UK context, there has been a 90% increase in the coverage of vines in the South Downs National Park (SDNP) since 2016 and an estimated further 40,000 ha of the park is suitable for viticulture under climate change projections (SDNPA 2021). However, SDNP is an important and diverse landscape, designated an Area of Outstanding Natural Beauty in 1966 and home to chalk grasslands, heathland and some of the world's oldest yew forests (SDNPA 2022). The traditional vineyard is also an intensively managed monoculture (Urruty et al 2016) with regularly mown grass or bare soil as vine inter-row ground cover. In many of the world's top wine-growing regions, habitat conversion to viticulture is threatening biodiversity, including California (Merenlender 2000), Chile (Armesto et al 2010) and South Africa (Fairbanks et al 2004). Although there is increasing movement toward environmentally-friendly practices globally, the need for adequate control of pests threatens sustainability (Daane et al 2018b).

Gardens, allotments and vineyards, therefore, have considerable and often overlooked potential for habitat management to benefit biodiversity and ecosystem services. Gardens and vineyards are traditionally intensively managed (Smith and Fellowes 2013; Urruty et al 2016) and a common obstacle to wildflower habitat management by land owners is the perceived loss of space in vineyards (Landis et al 2000) and lack of space in gardens (Goddard et al 2013). In gardens and allotments, however, the addition of a small mini-meadow supports a higher richness and abundance of bees, and the addition of a wildflower companion plant increases pollination services to a common garden crop (chapters 2 and 3). Therefore small-scale floral enhancements can attract more beneficial insects in fragmented urban landscapes, potentially supporting urban biodiversity and ecosystem services. Likewise in a vineyard (chapter 5), sown and spontaneous inter-row wildflowers also have positive effects on beneficial insects in a vineyard landscape, and this can be achieved with no loss of space for crops. Mown grass between vine rows is considered the default management in vineyards, and I found the majority of viticulturists regularly mow inter-row ground cover (chapter 6), yet this management has the lowest abundance and richness of pollinators, and lowest wasp family richness when compared to other treatments (chapter 5). Allowing the natural regeneration of wildflowers doubled the diversity, richness and abundance of floral cover in a vineyard compared to regular mowing, thereby providing increased

resources for pollinators and other beneficial insects (chapter 5).

7.3. Contribution of wildflowers to ecosystem services in gardens, allotments and vineyards

Globally, 800 million people practice urban agriculture (FAO 2019). The use of small plots to cultivate crops represents the oldest form of agriculture (Niñez 1984) and urban agriculture in such domestic spaces could aid sustainable intensification (Pretty and Bharucha 2014). Floral plantings have positive impacts on the abundance and diversity of pollinators and parasitoid wasps in gardens (Bennett and Gratton 2012; Garbuzov and Ratnieks, 2014; Pawelek et al 2009; Salisbury et al 2015). Such an increase in pollinator abundance and functional diversity enhances pollination services (Woodcock et al 2019), and similarly, wild bee richness positively enhances fruit quality (Garibaldi et al 2013) and more species-rich communities better support pest control services (Dainese et al 2019). Encouraging beneficial insects in a garden could enhance pollination services with increased abundance and richness of pollinators (chapter 3), as more diverse bee communities enhance fruit and vegetable production in the urban context (Lowenstein et al 2015). Furthermore, enhanced pest control services from increased abundance of solitary wasps (parasitoid wasps) could potentially reduce the need for synthetic insecticides (chapter 3) as encouraging parasitoid wasps enhances pest control in urban agriculture (Arnold 2022).

In Super Strawberries (chapter 2), borage companion planted with strawberry in gardens and allotments increased the yield and quality of the strawberry fruit. This suggests that increased pollination services were provided to the strawberry plant, which may otherwise have a pollination deficit. Including such companion planting in urban and community gardening could have positive benefits on the yield and quality of fruit production, with positive implications for urban growers. By increasing the pollination services to the crop using companion planting, the increase in yield could potentially reduce the need for managed pollinators. Additionally, increasing aesthetics of the fruit could help reduce food waste, as currently over a third of total farm production is lost due to aesthetics (Porter et al 2018).

Floral plantings also enhance abundance and diversity of pollinators and parasitoid wasps in vineyards (Judt et al 2019; Kratschmer et al 2019; Kratschmer et al 2021;

Nicholls et al 2000; Wilson et al 2018). Wildflowers in an inter-row vineyard will benefit from a suite of ecosystem services, including soil protection, weed suppression, biodiversity enhancement, increased aesthetics (Fiedler et al 2008), enhanced soil fungal networks and increased tolerance to abiotic stress (Trouvelot et al 2015). Vines do not have an obligate relationship with pollinators, but the encouragement of wildflowers will benefit local pollinator populations, as well as wider biodiversity. Importantly, provisioning of sown or spontaneous wildflowers provides refuge, pollen and nectar which is essential to the life cycle of natural enemies of pests, including parasitoid wasps and zoophagous hoverflies (Doyle et al 2020; Landis et al 2000; Tscharntke et al 1998; Wotton et al 2019). By allowing the natural regeneration of spontaneous floral species inter-row, the abundance of solitary wasps (the majority of which were parasitoid wasps) was significantly greater than with regularly mown grass (chapter 5) although further research is needed to identify if this translates into effective pest control.

7.4. Taxon-specific mixes for conservation action

Wildflower mixes in agricultural landscapes can be taxon-specific in their attractiveness depending on key plant species in the mix and this can facilitate conservation efforts targeted at particular insect groups (Warzecha et al 2018). I show that this can also be achieved in domestic gardens, allotments and vineyards, with mixes differing in terms of taxon specificity (chapters 3 and 5).

In Sow Wild! gardens and allotments (chapter 3), the commercially available ‘meadow mix’ was more effective than the specifically formulated ‘wild bee mix’ in encouraging a higher species richness and abundance of bumblebees and solitary bees. The ‘wild bee mix’ was, however, more effective at encouraging solitary wasps (the majority of which were parasitoid wasps). Conversely, in the vineyard project (chapter 5) the ‘wild bee mix’ was more effective at encouraging ‘all insect’ abundance and pollinator richness, whereas the ‘natural regeneration’ treatment encouraged more solitary wasps (again, the majority being parasitoid wasps). This suggests that different mixes are more or less successful in different environments, ecosystems and landscapes at encouraging different taxa. In chapter 5 the vineyard was previously arable farmland on chalk soil, whereas the gardens and allotments in chapter 3 had generally been private land for

decades with a mixture of soil types.

In the Sow wild! project (chapter 3) fewer 'sown' flowers germinated in the gardens with wild bee mix compared to meadow mix and there was greater abundance of the accompanying perennial grasses. At the vineyard (chapter 5) natural regeneration treatment also featured more long grasses compared to the mown treatment. Therefore anecdotally, as both these treatments had positive effects on solitary wasps (the majority being parasitoid wasps) these long perennial grasses might be beneficial in terms of providing refuge for parasitoid wasps. This has been documented previously, as perennial grasses may provide refuge for natural enemies during disturbances from mechanical management (Daane et al 2018a), and in an Australian vineyard, the abundance and diversity of parasitoids were higher in vines surrounded by perennial grasses (Danne et al 2010). However, these studies did not compare perennial grasses with wildflower plantings. It could have simply been the high numbers of unsown, spontaneous flowers in both the wild bee mix (chapter 3) and natural regeneration (chapter 5) providing flowers considered more attractive to solitary and parasitoid wasps. In the vineyard project (chapter 5) many top pollen and nectar-producing floral species germinated in the natural regeneration treatment but not amongst the mown treatment.

7.5. Potential for sustainable UK viticulture

Wildflowers can provide a natural alternative to herbicides, fungicides and insecticides for certain pests in vineyards (Abad et al 2021b; Pertot et al 2017), yet there are currently no vineyard-specific recommendations under the UK agri-environmental schemes. Provision of advice on effective methods of habitat management could contribute to a more sustainable environmentally-friendly sector. Before trying to promote sustainable practices in UK viticulture, it's important to understand the current land-use practices, pest control methods and perceived obstacles in habitat management as the sector is in its relative infancy.

To obtain land management statistics on synthetic chemical use, sowing of wildflowers, most prolific pests, and current inter-row ground cover management, I surveyed viticulturists working in UK vineyards. The findings on pesticide use and common pests were similar to European vineyards (Pertot et al 2017). Almost three quarters of

vineyards used synthetic pest control and almost two-thirds frequently mow the inter-row space (chapter 6). Despite the high proportion of vineyards that regularly mow inter-row ground cover, there was high awareness of the benefits of wildflowers, with 80% reporting the presence of wildflowers in headlands and 29% reporting the benefits of reduced mowing for pest control and biodiversity (chapter 6). Although headlands are more commonly allowed to naturally regenerate, this area is generally quite small compared to the land under vine. Additionally, wildflowers in the inter-row alleys would allow spill-over into the grapevines (Woodcock et al 2016a) possibly aiding pest control.

Crucially, there is high variability in information sources used by UK-based viticulturists, which could be a barrier in distributing advice on environmental and sustainable practices. As of 2021, 'Sustainable Wines of Great Britain' had 61 members accounting for 33% of the area of Great Britain under vine (WineGB 2021b) and with growth in members it has the potential to distribute standardised information on best practices and up to date findings on pest control and habitat management. However, for a sustainable future in the viticulture sector, monitoring, management and international knowledge exchange are crucial on a global level to allow rapid and effective response to ever-changing threats posed by arthropod pests (Daane et al 2018b). Increasing focus on the barriers to habitat management and international collaborations on pest control monitoring and techniques are essential to secure a sustainable future for viticulture.

7.6. Citizen science as a tool to monitor beneficial insects

The use of citizen science in experimental pollinator ecology is invaluable in gaining data which can inform conservation action, and both of my citizen science projects delivered large datasets, interesting results and engaged with the public. My projects required successful sowing and the establishment of healthy plants to obtain data, and a significant number of contributions were lost due to plant mortality, which has been recorded in other plant-focused citizen science projects (Kleinke et al 2018). Reporting of 'presence' data in citizen science projects has a good retention rate, yet when recording presence *and* absence participants may be more deterred (Maher et al 2019). For both of my projects (chapters 2 and 3) participants diligently collected 'zeros', watching flowering plants with a lack of insect visitors and collecting up pan traps with

(what seemed like) nothing exciting in the samples.

As unverified data records submitted by citizen scientists risk incorrect conclusions (Falk et al 2019) and bias and potential errors are poorly understood, validation of data collected in citizen science projects is important. Replicates of the Super strawberries (chapter 2) project were run alongside the experiments conducted by the citizen scientists. This allowed pre-empting any problems or questions, but most importantly it allowed comparison of patterns in results between the citizen scientists and myself, and the identification of 'suspect' data. Observational insect counts, yield and weight of strawberries and patterns of significant results were similar between citizen scientists and those conducted at the university, indicating projects of this type and complexity could be conducted by citizen scientists alone.

In the second year of the Sow Wild! project (chapter 3) I asked participants to conduct an insect watch alongside the standardised sampling methods (yellow sticky trap and pan trap). Apart from using supplied ID guides, the participants did not undertake any training and therefore insect watch was not included in the main project chapter (chapter 3). Instead, this method explored if this observation could replace destructive methods (chapter 4). The insect watch yielded different project results when compared to the verified sample-based data, which could have led to incorrect conclusions if this was relied upon alone, something that has been found before in a project on ladybirds (Gardiner et al 2012). Subconscious bias, underestimating the need for reporting 'zeros' in ecology, and lack of training were likely the cause of this difference.

For the insect counts in Sow Wild! (chapter 3) and for Super Strawberries (chapter 2), the methods were similar, yet while the results of the Super Strawberries observational counts were comparable between citizen scientists and researchers, this was not the case for the Sow Wild! project. This is most likely due to spatial differences between the two projects. Observational counts in the Super Strawberries projects asked participants to focus on insects landing on flowers, whereas the insect watch in Sow Wild! required insect counts in a 2x2 m patch. Most participants did not measure out this patch, and those participants in the control group may not be able to visualise a 2x2 m area without measuring out this area, compared to the groups actively working with a mini-meadow. Furthermore, in chapter 4, I found that solitary bees (as many species are small and inconspicuous) were misidentified or simply missed from counts conducted during the

insect watch and during pan trap specimen identifications, similar to conclusions by Maher et al (2019) and Kremen et al (2011). However, the identification of the more conspicuous groups such as bumblebees and honeybees was similar between myself and the citizen scientists.

7.7. Sampling method and capture rate

Multiple sampling methods are recommended for a more complete data set (McCravy 2018) and for the different projects, I used a variety of sampling methods. As pan traps are considered the "most efficient, unbiased, and cost-effective method for sampling bee diversity" (Westphal et al 2008) and are known to be effective sampling methods in a vineyard landscape (Krahner et al 2021) these were included in gardens and vineyards (chapters 3 and 5). Active trapping with a sweep net is labour intensive, inexpensive and standardised (McCravy 2018) so was included in chapter 5, yet is not suitable for citizen science projects due to equipment and training needs. Pan traps and yellow sticky traps can be set and collected without entomological training, and as a timed observational insect watch is an enjoyable and accessible approach to obtaining abundance information, these sampling methods were deemed suitable for use in the Sow Wild! project (chapter 3). Super Strawberries participants also conducted an observational insect watch, collecting insect counts landing on flowers (chapter 2).

In chapter 4, I found that the insect watch produced the most observations for all insect groups, except for social wasps (and citizen scientists were not asked to record solitary wasps). Insect watch was particularly useful for counting the more conspicuous insect groups, whereas yellow sticky traps were the most efficient at collecting data on social and solitary wasps. Pan traps were not as efficient at collecting insect data as insect watches or yellow sticky traps, but comparing the four colours of pan trap, white pan traps captured more insects overall, and higher richness of bees. In the vineyard project (chapter 5) the number of bee species caught during pan trapping was greater than those collected during the sweep netting of the transect walks, which has been documented in other studies (e.g. Hutchinson et al 2021b), perhaps as it is more difficult to collect faster species when sweep netting (McCravy 2018). However, as there is no way to gain a complete and unbiased assessment of local bee populations, I can't conclude if any of the sampling methods in any of the chapters over- or under-represent different

species/insect groups, or how representative the sampling is of the insect community.

In chapter 4, I have added to the growing literature on sampling methods in different landscapes and environments, by contributing knowledge on the effectiveness of such methods in urban gardens and allotments. Knowledge of which taxa are most effectively captured by different sampling methods can reduce by-catch and can be incorporated into monitoring schemes. For example, monitoring the invasive Japanese beetle was previously conducted using a combination of white, yellow and green pan traps. Yet upon finding large numbers of bumblebees as by-catch in yellow and white traps, these were dropped from the pan trap set (Hamilton et al 1971) and only green pan traps are used today (Spears and Ramirez 2015). I used destructive sampling techniques in chapters 3 and 5, and although there is no evidence of long-term population impacts on bees using lethal sampling methods (Gezon et al 2015) excessive sampling should be avoided whenever possible. By-catch that might be regarded as unimportant could contain specimens of interest to other projects and institutions. Keeping all data on by-catch can create reference collections, contribute to large biodiversity databases, and collaborations could benefit from simultaneously gathering by-catch data (Spears and Ramirez 2015). Pan trap sampling conducted during these projects did collect incidental by-catch, however, all parasitoid and aculeate wasps specimens have been stored for potential future use.

7.8. Project limitations and future research

7.8.1. Project limitations

One of the main limitations of the projects was the lack of space to adequately include within-site control plots. In the vineyard (chapter 5), larger distances between wildflower strips and creating blocks of treatments would have been desirable to limit cross-over of flowers and insects, yet unfortunately, the study was restricted to a single experimental plot. The size of gardens and allotments in cities and urban sites had to be considered when developing the project methodologies for chapters 2 and 3.

When creating the Sow Wild! project (chapter 3), I did not ask participants to record the abundance of the flowers in their mini-meadows in an attempt to keep the protocol as simple as possible. Instead, participants only listed the flowers that appeared each

month (thereby providing richness data). On reflection, the inclusion of abundance data would have allowed further analysis into the floral diversity of the mini-meadows. Photographs were also unstandardized, and although helpful to visualize what was the most abundant species in each of the mixes over the different months and years, the clarity of the photographs differed greatly between participants, rendering them of little value. This might be improved by attempting to provide more detailed instructions to standardise the way photographs were taken.

Another challenge for the Sow Wild! and Super Strawberries (chapters 2 and 3) was the lack of capacity and resources for training. Due to resources and the high initial number of participants, in-person training could not be provided, yet in retrospect, a YouTube channel featuring pre-recorded tutorials on plant care, project set-up and insect/flower identification would have been helpful for both the citizen science projects. As citizen science projects become more mainstream and complement traditional monitoring projects, attention should be paid to educating volunteers, and such learning objectives should be included in the project protocol. Few projects evaluate how they have engaged participants (Ellwood et al 2017) and perhaps citizen science projects overestimate how much they have contributed to participants' interaction and understanding of science. Indeed, surveys before and after a project should be conducted to see if learning objectives have been met (Druschke and Seltzer 2012), and I would recommend this in such future projects.

7.8.2. Next steps

Identification of specific insect-flower species interactions is an important next step for both the Sow Wild! and the vineyard project (chapters 3 and 5). Participants did not observe insects directly on flowers and I did not include insect-flower interactions in the protocol, but as the abundance and richness of solitary bees, bumblebees and solitary wasps are higher for certain mixes, key floral species may be present, and it would be an important next step to identify these species. Previous research on floral plantings and natural pest control has been dominated by the use of mixes with a limited number of plant species and it would be beneficial to investigate the potential of a more diverse range of flowers in providing resources for wild bees, parasitoid wasps and other beneficial insects. However, plants known to host or provide resources to particular pests must be avoided when considering companion plant pairs or wild seed mixes. A

flowering plant with positive effects on beneficial insects in a specific orchard, fruit farm or agricultural landscape might not be suitable for a different landscape. For example, ribwort plantain would be an ideal host for the rosy apple aphid in apple orchards and lady's bedstraw is an ideal host plant for black cherry aphid in sweet cherry orchards (Westbury 2021).

For the vineyard project (chapter 5), the recruitment of multiple vineyards, and the inclusion of yield data collection is a crucial next step. Inclusion of landscape-scale factors should also be included in the protocol, given these have been shown to affect bee diversity (Kratschmer et al 2018; Kratschmer et al 2019; Uzman et al 2020; Wilson et al 2017). Although I found that the richness of solitary wasps (the majority of which were parasitoid wasps) was positively enhanced by increased floral resources, the next step would be to investigate any effect on pest numbers, and if this translates into effective biological pest control. More detailed in-person interviews with viticulturists on habitat management preferences and perceived obstacles would be an interesting extension to chapter 6, as would detailed surveys amongst the vines to determine the presence of pests.

The Super Strawberries project (chapter 2) should be expanded to investigate companion planting of borage with strawberry plants in a commercial fruit farm under real agronomic conditions, as well as testing the effectiveness of other companion planting pairs. Consideration also needs to be paid to the potential pest control services provided by borage, acting as a 'banker plant' for strawberry, as borage is also documented to be particularly attractive to parasitoid wasps (Hatakeyama and Nemoto 2008). Investigating any effects of pest control provided by borage on this and other crops is, therefore, an interesting next step. The effect of companion planting was localised (chapter 2) - the control strawberry placed just three metres away had lesser fruit yield and reduced aesthetics - but linking the two projects by planting a mini-meadow (chapter 3) *and* measuring the effects of pollination services on common garden crop yield (chapter 2) would be interesting.

In Sow wild! (chapter 3), I found there was a higher abundance of solitary wasps and solitary bees in the wildflower patch compared to the area 10 m away. Bee dispersal and foraging range correlate with body size (Greenleaf et al 2007) and so this effect is probably due to the limited foraging range of these smaller foraging insects, and the

dense wildflower patch also may provide refuge in addition to pollen and nectar. As the assumption is that smaller solitary bees would be more localised in the mini-meadow, further analysis could consider bee species' body size by comparing mini-meadows to the area 10 m away. A further addendum to the Sow Wild! project (chapter 3) could include the investigation into a range of wildflower patch sizes, as pollinator density and diversity are affected by wildflower patch size (Blaauw and Isaacs 2014b), and floral additions in gardens may only be beneficial up to a point, with any further increases seeing negligible positive effects (Matteson and Langellotto 2011; Simao et al 2018). Of course, future projects would still need to be considerate of domestic garden sizes, especially in cities.

7.9. Concluding remarks

Domestic gardens, allotments and vineyards provide huge potential habitat for pollinators. The use of sown and spontaneous wildflowers increases beneficial insect abundance and richness in these environments.

A common obstacle to wildlife gardening is the perceived lack of space, but a small 4 m^2 wildflower mini-meadow enhances the abundance of beneficial insects and the richness of wild bees. Furthermore, the enhancement of pollination services to a crop using a companion plant can increase yield and aesthetics, potentially reducing the need for managed pollinators and food waste. In impervious, fragmented landscapes, urban green spaces can be a haven for pollinators, and coordinating the management of domestic gardens and allotments would have great benefits for biodiversity. I, therefore, support the notion that gardens and allotments be included in urban conservation planning as small-scale floral enhancements can attract more beneficial insects, potentially supporting urban biodiversity, pollination services and biological pest control. If many gardens contained such patches the combined effect may be considerable.

There is a lack of specific environmental recommendations for British viticulture yet we have the potential to promote sustainable practices as the sector is still in its infancy. Two-thirds of UK-based vineyard managers currently maintain frequently mown grass as inter-row ground cover yet mown grass has the least benefits for beneficial insects. Instead, sown or spontaneous wildflowers may provide a natural alternative to

herbicides, fungicides and insecticides for certain pests in vineyards. Natural colonisation of spontaneous flowers and simply reducing mowing could enhance pest management and biodiversity without the agronomic, management and resource challenges of adding floral plantings.

Based on the findings in my thesis, I encourage the establishment, management and restoration of floral plantings in vineyards, gardens and allotments. Wildflowers effectively contribute to ecosystem service delivery in these environments, enhancing biodiversity, natural pest regulation and contributing to a sustainable future of viticulture and urban agriculture.

CHAPTER 8

8. References

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APPENDICES

Chapter 2

Appendix A. Postcode locations of all citizen scientists enrolled in project

Appendix B. Citizen science workbook

Appendix C. Citizen science instructions

Appendix D. Citizen science pollinator ID guide

Chapter 3

Appendix E. Project instructions and data collection workbook sent to all participants

Appendix F. Wildflowers mix flower guides, and insect guides

Appendix G. Full species list for bees and hoverflies

Appendix H. GLMM results on effects of the diversity of garden flowers on the abundance of insects and richness of bees

Chapter 4

Appendix F. Wildflowers mix flower guides, and insect guides

Chapter 5

Appendix I. Wildflower and grass mix compositions, indicating which of the flowering species germinated, and in which year of the study

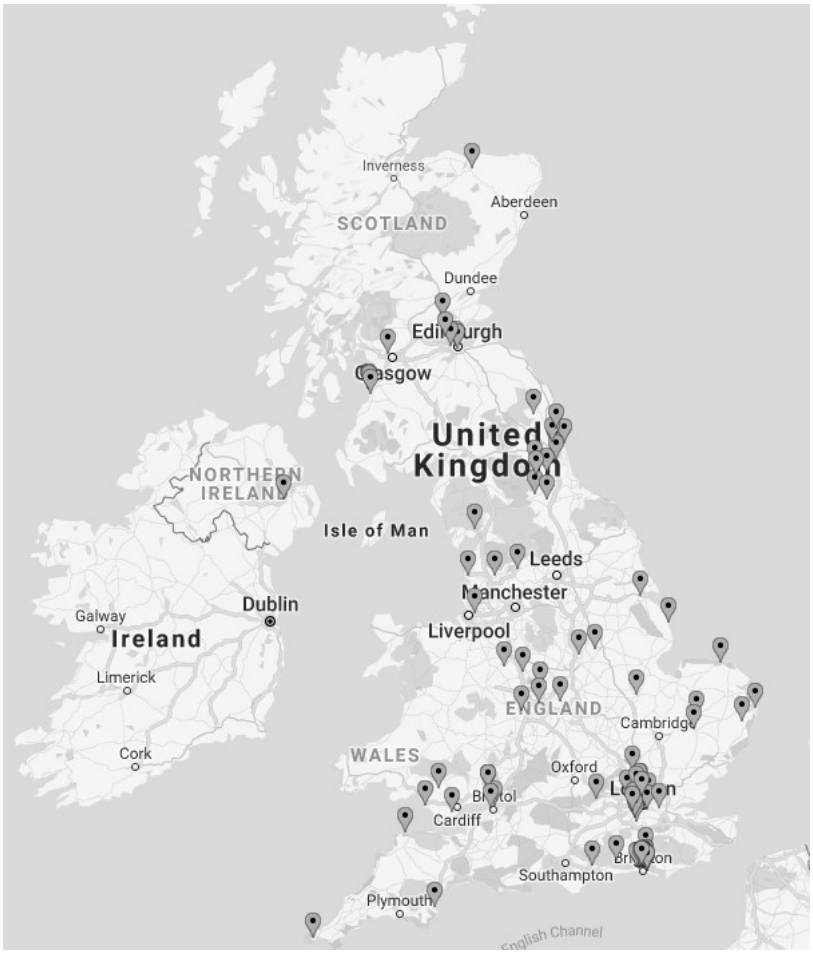
Appendix J. Arrangement of treatment rows in experimental plot

Appendix K. Full species list of bees and hoverflies

Chapter 6

Appendix L. List of survey questions circulated to UK based viticulturists

APPENDIX A. Postcode locations of all citizen scientists enrolled in project

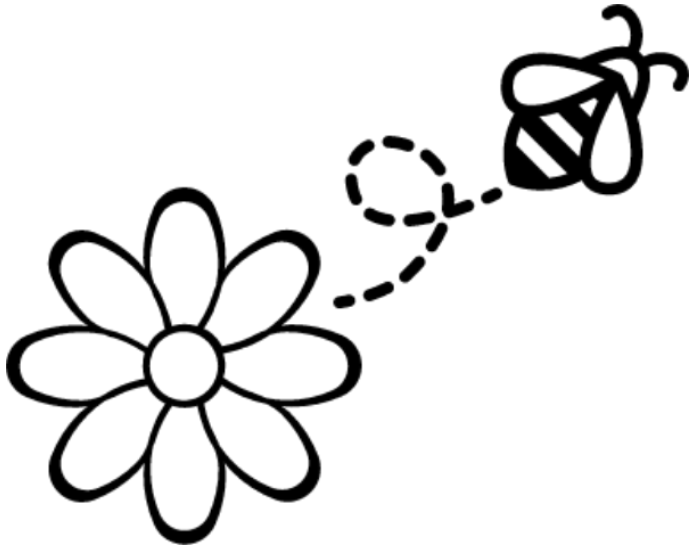

Inverness
Aberdeen
SCOTLAND
Dundee
Edinburgh
Glasgow
United Kingdom
NORTHERN IRELAND
Isle of Man
Leeds
Manchester
Liverpool
Dublin
Galway
Ireland
Limerick
Cork
ENGLAND
Cambridge
WALES
Oxford
Bristol
Cardiff
Southampton
Plymouth
English Channel

APPENDIX B. Citizen science workbook

team PollinATE : Super Strawberries: Companion planting project 2018

PROJECT WORKBOOK:

- Pollinator Survey
- Tell us about your garden or allotment
- Your Harvest



team PollinATE : Super Strawberries Pollinator Survey

WEEK ONE

Date:

Time:

Temp:

Sunny Cloudy Overcast

Wind: Leaves Still | Gently moving | Strongly moving

What to do

1. Note the date & time, and circle the applicable weather conditions
2. Tell us how many flowers are on each strawberry plant
3. Watch the 'test' strawberry for 5 minutes (this is the strawberry paired with borage) & tally how many insects you see visiting the flowers
4. Repeat this with the borage for 5 minutes
5. Repeat this with the 'control' strawberry for 5 minutes
6. If you think an insect has returned to the plant after flying away, count it as a new visitor

	Number of Flowers 	BEETLES Wings hidden Shiny body 	HOVERFLIES Often stripy Large eyes Short antenna 	FLIES Clear wings Short antenna 	BUTTERFLIES & MOTHS Large bright wings 	BUMBLEBEES Rounded hairy body 	HONEYBEES Shiny legs Pollen baskets 	SOLITARY BEES Smaller Hairy 	WASPS Smooth waist 	OTHER Please describe ?
TEST STRAWBERRY 										
BORAGE 										
CONTROL STRAWBERRY 										

team PollinATE : Super Strawberries Pollinator Survey

WEEK TWO

Date:

Time:

Temp:

Sunny Cloudy Overcast

Wind: Leaves Still | Gently moving | Strongly moving

What to do

1. Note the date & time, and circle the applicable weather conditions
2. Tell us how many flowers are on each strawberry plant
3. Watch the 'test' strawberry for 5 minutes (this is the strawberry paired with borage) & tally how many insects you see visiting the flowers
4. Repeat this with the borage for 5 minutes
5. Repeat this with the 'control' strawberry for 5 minutes
6. If you think an insect has returned to the plant after flying away, count it as a new visitor

	Number of Flowers 	BEETLES Wings hidden Shiny body 	HOVERFLIES Often stripy Large eyes Short antenna 	FLIES Clear wings Short antenna 	BUTTERFLIES & MOTHS Large bright wings 	BUMBLEBEES Rounded hairy body 	HONEYBEES Shiny legs Pollen baskets 	SOLITARY BEES Smaller Hairy 	WASPS Smooth waist 	OTHER Please describe ?
TEST STRAWBERRY 										
BORAGE 										
CONTROL STRAWBERRY 										

team PollinATE : Super Strawberries Pollinator Survey

WEEK THREE

Date:

Time:

Temp:

Sunny Cloudy Overcast

Wind: Leaves Still | Gently moving | Strongly moving

What to do

1. Note the date & time, and circle the applicable weather conditions
2. Tell us how many flowers are on each strawberry plant
3. Watch the 'test' strawberry for 5 minutes (this is the strawberry paired with borage) & tally how many insects you see visiting the flowers
4. Repeat this with the borage for 5 minutes
5. Repeat this with the 'control' strawberry for 5 minutes
6. If you think an insect has returned to the plant after flying away, count it as a new visitor

	Number of Flowers 	BEETLES Wings hidden Shiny body 	HOVERFLIES Often stripy Large eyes Short antenna 	FLIES Clear wings Short antenna 	BUTTERFLIES & MOTHS Large bright wings 	BUMBLEBEES Rounded hairy body 	HONEYBEES Shiny legs Pollen baskets 	SOLITARY BEES Smaller Hairy 	WASPS Smooth waist 	OTHER Please describe ?
TEST STRAWBERRY 										
BORAGE 										
CONTROL STRAWBERRY 										

team PollinATE : Super Strawberries Pollinator Survey

WEEK FOUR

Date:

Time:

Temp:

Sunny Cloudy Overcast

Wind: Leaves Still | Gently moving | Strongly moving

What to do

1. Note the date & time, and circle the applicable weather conditions
2. Tell us how many flowers are on each strawberry plant
3. Watch the 'test' strawberry for 5 minutes (this is the strawberry paired with borage) & tally how many insects you see visiting the flowers
4. Repeat this with the borage for 5 minutes
5. Repeat this with the 'control' strawberry for 5 minutes
6. If you think an insect has returned to the plant after flying away, count it as a new visitor

	Number of Flowers 	BEETLES Wings hidden Shiny body 	HOVERFLIES Often stripy Large eyes Short antenna 	FLIES Clear wings Short antenna 	BUTTERFLIES & MOTHS Large bright wings 	BUMBLEBEES Rounded hairy body 	HONEYBEES Shiny legs Pollen baskets 	SOLITARY BEES Smaller Hairy 	WASPS Smooth waist 	OTHER Please describe ?
TEST STRAWBERRY 										
BORAGE 										
CONTROL STRAWBERRY 										

team PollinATE : Super Strawberries Pollinator Survey

WEEK FIVE

Date:

Time:

Temp:

Sunny Cloudy Overcast

Wind: Leaves Still | Gently moving | Strongly moving

What to do

1. Note the date & time, and circle the applicable weather conditions
2. Tell us how many flowers are on each strawberry plant
3. Watch the 'test' strawberry for 5 minutes (this is the strawberry paired with borage) & tally how many insects you see visiting the flowers
4. Repeat this with the borage for 5 minutes
5. Repeat this with the 'control' strawberry for 5 minutes
6. If you think an insect has returned to the plant after flying away, count it as a new visitor

	Number of Flowers 	BEETLES Wings hidden Shiny body 	HOVERFLIES Often stripy Large eyes Short antenna 	FLIES Clear wings Short antenna 	BUTTERFLIES & MOTHS Large bright wings 	BUMBLEBEES Rounded hairy body 	HONEYBEES Shiny legs Pollen baskets 	SOLITARY BEES Smaller Hairy 	WASPS Smooth waist 	OTHER Please describe ?
TEST STRAWBERRY 										
BORAGE 										
CONTROL STRAWBERRY 										

team PollinATE : Super Strawberries Pollinator Survey

WEEK SIX

Date:

Time:

Temp:

Sunny Cloudy Overcast

Wind: Leaves Still | Gently moving | Strongly moving

What to do

1. Note the date & time, and circle the applicable weather conditions
2. Tell us how many flowers are on each strawberry plant
3. Watch the 'test' strawberry for 5 minutes (this is the strawberry paired with borage) & tally how many insects you see visiting the flowers
4. Repeat this with the borage for 5 minutes
5. Repeat this with the 'control' strawberry for 5 minutes
6. If you think an insect has returned to the plant after flying away, count it as a new visitor

	Number of Flowers 	BEETLES Wings hidden Shiny body 	HOVERFLIES Often stripy Large eyes Short antenna 	FLIES Clear wings Short antenna 	BUTTERFLIES & MOTHS Large bright wings 	BUMBLEBEES Rounded hairy body 	HONEYBEES Shiny legs Pollen baskets 	SOLITARY BEES Smaller Hairy 	WASPS Smooth waist 	OTHER Please describe ?
TEST STRAWBERRY 										
BORAGE 										
CONTROL STRAWBERRY 										

team PollinATE: Super Strawberries Tell us about your garden

What to do:

1. When borage and strawberry are both flowering (and in the height of summer) tell us what else is flowering on your site (don't forget to tell us the date!)
2. Write the name of the plants **flowering** on your site on a separate line in the table below
3. For each flowering plant, roughly estimate the percentage of the site that is covered in that plant. (For example, 5% could be covered in flowering broad beans, and 1% in lavender)
4. Let us know when the borage and strawberry stopped flowering, and any pests encountered on the strawberries

DATE COMPLETED:

Name of plant flowering on your site	% coverage
	CONTINUE OVER

Other things to let us know:

Date the strawberry plants stop flowering:

Date the borage stop flowering:

Were there any pests present on the strawberry:

If so, did you treat them, and how?

Name of plant flowering on your site	% coverage

team PollinATE

: Super Strawberries  The Harvest

What to do:

1.Count the unripe (green) and ripe (red) strawberries on your 'Test' strawberry and your 'Control' strawberry plants. **Don't pick the unripe fruit!**

2.Harvest the ripe fruit **Keep the fruit from both plants separate**

3.Tell us the number of strawberries and the overall weight of the harvest

4.Tell us if your berries have been eaten by pests, and the number if you know

5.Repeat this weekly

	COUNT THE FRUIT ON YOUR PLANTS				COLLECT YOUR HARVEST				BERRIES EATEN BY PESTS?	
	TEST STRAWBBERY		CONTROL STRAWBERRY		TEST STRAWBBERY		CONTROL STRAWBERRY			
	UNRIPE FRUIT (number)	RIPE FRUIT (number)	UNRIPE FRUIT (number)	RIPE FRUIT (number)	NUMBER OF BERRIES	WEIGHT (g/oz –circle)	NUMBER OF BERRIES	WEIGHT (g/oz–circle)	TEST STRAWBRRY NUMBER	CONTROL STRAWBRRY NUMBER
Week 1 **Date:**										
Week 2 **Date:**										
Week 3 **Date:**										
Week 4 **Date:**										
Week 5 **Date:**										
Week 6 **Date:**										

APPENDIX C. Citizen science instructions

Super Strawberries!

Welcome to Super Strawberries - a companion planting project for 2018. Companion planting can protect crops from pests and can attract beneficial insects such as pollinators. In this project, we will investigate whether planting bee-friendly borage (*Borago officinalis*) can improve the pollination of strawberry (*Fragaria* x *ananassa* 'Albion'), and result in bigger yields of fruit. To do this, we are asking you to record the number of pollinator visits, and then to compare the weight of fruit produced by strawberry plants grown both close to and away from a pot of borage.

The Project Kit

In your kit, you should have:

- 2 strawberry runners (these are bare root and dormant, and Albion variety)
- 1 bag of borage seeds
- 3 polypots (the containers for your plants, the **larger** polypot is for your borage)
- 2 punnets for collecting strawberry fruit for weighing
- Instructions, recording sheet workbook and pollinator ID guide.
- 2 lolly sticks (to put in the soil of your strawberry plants)

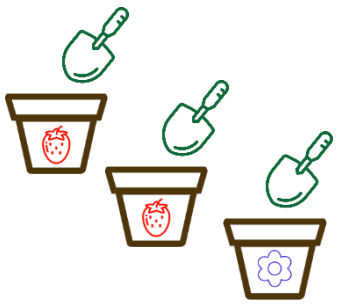
You will need:

- Compost (well-rotted garden compost, or a multi-purpose mix is fine, as long as all containers have the same) [*Please do not used peat-based compost as its extraction is very harmful to the environment*]
- Plant feed (strawberry feed, tomato feed or similar)
- Kitchen scales

The Project Plan

PART 1: Planting

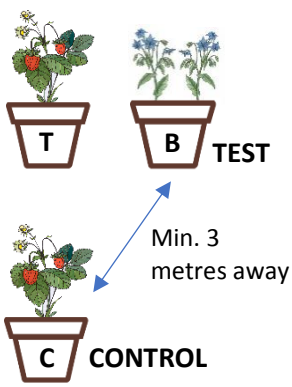
2 x strawberry runners
1 x pot of borage seeds



Sow in EARLY APRIL
Soak runners before planting
Keep well-watered and in sunny position

PART 2: Set Up

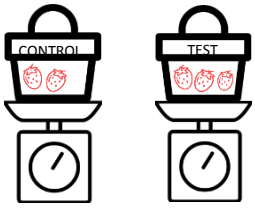
1 x 'Test' strawberry plant placed next to borage pot (B)
1 x 'Control' strawberry plant placed min. 3m away from borage pot



PART 3: Collect Data

A. Record flower visits by pollinators for Test, Control and Borage plants

B. Weigh fruit harvested from Control and Test plant (separately!)



PART ONE: Preparing your strawberry and borage plants

Step 1: Planting your strawberry runners

WHEN? Beginning of April

HOW? Your strawberry plants are bare root runners, and are completely dormant, so may look very dry. They should be planted out as soon as possible after arrival, then they will emerge from dormancy and start growth within 4-6 weeks.

When you are ready to plant, leave the plants to soak in tepid water for 20 minutes to rehydrate roots. Fill the two smaller polypot containers with compost (one for each strawberry plant) and prepare a planting hole – this should be twice as wide as the root system of your plant. Plant the strawberries so the crown (point where root meets stem) is at soil-level. Spread out the roots then refill with soil. Give them a good watering.

Poke one lolly stick in the soil of each plant (at random). One says 'control' and one says 'test'. This is so you know which plant is which when the experiment starts.

To care for your plants, keep them well-watered (especially when they are fruiting and in hot weather) and in a sunny spot. Give them plant feed (strawberry or tomato feed) every 2 or 3 weeks. Place a layer of mulch or straw on top of the soil under the plants – this is to stop pests and to stop the fruit touching the soil.

Remove any strawberry flowers that appear BEFORE borage flowers. Once borage flowers let the strawberry flowers bloom!

If strawberry runners develop cut them off

Remove (pinch) any strawberry flowers that may appear BEFORE borage is close to flowering. This gives the plant more energy to take root, and also helps us interpret results better. Any strawberry flowers that appear when borage is flowering let bloom!

If any runners develop cut them off. This is to preserve the plants energy in its first year of growth.

Step 2: Planting your borage seeds

WHEN? Beginning of April

HOW? Sow the seeds at a depth of around 6mm (1/4") in the larger polypot container and cover with soil. Sow all the seeds spaced out in the container. Give a good watering.

When the borage has germinated and they are large enough to handle, keep the strongest two plants in the container and space them well apart.

Borage loves full sun, so keep it in a sunny spot in your allotment/garden and water regularly. Borage should start to flower around 8 weeks after sowing, so around the beginning of June.

PART TWO: Setting up the experiment

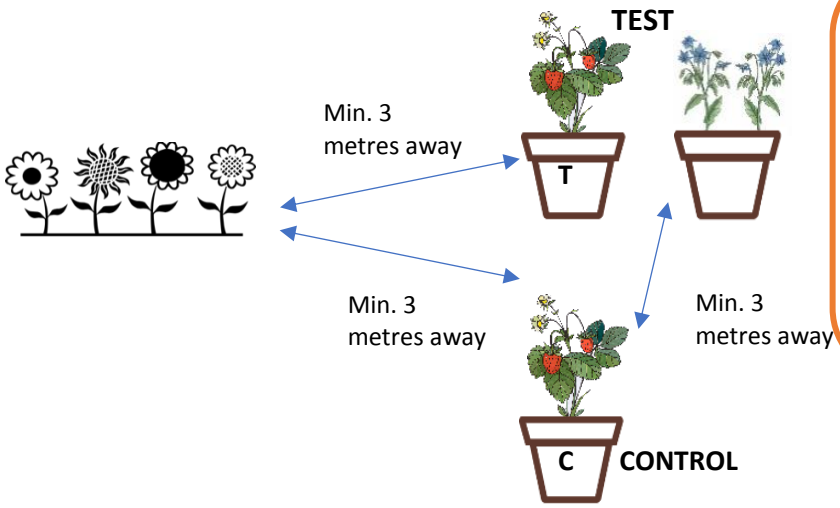
WHEN? As soon as you have sown your borage seeds and planted your strawberry runners, you can arrange your plants ready for the experiment.

HOW? We are keeping the plants in their polypot containers for the entire experiment. You will have three containers: two containing strawberry plants and one containing the borage. Your strawberry plants should both have a lolly stick poked into the soil - so you will always know which plant is which. Place your 'test' strawberry and the borage **next to each other** in a sunny spot in your garden or allotment. This is the main test: 'strawberry + borage'. Always keep them together.

Place the other strawberry plant (your 'control') at least 3 metres away from the test strawberry + borage, and also keep it in full sun.

Try and keep the 'test' plants and the 'control' at least 3 metres away from **other flowers** in your garden if you can. It's OK if your strawberry and borage plants are near other garden plants **not flowering** at the time, so you can move them around the garden – just make sure the straeberry plants don't get swapped around. And always keep them in full sun.

When BOTH the strawberry and borage are flowering it's time to do the experiment!



Keep your test plants and control 3m away from each other and other FLOWERS in your garden

You can move your plants around depending what is flowering at the time. Make sure you don't swap the strawberry plants around!

PART THREE: Data collection

Step 1: Recording pollinator visits to flowers

WHEN? When both strawberries AND borage are flowering.

Do this once per week for 4 - 6 weeks. Flowering is likely to be from June onwards and you don't have to commit to every week (allowing for holidays etc) just 4 out of 6 at least!

If you can, choose a day when its not raining, when its warm (above 13°c) and between 10am-4pm. This is prime time for pollinators!

HOW? Using the 'Pollinator Survey' recording sheet in your workbook. Firstly, tell us how many strawberry flowers you have on each plant. Then spend 5 minutes watching the test strawberry and record how many insects you see visiting the plant on your recording sheet. Then spend 5 minutes watching the borage and record how many insects you see visiting.

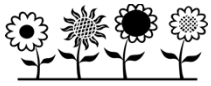
After this, spend 5 minutes watching the strawberry plant control, again record how many insects you see visiting.

If you think the same insect has returned to the plant after flying off – count it as a separate and new visit.

Record insect visits to the strawberry plants and the borage for 5 minutes each

Between 10am-4pm, on a warm day once a week

Remember your pollinator ID guide. Please don't be put off if you can't identify the different insect groups visiting the plants. You could just give us the total number of insects visiting if you find you are stuck, but do give it a go: you will be surprised how quickly you learn to differentiate!



Step 2: Tell us about your garden

WHEN? When both strawberries AND borage are flowering, during peak summer.

You only need to do this **once**!

HOW? Using the 'Tell us about your garden' recording sheet in your workbook. List the different species of plant that are FLOWERING on your site. Then tell us the % of your site that is covered by these different flowering plants. (For example, 5% of your site could be covered in flowering lavender, and 10% of your site covered in flowering broad beans).

Note any problems/pests present on the strawberry plant, such as weevils, frost damage or mould. (Also tell us if you used anything to treat the pest).

Tell us on your recording sheet when the strawberry and borage stop flowering.

Step 3: Harvesting fruits

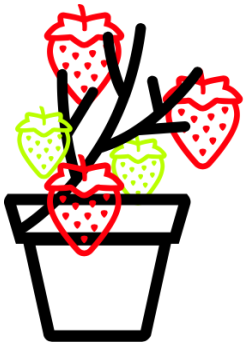
WHEN? Strawberries are usually ready to pick 4-6 weeks after blossom and when ripe should be bright-red all over. Do this once a week for 6 weeks.

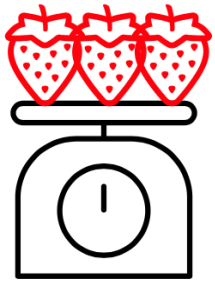
HOW? Using the 'Your Harvest' recording sheet in your workbook. Firstly, count the fruit on each plant, telling us how many green unripe fruit there are, and how many ripe fruit. **Don't harvest the unripe fruit!**

Collect the **ripe fruit** in the collection punnets provided, and harvest from both strawberry plants on the same day. Remember to keep the fruit from the plants separate!

On your recording sheet note the **NUMBER** of strawberries in your harvest. Then tell us the **WEIGHT** of the harvest (minus the weight of the punnet).

Once you have counted and weighed the fruit, add cream and enjoy!





Count the ripe and unripe fruit on the plant

Harvest and weigh the ripe fruit

PART FOUR: Sending us your data

You can fill in the online recording sheet at:
https://www.teampollinate.co.uk/superstrawberries
or you can take a photo of your recording sheet and send it to us via email, or you can post it to us!

Contact Information

Janine Griffiths-Lee
JMS PG Pigeonholes
University of Sussex
Falmer
Brighton
BN1 9QG

Email: **j.griffiths-lee@sussex.ac.uk**

I am also happy to talk on the telephone. Please email me with your telephone number and a good time to call!

APPENDIX D. Citizen science pollinator ID guide

Pollinator Identification Guide

A guide to the different groups of pollinating insects you might see visiting your plants and how to identify them. For more photos and information: www.bwars.com; www.bumblebeeconservation.org.

Created by Linda Birkin and Beth Nicholls, photos by Will George

BUMBLEBEES

LARGE, FURRY bees with **rounded bodies** and dark legs, bumblebees may have **stripes of yellow, white or brown** depending on the species. There are 24 different species of bumblebee in the UK.

Buff-tailed bumblebee

Common Carder bumblebee

Red-tailed bumblebee

Early bumblebee

HONEYBEES

There is one species of honeybee in the UK, **Smaller and more slender** than bumblebees, they are **orangey-yellow to brown with dark stripes** and have shiny back legs, which are often packed with pollen.

Bees have two pairs of wings

Honeybees- note pollen baskets on hind legs.

SOLITARY BEES

There are over 200 species of solitary bee in the UK, which vary in appearance and can be as **small as 6 mm long**. You can tell them apart from hoverflies by their **longer antennae**.

Solitary bees carry pollen on their body

Long antenna with 'elbow' joint

WASPS

Social wasps are **more SMOOTH looking** and much less hairy than bees. They usually have bright **yellow and black** stripes, and yellow legs.

Solitary wasps vary in colour and size, from small and black to metallic red, blue and green.

Social wasps are usually black and yellow

Solitary 'jewel' wasps are often parasites of solitary bees

HOVERFLIES

Many hoverflies mimic bees/wasps and have a stripy pattern. They have very **SHORT STUBBY ANTENNAE** and **LARGE EYES**. Hover/dart between flowers.

Hoverfly eyes make up most of their head

Very short antenna

One pair of clear wings

OTHER FLIES

Other flies, such as metallic soldier flies also visit flowers. They also have **short antennae**, **large eyes** and one pair of clear wings.

BEETLES

Beetles outer wings form a **hard protective cover** (elytra) which is often shiny or metallic and forms a t-shape on their back.

BUTTERFLIES and MOTHS

Butterflies have **BRIGHTLY COLOURED WINGS** and long antennae. Butterflies fly during the day and have **clubs at the end of their antennae**. Most moths fly at night and have feathery antennae.

APPENDIX E. Project instructions and data collection workbook sent to all participants

SOW WILD! INSTRUCTIONS 2016

Welcome to the *Sow Wild*! community and thank you for taking part!
This leaflet should tell you everything you need to know about your project.

PROJECT KIT

In your kit you should have:

- 1 pack of seeds (16g)
- 8 plastic jars and lids
- 6 pan traps (2 pink, 2 blue, 2 white)
- Small plastic bag for soil sample (to collect at the end of summer)
- 1 piece of pH paper and colour chart in a brown envelope
- 4 recording sheets
- The box in which your kit arrived – keep this to return your samples at the end of summer

You will need:

- Clear vinegar
- Natural washing-up liquid without strong scent (for example, Ecover)
- Permanent marker
- Access to a digital camera/camera phone

THE WILDFLOWER SEEDS

Your seeds are native to the UK and contain both flowers and grasses. Grasses are an important part of the mix as they stop weeds growing amongst the wildflowers. Your mix contains the following:

Yarrow
Betony
Common knapweed
Greater knapweed
Wild carrot
Meadowsweet
Hedge bedstraw
Lady's bedstraw
Rough hawkbit
Oxeye daisy
Bird's-foot-trefoil
Wild marjoram
Hoary plantain
Salad burnet
Smaller cat's-tail
Cowslip
Selfheal
Meadow buttercup
Yellow rattle
Common sorrel
Red campion
Ragged robin
Wild red clover
Tufted vetch
Cornflower
Common poppy
Common Bent
Crested dog's-tail
Slender-creeping red-fescue

Participants have been sent different mixes, so you might not have the same wildflowers as your friends!

Important note: In your 2x2m wildflower patch please only use the seeds provided by Sow Wild!

THE PROJECT PLAN

PART ONE: Plot preparation.

WHEN? As soon as you receive your pack

- Measure out your plot of 2m x 2m square (this is $4m^2$ in size)
- Remove any weeds, decomposing leaves, nettles and waste from the plot

PART TWO: Testing the pH of your soil

When? When you are preparing your plot

- Using the pH paper ('universal litmus' paper) from your pack
- With your hand or a shovel, collect some soil from your plot – collect soil at about 15 cm (6 inches) deep
- Collect a tablespoon of soil and put this in a jar (you could use a jam jar, or a jar that has been provided in your pack – wash it out after use)
- To the jar, add two tablespoons of tap water
- Shake the soil and water sample to mix it all up
- Let the sample settle for 2-5 minutes
- Keeping hold of one end of the paper, put the pH paper into the mixture for 5 seconds
- Take the paper out, and hold for a few seconds while the colour stabilizes
- Compare your pH paper to the colour chart included and note down the pH here:

pH of my soil:

Important note: Please also record this pH on your recording sheet

PART THREE: Sowing.

You have been provided with a 16g bag of seed mix – enough to sow at a rate of $4g/m^2$

When? During the first three weeks of April 2016

- Remove any weeds that have grown since you prepared the soil
- Dig to bury surface soil, and rake to produce a medium tilth
- Flatten the bare ground to produce a firm surface
- Give the pack of seeds a little shake, so all the seeds are well mixed up
- Sprinkle the seeds evenly over the plot by hand, do not cover the seeds with soil
- Gently press the seeds down onto the soil with your hand to stop them blowing away
- Water the plot lightly if no rain is forecast (and then continue to water the patch as you would the rest of your garden)

PART FOUR: Sampling.

When? During the first week of May, June, July and August. Make a note in your calendar as a reminder!

Preferably during a dry and sunny 48 hour period. (You can start the 48 hour period anytime of day you choose)

Firstly, lay your pan traps:

- Fill each of your pan traps ¾ full with water, and a couple of drops of perfume-free washing-up liquid
- Lay three pan traps (one pink, one white, one blue) alongside each other in the middle of your wildflower patch
- If it's very windy, you could place a stone in the bottom of the pan traps (to stop them blowing away!)
- Lay the remaining three pan traps (one pink, one white, one blue) 10 metres away from your wildflower patch
- Leave the pan traps undisturbed (it's OK if it rains during this time)
- Collect up your pan traps 48 hours later

Collecting up your pan traps:

- Collect up the **three** pan traps in the wildflower patch, scoop out all the insects you have collected and place into a single jar
- Using your recording sheet, see if you can identify any of the insects collected – you could use a teaspoon to scoop them out so you can take a closer look
- Drain the water (as much as you can!) and fill the jar with clear vinegar, enough to cover the insects and preserve them

- Label the jar using permanent marker or pencil (anything else might rub off if the jars get wet)
- On the jar write:
    'WP' (which stands for wildflower patch)
    Your full name
    Your postcode
    The date (day, month, year)

- Repeating as above for the **three** pan traps 10 metres away from the wildflower patch: scoop out all the insects you have collected into another single jar
- See if you can identify any of the insects
- Drain the water and fill the jar with white vinegar
- On the jar write:
    '10' (which stands for '10 metres from the wildflower patch')
    Your full name
    Your postcode
    The date (day, month, year)

- Tightly secure the lid on both jars, and store somewhere cool and dry until the end of the summer.

During this 48 hour period, take some pictures of your site:

Using your digital camera/camera phone:

- Please take a picture of your wildflower patch (so all of the patch is in view)
- Please take a picture of your whole allotment/garden (so we can see what other flowers are growing in your garden/allotment)
- Email these photos to j.griffiths-lee@sussex.ac.uk Or you could post them on Facebook (www.facebook.com/groups/SowWild/) if you are happy with other people seeing them.
- Note – please take photos in May, June, July and August, this is so we can see the flowers at different times over the summer. You can email them all at once at the end of the summer if you like, but please note the month in the name of the photo so we know which is which!

Also during this 48 hour period, tell us what you have found:

Using your recording sheet:

- Tell us about the weather when you collected your samples
- Tell us which pollinators/insects you think you have collected
- Tell us which flower species are present in the wildflower patch
- Tell us what other flowers you have grown in your garden/allotment, and how many plants on a scale of 1-10, 11-25, 26-100, 101-200, 201-1000, 1001-5000, 5000+

For help with identification, I will soon send you pictures of flowers and insects you might expect to find in your wildflower plot.

RETURNING YOUR SAMPLES

Before you return your samples, please take around a tablespoon of soil from your garden/allotment (about 15cm/6 inches deep) and put it in the small plastic bag provided.

- At the end of the summer –please return your collection of jars to us! You could use the box that we initially sent to you
- Please make sure the jars are labelled with your name, date, postcode and the code 'WP' or '10' using permanent marker or pencil
- Please secure the lids of the jars with sticky tape (tip –give the jars a little shake upside down –if they leak the lids aren't on properly!)
- Remember to include your recording sheets
- Remember to include soil sample
- Return the box to me at:

Janine Griffiths-Lee
JMS PG Pigeonholes
University of Sussex
Falmer
Brighton
BN1 9QG

Thank you! We are really looking forward to seeing your results!

Just a note - The cost of a second-class postage to the university is currently £2.80.

MANAGING YOUR WILDFLOWER PATCH

- **Year 1: 2016**

During the first year, you will just see annuals (probably poppy and cornflower). Let these flower and then cut back the wildflower patch as flowering declines. It is especially important during this first year to cut the wildflower patch before the flowers die back, set seed and collapse, and to remove all the cuttings.

Flowering decline will probably be mid-summer (late July – early August), depending on your location. Once the wildflowers are cut back it will reveal the developing meadow mixture below and give this the space it needs to develop.

Cut back/mow to about 5cm, or 2 inches.

- **Years 2 and 3: 2017 & 2018 (and onwards)**

This is when you will see a diverse and beautiful wildflower patch!

Cutting back should take place again before flowering die-back and collapse - this will probably be in August. Again remove all the cuttings, which prevents rotting vegetation stifling flower growth. Cut back/mow to about 5cm, or 2 inches.

In late Autumn/early winter cut back to about 5cm (2 inches) and then again in spring if needed.

In later years (2018 onwards) grasses may start to dominate the wildflower patch. If this happens you can also cut back mid-summer (late July/August).

NEXT STEPS:

- Please remember to keep your pan traps and instructions! You can use these again next year
- You will be sent new jars for 2017
- Once we have identified the species we will send you a list of what we found in your garden/allotment
- Once we have collected in the results over 3 years we hope to publish our results in a scientific journal and we will keep you up to date about this!

CONTACT DETAILS:

Email: j.griffiths-lee@sussex.ac.uk

Facebook: www.facebook.com/groups/SowWild/

I am also happy to talk on the phone – please email me with your phone number and I can call at a time to suit you!
If you would like to write to me, you can use the return address above.

THANK YOU!

MAY RECORDING SHEET – 2016

Your name	
Your postcode	
Date of the 24 hour sampling period (dd/mm/yy)	
What is the pH of your soil?	
What was the temperature (°C) during this 48 hour period? A rough average is fine!	
Did it rain during the 48 hour period (y/n)?	
If it did rain, was it light/medium/heavy/thunderstorm?	

How many of each type of insect did you collect in the pan traps placed in your wildflower patch:

INSECT	**NUMBER OF INSECTS IN SAMPLE**
BUMBLEBEE	
HONEYBEE	
SOLITARY BEE	
WASP	
HOVERFLY	
MOTH	
BUTTERFLY	
FLY	
OTHER	

How many of each type of insect did you collect in the pan traps that were placed 10 metres away from the wildflower patch:

INSECT	**NUMBER OF INSECTS IN SAMPLE**
BUMBLEBEE	
HONEYBEE	
SOLITARY BEE	
WASP	
HOVERFLY	
MOTH	
BUTTERFLY	
FLY	
OTHER	

If you think you know which species your samples contains (through previous knowledge or new research), please tell us the common or Latin name on another sheet. If you do not have any idea of the species, that's fine! The experts at Sussex will compare your results to theirs, so don't be afraid to have a go at identifying your species sample!

MAY RECORDING SHEET CONTINUED….

For help in identification: The list of the species in your wildflower mix can be found in the instruction leaflet, and the pictures sent via email.

Tell us which wildflowers are currently present in your wildflower patch. Please list these below!

Tell us which other flowering plants are present in your garden, using the following scale to estimate the number of **plants**: Scale: 1-10, 11-25, 26-100, 101-200, 201-1000, 1001-5000, 5000+

Other flowering plants in your garden/allotment	**Number of other flowering plants (see scale above)**

SOW WILD! 2017 INSTRUCTIONS

Welcome back to Sow Wild! We have made a few changes to the methods this year - the following instructions should tell you everything you need to know.

PROJECT KIT 2017

In your kit you should have:

- 32 plastic jars and lids (these are smaller than last year!)
- 8 pan traps (2 yellow, 2 pink, 2 blue, 2 white)
- 8 Yellow Sticky paper traps and 8 sticky labels
- Recording sheets
- ID guide for insects and flowers
- The box in which your kit arrived – keep this to return your samples at the end of summer

You will need:

- Clear vinegar
- Natural washing-up liquid without strong scent (for example, Ecover)
- Access to a digital camera/camera phone
- Ball of garden string and 2 sticks/bamboo cane (around ½ -1 metre long)
- Cling film or similar

CHANGES FOR 2017

1. We will be elevating pan traps (you can use upside down recycling boxes, buckets, or anything else from your shed!)
2. We only set pan traps for 24 hours
3. We will also use 'yellow sticky paper traps' when we sample each month
4. We will add a 10 minute 'bee watch' each month
5. We are interested in looking at what is attracted to the different colour pan traps, so we will separate the samples by colour

NOTES FOR 2017

1. The new pan traps have a 'nectar guide' on the bottom, so don't use last year's pan traps!
2. When collecting up samples, please **don't** keep slugs, snails, moths or butterflies, although please do mark them on your recording sheet. We found slugs and snails dissolved in the vinegar, making it very brown, smelly and sticky!

3. We found that people collected lots of flies. Its time consuming for you to count these, so just give us a rough estimate!
4. When recording flowers on your recording sheets, please only note those flowers actually in bloom at the time
5. When storing your pan traps – try to let these dry before storing them until the next month –this stops them flaking so badly.
6. We have added a 'bee watch' based on feedback from people saying their pan traps do not catch a representative sample of what's in their garden. Take your recording sheet and a cup of tea and relax in your garden each month. Bliss….
7. Due to the extra methods, the project will take you a bit of extra time each month. We hope you enjoy this, but if it's too much, just do as much as you are able. Even if you just stick to setting and collecting pan traps–we are very grateful!

THE PROJECT PLAN

STEP ONE: Preparing your wildflower plot

When? March/April

- Remove any obvious weeds or debris that have appeared overwinter
- Your seedlings may have already started to appear – if you are unsure what is seedling and what is weed, just leave them for now
- Start watering regularly

STEP TWO: Sampling!

When? During the beginning of May, June, July and August. Preferably during a dry and sunny 24-hour period.

This year we will be using THREE sampling methods, and we will do these during the first two weeks of each month:

- Sticky yellow traps
- Bee watch
- Pan traps

If you don't have enough time, or don't wish to do all 3 methods, don't worry! Just carry on pan trapping as normal.

We will be sampling in your wildflower patch, and the area 10 metres away from your wildflower patch, (this is where you set your second set of pan traps last year) from now on we will call this the '10 – metre away control area'.

Part one: Set your yellow sticky paper traps

- Using a piece of string, stick/bamboo cane (½ -1 metre long is fine), and a piece of yellow sticky trap paper from your kit
- Thread some string through the hole in the yellow sticky trap paper, and securely attach to the top of the stick.
- Push the bottom of the stick into the ground in your wildflower patch. The yellow sticky trap should sit around half a metre from the ground, and shouldn't flap around too much in the wind. (see photo)
- Peel off the clear film on both sides of the yellow sticky traps
- Repeat with a second yellow sticky trap and stick, placed in your 10 metre away control area
- Leave the sticky traps for two weeks (it doesn't matter if it rains – they are water proof)
- When collecting up the sticky traps cover in a single layer of cling film. Note - The sticky paper stays very sticky, and covered in cling film will allow us to look at the insects under a microscope
- Write the **Month** and **Code 'WP'** (wildflower patch) or **'10'** (10 metres away) and your **Name** on a label provided, and stick it on the cling film covering the yellow sticky paper trap

Part two: The bee watch!

During the first 2 weeks of each month, we would like you to take 10 minutes to relax in front of your wildflower patch, followed 10 minutes in front of your '10 metre away control area', and record what pollinators you see. If you don't have the time for the bee watch – please don't worry if you have to skip it.

If you can, please do your bee watch when it's a nice day, and between 10am-4pm (this is when bees are most active).

- Looking at your 2m x 2m wildflower patch and timing 10 minutes on a clock
- Record the types of insect you see visiting the wildflower patch, using your insect ID guide and 'bee watch' recording sheet
- Now go to your '10 metre away control area' and measure out a 2m x 2m square. You could even use string or a few sticks to show the boundaries of the area if you like
- Again, for 10 minutes record the types of insect visiting this area

Part three: Pan trap sampling

You are no doubt an expert at this bit now! But remember this time to elevate the pan traps, and you only need to leave them for 24 hours

- Fill each of your pan traps ¾ full with water, and a generous squeeze of washing-up liquid
- Lay four pan traps (one pink, one white, one blue, one yellow) alongside each other in the middle of your wildflower patch
- Elevate the pan traps off the ground using an upside down recycling box, bucket, or anything else you can find in the shed! (see photo)

- If it's very windy, you could place a stone in the bottom of the pan traps
- Lay the remaining four pan traps 10 metres away from your wildflower patch, and again elevate off the ground
- Leave the pan traps undisturbed and collect up your pan traps 24 hours later

Collecting up your pan traps:

This year we will be collecting up the pan traps and separating into jars by colour!

- You will need 4 jars for the wildflower patch, and 4 jars for the pan traps set 10 metres away
- Scoop out all the insects you have collected into 4 separate jars – one for each colour pan trap
- Using your recording sheet, see if you can identify any of the insects collected – you could use a teaspoon to scoop them out so you can take a closer look. NOTE- please don't send us slugs or snails, and don't worry about counting all the flies!
- Drain the water (as much as you can!) and fill the jar with clear vinegar, just enough to cover the insects and preserve them
- On the jar write:
    - 'WP' (which stands for wildflower patch)
    - Your full name
    - Your postcode
    - The date (day, month, year)
    - The colour of the pan trap (P= pink, W= white, B =blue, Y = yellow)

- Repeating as above for the **four** pan traps 10 metres away from the wildflower patch: scoop out all the insects you have collected into 4 separate jars
- On the jar write:
    '10' (which stands for '10 metres from the wildflower patch')
    Your full name
    Your postcode
    The date (day, month, year)
    The colour of the pan trap (P= pink, W= white, B =blue, Y = yellow)

- Tightly secure the lid on all jars, and store somewhere cool and dry until the end of the summer

Part four: Tell us about your garden

Also during this 24 hour period, tell us what you have found:

- Tell us about the weather when you collected your samples
- Tell us which pollinators/insects you think you have collected
- Tell us which flower species are FLOWERING in the wildflower patch
- Tell us what other flower species ARE FLOWERING in your garden/allotment, and how many PLANTS on a scale of 1-10, 11-25, 26-100, 101-200, 201-1000, 1001-5000, 5000+

During this 24 hour period, take some pictures of your site:

Using your digital camera/camera phone:

- Please take a picture of your wildflower patch (so all of the patch is in view)
- Please take a picture of your whole allotment/garden (so we can see what other flowers are growing in your garden/allotment)
- Email these photos to j.griffiths-lee@sussex.ac.uk Or you could post them on Facebook (www.facebook.com/groups/SowWild/) if you are happy with other people seeing them.
- Note – please take photos in May, June, July and August, this is so we can see the flowers at different times over the summer. You can email them all at once at the end of the summer if you like, but please note the month in the name of the photo so we know which is which!

RETURNING YOUR SAMPLES

At the end of the summer –please return your collection of jars to us! Remember to include your recording sheets and yellow sticky paper traps

- Include your yellow sticky traps covered in cling film
- Take a photocopy/photo of your recording sheets

- Please make sure the jars are labelled with your name, date, postcode and the code 'WP' or '10', **AND** the code 'P', 'Y', 'W' or 'B'
- Please secure the lids of the jars with insulation tape or parcel tape
- Only use enough vinegar to cover the insects, you don't need to fill the jar
- Place the samples in a bin liner or similar and tie it in a knot
- Return the box to me at:

Janine Griffiths-Lee
JMS PG Pigeonholes
University of Sussex
Falmer
Brighton
BN1 9QG

Just a note - The cost of a second-class postage to the university is currently £2.80.

MANAGING YOUR WILDFLOWER PATCH

- **Years 2 and 3: 2017 & 2018 (and onwards)**

This is when you will see a diverse and beautiful wildflower patch!

Cutting back should take place again before flowering die-back and collapse - this will probably be in August. Again remove all the cuttings, which prevents rotting vegetation stifling flower growth. Cut back/mow to about 5cm, or 2 inches.

In late Autumn/early winter cut back to about 5cm (2 inches) and then again in spring if needed.

In later years (2018 onwards) grasses may start to dominate the wildflower patch. If this happens you can also cut back mid-summer (late July/August).

CONTACT DETAILS:

Email: j.griffiths-lee@sussex.ac.uk

Facebook: www.facebook.com/groups/SowWild/

I am also happy to talk on the phone – please email me with your phone number and I can call at a time to suit you! If you would like to write to me, you can use the return address above.

THANK YOU!

MAY RECORDING SHEET -2017

Your name	
Your postcode	
Start date of the 24 hour pan trap sampling (dd/mm/yy)	
Temperature during 24 hour sampling (average)	
Did it rain during 24 hour period? (y/n)	
If yes- was it light/medium/heavy/thunderstorm?	
Start date yellow sticky paper traps set (dd/mm/yy)	

MAY - THE PAN TRAPS

Note - You don't need to tell us the exact number of flies- an estimate will do. Please don't put any slugs, snails, butterflies or moths in the sample. These disintegrate in vinegar!

Please record how many insects you found in the pan traps set in the **WILDFLOWER PATCH**

Number of insects in sample by pan trap colour

INSECT	YELLOW	PINK	WHITE	BLUE
BUMBLEBEE				
HONEYBEE				
SOLITARY BEE				
WASP				
HOVERFLY				
MOTH				
BUTTERFLY				
FLY (estimate!)				
OTHER				

Please record how many insects you found in the pan traps set **10 METRES AWAY**

Number of insects in sample by pan trap colour

INSECT	YELLOW	PINK	WHITE	BLUE
BUMBLEBEE				
HONEYBEE				
SOLITARY BEE				
WASP				
HOVERFLY				
MOTH				
BUTTERFLY				
FLY (estimate!)				
OTHER				

MAY - THE BEE WATCH

Date		Temperature	
Time started		Rain (y/n)	

Please record how many insects you spotted in the **WILDFLOWER PATCH** over 10 minutes

INSECT	**NUMBER**
BUMBLEBEE	
HONEYBEE	
SOLITARY BEE	
WASP	
HOVERFLY	
MOTH	
BUTTERFLY	
FLY	
OTHER	

Please record how many insects you spotted in the **10 METRE AWAY AREA** over 10 minutes

INSECT	**NUMBER**
BUMBLEBEE	
HONEYBEE	
SOLITARY BEE	
WASP	
HOVERFLY	
MOTH	
BUTTERFLY	
FLY	
OTHER	

MAY - THE FLOWERS

Tell us which wildflowers are currently present in your wildflower patch. Please list these below!

Tell us which other flowering plants are present in your garden, using the following scale to estimate the number of **plants**: Scale: 1-10, 11-25, 26-100, 101-200, 201-1000, 1001-5000, 5000+

Other flowering plants in your garden/allotment	**Number of other flowering plants (see scale above)**

You can continue on another sheet if necessary

APPENDIX F. Wildflowers mix flower guides, and insect guides

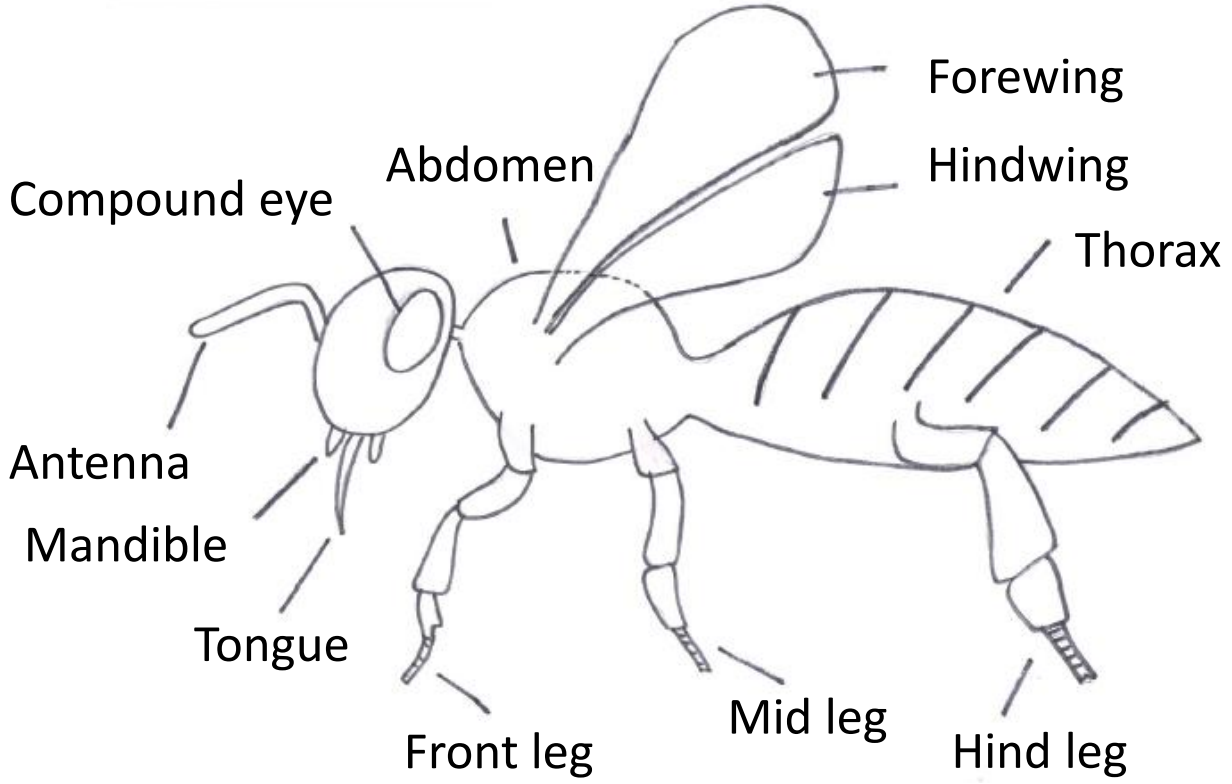
University of Sussex

Sow Wild! Insect Identification Guide

In this guide you will find photos and descriptions of some of the insects you might find in your pan traps, which may help you fill out your recording sheet. There are also lots of online resources which could help in identification.

If you have prior knowledge of bees (or any of the other insects!) and are confident to tell us which genus/species you think you have caught - please do!

If you can't identify which group you are looking at –don't worry! Once you send your samples back to us we can tell you which species of bee you have pollinating your garden or allotment.



UK Bees

There are around 250 species of bee in the UK. There is just one species of honeybee, there are 24 species of bumblebee and the remaining 225 species are grouped together and called 'solitary bees'. Some insects can look like bees, and some bees can look like wasps. To help you tell if it's a bee:

Bees have:

- 2 pairs of membranous wings
- There are mandibles present, between which there is a visible tongue
- There are 12-13 segments of the antennae
- There is a distinction between the thorax and abdomen (although this isn't easy to see in very hairy species!)
- Most bees have hairs which are used to carry pollen

Honeybees

There is just one species of honeybee in the UK, *Apis mellifera*.

Honeybees are 14mm long, and light brown and black, with characteristic stripes. They are a similar size and shape to a common social wasp, but they have hairs to collect pollen whereas common social wasps are smooth and waxy.

Honeybees also have hair on their eyes.

Bumblebees

There are 24 species of bumblebee in the UK.

Bumblebees are easy to recognise, with dense fur covering their bodies, and generally are larger than other bees.

Solitary bees

There are around 225 species of solitary bee in the UK. They come in all different sizes and colours.

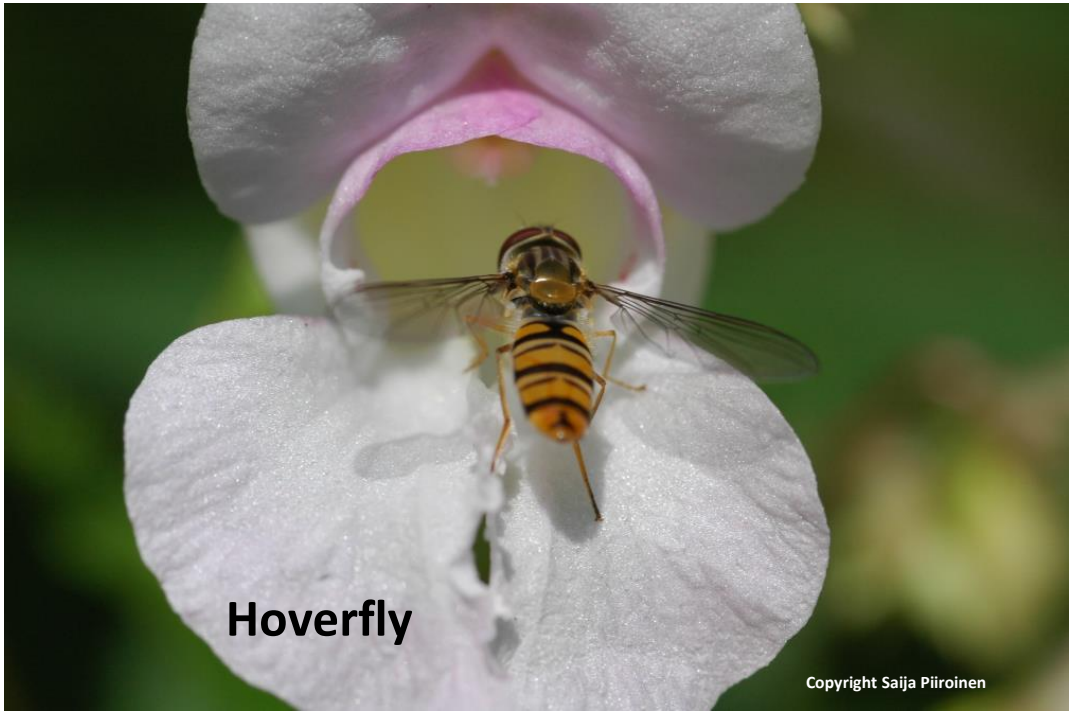
Differentiating between different solitary bees takes a lot of practice and usually a microscope!

Any bee that you find that isn't a bumblebee or a honeybee, please mark it as a solitary bee on your recording sheet.

Wasps

Common social wasps have a smooth waxy appearance, and are usually black and bright yellow. They have a narrow ‘waist’.

Some other species of wasp can look a lot like solitary bees – differentiating takes lots of practice. Your best guess will do!

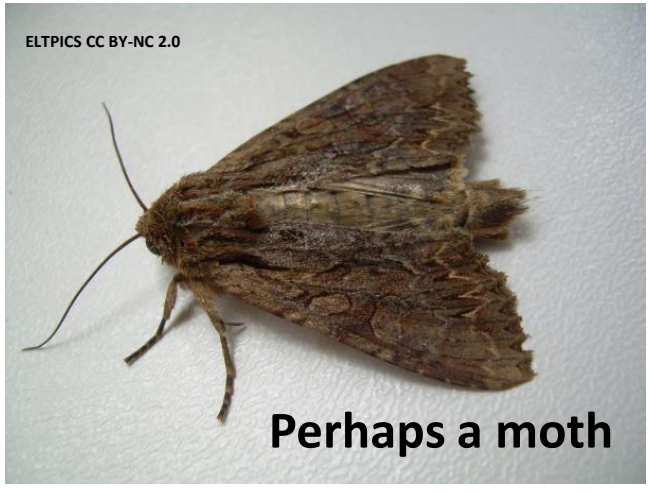


Hoverflies

Hoverflies are true flies, and only have one pair of wings (bees and wasps have two pairs). They are usually bright yellow and black with ornate patterns.

Hoverflies often mimic bees, but you can tell the difference as they only have one pair of wings, and shorter antennae. They generally also have larger eyes.

Other insects you may find in your pan trap…



All photos in this document courtesy of Emorsgate unless stated.

University of Sussex

Sow Wild! Flower Identification Guide

In this guide you will find photos of the flowering plants that are in your mix, with the exception of the grasses – as you don't need to identify these! Due to climate/soil differences, not all of these flowers will germinate and appear in your wildflower patch.

Its hard to tell some of the flowers apart, and in these cases I have given some tips on how to tell the difference. But it can be tricky – so if you can't decide which species you are looking at please don't worry! A good guess will do.

At the end of this document there is a key to some of the terms used.

Betony (*Betonica officinalis*)

Cornflower (*Centaurea cyanus*)

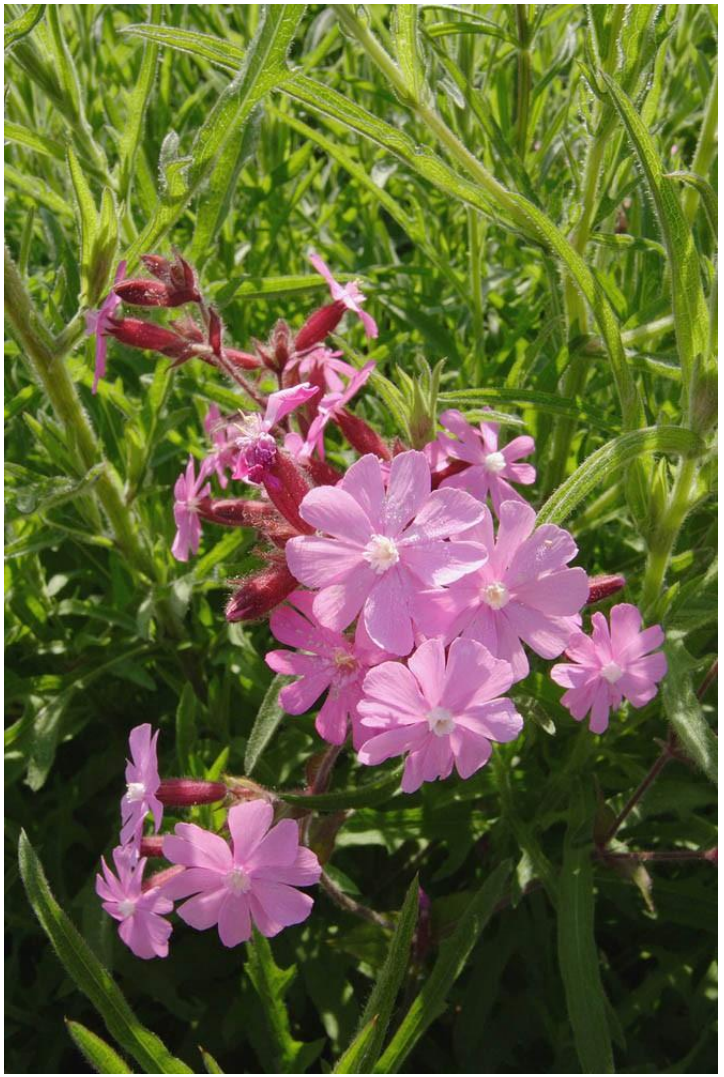
Tip - In Common knapweed the bracts that make up the 'hard head' are pale brown with black/brown bristly edges. However the degree of overlap obscures most of the pale brown. In Greater knapweed these bracts are grey-green with black/brown bristly edges but, because there is less overlapping, much of the bract is still visible. In Common knapweed the leaves of the upper stem are lanceolate (meaning 'pointy both ends') and in Greater knapweed they are toothed (or 'jagged').

Greater knapweed (*Centaurea scabiosa*)

Common knapweed (*Centaurea nigra*)

Ragged robin (*Silene flos-cuculi*)

Red campion (*Silene dioica*)



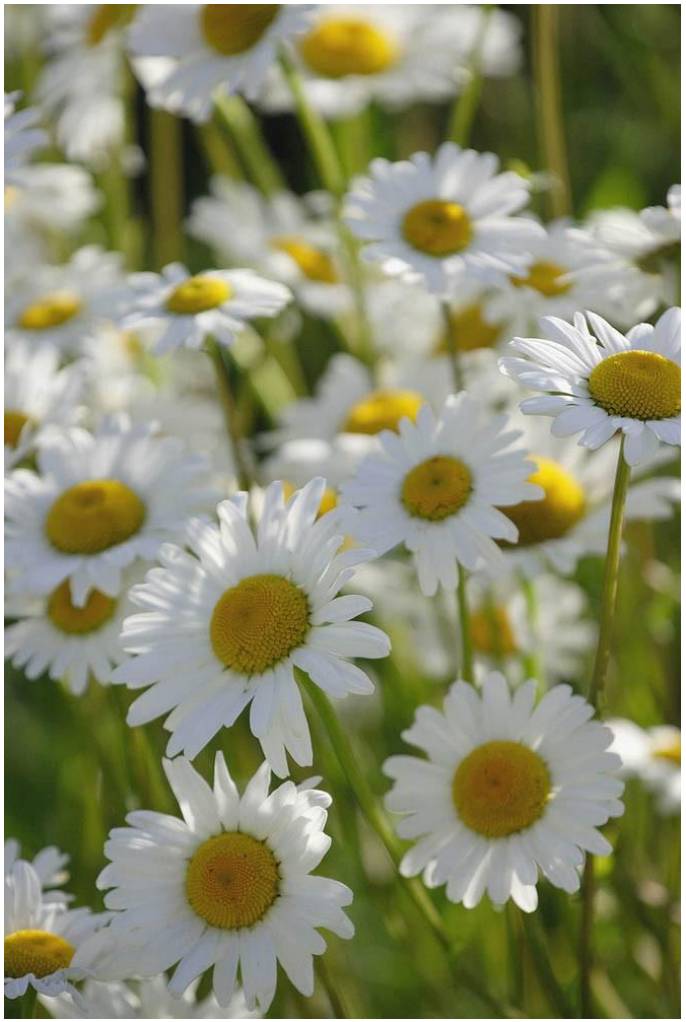
Common sorrel (*Rumex acetosa*)

Tufted vetch (*Vicia cracca*)

Salad burnet (*Poterium sanguisorba*)

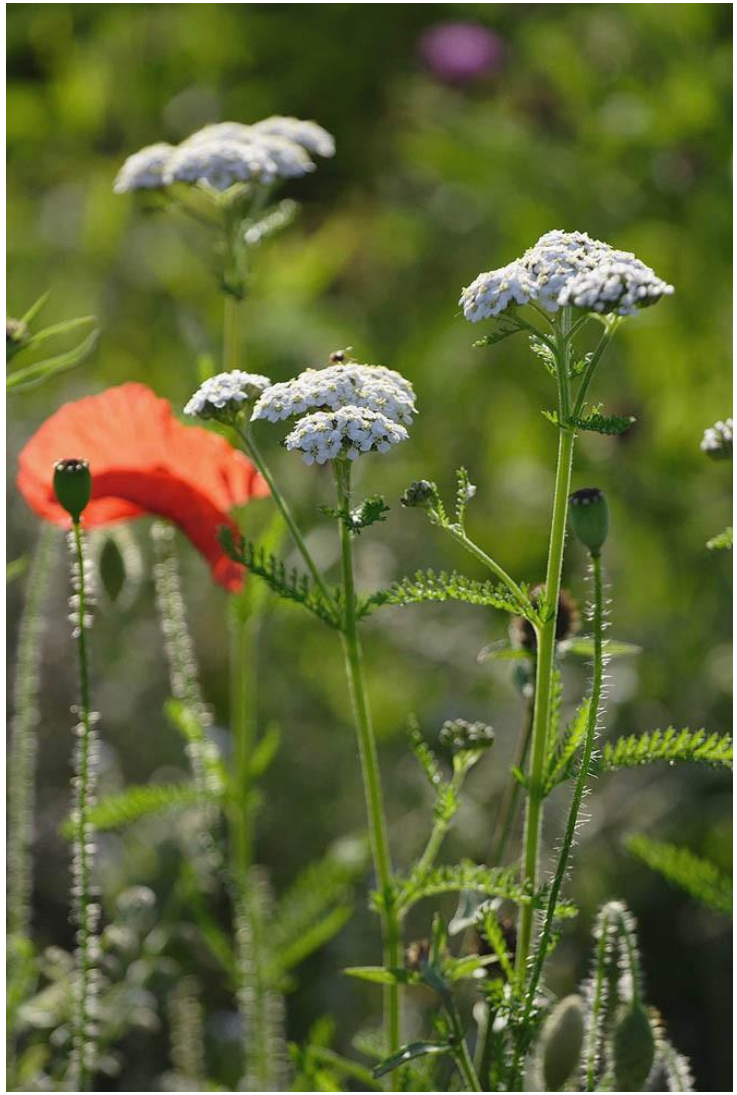
Selfheal (*Prunella vulgaris*)

Oxeye daisy (*Leucanthemum vulgare*)



Yellow rattle (*Rhinanthus minor*)

Yarrow (*Achillea millefolium*)

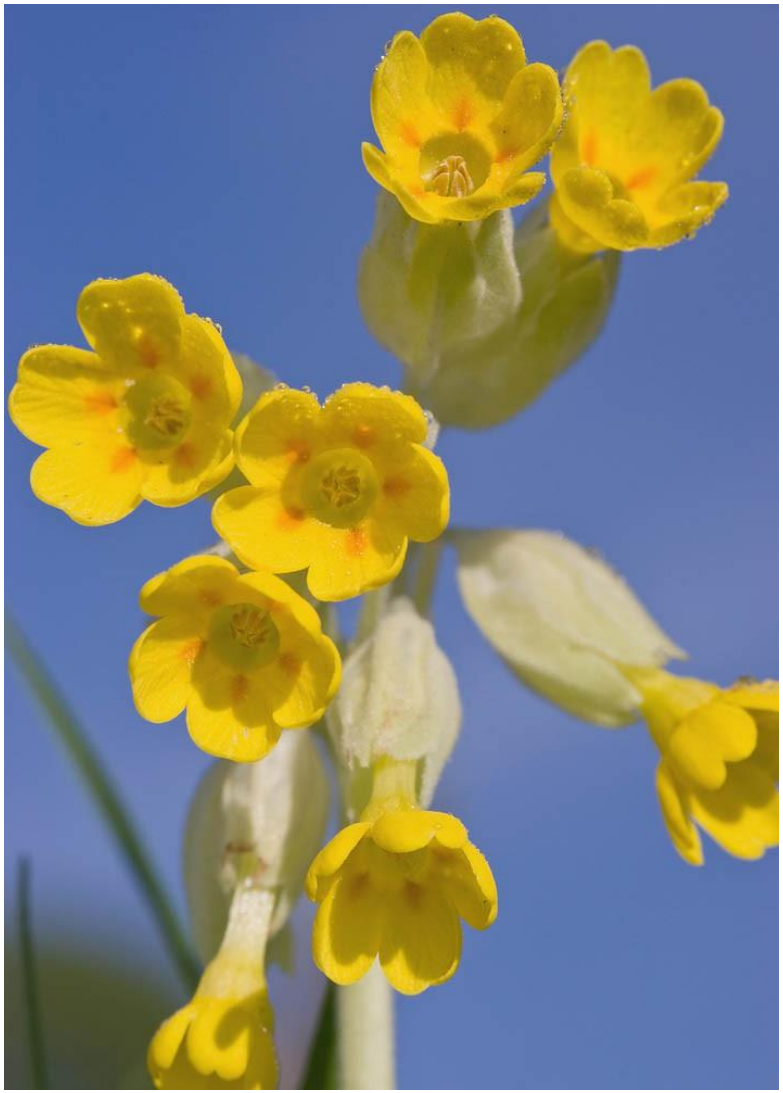


Wild carrot (*Daucus carota*)

Meadow buttercup (*Ranunculus acris*)

Rough hawkbit (*Leontodon hispidus*)

Cowslip (*Primula veris*)



Birdsfoot Trefoil (*Lotus corniculatus*)

Hedge bedstraw (*Galium album*)

Lady's bedstraw (*Galium verum*)

Meadowsweet (*Filipendula ulmaria*)

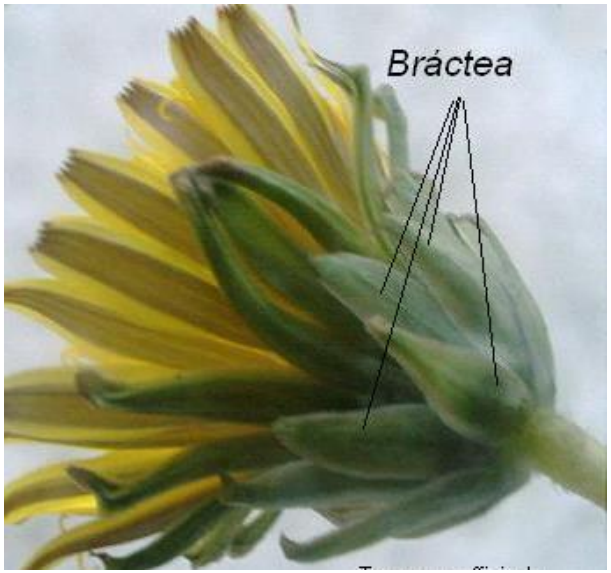
Wild marjoram (*Origanum vulgare*)

Hoary plantain (*Plantago media*)

Common poppy (*Papaver rhoeas*)

Wild red clover (*Trifolium pratense*)

Key to some of the terms used in this guide



Bracts

Basal rosette

Lobed leaf

Entire leaf margin

Toothed leaf margin

Lanceolate leaf

All photos in this document courtesy of Emorsgate unless stated.

University of Sussex

Sow Wild! Flower Identification Guide

In this guide you will find photos of the flowering plants that are in your mix, with the exception of the grasses – as you don't need to identify these! Due to climate/soil differences, not all of these flowers will germinate and appear in your wildflower patch.

Its hard to tell some of the flowers apart, and in these cases I have given some tips on how to tell the difference. But it can be tricky – so if you can't decide which species you are looking at please don't worry! A good guess will do.

At the end of this document there is a key to some of the terms used.

Sainfoin (*Onobrychis viciifolia*)

Clustered bellfower (*Campanula glomerata*)

Tip - In Common knapweed the bracts that make up the 'hard head' are pale brown with black/brown bristly edges. However the degree of overlap obscures most of the pale brown. In Greater knapweed these bracts are grey-green with black/brown bristly edges but, because there is less overlapping, much of the bract is still visible. In Common knapweed the leaves of the upper stem are lanceolate (meaning 'pointy both ends') and in Greater knapweed they are toothed (or 'jagged').

Greater knapweed (*Centaurea scabiosa*)

Common knapweed (*Centaurea nigra*)

Tip - Small scabious is smaller, slimmer and less hairy than field scabious, and the individual flowers that make up the flower head have five not four petal lobes.

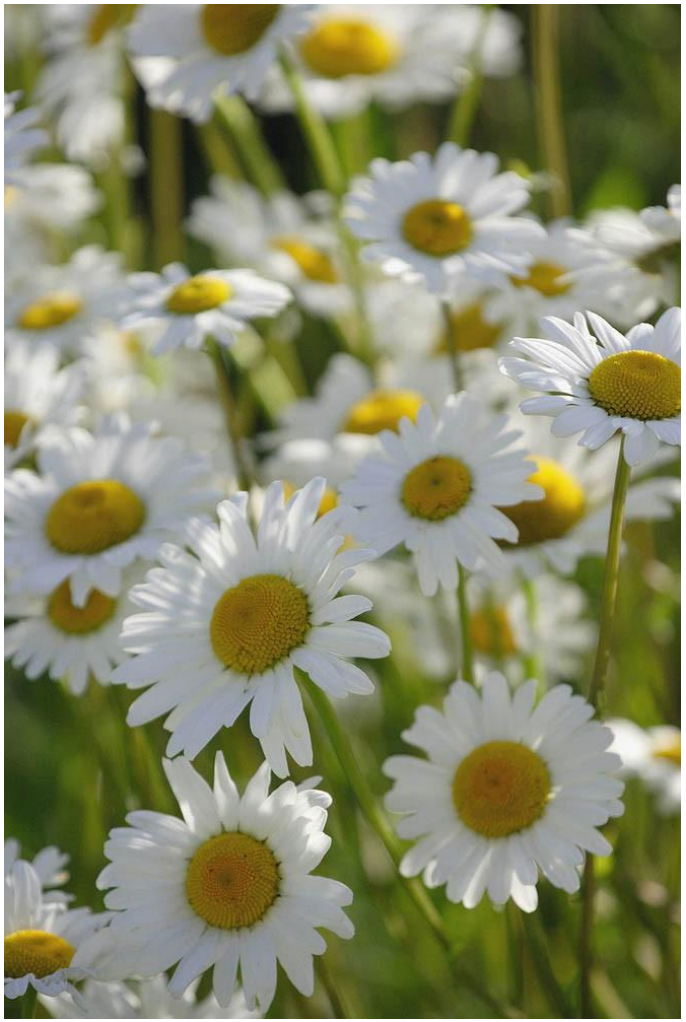
Small scabious (*Scabiosa columbaria*)

Field scabious (*Knautia arvensis*)

Cornflower (*Centaurea cyanus*)

Viper's bugloss (*Echium vulgare*)

Oxeye daisy (*Leucanthemum vulgare*)



Tip - Chamomile has divided leaves while those of oxeye daisy are entire and notched but not divided. Chamomile usually has many flowering heads on each flowering stem while oxeye daisy usually has a single flower.

Chamomile (*Matricaria chamomilla*)

Photo courtesy- Ettore Balocchi CC by 2.0

Garlic mustard (*Alliaria petiolata*)

Wild carrot (*Daucus carota*)

Meadow buttercup (*Ranunculus acris*)

Winter cress (*Barbarea vulgaris*)

Wild mignonette (*Reseda lutea*)

Birdsfoot Trefoil (*Lotus corniculatus*)

Common poppy (*Papaver rhoeas*)

Cat's-ear, Rough hawkbit and Autumn hawkbit are very easily confused, but there are subtle ways to tell them apart. The differences are described on the next page…

Cat's-ear (*Hypochaeris radicata*)

Photo courtesy -
Peter O'connor
CC by SA 2.0

Rough hawkbit (*Leontodon hispidus*)

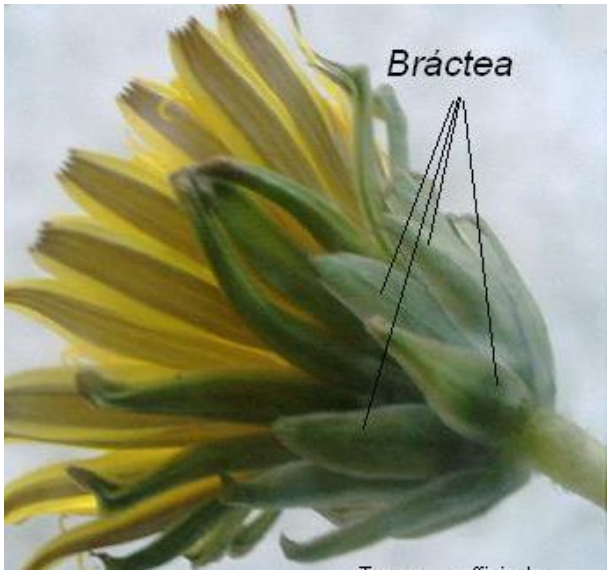
Autumn hawkbit (*Scorzoneroides autumnalis*)

Tip -
Autumn hawkbit has a stem that swells towards the top, no chaffy scales among the florets and with outer florets reddish beneath. The leaves of the basal rosette of the have sharper tips and sharper lobes.

Rough hawkbit is a rich golden yellow with the outer florets often reddish or orange and the bracts behind the flower appearing very shaggy. The leaves which make up the basal rosette are long and bluntly lobed (meaning deeply indented).

Cat's-ear has chaffy scales among the florets and with outer florets greyish/greenish. The leaves of the basal rosette are long and bluntly lobed.

Key to some of the terms used in this guide



Bracts

Basal rosette

Lobed leaf

Entire leaf margin

Toothed leaf margin

Lanceolate leaf

APPENDIX G. Full species list for bees and hoverflies

Abundance	No. Sites	% Sites	Species	Group	Year
8	1	1%	*Andrena barbilabris*	Solitary bee	2016
6	4	6%	*Andrena bicolor*	Solitary bee	2016
2	2	3%	*Andrena chrysosceles*	Solitary bee	2016
4	2	3%	*Andrena cineraria*	Solitary bee	2016
1	1	1%	*Andrena dorsata*	Solitary bee	2016
1	1	1%	*Andrena flavipes*	Solitary bee	2016
5	2	3%	*Andrena fulva*	Solitary bee	2016
12	7	10%	*Andrena haemorrhoa*	Solitary bee	2016
1	1	1%	*Andrena helvola*	Solitary bee	2016
6	3	4%	*Andrena labiata*	Solitary bee	2016
5	4	6%	*Andrena minutula*	Solitary bee	2016
2	2	3%	*Andrena nigroaenea*	Solitary bee	2016
4	2	3%	*Andrena nitida*	Solitary bee	2016
2	1	1%	*Andrena ovatula*	Solitary bee	2016
1	1	1%	*Andrena scotica*	Solitary bee	2016
3	2	3%	*Andrena semilaevis*	Solitary bee	2016
9	1	1%	*Anthidium manicatum*	Solitary bee	2016
6	6	9%	*Anthophora furcata*	Solitary bee	2016
2	2	3%	*Anthophora plumipes*	Solitary bee	2016
97	33	49%	*Apis mellifera*	Honeybee	2016
16	10	15%	*Bombus hortorum*	Bumblebee	2016
11	11	16%	*Bombus hypnorum*	Bumblebee	2016
17	14	21%	*Bombus lapidarius*	Bumblebee	2016
4	4	6%	*Bombus lucorum*	Bumblebee	2016
66	24	35%	*Bombus lucorum/terrestris*	Bumblebee	2016
1	1	1%	*Bombus muscorum*	Bumblebee	2016
43	23	34%	*Bombus pascuorum*	Bumblebee	2016
18	11	16%	*Bombus pratorum*	Bumblebee	2016
1	1	1%	*Bombus rupestris*	Bumblebee	2016
1	1	1%	*Bombus sylvestris*	Bumblebee	2016
25	16	24%	*Bombus terrestris*	Bumblebee	2016
5	4	6%	*Chelostoma campanularum*	Solitary bee	2016
5	5	7%	*Episyrphus balteatus*	Hoverfly	2016
1	1	1%	*Eristalis arbustorum*	Hoverfly	2016
1	1	1%	*Eristalis tenax*	Hoverfly	2016
4	3	4%	*Eupeodes corollae*	Hoverfly	2016
4	3	4%	*Halictus rubicundus*	Solitary bee	2016
16	9	13%	*Halictus tumulorum*	Solitary bee	2016
28	17	25%	*Helophilus pendulus*	Hoverfly	2016
1	1	1%	*Heriades truncorum*	Solitary bee	2016
1	1	1%	*Hylaeus brevicornis*	Solitary bee	2016
4	3	4%	*Hylaeus communis*	Solitary bee	2016
4	4	6%	*Hylaeus confusus*	Solitary bee	2016
2	2	3%	*Hylaeus dilatatus*	Solitary bee	2016
8	4	6%	*Hylaeus hyalinatus*	Solitary bee	2016
16	9	13%	*Lasioglossum albipes*	Solitary bee	2016
15	6	9%	*Lasioglossum calceatum*	Solitary bee	2016
12	4	6%	*Lasioglossum cupromicans*	Solitary bee	2016
1	1	1%	*Lasioglossum fratellum*	Solitary bee	2016
3	1	1%	*Lasioglossum fulvicorne*	Solitary bee	2016
1	1	1%	*Lasioglossum lativentre*	Solitary bee	2016
71	16	24%	*Lasioglossum leucopus*	Solitary bee	2016
16	7	10%	*Lasioglossum minutissimum*	Solitary bee	2016

28	11	16%	*Lasioglossum morio*	Solitary bee	2016
13	3	4%	*Lasioglossum pauxillum*	Solitary bee	2016
45	13	19%	*Lasioglossum smeathmanellum*	Solitary bee	2016
3	3	4%	*Lasioglossum sp.*	Solitary bee	2016
4	3	4%	*Lasioglossum villosulum*	Solitary bee	2016
7	3	4%	*Megachile centuncularis*	Solitary bee	2016
2	2	3%	*Megachile ligniseca*	Solitary bee	2016
1	1	1%	*Megachile versicolor*	Solitary bee	2016
4	3	4%	*Megachile willughbiella*	Solitary bee	2016
1	1	1%	*Melangyna umbellatarum*	Hoverfly	2016
3	3	4%	*Melanostoma scalare*	Hoverfly	2016
1	1	1%	*Melitta haemorrhoidalis*	Solitary bee	2016
3	2	3%	*Merodon equestris*	Hoverfly	2016
1	1	1%	*Myathropa florea*	Hoverfly	2016
1	1	1%	*Neoascia podagrica*	Hoverfly	2016
1	1	1%	*Nomada fabriciana*	Solitary bee	2016
1	1	1%	*Nomada flava*	Solitary bee	2016
11	7	10%	*Osmia bicornis*	Solitary bee	2016
4	4	6%	*Osmia caerulescens*	Solitary bee	2016
1	1	1%	*Osmia leaiana*	Solitary bee	2016
2	1	1%	*Platycheirus albimanus*	Hoverfly	2016
1	1	1%	*Platycheirus manicatus*	Hoverfly	2016
1	1	1%	*Sphaerophoria scripta*	Hoverfly	2016
2	2	3%	*Sphecodes geoffrellus*	Solitary bee	2016
1	1	1%	*Syritta pipiens*	Hoverfly	2016
1	1	1%	*Syrphus ribesii*	Hoverfly	2016

Abundance	No. Sites	% Sites	Species	Group	Year
1	1	2%	*Andrena barbilabris*	Solitary bee	2017
4	4	8%	*Andrena bicolor*	Solitary bee	2017
2	2	4%	*Andrena chrysosceles*	Solitary bee	2017
1	1	2%	*Andrena cineraria*	Solitary bee	2017
1	1	2%	*Andrena dorsata*	Solitary bee	2017
3	3	6%	*Andrena flavipes*	Solitary bee	2017
1	1	2%	*Andrena fulva*	Solitary bee	2017
5	3	6%	*Andrena haemorrhoa*	Solitary bee	2017
2	2	4%	*Andrena minutula*	Solitary bee	2017
1	1	2%	*Andrena nigroaenea*	Solitary bee	2017
2	2	4%	*Andrena nitida*	Solitary bee	2017
2	1	2%	*Andrena scotica*	Solitary bee	2017
6	3	6%	*Andrena semilaevis*	Solitary bee	2017
1	1	2%	*Andrena wilkella*	Solitary bee	2017
1	1	2%	*Anthidium manicatum*	Solitary bee	2017
1	1	2%	*Anthophora furcata*	Solitary bee	2017
1	1	2%	*Anthophora plumipes*	Solitary bee	2017
79	21	44%	*Apis mellifera*	Honeybee	2017
17	11	23%	*Bombus hortorum*	Bumblebee	2017
9	6	13%	*Bombus hypnorum*	Bumblebee	2017
5	5	10%	*Bombus lapidarius*	Bumblebee	2017
1	1	2%	*Bombus lucorum*	Bumblebee	2017
2	2	4%	*Bombus lucorum/terrestris*	Bumblebee	2017
13	13	27%	*Bombus pascuorum*	Bumblebee	2017
25	14	29%	*Bombus pratorum*	Bumblebee	2017
70	24	50%	*Bombus terrestris*	Bumblebee	2017
1	1	2%	*Chrysotoxum bicinctum*	Hoverfly	2017
1	1	2%	*Colletes daviesanus*	Solitary bee	2017
7	4	8%	*Episyrphus balteatus*	Hoverfly	2017
1	1	2%	*Eristalis pertinax*	Hoverfly	2017
3	3	6%	*Eristalis tenax*	Hoverfly	2017
5	4	8%	*Eupeodes corollae*	Hoverfly	2017
1	1	2%	*Eupeodes luniger*	Hoverfly	2017
1	1	2%	*Halictus rubicundus*	Solitary bee	2017
15	6	13%	*Halictus tumulorum*	Solitary bee	2017
13	8	17%	*Helophilus pendulus*	Hoverfly	2017
1	1	2%	*Heriades truncorum*	Solitary bee	2017
2	2	4%	*Hylaeus communis*	Solitary bee	2017
1	1	2%	*Hylaeus confusus*	Solitary bee	2017
2	2	4%	*Hylaeus dilatatus*	Solitary bee	2017
17	4	8%	*Hylaeus hyalinatus*	Solitary bee	2017
8	3	6%	*Lasioglossum albipes*	Solitary bee	2017
11	8	17%	*Lasioglossum calceatum*	Solitary bee	2017
1	1	2%	*Lasioglossum cupromicans*	Solitary bee	2017
1	1	2%	*Lasioglossum fratellum*	Solitary bee	2017
1	1	2%	*Lasioglossum fulvicorne*	Solitary bee	2017
1	1	2%	*Lasioglossum lativentre*	Solitary bee	2017
30	11	23%	*Lasioglossum leucopus*	Solitary bee	2017
2	2	4%	*Lasioglossum leucozonium*	Solitary bee	2017
7	5	10%	*Lasioglossum minutissimum*	Solitary bee	2017
46	11	23%	*Lasioglossum morio*	Solitary bee	2017
5	2	4%	*Lasioglossum pauxillum*	Solitary bee	2017

1	1	2%	*Lasioglossum punctatissimum*	Solitary bee	2017
34	8	17%	*Lasioglossum smeathmanellum*	Solitary bee	2017
2	1	2%	*Lasioglossum villosulum*	Solitary bee	2017
5	4	8%	*Megachile centuncularis*	Solitary bee	2017
1	1	2%	*Megachile ligniseca*	Solitary bee	2017
4	2	4%	*Megachile willughbiella*	Solitary bee	2017
1	1	2%	*Melanostoma mellinum*	Hoverfly	2017
2	2	4%	*Merodon equestris*	Hoverfly	2017
5	4	8%	*Myathropa florea*	Hoverfly	2017
3	2	4%	*Nomada fabriciana*	Solitary bee	2017
1	1	2%	*Nomada marshamella*	Solitary bee	2017
11	6	13%	*Osmia bicornis*	Solitary bee	2017
6	2	4%	*Syritta pipiens*	Hoverfly	2017
2	1	2%	*Syrphus ribesii*	Hoverfly	2017
2	1	2%	*Syrphus vitripennis*	Hoverfly	2017
1	1	2%	*Xylota segnis*	Hoverfly	2017

APPENDIX H. GLMM results on effects of the diversity of garden flowers on the abundance of insects and richness of bees

		GLMM by Mix (i)					GLMM all wildflowers (ii)				
Abundance	**Sample**	X^2	**df**	**p=**	**Sign.**	**Model**	X^2	**df**	**p=**	**Sign.**	**Model**
Total insect	PT Y1	0.79	1	0.37	NS	a	0.81	1	0.37	NS	a
Solitary wasp	PT Y1	1.38	1	0.24	NS	b	0.65	1	0.42	NS	b
Solitary bee	PT Y1	0.22	1	0.64	NS	b	1.17	1	0.28	NS	b
Bumblebee	PT Y1	<0.01	1	0.95	NS	b	0.04	1	0.84	NS	b
Hoverfly	PT Y1	0.01	1	0.93	NS	b	0.03	1	0.85	NS	b
Total insect	PT Y2	1.28	1	0.26	NS	b	1.06	1	0.30	NS	b
Solitary wasp	PT Y2	0.38	1	0.54	NS	b	1.68	1	0.20	NS	b
Solitary bee	PT Y2	1.09	1	0.30	NS	b	0.35	1	0.56	NS	b
Bumblebee	PT Y2	0.52	1	0.47	NS	b	0.29	1	0.59	NS	b
Hoverfly	PT Y2	0.94	1	0.33	NS	b	0.99	1	0.32	NS	b
Total insect	YT Y2	3.38	1	0.07	NS	a	0.37	1	0.54	NS	c
Solitary wasp	YT Y2	0.38	1	0.54	NS	b	0.32	1	0.57	NS	b
Solitary bee	YT Y2	0.14	1	0.71	NS	b	0.09	1	0.76	NS	b
Bumblebee	YT Y2	5.75	1	0.02	*	b	4.39	1	0.04	*	b
Hoverfly	YT Y2	0.33	1	0.57	NS	b	0.28	1	0.60	NS	b
Richness											
Bee richness	PT Y1	0.37	1	0.54	NS	b	<0.01	1	0.99	NS	b
Bee richness	PT Y2	0.36	1	0.55	NS	b	<0.01	1	0.97	NS	b

Supplementary information 3. ***Effect of Shannon's Diversity Index (SDI) of garden plants on insect abundance and bee richness.*** *Presented by pan traps Year 1 (PT Y1), pan traps Year 2 (PT Y2) and yellow sticky traps Year 2 (YT Y2). GLMM ANOVA results compare with Table 4 (main paper) where SDI is the predictor variable then compared with reduced model. (i) Model built with treatment (Mix 1, Mix 2 and Control) (ii) Model built with mini-meadow (all mixes) versus Control. Model: a = Poisson family; b = zero-inflated negative binomial family; c= Negative binomial family. Presented with chi-square X^2, degrees freedom df, significance (NS, not significant; *, $p < 0.05$).*

APPENDIX I. Wildflower and grass mix compositions, indicating which of the flowering species germinated, and in which year of the study

MEADOW MIX

Species	Common name	%Composition
Flowering plants		**20%**
Achillea millefolium [Ψ]*	yarrow	0.5
Anthyllis vulneraria	kidney vetch	0.8
Centaurea nigra *	common knapweed	1
Centaurea scabiosa	greater knapweed	2
Clinopodium vulgare	wild basil	0.4
Daucus carota *	wild carrot	0.6
Galium verum *	lady's bedstraw	1
Knautia arvensis *	field scabious	2
Leontodon hispidus [Ψ]*	rough hawkbit	0.4
Leucanthemum vulgare *	ox-eye daisy	1.5
Lotus corniculatus *	bird's-foot trefoil	2
Onobrychis viciifolia *	common sainfoin	1.2
Origanum vulgare *	wild marjoram	0.4
Plantago media *	hoary plantain	0.5
Poterium sanquisorba *	salad burnet	2
Primula veris [Ψ]	common cowslip	1
Ranunculus acris *	meadow buttercup	1.5
Reseda lutea *	wild mignonette	0.6
Scabiosa columbaria *	small scabious	0.6
Grasses		**80%**
Briza media	quaking grass	2.8
Cynosurus cristatus	crested dog's-tail	32
Festuca ovina	sheep's fescue	24
Festuca rubra	slender-creeping red-fescue	16
Koeleria macrantha	crested hair-grass	1.2
Phleum bertolonii	smaller cat's-tail	4

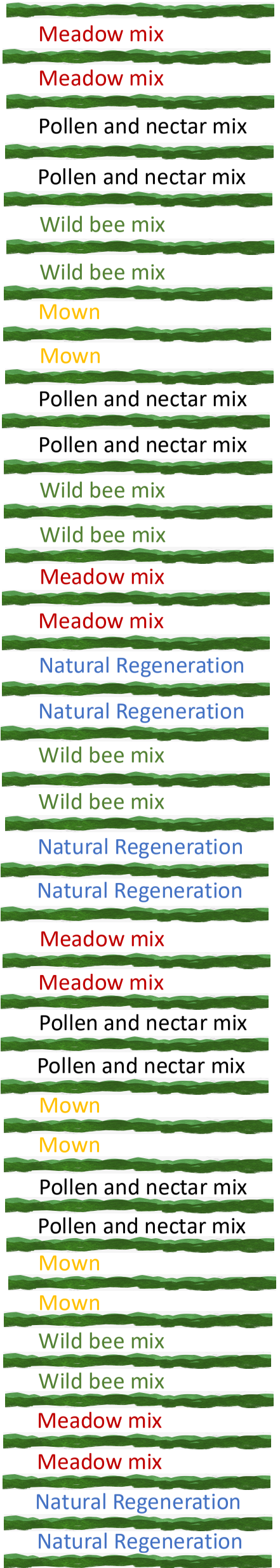
POLLEN AND NECTAR MIX

Species	Common name	%Composition
Centaurea nigra *	common knapweed	2
Lotus corniculatus *	bird's-foot trefoil	19.4
Malva moschata *	musk mallow	1
Onobrychis viciifolia	common sainfoin	38.8
Trifolium pratense	red clover	24.25
Trifolium hybridum [Ψ]*	alsike clover	14.55

WILD BEE MIX		
Species	**Common name**	**%Composition**
Flowering plants		**20%**
Alliaria petiolata *	garlic mustard	1.5
Anthemis austriaca Ψ*	corn chamomile	0.5
Barbarea vulgaris	winter cress	1.5
Campanula glomerata	clustered bellflower	0.2
Centaurea nigra *	common knapweed	1.5
Centaurea scabiosa *	greater knapweed	1.5
Daucus carota *	wild carrot	1
Echium vulgare Ψ*	viper's bugloss	1.5
Hypochaeris radicata	cat's-ear	0.5
Knautia arvensis *	field scabious	2
Leontodon hispidus Ψ*	rough hawkbit	1
Leucanthemum vulgare Ψ*	ox-eye daisy	0.8
Lotus corniculatus *	bird's-foot trefoil	1
Onobrychis viciifolia *	common sainfoin	2
Ranunculus acris *	meadow buttercup	1.5
Reseda lutea *	wild mignonette	1
Scabiosa columbaria Ψ*	small scabious	0.5
Scorzoneroides autumnalis Ψ	autumn hawkbit	0.5
Grasses		**80%**
Cynosurus cristatus	crested dog's-tail	16%
Festuca rubra ssp commutata	chewing's fescue	28%
Festuca rubra ssp juncea	red fescue	20%
Poa pratensis	common meadow-grass	16%

Ψ Established and identified in 2016 (year 1)
* Established and identified in 2017 (year 2)

APPENDIX J. Arrangement of treatment rows in experimental plot


Meadow mix
Meadow mix
Pollen and nectar mix
Pollen and nectar mix
Wild bee mix
Wild bee mix
Mown
Mown
Pollen and nectar mix
Pollen and nectar mix
Wild bee mix
Wild bee mix
Meadow mix
Meadow mix
Natural Regeneration
Natural Regeneration
Wild bee mix
Wild bee mix
Natural Regeneration
Natural Regeneration
Meadow mix
Meadow mix
Pollen and nectar mix
Pollen and nectar mix
Mown
Mown
Pollen and nectar mix
Pollen and nectar mix
Mown
Mown
Wild bee mix
Wild bee mix
Meadow mix
Meadow mix
Natural Regeneration
Natural Regeneration

APPENDIX K. Full species list of bees and hoverflies

Pollinator species	Group	Count
Lasioglossum minutissimum	Solitary bee	397
Halictus tumulorum	Solitary bee	114
Eupeodes corollae	Hoverfly	102
Andrena flavipes	Solitary bee	94
Lasioglossum calceatum	Solitary bee	47
Lasioglossum morio	Solitary bee	44
Sphaerophoria scripta	Hoverfly	42
Bombus lapidarius	Bumblebee	39
Bombus terrestris	Bumblebee	29
Melanostoma mellinum	Hoverfly	29
Lasioglossum malachurum	Solitary bee	24
Halictus rubicundus	Solitary bee	21
Apis mellifera	Honeybee	20
Lasioglossum pauxillum	Solitary bee	18
Andrena minutuloides	Solitary bee	14
Lasioglossum leucopus	Solitary bee	13
Sphaerophoria taeniata	Hoverfly	10
Episyrphus balteatus	Hoverfly	9
Syrphus ribesii	Hoverfly	8
Halictus eurygnathus	Solitary bee	6
Lasioglossum parvulum	Solitary bee	5
Lasioglossum leucozonium	Solitary bee	5
Lasioglossum lativentre	Solitary bee	5
Bombus hypnorum	Bumblebee	4
Lasioglossum xanthopus	Solitary bee	4
Osmia bicornis	Solitary bee	4
Melitta leporina	Solitary bee	3
Andrena dorsata	Solitary bee	3
Sphecodes geoffrellus	Solitary bee	3
Andrena bicolor	Solitary bee	3
Eupeodes luniger	Hoverfly	3
Nomada fucata	Solitary bee	2
Andrena nigroaenea	Solitary bee	2
Sphaerophoria sp.	Hoverfly	2
Platycheirus manicatus	Hoverfly	2
Melanostoma scalare	Hoverfly	2
Bombus pascuorum	Bumblebee	2
Bombus pratorum	Bumblebee	1
Sphecodes crassus	Solitary bee	1
Andrena cineraria	Solitary bee	1
Lasioglossum albipes	Solitary bee	1
Lasioglossum villosulum	Solitary bee	1

Sphecodes ephippius	Solitary bee	1
Andrena minutula	Solitary bee	1
Andrena semilaevis	Solitary bee	1
Lasioglossum fulvicorne	Solitary bee	1
Cheilosia vernalis	Hoverfly	1
Eristalis tenax	Hoverfly	1
Syritta pipiens	Hoverfly	1

APPENDIX L. List of survey questions circulated to UK based viticulturists

Survey questions

1. Name of vineyard (Please note we can only send a copy of publications to those vineyards who provide their name)

   Text box

2. Please tell us which area of the UK your vineyard is based

   South East
   South West
   East of England
   West Midlands
   East Midlands
   Greater London
   North East
   North West
   Yorkshire and the Humber
   Wales
   Scotland
   Northern Ireland

3. What is the size of your vineyard?

   Text box

4. How old is your vineyard?

   Under 5 years

   5-10 years

   10-15 years

   15-20 years

   20 years +

   Other/mixed age

   Text box

5. Are you an organic vineyard?

   Yes

No

Other

Text box

6. Could you please tell us about the pests that are a problem at your vineyard, including any you have eradicated, or are an on-going problem?

   Text box

7. Do you use any chemical treatments to eradicate insect pests or vine diseases at your vineyard?

   Yes

   No

   Yes - If you are happy to tell us more about the chemical treatments used for insect pests or vine diseases, please do so here.
   Such as: Chemical treatment name, Applications per year, Target pest, % Effectiveness

   Text box

8. Do you use any natural methods to eradicate insect pests or vine diseases at your vineyard?

   Yes

   No

   Yes -If you are happy to tell us more about the natural methods used for insect pest eradication or vine disease, please do so here. Such as: Natural method name, Applications per year, Target pest, % Effectiveness

   Text box

9. What type of ground cover do you have in-between your vines?

   Mown grass

   Sown wildflowers

   Other

Text box

Mown grass - How often do you mow the grass between vine rows on average in the spring/summer months? - Text box

10. Do you use weed killer or herbicide between vine rows?

Yes

No

Yes - If you are happy to do so, please tell us what weed killer or herbicide you use- Text box

11. Do you have any sown wildflower margins, or areas of natural flower regeneration in the land surrounding the vines?

Yes

No

Yes - Please tell us more, such as which wildflowers you sow – Text box

12. Where do you get advice on pest treatments and land management?

Text box

13. If you don't use flowers in-between vine rows or in the margins around your vines, is this something you are thinking about doing? If not, could you tell us why?

Text box

14. Please use this space to expand on any of the above questions, or add any comments or questions.

Text box

15. I understand that by checking the box below, I am agreeing to take part in the University of Sussex research described here, and that I have read and understood the information sheet.

I consent to taking part in this study [tick box]
I do not consent to taking part in this study [tick box]