UNIVERSITY OF SUSSEX

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(for) Doctor of Philosophy

Pollination ecosystem services and the urban environment

September 2017

Statement

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.

Signature: ....

Acknowledgements

I knew when I started this PhD that I was going to need an awful lot of bean seeds, but I don't think I quite realised how much the enthusiasm, encouragement, and gardening skills of so many other people would contribute to my research. So now it is time for me to express my gratitude to those who have 'bean' with me on the way.

First thanks have to go to my supervisors. To Professor Dave Goulson for giving me this opportunity, and then for his support and advice throughout the course of the last four years. For puzzling through my humour and my phraseology, and giving guidance on Statistical Analysis – and additionally for pints, proofreading, and reminders that publication is actually rather important! I would also like to thank Professor Francis Ratnieks for his comments, expertise and encouragement to consider all viewpoints.

I deeply grateful for the support from the "PhD Ladies of 5B20": Kate Basley, Andreia Penado and Janine Griffiths-Lee. We've had camaraderie, cakes, tears, battles with Excel, all while keeping each other (arguably) sane. Further thanks go to the others in the Goulson Lab Group, for listening to my updates (and my rants), offering suggestions, and generally being an excellent group of people to work with. Plus a particular mention to Rob Fowler for statistics help, tomato plant chauffeuring around Brighton, and putting up with the state of my greenhouses! And also to Leila Simpson, for planting assistance and video skills tuition in my first year.

My friends and family have been incredible, and I thank them all dearly for support, humour, and tea (in pretty much equal measures). Plus extra thanks are due to those who took part in the pilot questionnaires. A very special thank you here is due to my partner, Matt Oakley; for his love, patience and being a voice of reality. Also for his humour, and for being an enthusiastic enabler of emergency takeaways.

I am indebted to my parents (occasionally literally), Joan and Rob Birkin, for their unwavering support; their acceptance of late-night phone calls; for proofreading instructions and for running the best at-home field station I could have asked for, regardless of what odd thing I asked them to do. Putting jewellery bags on the alliums. Wrapping net curtains around the fox gloves. Distributing several large crates of plants to friends and neighbours. No problem!

Last, by no means the least (and certainly the most numerous group): I thank my volunteers, from all years. I am grateful to everyone who has sprouted, counted, weighed, podded, snipped, watered, calculated, measured, emailed, tweeted, fought slugs and battled with blackfly. They were *fantastic*, and I quite literally couldn't have done this PhD without them.

Summary

Insect pollination is a vital ecosystem service, essential for both wild and domesticated plants, yet to-date there are no standardised national schemes to monitor its status. Thus this PhD focused on assessment of pollination provision in UK urban green spaces, using a combination of citizen science and field/laboratory methods. Each of the following thesis chapters considers a specific pollination-related theme:

The need for pollination. Demonstrating how much gardeners *need* insect pollination is important to underpin public support for pollinator conservation. During 2014-2015, online questionnaires were used to collect information about the crops grown in domestic green spaces and gardening practices used. Participants highly valued 'growing their own', and three of five crops grown by the majority (tomatoes, apples, strawberries) have high requirements for insect pollination. A 'garden shop calculator' spreadsheet was also tested (positively) as a quick way to calculate the equivalent bought-value of garden crops and the proportion directly attributable to insect actions.

Assessment of pollination provision. Citizen science volunteers undertook a simple direct pollination experiment (exclusion, hand pollination, local), requiring treatment randomisation and accurate yield recording. The main '*Bees 'n Beans*' projects used *Vicia faba* to monitor bumblebee pollination, detecting no national deficit during 2014-2016. This suggests that the domestic pollination needs of *V. faba* are currently met, and that urban populations of long-tongued bumblebees are sufficient to provide it. The potential of using other plants to cover wider pollinator populations was also explored, identifying *Allium hollandicum* as suitable.

The effects of companion planting. Using tomato plants to examine whether co-planting crops with flowering plants boosts pollination provision ('magnet species' effects), or distracts insects. Provided plants were hosted in volunteered gardens and school grounds in Brighton in 2015 & 2016. No effect (improved or detrimental) of co-flowering plants was found on tomato yields at either site type.

Using citizen science to monitor pollination services. This chapter combined findings from other chapters and a final questionnaire, which focused on participants' motivations and willingness to make behavioural changes after taking part. It concludes that the projects have demonstrated volunteers' ability and willingness to follow experimental protocols under guidance, to collect meaningful data at otherwise-impractical geographical scales.

Suggested protocol. This details the finalised *Bees 'n Beans* approach and how it relates to other potential pollination monitoring methods. I propose that this style of project is suitable for incorporation into national monitoring scheme development.

Contents

Chapter 1: Ecosystem services and the urban environment – introduction and aims.

There are nearly seven billion of us living on the Earth, and the human population is increasing by more than two people every second; two hundred thousand people every day; nearly eighty million people every year. Each additional life needs food, energy, water, shelter, and hopefully a whole lot more (Attenborough, 2009).

Humans rely on the natural world for many things. Food, fuel and other physical resources; space to live, breathable air, and the ongoing cycles of nutrients and energy; as well as perhaps less-tangible benefits such as mental wellbeing and a sense of place. Yet our impact on the natural ecosystems of the Earth has never been greater (Crutzen, 2006; Butchart *et al.,* 2010; Goudie, 2013), and the corresponding need to better understand – and appropriately manage – the environments that support us is vital and too easily overlooked (De Young, 1993; de Groot *et al.,* 2010).

This chapter will set the scene for the PhD, introducing first the concept of ecosystem services and how that relates to the broader ecological idea of biodiversity, before focusing down specifically on pollination, where that is placed within existing ecosystem service classifications, and the underlying need for its monitoring. As urban environments are the focus of this PhD, I then consider the unique ecological questions raised in built-up areas, and summarise the current understanding of pollination requirements in such human-dominated spaces. Finally the overall aims and themes covered by this thesis are outlined, including my rationale for using citizen science methods.

1.1. Ecosystem Services

1.1.1. What is an ecosystem service?

The idea that natural environments and processes provide benefits is not a new one. These processes can be physical, chemical or biological, as long as they contribute to self-maintenance of the ecosystem (Wallace, 2007), and include functions such as nutrient cycling, decomposition and photosynthesis. Attempts to better assess and value these benefits, to better allow for long-term ecological planning to be incorporated into existing decision-making frameworks (Pimentel *et al.,* 1997; Balmford *et al.,* 2002; Turner *et al.,* 2003; Naidoo & Adamowicz, 2005) began in the late 1960s (Hein *et al.,* 2006), but it is in the last two decades that these ideas have been framed specifically as 'Ecosystem Services' (Costanza *et al.,* 1997; Millennium Ecosystem Assessment, 2005a). This has become an increasingly popular usage within research, policy and economic sectors; often considered as part of a wider, more-integrated 'Ecosystem Approach' (which includes natural processes that do *not* provide direct benefits to humans) (UNEP/CBD/COP/5, 2000). Understanding of how such benefits are produced or enhanced by the natural environment varies greatly between different sectors (Carpenter *et al.*, 2006); by the service(s) under consideration, particularly in regard to the effects of multiple processes and interactions (Mitchell *et al.*, 2013); and often by the scale at which the service is being considered, either in terms of delivery or effect (PEER, 2012, 2011).

Various methods of classification to describe ecosystem services have been produced, generally based on where the processes involved occur in relation to production of the final good or benefit. One of the first typologies for addressing this issue was the Millennium Ecosystem Assessment (MEA) framework, which divided ecosystem services into four categories (Millennium Ecosystem Assessment, 2005b), and subsequent categorisations have been based on this initial division.

The MEA framework uses the following categories:

1) **Provisioning services:** The products obtained directly from ecosystems, e.g. food; fibre; fresh water.
2) **Regulating services:** The benefits obtained from the regulation of ecosystem processes, e.g. regulation of water, air and soil quality; climate regulation; pollination and pest control.
3) **Cultural services:** The non-material benefits people obtain from ecosystems, e.g. recreation and tourism; aesthetic experience.
4) **Supporting services:** Ecosystem services that are necessary for the production of all other ecosystem services, e.g. soil formation; nutrient cycling; water cycling.

Although there are differences between existing typologies, depending mostly on the application they were developed for, there is also considerable crossover (recently reviewed by Medcalf *et al.* [2014]). For example, many of the 'Supporting' services from the MEA classification are described as 'Habitat Services' in the Economics of Ecosystems and Biodiversity study (TEEB), which is more commonly used in economic sectors (TEEB, 2010). In the UK, the National Ecosystem Assessment (UK NEA) uses similar definitions to the MEA, but focuses on fitting the process descriptions to a UK-applicable system (Mace *et al.,* 2011). The most recent addition is the Common International Classification of Ecosystem Services (CICES), developed on behalf of the European Environment Agency to standardise classification for European-level reporting which does not have a separate 'Supporting' category and instead considers 'support' elements to be underpinning processes to all services (Haines-Young & Potschin, 2013).

1.1.2. Valuing ecosystem services.

Ecosystem services have historically been poorly represented in markets and economic decision-making due to the complexity of their interactions and outputs, and the difficulty in quantifying those relationships (Costanza *et al.,* 1997; de Groot *et al.,* 2010). This omission has led to inadequate accounting and ultimately a loss of service provision as a result of damaging decisions made without full information (Millennium

Ecosystem Assessment, 2005a; Mace *et al.,* 2011; Norris, 2012; Bateman *et al.,* 2013). This is particularly the case when considering a natural *process*, such as pollination, which might ultimately result in a tangible good (e.g. fruit) that is comparatively easy to assign value to – but then what is the value of that pollination itself? Using a proportion of the resultant good's market value is a common method, but determining what proportion of that value is directly attributable to the pollination process – rather than the existence of the plant, its nutrient environment or growing conditions, for some examples – is difficult, and must avoid counting the same benefit twice (Fu *et al.,* 2011; Hein *et al.,* 2006). The value of such processes on other ecosystem functions (such as the pollination of wild plants) is even trickier to determine.

All of the ecosystem service classifications discussed above were developed with an assumption that a change to the biota of an ecosystem will alter the processes occurring within that system, and thus the overall service provision; although the idea of 'biodiversity' is handled slightly differently in each one. The MEA / NEA framework does not regard 'general' biodiversity as an ecosystem service in and of itself (Mace *et al.,* 2011), but considers it to underpin all other services. The TEEB 'habitat services' variation considers more general biodiversity services (TEEB, 2010) in terms of processes provided by biotic habitat elements, in a supporting / regulating role. CICES again treats biodiversity as an underpinning element of the whole framework, but with specific elements of biota considered to be services individually (Haines-Young & Potschin, 2013). Yet biodiversity *as a whole* may be considered to be a benefit in its own right, particularly in regard to conservation activities, although the ecosystem services concept may not be appropriate to apply to traditional conservation objectives in many cases – where not interacting much with humans is often the intention for the focal biota (Eastwood *et al.,* 2013).

Where a specific part of 'biodiversity' – a single species, or groups of species – is considered to be or provide a benefit or good, it is easier to demonstrate the need for protective actions. Extraction of medical plants, sightings of wildlife, and the cultural value of charismatic species are examples of 'goods' in this context, since the presence of the taxa itself is the goal (e.g. without whales, whale-watching is not going to happen!) Specific biodiversity also provides supporting or regulating roles to other services, with pollination and pest control being good examples, where the service is performed by specific animals in specific contexts – such as bats, or bees (Kremen *et al.,* 2007; Norris, 2012; Vanbergen & Insect Pollinators Initiative, 2013). The projects undertaken as part of this PhD focused on pollination services.

1.2. Pollination

1.2.1. The pollination service.

Pollination is considered in most typologies to be primarily a regulating service (Crossman *et al.,* 2013; Smith *et al.,* 2011); either via abiotic means (mostly by wind) or biotic as the result of the actions of pollinating animals (Ollerton & Winfree, 2011). Worldwide, pollination is undertaken by a variety of animals including birds, bats and possums, but in temperate regions the majority of this service is understood to be provided by insects – especially bees (Brittain *et al.,* 2013; Garibaldi *et al.,* 2013; Goulson, 2010; Goulson *et al.,* 2008; Jauker *et al.,* 2012; Klein *et al.,* 2007; Kremen *et al.,* 2007), with a significant contribution from hoverflies (Bates *et al.,* 2011; Jauker & Wolters, 2008; Jauker *et al.,* 2012). Pollination from other insects – including other Diptera, wasps, butterflies, moths and beetles – has been observed, but is less well documented (Free, 1993; Kremen *et al.,* 2007; Deguines *et al.,* 2012).

Since the concept of ecosystem services is focused on the benefits *to humans*, pollination that does not contribute to the production of human crops (either for food or for aesthetics) may not be suitable for consideration as an ecosystem service. This includes the pollination required by wild plants, since it is thought that between 78-94% of flowering species rely to some degree on biotic pollination (Ollerton & Winfree, 2011) but it is difficult to quantify the value of 'wild plants' to human societies. Estimating the value of pollination to agricultural activities is easier, based on existing understanding and manipulation of the insect-pollinator relationship and the value of the resulting crop (Winfree *et al.,* 2011). These values vary widely depending on the methods used, with recent assessments of the global value of pollination range $112 to $200 billion annually (Costanza *et al.,* 1997; Gallai *et al.,* 2009; Kremen *et al.,* 2007). They are not without debate (Ghazoul, 2005; Klein *et al.,* 2007; Steffan-Dewenter *et al.,* 2005) but this is still the most common method of valuing pollination service provision.

In European agriculture, the yields of 84% of crop species are either improved by or reliant on insect-mediated pollination (Klein *et al.,* 2007). In the UK, the recent National Ecosystem Assessment suggested that pollinator-dependent crops restricted to agricultural land (including oilseed rape, apples and strawberries) comprised 20% of the total UK cropped area in 2007 (England: 23%, Northern Ireland: 5%, Scotland: 8%, Wales: unknown); the NEA valued the pollination of these crops at £430 million in 2007, representing 8% of the market at the time (Smith *et al.,* 2011).

The provision of agricultural pollination can be enhanced by appropriate management of the crop and surrounding habitats (Carvell *et al.,* 2007; Rosa García & Miñarro, 2014; Samnegård *et al.,* 2011; Scheper *et al.,* 2013; Westphal *et al.,* 2003), or by supplementation with domesticated pollinators, which are often used in parts of the world where they are not native. European honeybees (*Apis melifera* L.) are the most common managed pollinator used in this way (Garibaldi *et al.,* 2013), although commercially-available nests of *Bombus* species are increasingly being used in glasshouses and with some open-field crops (Lye *et al.,* 2011). These species are certainly the most researched pollinator of human crops, but the contribution from wild bees and hoverflies is increasingly being shown to be much greater than originally thought (Breeze *et al.,* 2011; Garibaldi *et al.,* 2013; Jauker & Wolters, 2008; Ricketts *et al.,* 2008).

1.2.2. Measuring pollination

Most measures of pollination services on large scales use predicted or measured diversity and / or abundance of pollinators in an area as a proxy of service potential (Winfree *et al.,* 2011). Habitat proxies are also widely used. This does not show that the insects *are* pollinating – or what they are pollinating – but does indicate if potential pollinators are *present* in an area, although it relies on being able to accurately record or predict the local populations. How well such proxies actually relate to the provision of pollination in an area is debated (Lonsdorf *et al.,* 2009), as is the efficacy of existing methods of insect sampling (such as pan traps) in being able to demonstrate trends in pollinator populations (Popic *et al.,* 2013; Pocock *et al.,* 2014). Functional or temporal trait mismatch between pollinators and local plants is a concern (Burkle *et al.,* 2013), as insects which are technically and mechanically able to pollinate certain flower types may show a preference for others in real-world conditions; or flowering may occur during the insects' diapause, or when populations are low.

Proxies aside, it is also possible to measure pollination directly: pollen deposition counts, observations of at-flower insect behaviours, and genetic analysis of resulting seeds can provide in-depth information about the effectiveness of pollination actions, although these are all very time-consuming methods. The most common direct measurement method – and currently considered to be the best – is via exclusion manipulations (Carvell *et al.,* 2016; Garratt *et al.,* 2016). This is where insects are prevented from accessing a plant / flower by use of fine mesh, and is usually paired with at least a hand pollinated control, with the effects on pollination success measures then compared to those of plants with unrestricted insect access. Direct measurements of pollination provision can also act as a proxy for the health of pollinator populations: if there is sufficient pollination occurring, there must be enough pollinat**ors** present to achieve it.

1.2.3. Pollinator decline and conservation

Pollination is one of the 15 ecosystem services identified as under threat in the MEA and its successors, with a correspondingly risk of a massive knock-on effect for global biodiversity and food security (Klein *et al.,* 2007; Millennium Ecosystem Assessment, 2005a). Declines in pollinator numbers have been identified in many countries, accompanied by losses of wild plants and reductions in agricultural yields (Biesmeijer *et al.,* 2006; Breeze *et al.,* 2012; Potts *et al.,* 2010). Some of these effects have been very severe, such as the widespread loss of native pollinators in south-west China following changes in farming practise and pesticide over-use, resulting in a reliance on hand pollination in apple and pear orchards to achieve economically-reliable yields (Goulson, 2012). Concerns about the impacts on human health and wellbeing, as well as economies, have led to an expanding research effort looking into the health of pollinators and their populations (Sala *et al.,* 2012; DEFRA, 2013; Vanbergen & Insect Pollinators Initiative, 2013; Ellis *et al.,* 2015).

Why are we seeing these patterns? Pollinating animals are affected by the ongoing major global pressures faced by biodiversity as a whole – including habitat loss and fragmentation, agrochemical use, pathogens, the spread of 'alien' species, and climate change (Butchart *et al.,* 2010). Along with general loss of biodiversity and habitat connectivity in farmed regions (Carvalheiro *et al.,* 2013), pollinators may be at particular threat from changes to agricultural practices, given their close association with these managed landscapes (Biesmeijer *et al.,* 2006; Breeze *et al.,* 2012; Scheper *et al.,* 2013). This is highlighted by the recent concerns over the impacts of pesticides on non-target and beneficial insects (Henry *et al.,* 2012; Whitehorn *et al.,* 2012) and particularly the effects of neonicotinoids on bees (Goulson, 2013; Botías *et al.,* 2015; Woodcock *et al.,* 2017). There are also worries about the spread of pathogens between managed and wild bees (Goulson, 2003; Goulson *et al.,* 2008; Otterstatter and Thomson, 2008); the effects of mass-flowering crops on pollinator distributions (although there is also evidence to suggest this may be positive for some bumblebee species [Westphal *et al.,* 2003]), and dilution of the pollination provision to co-flowering wild flowers (Holzschuh *et al.,* 2011).

However, remedial actions can and are being taken. There is a variety of methods currently used in pollinator conservation efforts, as well as strong impetus amongst both scientific researchers and policy makers to develop more robust monitoring of pollinator communities, at country (DEFRA, 2013; Scottish Government, 2013; Welsh Government, 2013a) and EU scales (Potts *et al.,* 2011; Crossman *et al.,* 2013; Potts & Biesmeijer, 2015). Seed mixes and planting regimes under the European Common Agricultural Policy (CAP) include specific provisions for planting flower-rich borders on farmland (DEFRA, 2005a, 2005b), although the effectiveness of this intervention is under debate (Carvell *et al.,* 2007; Scheper *et al.,* 2013); and the planting of 'bee friendly' alternative crops such as borage is increasing in popularity (Goulson, 2003a). Such agri-environment prescriptions and pollinator-friendly management of worked farmland represent taking more of an ecosystems approach towards farming, particularly when Integrated Pest Management is also practised (Kogan, 1998; Zhang *et al.,* 2007), aiming to decrease agrochemical usage and promote more ecologically robust farming systems.

Outside of agriculture, nature reserves and other areas set aside for biodiversity protection have a role in maintaining pollinator diversity, potentially allowing for 'spill over' into surrounding landscapes (Kohler *et al.,* 2008; Holzschuh *et al.,* 2010), although the magnitude of this effect is likely to be closely related to the connectivity of the encompassed habitats, and the proximity of wild plants and crops outside of the reserve (Jauker *et al.,* 2009). But pollinator refuges are found in unusual places, and there has been increasing recent interest in the role of the urban environment in the future of biodiversity; pollinators included (Baldock *et al.,* 2015; Pickett & Cadenasso, 2017).

1.3. The buzz about town – urban areas and pollination

1.3.1. Biodiversity in urban spaces

More than 6.8% of the UK land area is considered to be urban, and is home to about 80% of the population (Davies *et al.,* 2011). When considering ecosystem service provision, the overlap with human populations means that urban areas are potentially very valuable, since services generated in these areas can be immediate to a large number of people (Bolund & Hunhammar, 1999; Armar-Klemesu, 2000; Sadler *et al.,* 2005; Tratalos *et al.,* 2007). Urban ecology as a specific field is a recent development (Forman, 2016; Pickett & Cadenasso, 2017), and the existing literature is not in universal agreement on the role of built-up areas for supporting biodiversity.

Despite a historical tendency to be represented as blank concrete on habitat maps, urban settings are not as homogeneous as they might initially appear (McKinney, 2006), incorporating a mosaic of habitats classifiable into grassland (Gaston *et al.,* 2005), urban greenspace (Tratalos *et al.,* 2007), woodland (Dreistadt *et al.,* 1990), and more novel types such as brownfield or derelict land (Sadler *et al.,* 2005; Macadam *et al.,* 2013). The resulting biotic community may support some species at high abundance due in part to the artificially-maintained floral resource (Comba *et al.,* 1999; Chapman *et al.,* 2003; Matteson & Ascher, 2009; Ahrné *et al.,* 2009; Samnegård *et al.,* 2011; Baldock *et al.,* 2015). For example, a famous long-term study by Owen (1999) recorded 51 bee species in a single garden in Leicestershire, representing about 20% of British bee species. Even graveyards are known to be important habitats for rare lichens (British Lichen Society, 2013). Similarly, brownfield (Macadam & Bairner, 2012) and Open Mosaic Habitat (Macadam *et al.,* 2013) sites are often characterised by the present of large proportions of early pioneer species and 'edge' specialists amongst their communities; species which are increasingly rare in less disturbed habitats (McKinney, 2006).

The reverse can also be true. Bates *et al.,* (2011) found lower diversity and abundance of native pollinator species associated with the more 'urban' end of an urban-rural gradient in and around the City of Birmingham, UK, with the native bumblebee fauna present biased towards more generalist species. This pattern is common in urban areas: generalists do well, and so do very specific species whose niches are catered for (such as those favoured by the communities of Open Mosaic Habitats) where conditions that are unusual in natural landscapes are artificially maintained in urban ones (McKinney, 2006; Goulson *et al.,* 2006; Cameron *et al.,* 2012).

In addition, several studies have suggested that the diversity of urban areas is most strongly influenced by the semi-natural habitat types present in the *surrounding* landscape, rather than those present in the urban zone; at least in part because species have to *get* there. There is also a risk of the observed diversity being provided by the presence of imported, non-native species (Thompson *et al.,* 2003; Matteson & Ascher, 2009; Ahrné *et al.,* 2009; Frankie *et al.,* 2009; Wojcik, 2012). Yet other work has demonstrated the importance of local habitat quality (mainly described diversity of flowering plants) as a driving factor for patterns of species richness and abundance, particularly for urban pollinators (Gaston *et al.,* 2006; Smith *et al.,* 2006; Bates *et al.,* 2011; Matteson & Langellotto, 2012).

So, the situation is complicated. For some taxa, urban environments may be inhospitable and inaccessible, acting as barriers in the landscape (Bhattacharya *et al.,* 2003; Pellissier *et al.,* 2012), while others seem to find city-living eminently suitable to their needs (Jones & Leather, 2013). For example, *Bombus terrestris*, a common British bumblebee, has been observed to fly during the winter in urban environments, with Stelzer *et al.* (2010) suggesting that the insects are able to find sufficient forage on non-native or ornamental plants that flower over winter. Nests of *B.terrestris* have also been found to have higher rates of growth in suburban areas compared with rural settings, suggesting a greater availability of forage (Goulson *et al.,* 2002). It has also been shown, in honeybees in particular, that some insects will vary their foraging range effort by time of year and the balance of available rewards (Garbuzov *et al.,* 2015), so the benefits and drawbacks of urban life may vary greatly with season.

Whether this results in urban spaces acting as an reservoir or refuge for pollinators is unclear (Tommasi *et al.,* 2004; Kohler *et al.,* 2008), although this may be more of a *biodiversity* concern than strictly an 'ecosystem service' one. Abundance of pollinators in urban areas (particularly gardens) can be high (Matteson & Ascher, 2009; Salisbury *et al.,* 2015) and as long as the local requirement for pollination is met by those species, then lower diversity may not be a concern purely for service provision (although this does not take into account redundancy or buffering in the ecosystem, or ability to respond to future environmental changes [Potts *et al.,* 2010]).

1.3.2. The need for pollination in urban areas

Many horticultural varieties of flowering plants have been developed for their appearance rather than their fruit-set (Comba *et al.,* 1999) and may have limited resources available for pollinators when compared to their wild cousins. The presence of some ornamentals is independent of pollination success, with annual bedding plants generally replaced with new stock rather than re-grown from seed on-site. However, as with agricultural crops many urban crops require or are enhanced by pollination (Matteson & Langellotto, 2009), particularly garden favourites such as strawberries, raspberries and beans / peas (Smith *et al.,* 2011). Pollination also facilitates production of seeds and fruit from plants not grown for human nutrition, but which act as food resources and shelter for wild animals.

It is thus reasonable to assume that there is both support for pollinator communities, and a requirement for pollination services present in urban environments – but it is not known if urban pollination in general represents an overall limiting or adequate service provision. Samnegård *et al.* (2011) showed evidence for greater seed set by *Campanula persicifolia* in sites closer to gardens in Sweden, although they noted that the beneficial effects of spillover from gardens or garden-boosted pollination is likely to vary with the specific plant-insect interaction in question. Cussans *et al.* (2010) also showed an improved seed set in bee-pollinated plants grown in an urban garden environment. Overall there has been little work done to examine the pollination service provision experienced by urban plants, and this was the main focus of my PhD.

1.4. Project aims and the use of citizen science

The projects reported in the following chapters focused on the use of experimental citizen science approaches for monitoring pollination services in UK urban areas, with all projects requiring volunteer participation to some degree. The rationale behind this choice was threefold, considering a) the scale of the data coverage that is needed to make robust conclusions about UK patterns, b) the current and future usage of citizen science data to inform environmental decision-making, and c) the importance in future success of conservation initiatives of engaging the public with the concept of ecosystem services.

Any monitoring scheme developed for UK pollination assessment would need to cover a large geographic scale that would be impractical to achieve with professional scientists alone (Schmeller *et al.,* 2009; Mackechnie *et al.,* 2011; Kremen *et al.,* 2011; Tweddle *et al.,* 2012). Not only does the UK already have a long history of public involvement in environmental monitoring (Pocock *et al.,* 2015), but the high population densities in urban areas mean that there is a large potential pool of volunteers present, who would not have to travel to pre-arranged sites to perform observations or experiments (such those outlined in the recent National Pollinator and Pollination Monitoring Framework [NPPMF] proposed by Carvell *et al.* [2016]). Good data – which citizen science can generate as long as the experiments are well-designed (Cohn, 2008; Dickinson *et al.,* 2012) – should thus be possible to record from across the country at the same time. For urban ecology in particular, it is economically advantageous to have volunteers record data from their own sites since domestic gardens make up a large proportion of urban green spaces (Gaston *et al.,* 2005; Loram *et al.,* 2007; Davies *et al.,* 2009) and surveying so many private sites with a research team would be very expensive, considering staff time, travel and access limitations.

Data collected by citizen scientists already contributes a huge proportion of the information derived from existing biodiversity surveillance schemes, which are used to inform environmental policy development (Roy *et al.,* 2012a; Dickinson *et al.,* 2012;

NBN Secretariat, 2015; Carvell *et al.,* 2016). The use of volunteer data collection is often highlighted as an important part of the process, and an area to be expanded on in new monitoring plans (DEFRA, 2014), but requiring volunteers to undertake more complex recording tasks poses questions about how effectively they can be expected to do this. Citizen science is not free, and projects must be designed to accurately take volunteer capacity and capability into account. Since my projects required performing direct pollination measurements – which are simple experiments, but do require following a scientific protocol rather than purely making observations – then it represented an opportunity to investigate if more 'experimental' citizen science is practical to incorporate into larger schemes, and able generate useful data.

Finally, there has been a recent focus on the promotion of 'wildlife friendly' gardening (Goddard *et al.,* 2010), but for long term success and beneficial changes in behaviour, gardeners must feel that their own actions can have a definite impact on the natural environment (Clayton, 2007). Engaging participants in science, showing how their own observations and actions can directly contribute to investigating large-scale questions, all contributes to demystification of the scientific process – and potentially helps volunteers to feel a more personal, affective connection with the environment around them (Kendle & Forbes, 2013). Demonstrating the relevance (and actual occurrence) of ecosystem services within something as personal and close as garden environments is an important step in creating support for policies such as Payments for Ecosystem Service (PES) schemes (Gutman, 2007), and a wider understanding of why environmental decisions need to be made in the way they are.

The following chapters divide the work of 2013-2016 by theme. More than one project or iteration of project is included in each, since methodology was developed and modified over the course of my PhD in response to results and participant feedback.

Chapter 2: Assessment of the existing requirement for pollination services in urban areas. This chapter considers the *need* for the pollination ecosystem service in urban greenspaces, focused primarily on production of garden crops.

Chapter 3: Assessment of pollination service provision in UK urban greenspace. This chapter introduces and develops the '*Bees 'n Beans*' protocol: an experimental citizen science approach to directly monitor pollination provision in urban environments, and the only then-current project that required participants to undertake experimental manipulation of plants (specifically of the Broad Bean, *Vicia faba*).

Chapter 4: Beyond Beans – monitoring the wider pollinator guild. The delivery of adequate pollination service requires the presence of *appropriate* pollinators. Both functional and temporal insect traits can thus be mismatched with plant requirements. This chapter investigates other plants, 'beyond' *Vicia faba*, that could be included in a monitoring scheme in order to provide more comprehensive coverage of UK pollination service provision.

Chapter 5: Vegetable-bedfellows – companion planting for pollinators and garden crop yields. Urban agriculture, from garden plots to small-scale farming within city limits, relies on pollination provision as much as larger-scale efforts do, but gardens are rarely dedicated exclusively to crop cultures. This chapter investigates the effect of co-flowering ornamental plantings on pollination provision to tomato (*Solanum lycopersicum*) within the UK city of Brighton.

Chapter 6: Using citizen science to monitor pollination services. This chapter uses the results of participant feedback questionnaires, and my own experiences, to assess the suitability of these projects for use as surveillance schemes, and provides recommendations on how to approach experimental citizen science both in general and specifically in regard to pollinator services.

Chapter 7: Measuring pollination service provision – where to go from here. This chapter considers the future of this work area, in the light of both my own findings and concurrent developments in the field. It includes a final recommended structure for *'Bees 'n Beans'*, and discusses how these projects are – or could be – complementary to other planned schemes, particularly those involved in monitoring pollinator populations directly.

Chapter 2: Assessment of the existing requirement for pollination services in urban areas.

2.1. Introduction: urbanisation, ecosystem services, and public understanding.

Urbanisation is increasing globally, with 66% of the world's population predicted to be living in built-up areas by 2050 (United Nations, 2014). This ongoing expansion of cities means that the more 'traditional' view of ecosystem services, where natural goods and services are considered to be provided by rural areas and consumed in urban ones (Gutman, 2007), is undergoing re-evaluation. More-natural ecosystems do provide a large proportion of the benefits used by humanity, but it would be misguided to assume that urbanisation immediately replaces an area with a lifeless sink for resources (Bolund & Hunhammar, 1999; McKinney, 2002; Loram *et al.,* 2008). Loss of biodiversity, loss of habitats and connectivity, and pollution of natural environments are all serious problems strongly associated with urban sprawl, yet these highly-managed human habitats do have biodiversity value of their own (Angold *et al.,* 2006; Goddard *et al.,* 2010; Davies *et al.,* 2011).

The wide variety of human activities conducted within urban areas, each with different requirements for space and modification of the environment, means that cities can be characterised not as an inevitable impenetrable 'concrete jungle', but as a diverse mosaic of habitats which provide an unusual selection of resources for cosmopolitan flora and fauna (Angold *et al.,* 2006). For example, conditions around high-rise buildings and rubbish dumps prove so attractive to raptors (Chace & Walsh, 2006) and scavengers like seagulls (Rock, 2005) that populations of these birds are rising in UK cities despite observed declines in their more 'natural' ranges (Balmer *et al.,* 2013). Similarly, edge-specialists and species associated with open-ground and disturbed areas may find that urban habitats, particularly 'brownfield' sites (such as the recently classified 'Open Mosaic Habitat' [BRIG, 2011]) maintain suitable conditions longer than in the wider countryside, where succession is less prone to interruption. These types of habitats are also increasingly being incorporated into planning for deliberate conservation interventions, such as green roofs (Brenneisen, 2006).

However, while appropriate management of urban areas may have potential for at least maintaining some biodiversity, there is certainly a risk of losing what is present, and reversing any gains. Some species do seem to benefit from these environments, but this is far from a universally shared experience – UK butterfly population trends, for example, show greater declines in urban areas than rural (Dennis *et al.,* 2017), and for many taxa it seems that the urban success stories come primarily from generalist species, with a few specialists taking advantage of specific conditions (McKinney, 2002; Goulson *et al.,* 2006; Frankie *et al.,* 2009). In addition to the pressures from urban expansion, infilling of city spaces (to avoiding development on greenbelt land) increases homogeneity of the built environment (Chipchase *et al.,* 2002; Pauleit *et al.,* 2005; McKinney, 2006), and the dense sealed surfaces of 'core' area of large cities require deliberate action to improve their usefulness to wildlife (McKinney, 2002). There are problems for the human population too, with a risk that alienation of urban dwellers from the natural environment (or even highly-managed equivalents such as parks), can lead to a corresponding disinterest in broader conservation actions (Miller, 2005; Dunn *et al.,* 2006). If 'wildlife' and 'nature' is always something that happens *elsewhere*, then there will be difficulty gaining widespread public support for more modern ecosystem approaches of managing natural resources.

Kendle & Forbes (2013) considered developing a well-informed public to be the most important application of the growing field of urban ecology, as well as a critical step in creating active consumer demand for ecosystem services, by underpinning the case for Payments for Ecosystem Service (PES) schemes (Gutman, 2007). The challenge then is how to make the concept of ecosystem services – or at least a recognition of the underlying ideas, if not the specific terminology itself – 'real' to an urban population who may have very limited contact with the wider countryside. Various options for bridging this gap have been presented and pursued as urban ecology has developed as a specialised field (Adams, 2005; Roy *et al.,* 2012a). This report – indeed, this entire

PhD – approaches the problem by focusing on an ecosystem service where humans are most obviously in partnership with some element of the natural world (McKinney, 2002). That ecosystem service is **pollination**.

A particular advantage using the study of pollination to introduce ecosystem services is that it has an easily-observable positive impact on the success of domestic fruit and vegetable production (Pawelek *et al.,* 2009; Matteson & Langellotto, 2009). Residential space can occupy more than 60% of the land area of UK cities (Gaston *et al.,* 2005), with 87% of UK households having access to a domestic garden (Gibbons *et al.,* 2014), so when considered collectively private gardens can constitute the largest single urban greenspace type that could be managed for the benefit of biodiversity. (Thompson *et al.,* 2003; Davies *et al.,* 2009). Gardening is a popular pastime (Clayton, 2007; Gaston *et al.,* 2007; van den Berg *et al.,* 2010; Cameron *et al.,* 2012), and many of the fruit and vegetables (and other edible plants, such as nuts) that are commonly grown in the UK rely on animal-mediated pollination to some extent. While horticultural varieties are often selected to reduce this pollination requirement and thus improve small-scale cropping under variable conditions (Comba *et al.,* 1999), 'better' pollination (such as cross-pollination rather than self-pollination) can still improve yields or the quality of the resulting crops. This has been shown for apples (Garratt *et al.,* 2014) and strawberries (Klatt *et al.,* 2014), and incomplete pollination is a noted problem in crops like raspberries (Lye *et al.,* 2011b), where unfertilised drupelets mar the appearance (and thus commercial value) of the final fruit. Hand-pollination of garden crop plants is possible but time-consuming, and it is both easier and quicker if local pollinators can do the job.

Demonstrating the importance of pollination to plants that people have bought, sown and tended to therefore represents a potent method of encouraging the public to think about ecosystem services, and about how their own gardening actions contribute to wider effects as well as immediate ones. The projects detailed in this chapter consider how to assess the likely *need* for pollination in urban gardens, and how to best relate that to the personal experiences of the participants. Sections 2.2. and 2.3. focus on the 2014 & 2015 questionnaire studies 'Growing Towns' and 'The Need for

Bees' respectively; both asked volunteers to detail the plants that they grow, expanded in the latter to consider motivations for choices and deliberate wildlife gardening interventions undertaken. Pollination requirements for the listed plants were researched, and compared with the degree that pollination is needed for horticultural success (e.g. to produce a fruit). These comparisons formed the basis for the garden 'value' calculators that follow in section 2.4.; a pair of projects that developed and tested out a spreadsheet-based method of producing a currency value for the effort of local pollinators; ending with discussion of the usefulness of these methods in ecology and outreach, and how this could be taken forward in the future.

2.2. 'Growing Towns' (2014)

There are relatively few studies that have examined the composition of UK garden flora (Goddard *et al.,* 2010). The most comprehensive recent work was the Biodiversity of Urban Gardens (BUGS II) project from the University of Sheffield (Loram *et al.,* 2007), which used quadrat sampling and complete census of vascular plants to record diversity details from 267 urban domestic gardens in five UK cities. My study did not attempt to replicate the BUGS methods; instead, work was undertaken as an online questionnaire, asking participants to record information about their gardens and planting choices. While this approach is not likely to capture the full extent of the floral resource ('weeds' in particular are unlikely to be listed by participants as garden plants, despite their value to biodiversity [Comba *et al.,* 1999; Marshall *et al.,* 2003]), focusing on the plants that gardeners deliberately plant and make an effort to cultivate highlights where discussion of the importance of pollination may be best targeted.

If pollination is not required for the 'success' of garden planting – if only leaf crops and highly-modified ornamentals are grown, for example – then there is little pollination service *need* in that garden, and demonstrating a practical difference of improved pollination provision will be more difficult. In contrast, if there is a large focus on growing crops that need to be pollinated by insects to set fruit or seed, then encouraging more pollinator-friendly gardening is a logical step to take.

2.2.1. Methods

Since there is no systematic scheme currently in place in the UK to record planting or yields from garden crops, the first stage of this work was to gather information about gardening habits, knowledge, and the type of plants that are commonly grown, in order to be able to quantify the degree to which insect pollination is needed for success. This approach was well-suited to use of citizen science methods, as the focus was on data about private gardening choices, and perceptions of citizens. Once baseline information was collected on the types of crops being grown, and the methods used to do so, the project looked into comparing successful harvest yields with the amount of insect pollination needed to produce that crop, determining how to 'value' that output.

The first questionnaire carried out as part of this PhD programme of work was titled *'Growing Towns'*, and run in 2014 from February to April alongside recruitment for the *Bees 'n Beans* project (Chapter 3). Participants were enrolled via social media (the PhD twitter account, @LJBees, and website http://ljbees.org.uk) as well as encouraging those taking part in the *Bees* study to also complete the questionnaire. Offering the study via the 'Survey Monkey' website (www.surveymoney.com) allowed responses to be anonymous, other than requesting a postcode so the distribution of participants across the UK could be mapped. The survey consisted of ten questions: a mixture of multiple choice and free text boxes (shown in Table 1). No demographics (age / sex) were included since this was decided not to be relevant personal data in regard to the overall project aims, so was not asked for to reduce potential data security concerns.

The first two questions characterised the garden in question by size and type. Participants were then asked to consider the fruit trees / bushes present on their sites, as well as whether they collected fruit or nuts from trees that they did not own, and the importance of being able to do this. These plants all may require pollination, so even participants who only foraged have a need for pollination provision. The following questions on existing fruit trees, forage choices, and planned planting of vegetables and ornamentals all provided open text boxes for responses, requesting that volunteers comma-separated their answers for ease of later analysis.

Two further questions asked if participants took any steps to modify the pollination service their garden received, either by planting to support insects, or by hand pollinating.

Table 1: The ten questions used in the *Growing Towns* survey in 2014.

	Question text	**Response / categories**
1	Postcode	Text
2	What type of growing space do you have?	Individual garden Communal garden Allotment Roof garden Balcony Other (please specify)
3	Size of site	In m^2 / square feet
4	Are there any existing fruit trees or bushes on your site? If so, what sort are they?	Y/N List
5	Do you collect other fruit (or nuts) from within your local area (walking distance)? E.g. blackberries, elderberries, other wild fruits, chestnuts etc. If so, what sort are they?	Y/N List
6	(Following from #5) If you DO collect wild fruit / nuts from the local area - how important do you find being able to do so?	Nice (but not very important) Fairly important Essential
7	What vegetable / fruit crops are you intending to plant this year? (please list, separated by commas)	List
8	Do you plant flowers as well as crop plants? Is this mostly for the visual display - or specifically to support pollinators?	Category
9	If you do plant to support pollinators, what do you plant? (please list all, separated by commas)	List
10	Do you hand-pollinate any of your crops?	Category

2.2.2. Results and progress

The survey received 341 responses between February and end-April 2014; these were primarily from England, with some clustering in the South/South East observed. The distribution of responses based on georeferenced postcodes is shown in Figure 1.

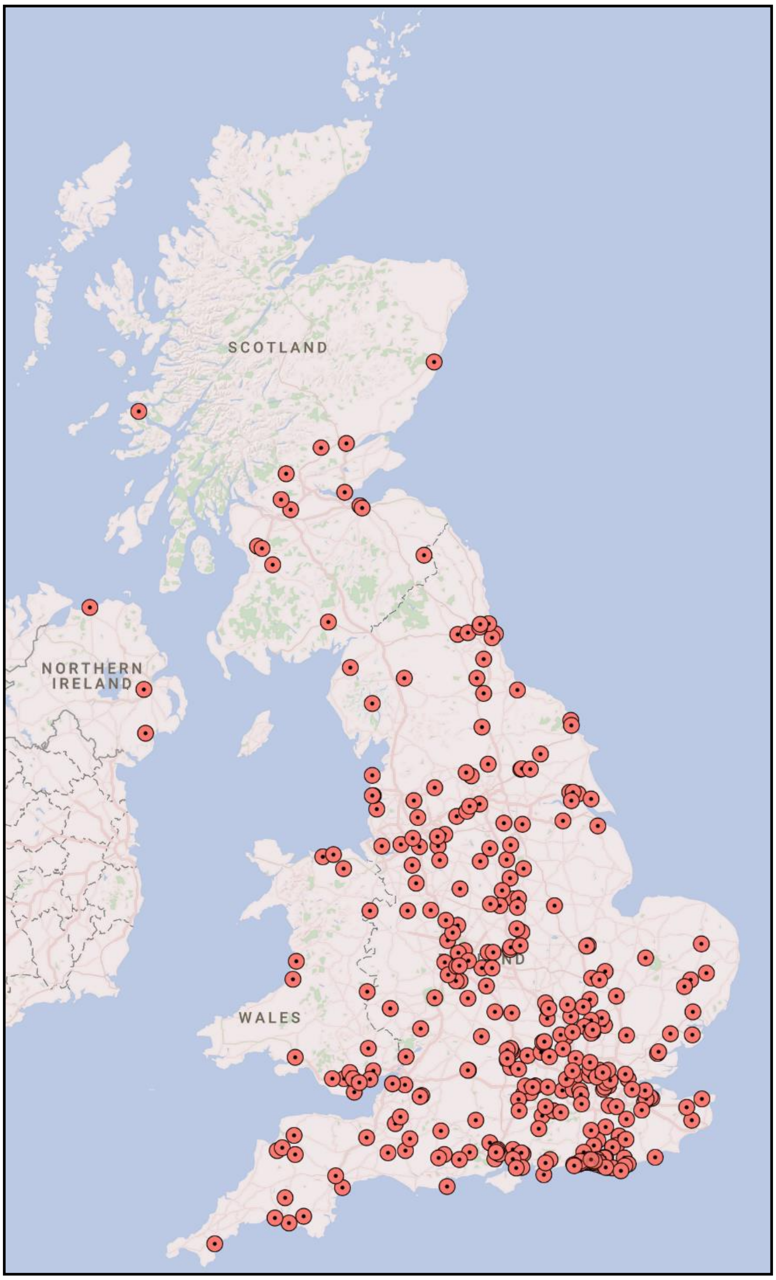


Figure 1: Location of *Growing Towns* 2014 sites, mapped by postcode.

Eighty-four percent of the respondents had individual domestic gardens (Table 2). The majority (57%) of these gardens were reported as under 100m^2 in area, although this ranged between 0.28m^2 and 101,115m^2 (10 hectares). Participants calculated these, so it is possible that the very large or very small estimates result from confusion.

Fruit trees or bushes were present on sites of 272 participants (80% of t otal); 69 (20%) had none. The most common type of fruit grown were apples, with over half of gardens that grew fruit having apple trees (representing 48% of total gardens surveyed), summarised in Table 3. There was some confusion indicated over the question wording, asking if "existing" fruit trees and bushes meant ones that the participants did not plant themselves, or only meant ones present in the garden before the current residents moved in.

Fruits or nuts were collected from the local area by 234 participants (69% of total); 100 (29%) did not forage. The most commonly-collected forage fruits were blackberries and elderberries; summarised in Table 4. Of those who foraged, 37 participants (11%) ranked being able to do so as 'Essential'; 115 (34%) as 'Important'; 98 (29%) as 'Nice'.

Table 2: Site types from 2014 'Growing towns' questionnaire.
Total n = 341 returns.

Site type	Number
Allotment	42
Balcony	3
Communal garden	8
Individual garden	**287**
Roof garden	1

Table 3: Top ten fruit trees or bushes grown in 2014; showing total number growing, and what percentage of fruit-growers had that plant (n=272).

Rank	Type	Total	% of fruit growers
1	Apple	162	60%
2	Raspberries	115	42%
3	Blackberries	93	34%
4	Blackcurrants	87	32%
5	Plum	85	31%
6	Gooseberries	78	29%
7	Pear	72	26%
8	Redcurrant	60	22%
9	Cherry	58	21%
10	Strawberries	53	19%

Table 4: Top 10 types of fruits or nuts gathered locally in 2014; showing total number who foraged, and what percentage of foragers took that fruit or nut (n = 234).

Rank	Type	Total	% of foragers
1	Blackberries	210	90%
2	Elderberries	90	38%
3	Sloes	35	15%
4	Hazel	34	15%
5	Sweet chestnut	25	11%
6	Apple	23	10%
7	Rosehips	16	7%
8	Damson	13	6%
9	Raspberries	9	4%
10	Crab apple	8	3%
10	Hawthorn	8	3%
10	Walnuts	8	3%

Almost all participants (97%) indicated that they were growing fruit or vegetable crops in 2014; ten were not. Tomatoes were the most common plant, grown by over half of participants who grew crops (50% of overall total). Table 5 shows the top ten crops planned by participants, and whether or not these plants have some need for insect-pollination. Five out of these ten crops have a pollination requirement to some degree (or might, in the case of 'green beans', which is a broad category that can include both runner beans and French beans, although only the former requires pollination).

Table 5: Top ten types of fruit or vegetable crops planted for 2014; showing total number who planned these crops; and what percentage of n = 331 'yes' responses included that crop (total participants n = 341). Grey boxes show where a crop needs insect pollination.

Rank	Type	Totals	Percentage of Yes responses	Pollinated?
1	Tomatoes	170	51%	Yes
2	Potato	162	49%	No
3	Green beans	108	33%	Yes *(depends on type)*
4	Carrot	105	32%	No
5	Peas	104	31%	No
6	Courgette	100	30%	Yes
7	Strawberries	95	29%	Yes
8	Onions	91	27%	No
9	Broad Beans	90	27%	Yes
10	Lettuce	80	24%	No

Eighty-nine percent of participants (303 people) planted ornamental flowers in 2014, as well as crops. Of these, 148 (49%) indicated that their motivation for doing so was for **both** the display and pollinator support; 51 (17%) primarily to support pollinators; and 104 (34%) primarily for the visual display. In total, 66% of total participants displayed a willingness to support pollinators with their planting choices.

The types of ornamental flowers planted to support pollinators were listed by 212 participants, and the top ten are shown in Table 6. There was some confusion about how to answer this question, with some participants who had *not* indicated that their planting was to support pollinators giving answers, while some who did plant for support left it blank, or gave responses such as 'too many to count' or 'lots!'. Little pattern was observed in the planting choices, with no type of flower being grown by over 50%. The most common were lavender, marigolds, and commercial wildflower seed mixes marketed as 'bee friendly', and these are broad type categories.

Table 6: Top ten most common flowers grown / planted to support pollinators in 2014; showing total number who planned these ornamentals, and what percentage of n = 212 'yes' responses included that flower.

Rank	Entry	Family	Genus	Totals	Percentage of "Yes"
1	Lavender	Lamiaceae	*Lavandula*	73	34%
2	Marigold	Asteraceae	*Tagetes*	60	28%
3	Wild flower seed mix	(various)	(various)	50	24%
4	Borage	Boraginaceae	*Borago*	43	20%
5	Buddleja	Scrophulariaceae	*Buddleja*	37	17%
6	Corn poppy	Papaveraceae	*Papaver*	35	17%
7	Foxglove	Plantaginaceae	*Digitatlis*	34	16%
8	Sweet peas	Fabaceae	*Lathyrus*	32	15%
8	Nasturtium	Tropaeolaceae	*Tropaeolum*	32	15%
9	Cosmos	Asteraceae	*Cosmos*	29	14%
9	Sunflower	Asteraceae	*Helianthus*	29	14%
10	Calendula	Asteraceae	*Calendula*	27	13%

Undertaking hand-pollination was much less common than planting for pollinators, with 300 participants (88% of total) responding that they did **not** hand-pollinate. Of the 41 that did, 34 indicated that this was as backup for local pollination, six as a primary source of pollination, and one deliberately for cross-breeding seeds.

The survey was generally positively received by participants, with confusion voiced over exact wording in certain questions, particularly the difference between 'important' and 'nice'. The use of free text boxes, while meaning that a wide range of plants were recorded, resulted in considerable need for data curation (particularly standardising of spellings). Assumptions also had to be made when participants had provided answers such as 'green bean' or 'just beans'.

2.2.3. Discussion

Results from the 2014 questionnaire suggest that UK gardens have a strong need for pollination provision. Fruit trees need to be pollinated by insects to set a good crop, demonstrated particularly strongly in apples (Garratt *et al.,* 2016) which were grown by just under half of all participants. The next most frequently-grown fruits also have notable insect pollination needs (raspberries and blackberries; also the main foraged fruit) (Cane, 2005; Lye *et al.,* 2011b), and soft fruits in general tend to be high value, popular crops (see Appendix B for a comparison of UK produce values and pollination requirements). Tomatoes were also grown by the majority and do benefit from buzz-pollination (Banda & Paxton, 1990), but vegetables in general have less need for pollination since many are roots or leaves, and legumes such as peas can be self-pollinating. The unclear categorisation of 'green beans' complicates this further.

Participants displayed willingness to undertake gardening actions to specifically benefit pollinator populations, with over sixty percent devoting space in their gardens to ornamental plants grown with an intention to support bees. That these actions were specifically in the form of wildlife-friendly *planting* suggests that the '*Growing Towns'* survey was mostly answered by active gardeners. While a fairly large proportion of UK households do undertake some form of wildlife-supporting action, this is mostly providing bird food (Gaston *et al.,* 2005). Exactly what types of ornamental were the most grown is less clear, since the open text boxes meant that the detail level of responses from participants was very variable. Little pattern could be determined from the flowers listed other than *Asteraceae* being common, which is not unexpected for such a large family of plants (Royal Botanic Gardens Kew & Missouri Botanic Garden, 2013). Garden plant choices are influenced by what is available to buy, and likely also by advice lists for 'pollinator friendly' plants, which themselves contain considerable variation and little crossover between lists (Garbuzov & Ratnieks, 2014b).

The results do suggest that there is awareness amongst UK gardeners of the importance of pollinators to harvest success, and that pollination provision potentially impacts a large proportion of the crops that are grown. For emphasising the value of ecosystem services to gardeners, using pollination as the focal example is thus likely to be a strong choice, although it is less clear how well it would work with people who do less of their own growing. But with the potential for even quite small gardens to be biologically diverse if managed well (Owen, 1991; Smith *et al.,* 2006), and grow-your-own on the increase (Garnett, 1996; Church *et al.,* 2015; Edible Garden Show, 2016), it is important to demonstrate the benefits of wildlife-friendly gardening, to establish good conservation practise for both experienced gardeners and people starting out.

In regard to the number of returns and the geographical locations of those gardens, it is likely that the majority of responses were from participants who were subsequently recruited to *Bees 'n Beans* in 2014. The questionnaire did not specifically ask this, but since this was the first year of the research and the project social media (the primary method of advertising) was also new, the reach of the open advert is unlikely to have been much different for the 2014 projects. Participants joining *Bees 'n Beans* were encouraged to complete the 'Growing Towns' survey (and were reminded about doing so, which is known to encourage responses [Crawford, 1997]), although since it was open to access online an accurate response rate cannot be calculated. The clustering observed around the south of England is likely partly in relation to greater population density in that part of the country, and also because Sussex University is located on the South coast and so local media traction is likely to be biased in that area.

2.3. 'The Need for Bees' (2015)

The second questionnaire of this chapter – titled 'Need for Bees' – was undertaken in 2015 to collect further information about planting choices, and include new questions about relevant gardening practices, as well as specifically looking at the popularity of insect-pollinated crops. The number of questions was increased to 24, with the majority being multiple choice. Although this expanded the physical length of the questionnaire it made answering the questions clearer and easier. The survey was piloted in December 2014 on ten volunteers of varying gardening experience (drawn from personal contacts), and modifications were made based on detailed feedback from these early participants (Crawford, 1997). The 15 to 20 minutes taken for completion was considered acceptable by these volunteers.

The questions were divided into sections, covering garden characteristics, public perceptions, gardening behaviour, and interaction with pollinators, in more detail. The full list of questions is provided in Appendix A, divided into the following sections:

1 – 5:	Site type, characteristics, and equipment.
6 – 8:	Fruit and nut trees
9 – 11:	Foraging, availability and importance.
12 – 15:	Vegetables, herbs, and the value of growing-your-own
16 – 20:	Growing flowers, supporting or providing pollination actions
21 – 24:	Pest control and level of gardening experience.

Multiple-choice options rather than open text boxes were used for extra clarity, and to allow for improved analysis of returns. Area measurements were requested in length x width rather than requiring calculation by participants. The live version of the survey was opened online in January 2015 and ran until August, again offered electronically via the 'Survey Monkey' website (www.surveymoney.com), with recruitment and social media methods used the same as in 2.2.1.

2.3.1. Results

'Need for Bees' received 348 responses between January and August 2015. Responses were received from all countries in the UK, although the majority were from England and Wales, clustering around the central South / South East (Figure 2).

Figure 2: Postcode distribution of the 'Need for Bees' returns in

Site type, characteristics, and equipment

The majority of sites were individual gardens, with some allotments, and a few other types of site (summarised in Table 7). Fifty-five percent of sites were south-facing (S, SW, SE) to some degree.

Table 7: Site types and frequencies from the '*Need for Bees'* questionnaire.

Site type	Number	Percentage
Allotment	44	13%
Balcony	4	1%
Communal garden	2	1%
Individual garden	294	84%
Other	5	1%

Table 8: How participants in *'Need for Bees'* rated their experience as gardeners.

Gardening experience	Number	Percentage
Amateur	182	52%
Experienced amateur	121	35%
Just starting	36	10%
Professional gardener	6	2%
No response	3	1%

The majority of participants identified as amateur gardeners or experienced amateurs, indicating a reasonable level of gardening knowledge (Table 8). Reflecting this, most sites contained compost bins, sheds and water storage, with more-specialist equipment (e.g. fruit cages / polytunnels) less common (Table 9).

Over half of participants indicated that they used the internet or television programmes to obtain information on how to grow plants successfully, in addition to advice from family and friends (Table 10).

Table 9: The types of gardening equipment present on participants' sites in 2015.

Equipment	Number	Percentage
Composting bins	246	71%
Shed	229	66%
Water storage containers (e.g. water butts)	220	63%
Greenhouse (not heated)	140	40%
Cloches (or garden fleece)	98	28%
Coldframe	71	20%
Fruit or vegetable cages	53	15%
None of these	35	10%
Polytunnel (walk-in)	15	4%
Greenhouse (heated)	8	2%

Table 10: Where *Need for Bees* participants obtained information about gardening.

Source	Number	Percentage
Internet sites	235	68%
Family members or friends	201	58%
Television programmes	184	53%
Magazines	132	38%
Radio programmes	84	24%
Newspapers	74	21%
Books	62	18%
Belonging to a gardening society	49	14%
Employing a gardener / horticultural professional	10	3%
Other	0	0%

Fruit trees and bushes

Apples and strawberries were the only fruits grown by the majority of participants. The next most common fruits were plum and pears in terms of trees (Table 11), and raspberries and blackberries for soft fruit (Table 12).

Table 11: Types of fruit trees present in the gardens of 2015 *Need for Bees* participants.

Fruit tree	Number	Percentage
Apple	185	53%
Plum	110	32%
No fruit trees	90	26%
Pear	85	24%
Cherry	81	23%
Crab apple	45	13%
Elder	45	13%
Damson	30	9%
Other	28	8%
Peaches / apricots	22	6%

Table 12: Types of fruit bushes in the gardens of 2015 *Need for Bees* participants.

Fruit bush	Number	Percentage
Strawberries	194	56%
Raspberries	156	45%
Blackberries	131	38%
Gooseberries	128	37%
Blackcurrants	121	35%
Redcurrants	75	22%
Blueberries	74	21%
No fruit bushes	73	21%
Loganberries / Tayberries	43	12%
Other	26	7%

Vegetables and herbs

Over half of participants grew tomatoes, salad leaves, and runner / French beans. Potatoes, courgettes / marrows, peas, rhubarb and broad beans were the next most popular categories (Table 13), although not grown by a majority.

Table 13: Vegetables grown or planned by participants in *Need for Bees* 2015.

Vegetables	Number	Percentage
Tomatoes	233	67%
Lettuce etc	204	59%
Runner or French beans	183	53%
Potatoes	172	49 %
Courgettes / marrows	168	48 %
Peas (any)	164	47 %
Rhubarb	160	46%
Broad beans	156	45%
Brassicas	130	37%
Carrots	127	36 %
Onions	127	36 %
Beetroot	125	36%
Peppers / chillis	122	35%
Leeks	113	32%
Cucumbers	107	31%

Table 13: Vegetables *continued*

Squashes	97	28%
Sweetcorn	76	22%
Parsnips	68	20%

Table 14: Herbs grown or planned by participants in *Need for Bees* 2015.

Herbs	Number	Percentage
Mint	255	73%
Rosemary	255	73%
Chives	223	64%
Thyme	222	64%
Sage	178	51%
Parsley	170	49%
Oregano	127	36%
Marjoram	115	33.%
Basil	104	30%
Coriander	73	21%
Other	51	15%

Of these, insect pollination contributes to tomato, runner bean, courgette / marrow and broad bean crops (Appendix B). Five herbs were grown by over half the participants: Mint, rosemary, chives, thyme, and sage (Table 14).

Flowers and forage

Very few participants did not plant flowers in addition to crop (Table 15), the majority (65%) deliberately motivated by supporting of pollinators, and with 17% of that 65% indicating that it was a primary objective. Perennials were the most popular type of flower grown, followed by bulbs (Table 16). Most participants indicated that they kept flower and crop planting separate within the garden, with less than half intermixing crops and ornamentals (Table 17).

Table 15: If participants grew flowers in addition to crop plants in 2015; and if so, why?

Additional flowers?	Number	Percentage
No	18	5%
Yes - for visual display, AND to support my crops	166	48%
Yes - mainly for visual display	102	29%
Yes - mainly to support pollinators for my crop plants	60	17%

Table 16: If additional flowers were grown, what types were grown.

Types of flowers	Number	Percentage
Perennial plants	281	81%
Bulbs	263	76%
Seeds or mixes	247	71%
Annual plants	232	67%

Table 17: If additional flowers were grown, where in the garden they were positioned.

Positioning of flowers	Number	Percentage
Close by, but in separate beds or containers	178	51%
Mixed in with fruits and vegetables	145	42%
In flower beds or containers in other part of the site, away from the fruit and vegetables	62	18%
Only flowers; there are no herbs, fruit or vegetables	13	4%

In terms of wild forage, the majority of participants sought out edible chestnuts, but none had chestnut trees present in their gardens (Table 18 and 19). Sloes and elderberries were the next most common forage items. Nearly half of responses considered being able to find wild fruits or nuts to be important or essential; 44% considered it 'nice' but not important (Table 20).

Table 18: Did participants collect any fruits or nuts from trees within easy walking distance?

Type of forage	Number	Percentage
Chestnuts	217	62%
None	99	28%
Sloes	94	27%
Elderberries	81	23%
Apples	51	15%
Rosehips	35	10%
Other	32	9%
Hazelnuts	24	7%

Table 19: If there were any nut trees present in participants' gardens.

Types of nuts	Number	Percentage
No nut trees	235	68%
Hazel	61	18%
Other	6	2%
Almonds	2	1%
Chestnut (edible)	0	0%

Table 20: Perception of the importance of being able to collect wild fruit / nuts.

Importance	Number	Percentage
Essential	37	11%
Fairly / quite important	133	38%
Nice, but not very important	154	44%
Not important	23	7%

Growing your own

The majority of responses (69%) considered being able to grow their own food **important** or **essential** (Table 21). In respect of motivations for growing your own, the most common reason was 'satisfaction from growing your own food', followed by 'gardening is an enjoyable hobby'. Healthier or more flavourful food were also common considerations ('knowing how it is grown' and 'the taste is better'), and just over half wanted to reduce their environmental impact ('being more sustainable'); detailed in Table 22.

Table 21: How important *Need for Bees* participants considered being able to grow their own food.

Importance	Number	Percentage
Essential	98	28%
Fairly / quite important	144	41%
Nice, but not very important	99	28%
Not important	6	2%

Table 22: *Need for Bees* participants' motivations for growing fruits and vegetables.

Reason for growing produce	Number	Percentage
Satisfaction from growing your own food	292	84%
Gardening is an enjoyable hobby	262	75%
Knowing how it has been grown - what fertilisers or pesticides (etc) have been used	220	63%
The taste is better than bought produce	205	59%
Being more 'sustainable' / reducing my 'carbon footprint'	183	53%
Gardening is an exercise	163	47%
Saving money on produce	88	25%
Social benefit of belonging to an allotment or gardening group	52	15%
Would be unable to buy the produce that I grow (type or variety)	44	13%
Not applicable; do not grow food plants	21	6%

Pollination and pest control

The majority of participants (86%) indicated that they took some form of specific action (other than planting choices) to support pollinators in their gardens (Table 23). The most common actions were reducing pesticide use and providing logs or wood piles. Only 12% of participants hand-pollinated their crops, primarily to supplement local pollination (Table 24; note that percentages are rounded). The most common pest control method was physical removal (Table 25).

Table 23: Specific actions taken by *Need for Bees* participants to help support pollinators.

Actions taken to support pollinators	Number	Percentage
Reducing or stopping pesticide use	239	67%
Providing logs or wood piles	200	57%
Providing bare soil.	136	39%
Providing 'bee hotels' (either purchased or home-made)	129	37%
Cut lawns less often	129	37%
Providing nesting spaces for bumblebees (e.g. boxes or holes)	112	32%
Using 'green manure'	92	26%
None	49	14%

Table 24: Number of participants who hand-pollinated their crops, and why.

Do you hand-pollinate?	Number	Percentage
No	305	88%
Yes, as **back-up** of main pollination for that plant	30	9%
Yes, as the **main** source of pollination for that plant	11	3%
Yes, for deliberate crossing to make hybrid seeds	2	1%

Table 25: Pest control methods used by participants in *Need for Bees*.

Control method	Number	Percentage
Physical removal (e.g. squashing, or pulling up)	214	61%
Physical barriers (e.g. copper tape, insect netting, cardboard)	125	36%
Slug pellets	122	35%
Planting pest-repellent plants (e.g. marigolds)	121	35%
Soap sprays	92	26%
Planting to encourage natural predators	81	23%
No pest control used	66	19%
Weedkillers (commercial)	59	17%
Moving of existing predators (e.g. ladybirds) around the garden	51	15%
Slug traps	38	11%
Insecticides (commercial)	31	9%
Purchased natural predators (e.g. nematodes)	26	7%
Insecticides (homemade)	15	4%
Weedkillers (homemade)	5	1%

2.3.2. Discussion

Similar to the findings of the 2014 'Growing Towns' survey, in 2015 tomatoes, apples and strawberries were grown by the majority of participants. Better pollination has been shown to improve not only the set but also the resulting quality of these fruits (Roselino & Santos, 2009; Hogendoorn *et al.,* 2010; Ramírez & Davenport, 2013; Garratt, *et al.,* 2014). Squashes and soft fruit, particularly *Ribes* fruit, were frequent plant choices as well and while the pollination requirements differ between species (Bisognin, 2002; Kampuss & Pedersen, 2003; Cane, 2005; Klein *et al.,* 2007) insects do make a contribution. A similar situation is found in beans and peas, which vary substantially in their selfing capability and were also widely grown. The popular crops definitely *not* requiring any pollination were potatoes, rhubarb and salad leaves; which, except for salad leaves, are comparatively low-value crops (Corbet *et al.,* 1991; Carreck & Williams, 1998; also see Appendix B for a comparison of UK crop values).

Participants in 'Need for Bees' highly valued being able to grow their own food, and were certainly aware of the environmental benefits of doing so, with over half indicating that reducing their own environmental impacts was a driving factor. It was not, however, the most quoted reason: 'satisfaction' with growing food, and the enjoyment of gardening in and of itself, were driving reasons for the majority of participants, followed by a desire for certainty about production methods (especially use of chemicals) and the resulting produce itself being viewed as higher quality than bought goods. Insect-mediated pollination contributes considerably to fulfilling those aims.

'Satisfaction' of growing your own food is not entirely reliant on yields, or money-saving (which was itself a fairly infrequent driver in this study), but producing more fruit or vegetables from the same space is likely to be more satisfying than a poor harvest. The reliable cropping of popular varieties is a big part of their success (Armitage *et al.,* 2016), yet many of those do rely on insect pollination to some degree, and the current low levels of hand pollination suggest that replacing it manually – even in just those plants for which it is obligate, such as squashes – would entail a significant change in behaviour for gardeners. Therefore, emphasising the co-operative element of pollination – working *with* 'your' bees, for better success and better quality of food – is likely to be an appealing approach to promote the concept of pollination as an important ecosystem service to general public.

The majority of respondents said that they did indeed forage for fruit or nuts (mostly chestnuts), indicating that foraging in some form is a reasonably widespread – but probably seasonal – activity which engages people with non-domestic outdoor green spaces. In 2015 more people than in 2014 indicated that they actively foraged for chestnuts (*Castanea sativa*) in their local area, but none grew the trees on their own sites. Chestnut is self-sterile and mainly pollinated by wind, although insect pollination does contribute, particularly for more-isolated trees outside the likely distribution distance of chestnut pollen (Clapper, 1954; Manino *et al.,* 1991). Blackberries were by far the most commonly foraged fruit in 2014, and were not included in this section in 2015 to avoid double-counting confusion with the garden-fruit question – but it is probably safe to assume that wild blackberries are also a valued part of forage fruits. Cultivated *Rubus* species (blackberries and raspberries) tend to be self-fertile, but wild species and hybrids vary in their pollination requirements (Cane, 2005), so it is likely that foraged wild blackberries would have more need for insect pollination than cultivated varieties (Woodcock, 2012). With approximately half of participants rating the ability to forage as being relevant to them, emphasis on the importance of bees to support foraging represents another angle of approach to promote the value of pollination.

There was not a question covering the use of fruit/berries as photographic or artistic subjects, as this would have lengthened the questionnaire and altered the focus. However artists and photographers represent other groups who have a vested interest in pollination services and could be engaged with to promote its importance via their extended working practice (e.g. workshop activities).

Two-thirds of participants indicated they already devoted space in their gardens to growing ornamental plants, at least partly with an intention to support bees and other pollinators. These were mostly perennial plants and bulbs, many of which are specifically marketed as pollinator-friendly (Royal Horticultural Society, 2011; Garbuzov & Ratnieks, 2014b) and flowers and crops tended to be planted separately (the effects of positioning crop plants and ornamentals in gardens will be examined in Chapter 5). Herbs were very commonly grown, with several typical ‘kitchen garden’ herbs present on most sites. The vegetative growth of these plants (such as thyme and chives) are what they are cultivated for, but they are very attractive to bees if allowed to flower (Fussell & Corbet, 1992; Little, 2013; Bumblebee Conservation Trust, 2015). Since the majority of participants are growing herbs, suggesting that some are left to mature is an easy method of adding more pollinator support to a garden.

Participants in *Need for Bees* were primarily hobbyist gardeners with individual gardens; half of whom identified themselves as amateurs, and a third again as experienced amateurs. This was reflected in the garden equipment present, with compost bins, sheds and water containers common, but fewer with more-specialised or higher-cost equipment like greenhouses. They seemed to be quite hands-on, being much more likely to be physically removing pests from plants than using chemical controls or sprays. It is not clear from the study if the physical control measure of pest removal is undertaken due to economic consideration (because it is free) or if this is an ecologically-motivated choice. However, the most common non-planting actions done to support pollinators were both methods that have recently received quite high-profile emphasis – reducing pesticide use and retaining dead wood (Hammond, 2008; Royal Horticultural Society, 2014a, 2016; Buglife, 2017a). Whether 'dead wood' was in the form of log piles for overwintering insects (used by pollinating beetles and some butterflies), or meant dead wood with e.g. holes drilled in for cavity-nesting bees to use, was not asked, but both methods tend to be discussed together in advice and campaign material. This suggests that participants are willing to adjust their behaviour based on robust information that is accessible and reliable, which is encouraging.

Similar to the 2014 questionnaire, since this was an open survey advertised online no measure of response rate can be made. The survey was open for twice as long as the 2014 survey, but did not receive twice the responses, suggesting that again the population answering were primarily those who were already engaged with the *Bees 'n Beans* projects. If this type of survey were to be repeated in future, targeting specific populations (through partnership with e.g. gardening societies, local Wildlife Trusts, or the Women's Institute) would be advised, since it is easier to remind a specifically-targeted group to return responses (Crawford, 1997).

The participants in this survey were competent users of online resources, since the questionnaire itself was online and 68% of participants indicated they used internet resources specifically to search for gardening advice, in addition to television (53%). Word of mouth from family and friends was also a popular method of information communication (58%), emphasising that there is a significant social element to gardening. Although since only 14% belonged to a gardening society and 13% of green spaces were allotments (which can be perceived as a society), the social aspect may be more on a one-to-one basis rather than group activity for the majority of people. Outreach that is intended to influence behaviour towards more pollinator support must therefore be clear, with concise messages that are easy to remember and discuss with others.

2.4. Bringing ecosystem services home: the value of gardens.

Urban environments are typically characterised by a mosaic of different habitat types in close proximity (BRIG, 2011; Macadam *et al.,* 2013), with the biodiversity present within those sites strongly linked to local vegetation characteristics and management, as well as the surrounding semi-natural landscape (Ahrné *et al.,* 2009; Matteson & Langellotto, 2012; Pardee & Philpott, 2014). Recent UK policies in regard to urban spaces emphasise supporting contributions to 'Green Infrastructure' and ecosystem service frameworks, recognising the importance of increasing and maintaining heterogeneity at larger scales (Goddard *et al.,* 2010; DEFRA, 2014). Modifying the management of private land cannot be prescriptive in the manner possible for civic spaces, and thus there is a need to ensure that the public are engaged with efforts to protect urban wildlife, by at least maintaining – and preferably increasing – the biodiversity in their gardens (DEFRA, 2014; Carvell *et al.,* 2016).

In order to motivate people to modify their behaviour to contribute to wider conservation actions, gardeners must feel that their own actions can have a definite impact on the natural environment (Clayton, 2007), so it is necessary to be able to clearly demonstrate real, practical impacts of appropriate management in even these quite small spaces. Benefits expressed in terms of savings against supermarket prices is a more accessible concept on a personal level than the magnitude of global pollination (Winfree, 2013).

The preceding sections of this chapter documented the wide variety of flowering fruits and vegetables present in or planned for participants' gardens. Building on that work, the aim of this stage was to demonstrate the degree to which pollinators are actively responsible for the success of such effort; and quantify the value of yields in terms of:

1) An estimated commercial value, based on the weight / number of fruits and vegetables harvested
2) A garden pollinator 'bee value' based on the pollination requirement of different crops.

This project ran in two years, with the 2015 variant titled 'Shopping in the Garden', and 2016 titled 'How much does your garden grow?' (Figure 3).

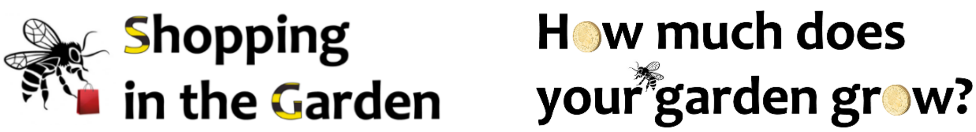


Figure 3: Logos used for the 2015 (left) and 2016 (right) garden yields projects.

2.4.1. Valuation of garden crop yields.

Assigning value to home-grown produce could potentially be a very complex calculation, because exactly what measure of 'value' participants are using as the major driver for their actions may well differ substantially from person to person. Externalities to traditional valuation methods, such as cultural perceptions and the physical and mental health benefits of gardening are also not easily captured (Wakefield *et al.,* 2007; van den Berg *et al.,* 2010). For example, the previous questionnaire study (2.3.1.) ranked "*satisfaction from growing your own food*" (at 83%) and "*gardening is an enjoyable hobby*" (at 75%) as the main reasons why people grow their own food, with "saving money" down at 25%. In contrast, a 'Which?' telephone survey of 1009 UK residents, undertaken in June 2011, found that of the 24% who were growing their own crops, *'Increases in food prices mean I'm trying to be more economical'* was the main driver for 59% of responders.

Quantification of set up costs is also difficult, as many parameters need to be considered: Do gardeners start from 'scratch'? Is there infrastructure already in place? How does access to a gardening community affect this? What counts as labour hours? These *can* be estimated, but may represent both an action and a goal – with labour hours also representing time spent exercising, for example, which would need to be assessed differently – which means that models can become very complex, very quickly (Church *et al.,* 2015).

This is not to say that valuations cannot be done, but out of practicality they are often relatively crude. For example, a recent phone-based questionnaire study conducted on behalf of 'The Edible Garden Show' (of 1000 UK residents, undertaken in 2016 as part of PR for the event) calculated an average saving from 'growing your own' of £268/year in UK gardens, based on subjective valuation from the participants of their weekly grocery bill saving (Edible Garden Show, 2016). A trial carried out by DT Brown Seeds (Bury Road, Newmarket, Suffolk) in summer 2009 and repeated in 2011 (Rosenberg, 2012) produced a similar estimate, suggesting crops valuing £262.54/year could be grown in a 10m x 3m plot – deemed a 'typical' area that could be expected in a UK garden (DT Brown Seeds, 2009). Valuation of the DT Brown study produce was based on Waitrose supermarket's online prices at the time of harvest.

There are few comprehensive sources of information about the commercial value of home grown crops in the UK. DEFRA maintains a weekly and historical list of the wholesale value of fruits and vegetables and provides current / previous market values, as well as upper and lower bounds of the most usual prices (https://www.gov.uk/government/statistical-data-sets/wholesale-fruit-and-vegetable-prices-weekly-average), but these are wholesale values from the primary produce markets in the UK, and does not cover the full selection of produce potentially grown at home. The point-of-sale value of produce in supermarkets or local shops / markets will reflect a combination of the wholesale price plus additional margins of the retail business, thus the cost to the consumer will be higher than this. Exact values of produce vary with the market, variety and seasonality.

2.4.2. The need for pollination

The requirement for insect-mediated pollination varies greatly between fruits and vegetables and their different cultivars, as does the depth of the existing knowledge base about those requirements (McGregor, 1976; Free, 1993). Some crops are capable of different degrees of self-pollination, or are primarily wind pollinated (many grains), but the yield or quality may still be enhanced by insect-mediated pollination (Corbet *et al.,* 1991; Delaplane *et al.,* 2000; Breeze *et al.,* 2011). Perfect flowers may not tend towards selfing, either as a result of genetic incompatibility or mechanical / temporal isolation, where the pollen and the stigma mature at different times or are positioned in such a way that accidental shedding of pollen onto the receptive surface is unlikely. Some monoecious crops like cucumbers and squashes, which produce both male and female flowers separately on the same plant, are not necessarily self-incompatible but while only one plant may be needed to produce a crop, insect action is required to move pollen from the male to the female flowers (Bisognin, 2002).

The insect pollination needs of some commercially important crops are very well understood (Corbet *et al.,* 1991; Westerkamp & Gottsberger, 2000; Williams, 2002), but others are less so, and garden crops often have many varieties available. To estimate the insect contribution to crop, some measure of the *need* for pollination of those crops has to be estimated. There have been several reviews of the state of knowledge of common crop pollination requirements (Robinson *et al.,* 1989; Corbet *et* *al.,* 1991; Delaplane *et al.,* 2000; Williams, 2002), and some specifically focused on UK varieties (Carreck & Williams, 1998). The most recent of these was a particularly detailed review from Klein *et al.* (2007), which focused on evaluating the dependence on animal-mediated pollination of world crops that are directly consumed by humans, and categorises them accordingly, expanding on previous reviews with new data.

2.4.3. Methods

The basis of the methodology was to ask volunteers to record the number / weight of crops they harvested over the growing season. Using that information and the cost of purchasing those crops at market value, a total value (or saving) of the year's harvest was calculated. These values per crop were then compared to the proportion of that crop's yield that could be directly attributed to insect pollinator action (ranging from 0 – 1, i.e. not insect pollinated to obligatory), and thus a currency value could be placed on the pollinator contribution to that year's gardening success.

Crop value and the crop list

Values used for crops were determined by comparing the cost of the same or similar items in supermarkets, farmer's markets and grocers – using fresh, British-grown, in-season options if available – and calculating a cost per gram based on this. After an initial comparison of the prices in different supermarkets, Waitrose 'basic' prices were used as the basis for the value table as this supermarket had the widest range of UK produce available at the time of survey; similar to the method used by DT Brown Seeds (2009). More expensive, specialist versions of the same produce (such as 'Organic' labels) were not included unless there was no alternative available. While it is likely that some home gardening would actually fulfil organic standards (Badgley *et al.,* 2007), it is not a certainty, and the decision was taken that lower bounds of the value estimates from basic ranges would avoid appearing to inflate the values by deliberately choosing the most expensive option for comparison.

For species of crop plants that were not found for sale in Waitrose, values were based on online purchase, or those found at farmers' markets. For crops that are not commonly commercially-available, the cost used was that of the most similar item, either in terms of relatedness or the use of the produce (for example, medlars used the quince value, as both are specialist fruits primarily used for making preserves). Appendix B describes where the values used were sourced, with links and access dates.

In 2015, participants in the yields survey were asked to list any pollinated crops they were growing; in 2016 categories to select from were provided, based on the returns from 2015 and the previous sections' questionnaires ('Growing towns' and 'the Need for Bees'). The 2016 list also included non-pollinated crops – such as root vegetables, leaf crops, or any others that have no insect pollination requirement – since participants in 2015 had queried why these were not included (and some had returned that information). Inclusion provided a more relatable overall valuation of garden produce, and meant that respondents did not have to decide if a crop was pollinated or not, simplifying the methodology from the volunteer perspective. The 2016 study allowed volunteers to input their harvests in grams, ounces, or counts of item, and the spreadsheet converted between them.

Pollination requirement

The pollination requirement for crops used in the value calculations was based primarily on: the supplemental data from the 2007 paper (Klein *et al.,* 2007), which scored the dependence on bees into five classes (>90% = Essential; 40%-90% = High; 10%-40% = Modest; <10% = low; unknown); Table 5 from Corbet *et al.* (1992), which summarises reliance of crops on honeybees from previous reviews and gives a proportion score; and Tables 1 and 2 from Carrek & Williams (1998), which score pollination requirement as low / medium / high at 0.1 / 0.5 / 0.9 respectively. For ordinal value categories, a mid-value was used as the proportion of insect-requirement (i.e. for something classed as 'modest' by Klein *et al.,* between 10%-40%, the pollination requirement was scored at 0.25). For fruits and vegetables not included in these reports, the literature was searched more specifically, or a value from the closest equivalent that is commercially available was used (e.g. most of the various *Ribes* hybrids used the *Ribes rubrum* "redcurrant" value). Appendix B of this document details the pollination requirements used, indicating where chosen values were sourced from, and any approximations or category combintionations that were made.

There was no distinction made between exactly how the pollination 'requirement' is realised for each plant; whether the association with insect action results in greater fruit set, weight of crop produced or quality of fruit and so on, since this is very variable between species.

2.4.4. Recruitment and recording

Recruitment to the projects began in April of 2015 and 2016, and a final cut-off point of the end of November was put in place for data return – this is quite late, but apple harvests/counting in particular were later than anticipated in both years due to the weather, and apples have a potentially large effect on the 'bee value' of a garden.

Participants were recruited from the *Bees 'n Beans* (Chapter 3) projects' 'interested' mailing list, primarily by personal email contact. Webpages on the LJBees site were maintained for each year, archiving project documents and email updates (https://www.ljbees.org.uk/yields and http://www.ljbees.org.uk/gardengrow, respectively). Volunteers were required to count and weigh the produce harvested from their gardens and / or allotments and input the information on recording sheets, which were provided by email. This could be done sequentially or as a final total, depending on personal preference; only the total would be used in value calculations.

News and updates were provided using the social media platforms already established as part of *Bees 'n Beans*, and individual queries were answered in a timely manner to facilitate good personal relationships. The 2015 project collected email addresses of all participants before the project began and monthly contact was maintained with the group; in 2016 a sign-up form was provided in addition to the downloadable calculator, allowing people to provide an email address to indicate if they were willing to return data later. 2016 had less-frequent routine contact with participants, to determine what level of reminders and involvement is needed from the project.

Figure 4 shows how the value calculation was carried out. The crop **total value** is an estimated purchase price; **bee value** multiplies each total with the proportion of yield that insect-mediated pollination can be considered to be directly responsible for.

Crop	Pollination requirement	Number	Weight of one unit g	Weight in g	Cost per g	Total value	Bee value
Aubergine	0.25	3	250	750	0.0032	£2.40	£0.60
Blackcurrants	0.9			500	0.01667	£8.34	£7.50
	↑ Calculated	↑ **Input:** If not weighed	↑ Average weight	↑ **Input:** If weighed Calc. if not	↑ Calculated	↑ Weight x cost	↑ Total value x poll.req.

Figure 4: Example of how the yield calculation spreadsheet works.

For the 2015 run of this project, the values of the yields were calculated after the recording spreadsheet had been returned. A short report was subsequently provided to each volunteer, giving their own total- and bee- yield values per crop and overall.

The 2016 project adjusted how the valuation would be presented to participants. A new spreadsheet, based on the yield calculation in Figure 4, was created for volunteers to download and fill in directly, rather than returning data on recording sheets (Figure 5). This spreadsheet, deemed the 'Garden Shop Calculator', produced running totals for users, including a short report summarising the total- and bee- values (Figure 6).

Crop	Weight of harvest in g	(or) Weight of harvest in oz	(or) # items	Individual crop value	Individual crop bee value
Almonds					
Amaranth					
Apples					
Apricots					

Figure 5: Example of the input section of the spreadsheet for the 2016 run of the project. Green boxes were editable.

Only **green** cells can be edited. Please enter: the **weight** of your harvest in g.
(or) the weight in oz
(or) the number of items

The report table below will automatically calculate the values.

REPORT

Name	Joan Birkin
Date	
Total crop value	£471.04
Bee value	£229.19
% directly from bees	49%

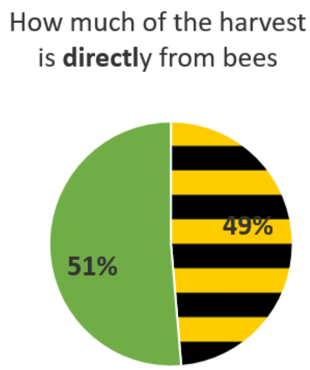


Figure 6: Report section of the calculator. Value, bee %, and the graph updated automatically.

2.4.5. Results

2015 garden values

52 volunteers indicated they would be willing to take part in 2015, and 19 returned their yield questionnaires (37% engagement). The total valuation of produce grown from pollinated crops was £4,555.68, of which the 'bee value' totalled £2,682.44, indicating insect pollinators as directly responsible for the production of 58.9% of crops recorded; the breakdown is shown in Table 26. For most participants (13 people, 68% of total) the 'bee yield' value was over 50% of pollinated crops total value (Figure 7).

Table 26: The total value of crop yields from each 'Shopping in the garden' participant's garden in 2015; as well as the calculated percentage of that yield that can be directly attributed to insect action (% bee values), based on the literature about that species' pollination requirements. The 'bee value' is the value of the proportion of the total yield thus directly attributable to insect pollination.

Participant	**Total Yield value**	**Bee value**	**Percentage of yield due to bees** *(>50% in bold)*
P1	£426.00	£381.83	**90%**
P2	£29.43	£25.22	**86%**
P3	£205.65	£177.94	**87%**
P4	£189.87	£90.75	48%
P5	£277.57	£164.66	**59%**
P6	£147.48	£98.77	**67%**
P7	£69.91	£51.17	**73%**
P8	£97.52	£78.17	**80%**
P9	£148.17	£110.28	**74%**
P10	£135.46	£34.73	26%
P11	£6.80	£2.09	31%
P12	£638.76	£300.05	47%
P13	£807.29	£354.83	44%
P14	£252.84	£158.91	**63%**
P15	£106.65	£66.51	**62%**
P16	£771.41	£427.24	**55%**
P17	£17.50	£2.03	12%
P18	£127.19	£92.66	**73%**
P19	£100.19	£64.62	**64%**

The average total yield per participant was £239.77, although this ranged from £807.29 down to £6.80; the median was £147.48, with 14 (74%) gardens being above £100. The much lower values were from participants who did not grow several different crops, or had little room to do so.

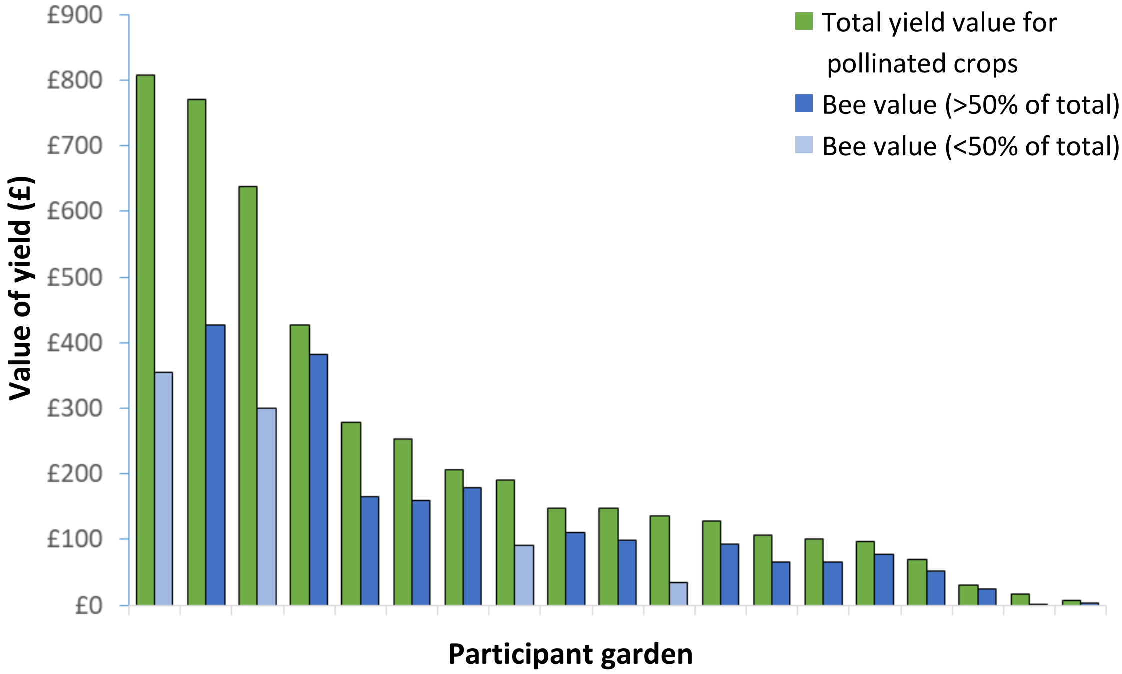


Figure 7: Total garden yields of flowering crops compared to bee values from 2015. The participant garden category is each individual garden involved, showing the total value of crops yielded (green) and the proportion of that yield directly attributed to insect action (blue). Dark blue bars indicate where the insect pollination was responsible for over 50% of the total yield value; light blue bars are for under 50%.

A reasonable generalisation for gardens / allotments from the 2015 study would be that gardeners can fairly easily obtain at least £100-£150 worth of flowering fruit / vegetables from their gardens in a season.

2016 garden values

20 participants indicated that they had downloaded and were planning to use the spreadsheet. Of these, 12 returned the spreadsheet by the end of the harvest period, and three more indicated that they had been unable to record their harvests (75% engagement). A total value of produce of £4,291.16 was recorded, ranging from £747.81 down to £22.81. Of this, the ‘bee effort’ value totalled £2,352.10 (55%), ranging from contributions of 22% to 100% (Table 27). The average garden produce total was £357.60, with the average bee value £196.01 (55%).

For most participants, (7/12 = 58%), the bee value contributed over 50% of the value of their crop yields (Figure 8).

Table 27: The total value of crop yields from each 'How much does your garden grow' participant's garden in 2016; as well as the calculated percentage of that yield that can be directly attributed to insect action (% bee values), based on the literature about that species' pollination requirements. The 'bee value' is the value of the proportion of the total yield thus directly attributable to insect pollination.

Participant	**Total yield value**	**Bee value**	**Percentage of yield due to bees** *(>50% in bold)*
1	£290.00	£62.94	22%
2	£317.02	£164.95	**52%**
3	£52.98	£52.98	**100%**
4	£746.42	£384.43	**52%**
5	£364.04	£131.07	36%
6	£405.54	£268.64	**66%**
7	£471.04	£229.19	49%
8	£135.81	£50.82	37%
9	£22.81	£10.87	48%
10	£747.98	£429.52	**57%**
11	£72.70	£37.88	**52%**
12	£664.83	£528.82	**80%**

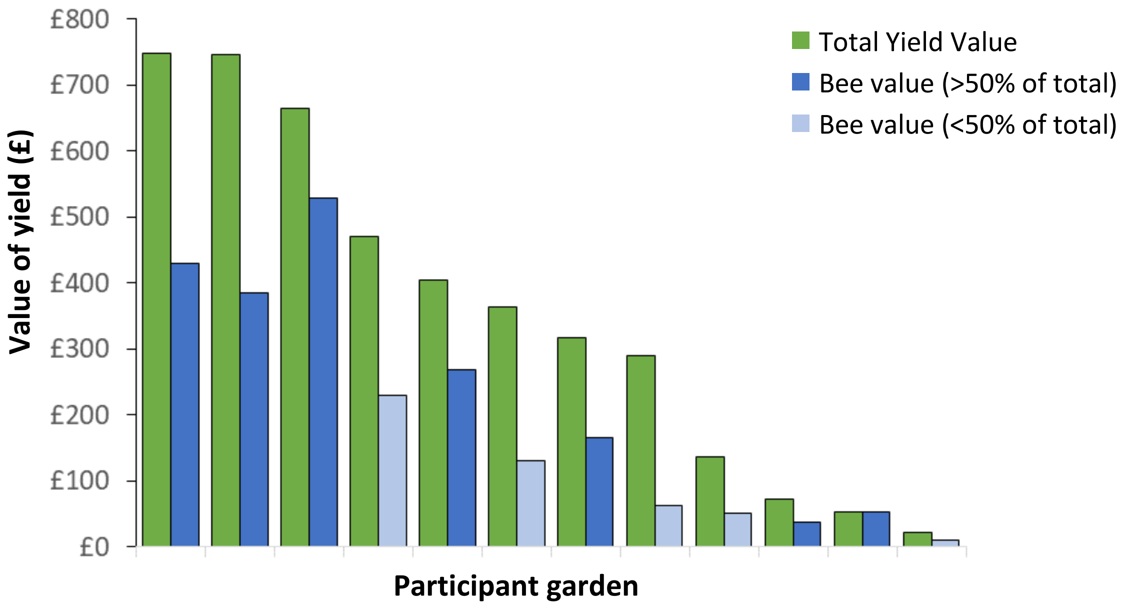


Figure 8: Total garden crop yield values in 2016 (green), compared to the proportion of that yield that was directly attributable to insect action (blue). Dark blue bars show where insect pollination was responsible for over 50% of the total; light blue bars are for under 50%. Note that this year included *non-flowering* crops as well in the total values. Participant garden categories are for each individual garden taking part.

Crop choices, value and pollination needs

Flowering crop plants tend to represent the more expensive types of produce, with an average £0.91 per 100g purchase price for crops with a pollination requirement (regardless of how much that was), and £0.42 per 100g for crops with no need for insect-mediated pollination. The ten most valuable crops grown (by overall total) were the same in both years – with the addition of potatoes in 2016 (not included in the 2015 listings) replacing blackberries from 2015 (Figures 9 and 10).

Whilst the sample sizes in 2015 and 2016 for the yield calculation projects was quite small – 19 and 12 gardens, respectively – the types of flowering crops grown by participants does seem to be similar to that seen in the much larger "Need for Bees" questionnaire 2015 (n=348), and in the 2014 "Growing Towns" questionnaire (n=331). This suggests that the patterns seen in analysis of these data would be similar in larger-scale surveys.

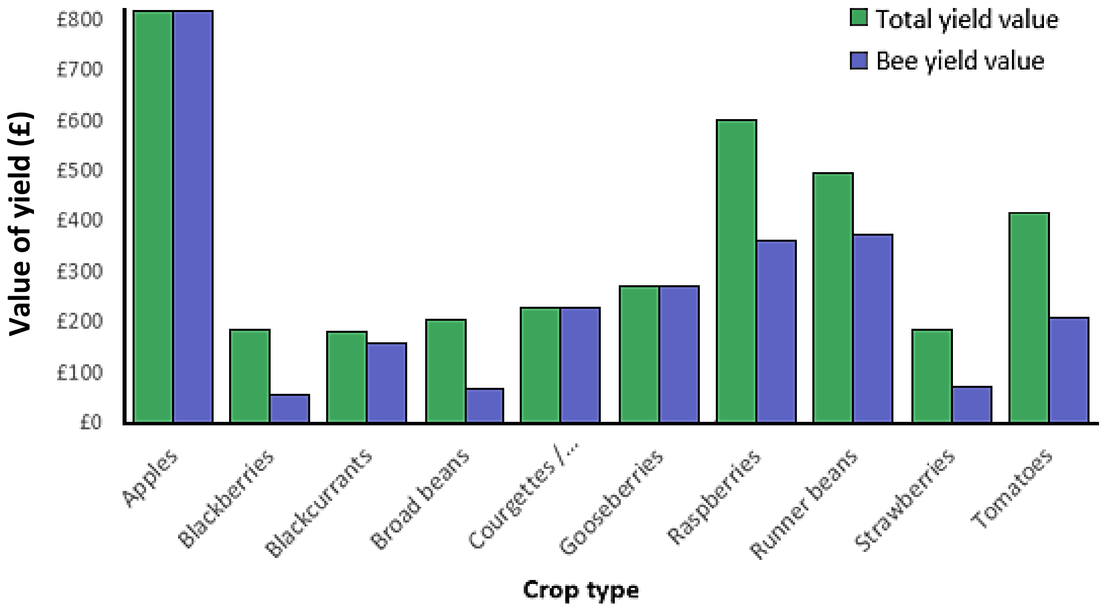


Figure 9: The top ten most valuable crop totals recorded from the 'Shopping in the garden' project 2015. Both the total value of that crop yield is shown (green), and the 'bee yield' value (blue), which is the proportion of that total yield that is directly attributable to insect action (based on the literature knowledge of that species' pollination requirements.

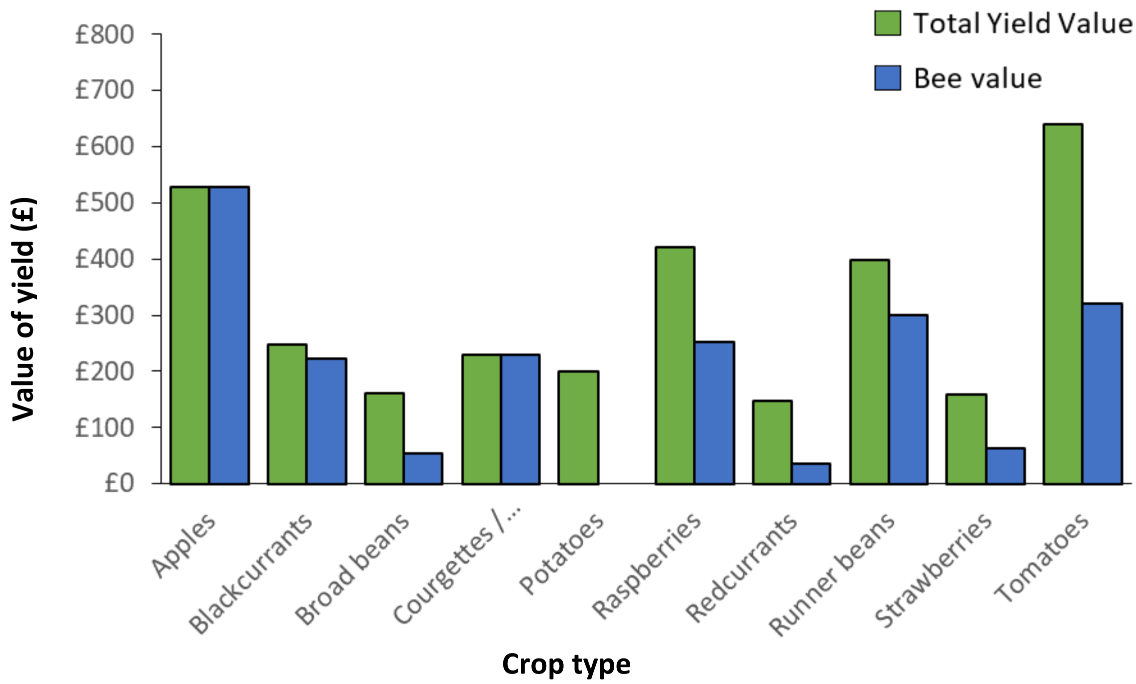


Figure 10: The top ten most valuable crop totals recorded from the 'How much does your garden grown' project 2016. Both the total value of that crop yield is shown (green), and 'bee yield' value (blue), which is the proportion of that total yield that is directly attributa insect action (based on the literature knowledge of that species' pollination requirements

Table 28: The most-grown crops across all four studies, showing ranking and the percentage of participants growing each one. Yellow label = no need for insect pollination; Green = insects needed.
(* NFB=Need for bees **GT= growing towns). Grey box = not specifically asked for in this study, or category was different. LIR = lower down in the ranking.

Crop	Position in project…				Percentage growing in project…			
	Garden Shop	Yields	NFB*	GT**	Garden Shop	Yields	NFB*	GT**
Tomatoes	1	1	1	1	**75%**	**63%**	**67%**	**51%**
Strawberries	4	2	11	9	**50%**	**58%**	**56%**	29%
Runner beans	2	3	4	5	**67%**	**53%**	**53%**	33%
Broad beans	3	4	6	LIR	**58%**	**53%**	45%	27%
French beans	4	5	5	5	**58%**	**53%**	**53%**	21%
Apples	4	6	4	2	**50%**	47%	**53%**	**60%**
Raspberries	3	7	10	4	**58%**	42%	45%	43%
Courgettes etc	6	8	7	8	33%	42%	48%	30%
Blackcurrants	4	9	LIR	6	**50%**	42%	35%	32%
Cucumbers	3	10	LIR	LIR	**58%**	42%	31%	18%
Gooseberries	5	11	LIR	LIR	42%	42%	37%	29%
Potatoes	3		6	3	**58%**		49%	
Salad leaves	6		2	LIR	33%		47%	
Peas (any edible type)	6		8	6	33%		**59%**	

Although there is some variation in the absolute percentages between studies for a given plant, the overall pattern of crop planting choices is similar (Table 28). Tomatoes were consistently the top crop, and with a 30-50% pollination requirement as well as a high purchase value (£7/kg for on-the-vine) score highly on 'bee value' as well. Soft fruit, beans, apples and courgettes rank highly in all studies, and are also crops that have a high pollination requirement. Potatoes, French beans and salad leaves are the most common non-pollinated crops, with salad leaves being a high value crop at £10/kg, but the other two only £3/kg.

Taking part – feedback

Feedback from participants in both years was positive, indicating that taking part in the project was enjoyable to the volunteers, who found both the total value and the bee value proportions interesting. Some form of on-going comparison, so that participants could get some idea of 'how well they were doing' compared to other users of the calculator, was also indicated as desirable.

The 2016 improved calculator was preferred to the original, because more crops were included, and because the value could be seen to be increasing as data was inputted. However, remembering to fill in a spreadsheet was still noted as a problem for some volunteers, who did not have a computer to hand when harvesting / weighing, and having less frequent communication seemed to be at a detriment to the project – with half of the 2016 returns coming in late, after individual reminders were sent out.

2.4.6. Discussion

Some degree of insect-mediated pollination was required for the production of over 50% of the recorded harvests in both 2015 and 2016. Many of the most valuable crops (both by total harvested value, and by the base retail value e.g. per 100g) were those that had some need for pollination, highlighting the importance of bees and other insect to the success of domestic food production. Similar crops, with some region-specific variations, were also shown in summaries of American studies by Lanellotto in 2014 where: *"Tomatoes ranked among the top 5 most profitable garden crops. Others included: Leafy veg, peas, strawberries, squash, and eggplant."*

This represents a huge proportion of home-grown food, and its value, which could be under threat if losses of pollinators continue (Potts *et al.,* 2010), and potentially provides a good engagement point with the general public. Without sufficient service provision by insects, gardeners would need to increase the hand-pollination of crops (where this is possible), or alter planting choices, perhaps to less valuable or desirable plants (Partap & Ya, 2012; Motzke *et al.,* 2015)

The average garden produce values for each year (£239.77 in 2015; £357.60 in 2016) are similar to the estimates reached by both the Edible Garden survey (2016) of £268/year and DT Brown Seeds (2009) of £262.54/year. The crops involved were similar in all studies, suggesting that even with this small sample size they are representative of UK gardens and not from a specialised subset of amateur growers.

Both calculator projects had quite small numbers of participants, likely because the target population for recruitment was drawn from the existing *Bees 'n Beans* mailing lists. While this group were already involved with the PhD projects, and positively disposed towards taking part, the calculators were very different projects than the *Bees 'n Beans*; requiring that people were already growing crops, and were willing to record extra details about any that were being grown. As pilot projects to test the method, these small numbers were acceptable; although any further use of the calculators should target larger groups, ideally through partnership with gardening organisations such as the Royal Horticultural Society.

The reduced contact with volunteers used in 2016 resulted in less returns, suggesting that a wider-run calculator project would need to have lot of communication from the beginning. Even quite dedicated volunteers needed to be reminded to return the spreadsheet, rather than them remembering to do it, and following up on these individually meant that little time was saved overall by the intended change to contact frequency. However, feedback in both years indicated that participants enjoyed taking part in the project. The value calculations were appreciated, and in many cases found to be surprising, even at quite low overall totals. Feedback from one volunteer indicated that the bee value (£355 of an £807 total) could be considered to have effectively paid for the cost of their allotment rent (£225 annually). Two others had used the information as part of educational activity with the children in the family.

Several participants indicated that they did not previously have an idea of how much their yield could be valued at, suggesting that subjective measures of value (acquired by participants personally estimating their savings) are likely to be inaccurate. Once valued, the proportion of that total that was attributable to insects was reported as very interesting to volunteers, producing further discussions of the benefits of wildlife gardening and support for pollinators in subsequent communications. Therefore, as an outreach tool, this level and type of information is potentially very valuable for giving interested members of the public an improved mechanism for conceptualising how 'pollination services' relate to their own actions, hobbies and success in growing food (Lowenstein *et al.,* 2015).

Studies that focus on what is grown domestically, and the value of that crop, seem to be relatively frequently done by private groups or as part of PR for specific events (such as the Edible Garden Show survey, or the Which? phone poll), with widely-distributed press releases at the time but no long-term data recorded. This would be useful data to collect on a regional and national scale, as it would allow for more targeted application of incentives in areas of low-growing; in addition, comparing different areas in terms of the pollination success in a year should allow for modelling of service need and provision. For landscape-scale planning of urban green space usage (Goddard *et al.,* 2010), having models that can indicate if there may have been an unusually low level of pollination (represented by lower crop success) could be used to assess the success of – or requirement for – local actions (this style of approach to pollination service monitoring forms the basis for the *Bees 'n Beans* protocol, discussed in Chapter 3). Any models would have to include other data sets, such as weather patterns, to reduce the risk of false attribution of pollination deficits, but this should be possible using current GIS technology (Medcalf *et al.,* 2014).

Presentation of the calculator solely via the current web site is not optimal for securing future volunteer engagement, and it is likely that several different angles of access would be useful. A dedicated website, similar to those for other 'big garden' studies such as Big Garden Birdwatch (https://ww2.rspb.org.uk/get-involved/activities/birdwatch), would provide a central focus of any larger-scale project based on this method. Given that the demographics of gardening are broad, in terms of both age and income classes (van den Berg *et al.,* 2010; Church *et al.,* 2015; Shiue, 2016), several methods of collecting and returning data to a central source would be required.

Printable recording sheets with an eye-catching design and plenty of space for notes would allow volunteers to keep track of their harvests on paper easily (and post it in, if they preferred). Clear branding would reduce the risk of note paper being thrown away by accident. With further investment, a bespoke web interface that allowed for the calculator to be accessible online and participants' totals updated sequentially would reduce the problems of waiting for several months to get any data return, and more frequent interaction with a web base would encourage participants to remember to return their information. It would also allow for display of ongoing total values for that year, split down by region, and perhaps a list of the current most popular / valuable crops could act as additional incentive to update frequently, as well as giving volunteers an idea of how 'well' they were doing.

Any online platform should also be able to emphasise the importance of pollinators to cropping success. Partnership with pre-existing charities / NGOs to provide identification, natural history information and wildlife gardening advice (Ryall & Hatherell, 2003) – feeding any ad hoc records back into databases via systems such as iSpot (http://www.ispotnature.org/communities/uk-and-ireland) or iRecord (http://www.brc.ac.uk/irecord) – offers potential for capturing more data, as well as training people who are already outside and interacting with the natural environment to improve their survey skills (Roy *et al.,* 2012a; West *et al.,* 2015; Roy *et al.,* 2016). These approaches also have potential value for schools and gardening organisations, providing a curated and reliable basis for the development of ecologically sensitive gardening practises, and greater understanding of the natural processes underway even in urban centres.

Appendix A: *Need for Bees* (2015) questions.

The questions used in the 2015 project *Need for Bees*, in the order presented in the online questionnaire.

1. Surname and postcode (so we can compare different areas, and remove duplicates. None of this will be shared).	
Postcode	
Surname	
2. What type of growing site do you have access to?	
No access to own growing site	Allotment
Individual garden - mostly lawn	Roof garden only
Individual garden - mostly hard surface (e.g. decking / patio / courtyard / yard)	Balcony only
Individual garden - mostly vegetable / flower beds	Window box or ledge only
Communal garden	Other (please specify)
3. Which way does your site face (i.e. its aspect)?	
North	South West
North East	East
North West	West
South	Not sure
South East	Not applicable
4. Approximate size of your site:	
Length in metres	(or) Length in yards
Width in metres	(or) Width in yards
5. On your site, do you use any of the following:	
Cloches (or garden fleece)	Fruit or vegetable cages
Coldframe	Polytunnel (walk-in)
Composting bins	Shed
Greenhouse (heated)	Water storage containers (e.g. water butts)
Greenhouse (not heated)	None of these
6. Are there any fruit trees on your site? If so, what sort are they?	
There are no fruit trees	Damson
Apple	Cherry
Crab apple	Elder
Pear	Peach / apricots
Plum	Other (please list below). If more than one 'other', please list all, separated by commas

7. Are there any fruit bushes on your site? If so, what sort are they?	
There are no fruit bushes	Strawberries
Blackberries	Loganberries / Tayberries
Blueberries	Blackcurrants
Gooseberries	Redcurrants
Raspberries	Other (please list below). If more than one 'other', please list all, separated by commas
8. Are there any nut trees on your site? If so, what sort are they?	
There are no nut trees	Hazel
Almonds	Walnuts
Chestnut (edible)	Other (please list below). If more than one 'other', please list all, separated by commas
9. Can fruits or nuts be found growing in your local area (within easy walking distance), either wild or in communal sites. E.g. blackberries, elderberries, other wild fruits, chestnuts etc.	
Yes	
No	
Don't know	
10. Do you collect any of the wild fruits or nuts that grow in your local area (within easy walking distance)?	
No	Elderberries
Apples	Hazelnuts
Bilberries	Rosehips
Blackberries	Sloes
Chestnuts (edible)	Other (please list below). If more than one 'other', please list all, separated by commas
11. How important do you find being able to collect wild fruit / nuts from the local area (within easy walking distance), even if you yourself do not currently do so?	
Not important	Fairly / quite important
Nice, but not very important	Essential
12. What herbs do you grow (outside)?	
None	Oregano
Basil	Parsley
Chives	Rosemary
Coriander	Sage
Marjoram	Thyme
Mint	Other (please list below). If more than one 'other', please list all, separated by commas

13. What vegetables did you grow in 2014, or intend to grow in 2015?		
None	Leeks	Rhubarb
Beetroot	Lettuce / salad leaves	Runner or French beans
Brassicas (cabbage, broccoli, etc)	Onions	Squashes
Broad beans	Parsnips	Strawberries
Carrots	Peas (any edible type)	Sweetcorn
Courgettes / marrows	Peppers / chillis	Tomatoes
Cucumbers	Potatoes	If other, please list, separated by commas

14. How important is it to you, to be able to grow your own food?	
Not important	Fairly / quite important
Nice, but not very important	Essential

15. What benefits do you feel that you get from growing your own food?	
Not applicable because I do not grow food plants	Gardening is an enjoyable hobby
The taste is better than bought produce	Gardening is an exercise
Satisfaction from growing your own food	Being more 'sustainable' / reducing my 'carbon footprint'
Knowing how it has been grown - what fertilisers or pesticides (etc) have been used	Social benefit of belonging to an allotment or gardening group
Would be unable to buy the produce that I grow (type or variety)	Other (please specify):
Saving money on produce	

16. Do you grow flowers ? Is this mostly for the visual display - or specifically to support pollinators?
No - I do not plant additional flowers (if so - please skip to Question 19)
Yes - mainly for visual display
Yes - mainly to support pollinators for my crop plants
Yes - deliberately for visual display, AND to support my crops

17. If you plant flowers, where are they grown in relation to your fruits and vegetables?
I only grow flowers; there are no herbs, fruit or vegetables
Mixed in with fruits and vegetables
Close by, but in separate beds or containers
In flower beds or containers in other part of the site, away from the fruit and vegetables

18. If you DO grow flowers, what do you plant?
Seeds or seed mixes
Bulbs
Annual plants
Perennial plants

19. Do you hand-pollinate any of your crops?		
No		
Yes, as the main source of pollination for that plant		
Yes, for back-up of the main pollination		
Yes, for deliberate crossing to make hybrid seeds		
Please list any plants that you hand-pollinate, separated by commas		
20. Do you take any other actions on your site to encourage or support pollinator populations?		
No	Cut lawns less often	
Providing nesting spaces for bumblebees (e.g. nesting boxes or holes)	Reducing or stopping pesticide use	
Providing 'bee hotels' (either purchased or home-made)	Using 'green manure'	
Providing logs or wood piles	Other actions	
Providing bare soil		
21. What methods of pest / weed control do you use?		
No pest control used	Physical barriers (e.g. copper tape, insect netting, cardboard)	Slug pellets
Insecticides (commercial)	Physical removal (e.g. squashing, or pulling up)	Slug traps
Insecticides (homemade)	Planting pest-repellant plants (e.g. marigolds)	Weedkillers (commercial)
Soap sprays	Planting to encourage natural predators	Weedkillers (homemade)
Moving of existing predators (e.g. ladybirds) around the garden	Purchased natural predators (e.g. nematodes)	Other (please specify)
22. How would you describe your experience as a gardener?		
Professional gardener		
Experienced amateur		
Amateur		
Just starting		
23. How do you get your information on growing plants, in general?		
Television programmes	Family members or friends	
Internet / websites	Belonging to a gardening society	
Radio programmes	Employ a gardening / horticultural professional	
Magazines	Other (please specify)	
Newspapers		
24. Last one! How did you find out about this survey?		
Twitter	Seen in a magazine or newspaper	
Email	Delivered to my house / by post	
Internet search	Direct approach from research group	
Newsletter	Other?	
Recommended by a friend or colleague		

Appendix B: The Garden Shop calculator

B.1. Value table for Garden Shop calculator

Table 1 below gives the values used in the *Garden Shop calculator,* discussed in Section 2.4. Values per 100g are primarily based on the value of that produce at Waitrose supermarkets in 2015; where something was not sold by Waitrose, either another supermarket equivalent was used, or the value from farmers' markets in 2015 (personal observation); or the value for the closest type of produce that *had* a value was used. Pollination requirement was primarily based on four review papers: Free & Williams, 1977; Corbet *et al.,* 1991; Carreck & Williams, 1998; Klein *et al.,* 2007. Where a plant was not included in any of those papers, other sources of pollination study were used, or the best estimate based on known biology made.

Values for non-insect pollinated crops are included in Table 2. Although insects made no contribution to the crop of these plants, they were included in the calculator order to a) not confuse volunteers, particularly as some do flower but will self anyway; and to b) produce a more accurate total garden value.

The crops included were selected based the produce reported in 2015 by participants in the calculator project, who were asked to list what they were growing; with additional categories added based on the returns from the two questionnaire studies ('Growing towns' and 'the Need for Bees').

The tables are followed by a copy of the instructions provided alongside the *Calculator* spreadsheet.

Table 1: Values used in *Garden Shop Calculator.* Reliance on insect-mediated pollination – proportion of yield attributable to insect action.

Crop	Value		Pollinated Crops					
	Price per 100g	Source	**Proportion of yield due to insect pollination**	*In:* Corbet *et al* 1992 (based on Robinson *et al* 1989)	*In:* Free & Williams 1977	*In:* Carrek & Williams 1998	Klein *et al* 2007	Other source / reason?
Almonds *Prunus dulcis*	£1.99	Waitrose (2015)	1	1	Essential			
Apples *Malus domestica /pumila*	£0.33	Waitrose (2015)	1	1	Essential	High	40 – 90%	
Courgettes / marrows *Cucurbita pepo*	£0.47	Waitrose (2015)	1					Same pollination value as other squash.
Crab apples *Malus sylvestris*	£0.50	Farmer's market (2015)	1					
Cranberries *Vaccinium oxycoccos / macrocarpa*	£0.83	Waitrose (2015)	1					

Holly berries *Ilex aquifolium* (Used for decorations)			1						Dioecious plant.
Kiwi *Actinidia deliciosa,*	£0.50	Waitrose (2015)	1					Essential	Gonzalez *et al.,* 1998
Quinces *Cydonia oblonga*	£0.50	Farmer's market (2015)	1						Self-sterile. (Benedek *et al.,* 2000)
Rowan *Sorbus aucuparia*	£1.20		1					Essential	
Squash / pumpkins *Cucurbita maxima / pepo moschata*	£0.20	Waitrose (2015)	1					90%	
Blackcurrants *Ribes nigrum*	£1.67	Waitrose (2015)	0.9			Essential		10 – 40%	
Cherry *Prunus avium*	£0.91	Waitrose (2015)	0.9		0.80	Essential	0.9	40 – 90%	

Cucamelon *Melothria scabra*	£0.79	Estimate (gherkins)	0.9					Gherkins are another small cucurbit, used in salads and pickling.
Cucumbers *Cucumis sativus*	£0.19	Waitrose (2015)	0.9	0.90	Essential		40 – 90%	
Hawthorn *Crataegus monogyna*	£2.35		0.9					Mostly self-incompatible (Jacobs *et al.,* 2009)
Snowberry *Symphoricarpos albus*	Not available for purchase		0.8					Low self-fertility (showed ~ 15% from self-pollen; 84% from cross-pollination; no formation of fruit without seeds) (Pelton, 1953)
Apricots *Symphoricarpos albus*	£0.57	Waitrose (2015)	0.75	0.70	Great		40 – 90%	
Runner beans *Phaseolus coccineus*	£0.62	Waitrose (2015)	0.75		Essential	Medium		
Bilberries *Vaccinium myrtillus*	£0.89	Estimate	0.6				Great	Value based on bilberries in syrup (http://shopintideswell.co.uk/shop/sundries/krakus-bilberries-in-syrup)

Japanese wineberries *Rubus phoenicolasius*		Estimate	0.6						Used same value as raspberries.
Nectarine *Prunus persica*	£1.25	Waitrose (2015)	0.6					Great	Used same values as peach.
Peach *Prunus persica*	£0.43	Waitrose (2015)	0.6	0.60	Great		40 – 90%		
Raspberries *Prunus persica*	£1.40	Waitrose (2015)	0.6		Moderate	40 – 90%			
Rosehips *Rosa canina*	£0.92	Estimate	0.6					Great	Based on 2015 www.buywholefoodsonline.co.uk
Bullace *Prunus domestica subsp. Insititia*	£0.40	Estimate	0.5						Used same value as plum.
Damsons *Prunus domestica subsp. Insititia*	£0.40	Estimate	0.5						Used same value as plum.
Greengage *Prunus domestica subsp. Italic*	£0.60	Estimate	0.5					Great	Used same value as plum.

Medlar *Mespilus germanica*	£0.50	Estimate	0.5				(unknown)	Used same value as for quince (specialised fruit, and used mainly for jam).
Pears *Pyrus communis*	£0.20	Waitrose (2015)	0.5	0.50	Essential		40 – 90%	
Plum *Prunus domestica*	£0.40	Waitrose (2015)	0.5			Medium (0.5)	40 – 90%	Many self-fertile (Benedek *et al.,* 2000)
Sloe *Prunus spinosa*	£1.10	Waitrose (Wallop, 2007)	0.5				Great	Used same value as plum; both stone 'hedge fruit'.
Tomatoes *Solanum lycopersicum*	£0.70	Waitrose (2015)	0.5		Moderate	Medium (0.5)	0 - 10%	Also: 0.5 by (Greenleaf & Kremen, 2006a); 0.7 (Morandin *et al.,* 2001). Varied opinions in the literature.
Jostaberries *Ribes nidigrolaria*	£1.67	Estimate	0.4					Hybrid between gooseberries and blackberry, so mid-way between those values.
Strawberries *Fragaria* x *ananassa*	£0.80	Waitrose (2015)	0.4	0.40			10 – 40%	
Worcesterberry *Ribes divaricatum*	£1.02	Estimate	0.4					Hybrid between gooseberry and blackberry: so values used mid-way between those.

Broad Beans *Vicia faba*	£0.50	Waitrose (2015)	0.33		Moderate	Low (0.1)	10 – 40%	
Blackberries *Rubus fruticosus*	£1.47	Waitrose (2015)	0.3			Low (0.1)		0.3 (Cane 2005)
Boysenberry *Rubus boysenberry*	£1.47	Estimate	0.3					Used the same as blackberries (hybrid; self-fertile but yield improved with pollination)
Pyracantha - *Pyracantha coccinea* Used for decoration	can't buy these		0.3					Royal Horticultural Society 2014
Aubergine *Pyracantha coccinea*	£0.32	Waitrose (2015)	0.25				Modest	
Blueberries *Vaccinium corymbosum, V. angustifolium*	*£1.17*	*Waitrose (2015)*	*0.25*					
Cape Gooseberry *Physalis peruviana*	£1.00	Waitrose (2015)	0.25					30% increase in fruit size with insect pollination (Chautá-Mellizo *et al.,* 2012)

Chestnut (edible) *Castanea sativa*	£1.25	Waitrose (2015)	0.25				Modest	Wind and insects; probably mostly wind (Clapper, 1954)
Elder *Sambucus nigra*	£3.56	Estimate	0.25				Modest	Partly self-fertile, some wind, some insects. (Way, 1981) Note: price based on http://www.realfoods.co.uk/product/1024/organic-elderberries-dried
Redcurrants *Ribes rubrum*	£1.25	Waitrose (2015)	0.25		Moderate	Low	10 – 40%	
Strawberry tree *Arbutus unedo*	can't buy these		0.25			Modest		
White currants *Ribes rubrum*	£1.67	Farmer's market (2015)	0.25		Moderate	Low		
Lemon *Citrus x limon*	£0.65	Waitrose (2015)	0.2	0.20			>0 – 10%	
Limes *Citrus × aurantiifolia*	£0.35	Waitrose (2015)	0.2					
Borlotti beans *Phaseolus vulgaris*	£0.24	Waitrose (2015)	0.1					

Chillis *Capsicum annuum*	£1.34	Waitrose (2015)	0.1		Moderate	Low (0.1)			
Gooseberries *Ribes uva-crispa*	£0.57	Waitrose (2015)	0.1		Moderate	Low			
Loganberries / Tayberries *Rubus × loganobaccus/ Rubus fruticosus x idaeus*	£1.47	Farmer's market / estimate	0.1			Low			
Orange *Citrus reticulate*	£0.67	Waitrose (2015)	0.1				Little		
Peppers *Capsicum annuum*	£0.75	Waitrose (2015)	0.1		Moderate	Low (0.1)			

Table 2: Values used in *Garden Shop Calculator*, for non-insect pollinated crops.

Crop	**Price per 100g**	Source	Other source / reason?
Amaranth *Amaranthus spp*	£0.80	Waitrose (2015)	Not a pollinated crop
Globe artichokes *Cynara scolymus*	£0.66	Waitrose (2015)	Not a pollinated crop
Asparagus *Asparagus officinalis*	£1.99	Waitrose (2015)	Not a pollinated crop
Beech nuts *Fagus sylvatica*	Can't buy these		Wind pollinated
Beetroot *Beta vulgaris*	£0.43	Waitrose (2015)	Root crop
Broccoli *Brassica oleracea var. italica*	£0.14	Waitrose (2015)	Not a pollinated crop
Cabbage *Brassica oleracea var. capitata*	£0.63	Waitrose (2015)	Not a pollinated crop
Carrots *Daucus carota subsp. sativus*	£0.15	Waitrose (2015)	Root crop
Celeriac *Apium graveolens var. rapaceum*	£0.16	Waitrose (2015)	Root crop
Celery *Apium graveolens*	£0.18	Waitrose (2015)	Not a pollinated crop
Chard *Beta vulgaris subsp. vulgaris*	£0.75	Waitrose (2015)	Not a pollinated crop
Chicory *Cichorium intybus*	£0.60	Waitrose (2015)	Not a pollinated crop
Chives *Allium schoenoprasum*	£3.60	Waitrose (2015)	Not a pollinated crop

Coriander *Coriandrum sativum*	£3.39	Waitrose (2015)	Not a pollinated crop
Daikon / Mooli *Raphanus sativus var. Longipinnatus*	£0.13	Sainsburys (2015)	Root crop
Fennel *Foeniculum vulgare*	£1.25	Waitrose (2015)	Root crop
Figs *Ficus carica*	£1.00	Waitrose (2015)	Selfing. Fig wasps in tropical varieties.
French beans *Phaseolus vulgaris*	£0.30	Waitrose (2015)	Selfs
Garlic *Allium sativum*	£0.25	Waitrose (2015)	Root crop
Grapes *Vitis vinifera*	£0.50	Waitrose (2015)	Selfs
Hazelnuts *Corylus avellana*	£1.99	Waitrose (2015)	Wind pollinated
Jerusalem artichokes *Helianthus tuberosus*	£0.35	Waitrose (2015)	Root crop
Kale *Brassica oleracea var. sabellica*	0.004	Waitrose (2015)	Not a pollinated crop
Kohlrabi *Brassica oleracea*	0.01	Waitrose (2015)	Not a pollinated crop
Leeks *Brassica oleracea*	£0.50	Waitrose (2015)	Not a pollinated crop
Lentils *Lens culinaris*	£0.59	Waitrose (2015)	Selfs
Lettuce / salad leaves e.g rocket *Lactuca sativa / e.g. Eruca sativa*	£1.00	Waitrose (2015)	Not a pollinated crop

Mullberry *Morus nigra*	£2.47	Farmer's market (2015)	Wind pollinated
Mushrooms *Various*	0.0033 33	Waitrose (2015)	Not a pollinated crop
New potatoes *Solanum tuberosum*	£0.30	Waitrose (2015)	Root crop
Onions *Allium cepa*	£0.15	Waitrose (2015)	Not a pollinated crop
Other brassicas *Brassica*	£0.47	Waitrose (2015)	Not a pollinated crop
Pak choi *Brassica rapa subsp. chinensis*	£0.68	Waitrose (2015)	Not a pollinated crop
Parsnips *Pastinaca sativa*	£0.35	Waitrose (2015)	Not a pollinated crop
Peas (any edible type) *Pisum sativum*	£0.80	Waitrose (2015)	Selfs
Quinoa *Chenopodium quinoa*	£0.66	Waitrose (2015)	Selfs
Radish *Raphanus raphanistrum subsp. sativus*	£0.30	Waitrose (2015)	Root crop
Rhubarb *Rheum rhabarbarum*	£0.75	Waitrose (2015)	Not a pollinated crop
Salsify *Tragopogon porrifolius*	£1.45	Farmer's market (2015)	Not a pollinated crop
Sprouts *Brassica oleracea var. gemmifera*	£0.12	Waitrose (2015)	Not a pollinated crop
Swede *Brassica napobrassica*	£0.16	Waitrose (2015)	Root crop

Sweetcorn *Zea mays L. var. rugosa*	£2.00	Waitrose (2015)	Wind pollinated
Turnip *Brassica rapa subsp. rapa*	£0.29	Waitrose (2015)	Root crop
Walnuts *Juglans regia*	£1.99	Waitrose (2015)	Wind pollinated

B.2. Garden Shop calculator – instructions (2016)

How much does your garden grow?

How to use:

• Fill in only the **GREEN** boxes on the spreadsheet.

• Enter either the weight of your harvest, in grams or in ounces; or the number of items picked (such as, 5 apples).

• These categories are quite broad and do not take variety in account; the estimated values are based on an average of many different varieties of crop types. We might make this more detailed in future, but for now please just put all of the same type of crop together

Crop	Weight of harvest in g	(or) Weight of harvest in oz	(or) # items	Individual crop value	Individual crop bee value
Almonds					
Amaranth					
Apples					
Apricots					

1 - **Total harvest.** Keep a record of what you pick over the harvest season (in a notebook or similar). Add up the final total for each crop and add that total to the spreadsheet when you finish picking from that type of plant. This is the easiest option if you're not very familiar with spreadsheets!

2 - **Ongoing.** Add in numbers as you go along. For example, using apples:

If you have picked 500g of apples one day, type =500 in the "weight in grams" box, on the line for apples. If you then pick 450g the next time - double click the box that currently has 500 in then type 950 into the box (i.e. 500+450). Excel will update with the new number.

Repeat the above process each time you have more numbers to add. Please remember to save the spreadsheet after each successful addition.

Step 1

Crop	Weight of harvest in g
Almonds	
Amaranth	
Apples	=500
Apricots	
Artichokes	

For the first pick of 500g, type =500 in the box.
(The = is so Excel knows this is going to be a sum.)

Crop	Weight of harvest in g
Almonds	
Amaranth	
Apples	500
Apricots	
Artichokes	

Press enter. The box will now just display 500, as that is the only number in there.
If you double-click on the cell, it will show you the =500 again.

Step 2

Crop	Weight of harvest in g
Almonds	
Amaranth	
Apples	=500+450
Apricots	
Artichokes	

For the second pick of 450g, double-click in front of the 500 until you can edit.
Type +450 after the 500 to add it to the sum.

Crop	Weight of harvest in g
Almonds	
Amaranth	
Apples	950
Apricots	
Artichokes	

Excel will add up the numbers and display the total.

Ongoing

Crop	Weight of harvest in g
Almonds	
Amaranth	
Apples	=500+450+300+400
Apricots	
Artichokes	

Continue to do this for each harvest you do, and Excel will add up the totals for you.

Chapter 3: Assessment of pollination service provision in UK urban greenspace.

3.1. Monitoring urban pollination services – a role for citizen science.

Human societies receive goods and benefits from the natural environment, both directly, in the case of physical goods such as harvested plants or animals, or indirectly from processes such as water cycling. Described as 'ecosystem services', these benefits are hugely valuable and many may be irreplaceable by practical artificial means (Ehrlich & Mooney, 1983; Costanza *et al.,* 1997; Haines-Young & Potschin, 2010; Bateman *et al.,* 2013). Yet the impact of anthropogenic activities on the world is increasing, putting these vital natural processes at risk (Loreau *et al.,* 2001; Vitousek *et al.,* 2008). Well-informed assessment of ecosystem services is thus required to understand our reliance – and impacts – on these provisions (Carpenter *et al.,* 2009).

Animal-mediated pollination ('pollination' hereafter refers to this type, rather than passive pollination or wind action) is one such service, critically important for the production of many crops and the maintenance of robust natural ecosystems (Dicks *et al.,* 2013; Vanbergen *et al.,* 2014). A wide variety of taxa play a role in pollination globally (Ollerton & Winfree, 2011; Abrol, 2011), but by far the majority is undertaken by insects – especially bees and hoverflies (Kremen *et al.,* 2007; Klein *et al.,* 2007; Jauker & Wolters, 2008) – and diversity within the pool of pollinator species is thought to be particularly important for supporting natural habitats (Steffan-Dewenter *et al.,* 2005; Blitzer *et al.,* 2016).

Any realistic assessment of the value of ecosystem services relies on gathering accurate information about the *need* for those services, along with a strong understanding of the processes involved in their delivery (Costanza *et al.,* 1997; Haines-Young & Potschin, 2010; Bateman *et al.,* 2013), and pollination is no exception (Winfree *et al.,* 2011). Current valuation methods for pollination services – based on existing scientific understanding of plant-insect interactions – are not without debate

(Ghazoul, 2005; Steffan-Dewenter *et al.,* 2005; Klein *et al.,* 2007), but even widely varying estimates illustrate the sheer scale of the question. Recent valuations of global pollination range between $112 to $200 billion annually (Costanza *et al.,* 1997; Kremen *et al.,* 2007), and agricultural pollination alone is estimated as worth €153 billion a year (Gallai *et al.,* 2009). In Europe, 84% of crop species are dependent on pollination for improving yield and quality to some extent (Klein *et al.,* 2007), and the recent UK National Ecosystem Assessment (NEA) valued the contribution to UK crop yields at £430 million in 2007, representing 8% of the market at the time (Smith *et al.,* 2011).

In the UK to date, there is no standard method of valuing pollination, and no long-term monitoring programmes in place to assess it – although this is acknowledged as a priority area for development (Dicks *et al.,* 2013). The National Pollinator Monitoring Strategy for England (DEFRA, 2014) sets out a 10-year plan for supporting pollination services, emphasising the need to develop an appropriate monitoring framework using 'citizen scientists' i.e. volunteers, participating in data collection under instructions from professional scientists. Many other existing systematic wildlife monitoring schemes already use a similar approach (Dickinson *et al.,* 2010), since it allows for coverage of much larger spatial and temporal scales than would otherwise be possible due to time, cost or personnel restrictions, but to still gather reliable information (Schmeller *et al.,* 2009; Silvertown 2009; Kremen *et al.,* 2011). These large-scale observational projects provide important information for advising conservation planning (Mackechnie *et al.,* 2011; Roy *et al.,* 2012b).

One of the issues often faced in the development of citizen science based schemes is physically getting volunteers to the monitoring locations. For biodiversity monitoring, areas of high species richness are often located quite far away from human population centres, raising problems with travel time and ability, as well as access, for participants. However, this may be less of a problem for monitoring pollination services, because the *requirement* for their provision is not restricted to agricultural settings or potentially-distant semi-natural areas.

As the world's population continues to increase, so does the proportion of global land area that can be considered to be 'urbanised'. Fifty-four percent of the world's population now live in urban areas (WHO, 2014), which are particularly amenable to citizen science schemes because of the large population of potential observers, allowing participants to literally 'do it at home' (Davies *et al.,* 2011). Urban environments vary greatly in the characteristics of their green spaces, but pollination is still required for urban / peri-urban agriculture, for garden and allotment produce, and by wild plants growing in built environments. Urban crop yields are not recorded on any systematic basis, and although some studies have shown greater seed set in garden plants compared to rural ones (Cussans *et al.,* 2010; Samnegård *et al.,* 2011), it is not known if provision of urban pollination represents a limiting or adequate service.

There are a number of projects currently underway both in the UK and internationally which aim to survey the make-up of the urban pollinator community (such as the Urban Pollinators Project led by the University of Bristol, under the Insect Pollinators Initiative); or to generate trend data for pollinator populations (particularly schemes such as the Bumblebee Conservation Trust's 'Beewalks' and the Great British Bee Count) (Westphal *et al.,* 2008). In the US, the Great Sunflower Project requires participants across the country to grow a sunflower at home and record the frequency of insect visitors (Oberhauser & LeBuhn, 2012), illustrating application of citizen science observational studies at a national scale. In addition, the Urban Pollination Project currently underway at Washington University uses a similarly detailed protocol (with hand-pollinated, local-pollinated and pollinator-excluded plants) to measure the yield of tomato plants and pollination success in Seattle community gardens (Potter & LeBuhn, 2015).

However these do not assess this service directly – by examining the level of pollination occurring – but rather by extrapolating from the potential population of relevant insects present (with the exception of the Seattle study, which focuses on one city). Thus, the aims of *this* project were: to test if citizen science can be used to collect appropriate data for monitoring the level of pollination service provision present in urban green spaces; and see if such an approach reveals a current deficit in the UK.

Focusing on the three-year study '*Bees 'n Beans'*, this chapter first details the development of the initial protocol and selection of focal plants (3.2.), how this was advertised to- and applied by- volunteers, and the modifications made following participant feedback (3.3.). Exact methodological variations and results are presented by year in section 3.4., followed by analysis of results from across the project, and overall discussion (3.5.). This chapter also includes a substantial Appendix, detailing the smaller pieces of work that occurred alongside the main *Bees 'n Beans* project, representing either exploratory experiments or analyses to investigate improvements or alternatives to ongoing methods.

3.2. Developing the protocol

3.2.1. Selecting the phytometer

The protocol required participants to grow pollination-dependent plants, conduct simple manipulations and record the resulting yields, to determine if the existing pollinator community is providing an adequate or limiting service. This is a direct measure of pollination provision (Carvell *et al.,* 2016).

Since the intended distribution of this project potentially included anywhere within the UK, there may be considerable variation between sites. While Loram *et al.* (2008) showed similarity across the country in the species richness and composition of the vegetation typically found in gardens (with commercial plant availability and widespread management advice driving this effect), gardens sites will still vary in terms of underlying soil type, weather and the surrounding landscape conditions, which may affect the pollinator community available, and thus the potential for service provision in the area (Jauker *et al.,* 2009; Holzschuh *et al.,* 2010; Goulson *et al.,* 2010). The characteristics of individual sites were needed, in order to be able to compare them. Colder climatic conditions in higher latitudes also affect the time that plants can be placed outdoors *in situ*, so any experimental plant had to be robust enough to grow well across the UK.

The following criteria were drawn up at the start of the study to choose the experimental plant:

1. **Reliant on pollination.**
   A limited degree of self-pollination was acceptable, but there needed to be a *measurable* difference between pollinated and un-pollinated plants in yield / seed set, to compare differences between local pollination service at sites.
2. **Easy to grow, from seed.**
   It is impractical to send e.g. plant plugs or small plants in the post.
3. **Quick to flower / annual.**
   The plant needed to mature and flower in the same year as the seeds were sown.
4. **Compact growth habit.**
   Asking volunteers to grow experimental plants should be a manageable task. The plants should not require complex husbandry or threaten to dominate / invade their garden / green space.
5. **Attractive.**
   Plants being aesthetically pleasing, or producing an edible yield, helps the experiment to be more appealing to volunteers drawn from the general public.

Based on the above criteria, a selection of potentially-suitable plants were identified for further investigation (Table 1). However it was necessary to select one species to be used as the pilot plant, in order to test the citizen science aspect of the protocol – including the efficacy of recruitment / engagement of volunteers, and their subsequent ability to grow the plants and carry out the experiment.

Table 1: The list of plants investigated in 2014 for potential use as phytometers in citizen science pollination studies.

Broad bean	Garlic chive
Buckwheat	Poppy
Coriander	Radish
Cornflower	Sunflower
Fennel	

After literature review *Vicia faba*, commonly known as 'Broad' or 'Field' bean, was selected as the first experimental plant. This was due its pollination requirement, reliable germination, compact growth habit and popularity as an easily-maintained garden crop in the UK (Free, 1966; Kendall & Smith, 1975). The other plants identified as potential alternative phytometers were grown at the University of Sussex under laboratory and field conditions in the summer of 2014 – the results of this branch of the project is covered in Chapter 4. If additional suitable species alongside *V. faba* were identified then they would be added or substituted into the project in later years.

Broad beans are known to benefit from insect-mediated pollination, by improving both the yield of crops (Rowlands, 1960; Free & Williams, 1976) and the quality of seed obtained for planting-on (Bond & Pope, 1974, 1987; Corbet *et al.,* 1991). Cage experiments to manipulate pollinator access to *V. faba* flowers have shown that, while the plant is capable of some self-compatibility (with the amount varying by cultivar), mechanical action by insect pollinators (or by manual 'tripping' of the flowers) increases yield by about a third, because a protective cuticle across the stigma must first be ruptured to allow for pollen tube formation (Drayner, 1959; Hanna & Lawes, 1967; Kendall & Smith, 1975; Free & Williams, 1976; Stoddard & Bond, 1987). Thus, a pollination event can just be the opening and closing of a flower by an insect – potentially giving a clearer indication of the presence of appropriate pollinators than requiring pollen transfer to occur as well. Bees can be prevented from accessing flowers with a bag made from insect-proof mesh, either enclosing individual flower clusters or the entire plant, and the large flowers are easy to hand-pollinate.

Due to the deep corolla of *V. faba* flowers, pollination is usually carried out by long-tongued bumblebees, although some less-effective pollination by honeybees has been observed (Stoddard & Bond, 1987; Garratt *et al.,* 2014), and short-tongued bumblebees such as *Bombus terrestris* are known to 'rob' nectar by biting through the base of the flowers (Free, 1962; Newton & Hill, 1983). Robbing may also have some pollination value, if the interaction is enough to trip the flowers.

3.2.2. Developing the methodology

The protocol for this experiment used 'The Sutton' dwarf variety of *V. faba*, and was developed and tested on greenhouse-grown beans over winter (November 2013 – February 2014). This dwarf variety was considered suitable because the plants are small (~50cm tall), compact, and specifically bred for container growing. The aim was to ascertain if the methodology to be applied to the plants was sound, particularly the hand pollination technique.

Forty *V. faba* seeds were germinated on trays with damp paper towel placed under and above the seeds, for ease of observation and recording any failures (Figure 1).

Figure 1: Sprouting bean seeds. Mould occurred on some of the damp beans, but was easily washed off and did not generally impede growth.

Germination took approximately 48-72 hours and the seeds were then transferred to individual 1L plant pots, with two seeds per pot at 4cm depth. Compost was Levington M2 (manufactured by Everris; West Rd, Ipswich).

The plants took approximately five weeks to reach 10cm high, at which point the pots were thinned to a single plant and moved outside to harden off. Flowering began seven weeks after germination. Photographs and observations were used to develop the instruction sheet for 2014, and as the study proceeded to update the web site with pictures of then-current stages.

Insects needed to be excluded from one treatment to compare the level of self- or wind- pollination received by the plants. In accordance with typical methods for exclusion (Jacobs *et al.,* 2009; Carvell *et al.,* 2016), plants were covered with net cylinders / bags of <0.5mm ('Insect Mesh Woven Fine Netting', manufactured by Intermas Group; INTERMAS NETS S.A., Ronda Collsabadell Barcelona, España). Several types of netting were tried out and priced up, and it was decided that $1m^2$ would be enough to cover a mature plant with sufficient growing space.

To compare local pollination yields to those achieved by maximum pollination on that site, one treatment needed to include hand pollination. Several methods of hand pollinating were tried out, including pollen transfer with a paintbrush; disassembling flowers to remove pollen-bearing anthers; and 'tripping' (Stoddard & Bond, 1987). As this was done out of season, prior to recruitment to the main project, pod development was unable to continue fully. This was mostly to test how easy it was to perform these actions, to take photographs of the method, and to make sure that the hand pollination did not damage the flowers. A more thorough comparison of hand pollination methods was completed during the 2014 field season.

As the 2014 project asked volunteers to attempt identification of insects observed on their bean flowers, a simple identification sheet was also developed, to be included alongside the instructions. This was not intended to be comprehensive, as identifying bees in detail requires training (Kremen *et al.,* 2011; Roy *et al.,* 2016), but to give volunteers who might be entirely naïve a starting point. Links to more detailed online resources were also provided (http://bumblebeeconservation.org/about-bees/identification; http://www.bwars.com/category/taxonomic-hierarchy/bee).

3.3. Bees 'n Beans citizen science experiment 2014 to 2016

Figure 2: The *Bees 'n Beans* logo; this branding was used on all official project documents 2014- 16 to maintain continuity between years.

3.3.1. Methodology: Bees 'n Beans

The project advertised and run under the logo *'Beans n Bees'* (Figure 2) was completed three times (2014, 2015, and 2016) as a citizen science experiment. The core methodology using *V. faba* developed in 2014 was further modified in 2015 and 2016, based on project outcomes and volunteer feedback.

Recruitment of volunteers

In 2014 the project was advertised for the first time on social media, using the Beans 'n Bees web site (http://ljbees.org.uk), Twitter account (www.twitter.com/ljbees), and the Sussex University news website (http://www.sussex.ac.uk/broadcast/read/29334), as well as personal contacts. All volunteers were directed to the project website where a sign-up form was provided, collecting email and postal addresses.

The first 550 people who volunteered for the project (and had a UK postcode) were accepted, provided that they had some outside space and agreed to purchase some compost. 550 was selected as the target number of participants in the first year (500 + 10%) as possible and practical to make up enough field kits for in the time and budget available. In addition to the experiment undertaken by volunteers, it was also carried out on the Sussex campus to assess progression and to try to anticipate any problems that volunteers might experience. It also allowed for more photographs to be taken of a full project on-going, to keep the website updated for volunteer support.

In 2015 the same social media methods were used as 2014, with some additional recruitment avenues as a result of crossover of work with the new University of Sussex *Buzz Club* initiative (http://thebuzzclub.uk). Volunteers who had participated in 2014 (minus those who had dropped out for lack of interest) were also asked if they were willing to take part again.

As part of participant selection in 2015 the initial questions were modified, asking volunteers to provide netting / garden fleece, since in 2014 it proved time consuming to prepare and caused problems in postage by splitting envelopes. Garden / horticultural fleece is permeable to light, wind and water, but not insects, and is a common piece of gardening equipment. Volunteers were also asked to indicate if they were also willing to try growing an additional species of plant that year (see Chapter 4 for details). Volunteers who could not provide netting were not included, and priority was given to those who would be able to grow both plants.

In 2016 the same social media recruitment methods were used as in 2015. No additional species of plants were included this year, but volunteers were asked to supply their own pots (as well as fleece), and to indicate if they would be able to grow additional bean plants in existing soil beds. This aimed to further target people who already had some interest in gardening, and were thus more likely to successfully carry out the project.

Project packs and instructions for volunteers

Project kits were posted from Sussex University to participants in March of each experimental year. These kits contained 12 seeds of the dwarf variety of *V. faba* ("The Sutton"); in 2014 these were supplied by D.T. Brown Seeds (www.dtbrownseeds.co.uk); in 2015-16 the supplier was changed to Sutton Seeds (http://suttons.co.uk). From these seeds, sufficient similar-sized experimental plants needed to be grown to maturity (this was four plants in 2014, reduced to three in 2015 & 2016, when cross pollination was omitted in favour of 'tripping'; see section 2.3.3). In 2016 extra seeds (18 per kit in total) were also provided to allow for the additional plants needed for that year's project variation.

In 2014 the project provided eight 1.5L plastic fold-down PVC 'Hadopots' (http://www.hadopots.co.uk); in 2015 this was amended to ten 3L fold-down PVC 'Hadopots' per kit, as the 1.5L pots had been noted by volunteers as suffering from drying-out as a result of small soil volumes. This was checked in-house by a supplementary plant health assessment in late summer 2014, detailed in Appendix A.3., therefore in 2015 these were increased to 3L pots. Ten pots were required because of the additional phytometer plant included that year. In 2016 volunteers were requested to use their own 3L pots to ascertain if this was acceptable to participants, and to reduce kit costs.

Volunteers were asked to purchase commercially available compost as the growing medium. Soil quality and other environmental conditions were thus standardised within sites, but not between them.

Instructions and recording sheets were provided (see Chapter 7, Appendix A for an updated overall example). A web-based version of the recording form was also produced, to allow data collection to be done online via Survey Monkey (https://www.surveymonkey.co.uk). Any updates to the instructions, including video recording showing the methodology, and ongoing communication with participants were sent by email. A help-line was provided by email and telephone to cover requests for assistance, and additional advice sheets were provided electronically (e.g. on slug control).

Applying the method

Participants were required to germinate all seeds in the pack, using the provided pots and commercially-available compost, in accordance with the detailed instructions provided. After four-five weeks, and / or when the plants were roughly 10cm high, they were moved outside into a sheltered location and maintained until flowers appeared after approximately seven weeks (variable depending on location). When flower trusses appeared, the experimental plants were selected – as close to the same height and number of stems as possible – and the pollination treatments applied; these are detailed in Table 2 below, and a typical setup is shown in Figure 3.

Table 2: The pollination treatments used in the *Bees 'n Beans* protocol.

Treatment group name	**Treatment applied**
Netted	Plant covered in netting or horticultural fleece to exclude pollinators
Local Pollinated	Plant allowed to be pollinated by the local pollinators
Hand pollinated	Plant allowed to be pollinated by the local pollinators and pollination supplemented by hand pollination every two days

Figure 3: An example of a *Bees 'n Beans* experimental setup *in situ*.

The three treatments were randomly allocated using an online random number generator (http://www.random.org), or randomising by dice roll, to select which plant received which treatment; advice on how to carry out randomisation was provided in the instructions. Volunteers were advised to water the plants at least twice a week, and not to let the soil dry out.

After randomisation plants were grown on under the treatments for approximately nine weeks, with the experiment intended to end 16 weeks after sowing. However, it was noted in the instructions that this was *approximate*, since experiments in the south of England would finish much faster than those in Scotland.

In 2014, the hand pollination method was more complex, because at the time it was not certain if cross-pollination was important for seed set in this variety of *V. faba*. Participants were required to remove pollen-bearing anthers from their 'spare' fourth plant, open the flower on the hand pollination plant and rub the anthers onto the exposed stigma. Both written instructions and video demonstration for this method were provided (video hosted on Youtube: https://youtu.be/OS-OMzlLD14).

Approximately ten weeks after flowering started volunteers counted and recorded the number and weight of the resulting pods, plus the number and weight of bean seeds from each treatment. Because of differences in access to sites, and participants needing to be away from home during the experiment, there was some variation in timings in individual households. Electronic kitchen scales, correct to the nearest gram, were predominantly used to weigh the beans, although this varied slightly depending on what equipment volunteers had access to.

In addition to the weight and number of bean yields, participants were asked to record information about the environmental characteristics of the individual sites involved (the recording sheet categories are listed in Table 3). In 2014, ARC GIS was used to extract the 'private garden' polygons from an OS Mastermap Topographic layer, in 500-m circles centred around each site address (or postcode centre, if the address could not be geocoded). The area of the OS Mastermap category 'private gardens' within each surrounding 500-m circle was included in the analysis, to examine if 'urban' areas with a different proportion of managed garden spaces showed differences in the pollination provision within those sites. This was not continued in 2015-16.

Table 3: Site characteristics recorded by *Bees 'n Beans* participants, so these can be used as factors in the GLMs for *V. faba* yields.

Factor/covariate	**Measurement**
Treatment category	Local pollinated / netted / hand-pollinated
Size of garden / allotment	In m^2
Aspect	Main direction garden is facing
Latitude	Latitude of site postcode
Location type	Garden: Individual Garden: Communal Allotment Other
Area of surrounding gardens	Area of gardens in the surrounding 500m
Were extra beans grown?	*Were additional broad beans grown on site?* Yes; no flowering overlap Yes; flowering overlap No
Flowering vs. Harvest	Days between first flowering time, and date of harvest

Volunteers were asked to take note of any insects seen on the flowers. In 2014 this was to be done for a standardised time of 15min once a week, but this was not successful, with few returns and considerable volunteer confusion. In subsequent years this observation was changed to record casual sightings. Similarly, the 2014 project asked participants to estimate what proportion of flowers had suffered from robbing, but this was also subsequently replaced with a 'yes or no' observation of robbing, as it proved too difficult or unclear to record. Between 2015 and 2016 site characteristics recordings remained the same.

In all years, volunteers were asked to inform the researcher if their experiment failed, and to provide information on why this had occurred (regardless of the reason). They were encouraged via email reminders to return the final results using an online version of the recording sheet (using http://surveymonkey.com). Evaluation forms were provided at the end of each experiment for all returns, successful and not.

3.3.2. Modifications to the methods, by year

Although the core method and data required (number / weight of yields) remained the same each year, the protocol was updated as the project progressed, in accordance with volunteer feedback and the results obtained. Table 4 summarises the differences between the three years' projects.

Table 4: Summary of the by-year modifications made to the *Bees 'n Beans* methods.

Year	Treatment	Netting	Pots	Plants
2014	**Hand pollination** required by cross-pollination.	**Netting** provided to net plants.	**1.5L Hadopots** provided.	Beans only.
2015	Manual hand pollination by tripping but **no** cross pollination required.	Netting **not** provided, volunteers provided fleece.	**3L Hadopots** provided.	Beans and **radishes** (Chapter 4).
2016	Manual hand pollination by tripping but **no** cross pollination required.	Netting not provided; volunteers provided fleece.	Pots **not** provided. Volunteers to provide 3L pots.	Beans – **2 sets** For growing in pots and additionally in the soil in the garden.

3.3.3. Cross-pollination vs. tripping requirements in Bees 'n Beans

The supplementary hand pollination method used in the 2014 protocol required cross-pollination from spare plants, in accordance with the methods used in agricultural field studies (Free, 1966; Garratt *et al.,* 2014). However, *V. faba* varieties vary in their level of self-compatibility (Drayner, 1959; Hanna & Lawes, 1967). The 2014 protocol used cross-pollination because when the 2014 experiment had to start it had not been possible to test if there was a difference in yield produced by cross-pollination and mechanical tripping alone in 'The Sutton' variety of *V. faba*. The crossing method is more complex, and involves more physical handling of the flowers than tripping requires, so tripping would be more suitable for a citizen science protocol if it was equally effective.

To enable comparison of hand-pollination methods, with the potential to simplify the protocol for citizen scientists in future years, a supplementary study was carried out in spring and summer 2014.

Seventy-five seeds were planted in 1.5L pots in a greenhouse at the University of Sussex. At seven weeks, before flowering began, 50 plants were paired for growth habit (same height, number of stems), and one of each pair assigned randomly to either the hand pollination treatment (using cross-pollination described in 2.3.2.) or to a treatment where the flowers were 'tripped' only (opened and closed five times; Figure 5), with no cross-pollination. The remaining plants were separately kept under the same conditions, as sources of fresh pollen.

The test plants were randomly positioned in a pollinator-excluded greenhouse, created by covering all vents in mesh fabric. Plants were well-watered, hand-pollinated every two days, and fed 25ml of a domestic-use tomato feed ('J. Arthur Bower's – Ready To Use'; Manufactured by William Sinclair Horticulture Ltd., Lincoln, England) twice a week. Flowering occurred approximately six weeks after planting; pods were harvested ten weeks after flowering, with number and weight of pods and beans recorded.

Step 1
Find open flowers. The black part should be visible.

Step 2
Gently grip the top petals. Gently grip the bottom petals.

Step 3
Pull gently on the bottom petals, opening the flower to show the pollen.
Repeat 5x per flower.

Figure 5: Hand pollination of *V. faba* flowers by the 'tripping' method, used in *Bees 'n Beans*.

3.4. Results – by year

As the protocol was updated each year, the results from each year are considered separately below, followed by an overview of the whole project. At the time of writing, the 2014 findings were published in Ecological Entomology (Birkin & Goulson 2015); 2015 and 2016 data have not been published yet.

Data from all three years was analysed in SPSS (SPSS 22 for 2014 and 2015; SPSS 23 for 2016 because the University licence updated), using Generalised Linear Models (GLMs) and appropriate error structures for the data. The square root was taken of the weights of pods and beans, and analysed with normal errors; counts of pod and bean numbers were analysed with negative binomial errors. The completion rate was calculated from the number of returns that were successful, compared to the number of initial participants; from each year. The *engagement* rate was the number of participants who remained in contact with the project, either successfully returning data or explaining why they had not been able to; compared to the initial participants in each year.

3.4.1. 2014 project and results

Completion rates and cost-effectiveness

Of the 551 initial participants in 2014, 80 successfully completed all parts of the experiment and returned a full data set. The statistical analysis was carried out on these 80 returns. A further 96 participants reported that their project had failed over the course of the experiment. While the majority of the data were from England, with a bias towards the south, the spread of successful participants also encompassed Wales and Scotland (Figure 6).

The majority of returns were from individual gardens (61/80), with three allotments, two communal gardens, two ‘other’, and 11 non-responses. Gardens were generally small, with 48 sites (60%) under 200 square metres in area. Sites were predominantly in urban / suburban areas: 24 sites had over 50% of the surrounding 500m square classified in the OS Mastermap topographic layer as ‘private gardens’, 32 sites with 25 % – 50% of surroundings as private gardens, and 22 sites with <25% of surroundings as private gardens.

The most common reported reasons for failure to return data were: failed germination of the seeds, loss of plants to pests, or because the participants forgot to water them.

Excluding staff time, the project cost £2500 to run in 2014; with most of that cost taken up by printing (£431), postage (£500), the cost of the netting (£468), and membership of the SurveyMonkey website (£200) for online collection of responses. This equates to £31 per set of useable data.

Figure 6: Location of completed returns (n=80) from *Bees 'n Beans* 2014.

Pollination treatment results

All factors listed in Table 3 (reproduced below) were fitted to the initial model as main effects and relevant interaction terms, with model simplification via stepwise removal of non-significant factors.

Table 3 (copied): Site characteristics recorded by *Bees 'n Beans* participants, so these can be used as factors in the GLMs for *V. faba* yields.

Factor/covariate	**Measurement**
Treatment category	Local pollinated / netted / hand-pollinated
Size of garden / allotment	In m^2
Aspect	Main direction garden is facing
Latitude	Latitude of site postcode
Location type	Garden: Individual Garden: Communal Allotment Other
Area of surrounding gardens	Area of gardens in the surrounding 500m
Were extra beans grown?	*Were additional broad beans grown on site?* Yes; no flowering overlap Yes; flowering overlap No
Flowering vs. Harvest	Days between first flowering time, and date of harvest

Analysis of the 2014 results showed that only the treatment applied (netted, local, or hand-pollinated) was a significant factor influencing the total number of pods (χ^2_2 = 26.8, p = <0.001, Figure 7a), number of beans (χ^2_2 = 41.5, p = <0.001, Figure 7b), or weight of beans (χ^2_2 = 23.4, p = <0.001, Figure 7d) produced by the experimental plants. The total weight of pods produced by each experimental plants was significantly influenced by treatment (χ^2_2 = 25.4, p = <0.001, Figure 7c), and tended to be higher at sites where the participant was growing additional *V. faba* (χ^2_3 = 10.5, p = 0.015; Figure 8).

Post-hoc pairwise comparison through the GLM interface, with local pollination dummy coded as the reference group, showed the same effect of treatment on all yield measures. Netted plants produced significantly fewer pods (χ^2_1 = 24.8, p = <0.001), fewer beans (χ^2_1 = 36.0, p = 0.001), a lower total weight of pods (χ^2_1 = 21.0, p = 0.001), and a lower total weight of beans (χ^2_1 = 18.4, p = 0.001) than the local pollinated plants. Hand-pollinated plants did not produce significantly different numbers of pods (χ^2_1 = 0.98, p = 0.382); numbers of beans (χ^2_1 = 0.634, p = 0.426); total weights of pods (χ^2_1 = 0.228, p = 0.633); or total weights of beans (χ^2_1 = 0.052, p = 0.820) compared to the local pollinated plants.

There was no difference between the average weight of the individual beans produced by the local pollinated plants and beans from either the netted plants (χ^2_1 = 0.089, p = 0.765) or the hand-pollinated plants (χ^2_1 = 0.029, p = 0.864). Individual beans were lighter from plants where the period between first flowering and harvest was longer (χ^2_1 = 4.01, p = 0.045).

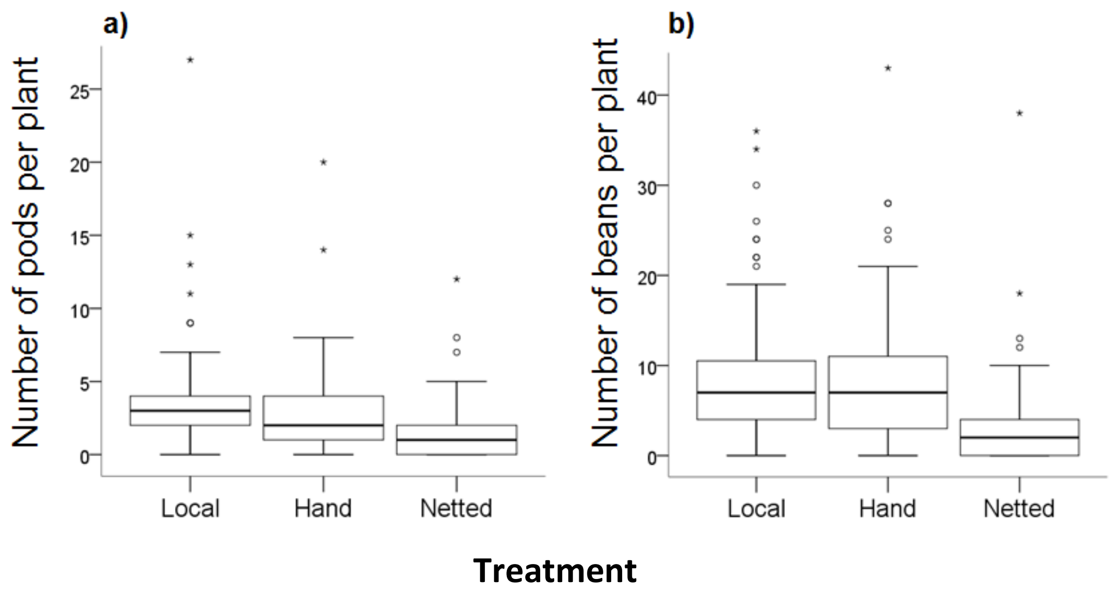


Figure 7: a) Number of pods, b) number of beans, produced by experimental plants in 2014, compared across Treatment categories. The difference between treatments was highly significant in all cases (p<0.001) and post hoc tests revealed ‘local pollinated’ yields were significantly different from ‘netted’ but not from ‘hand pollinated’.

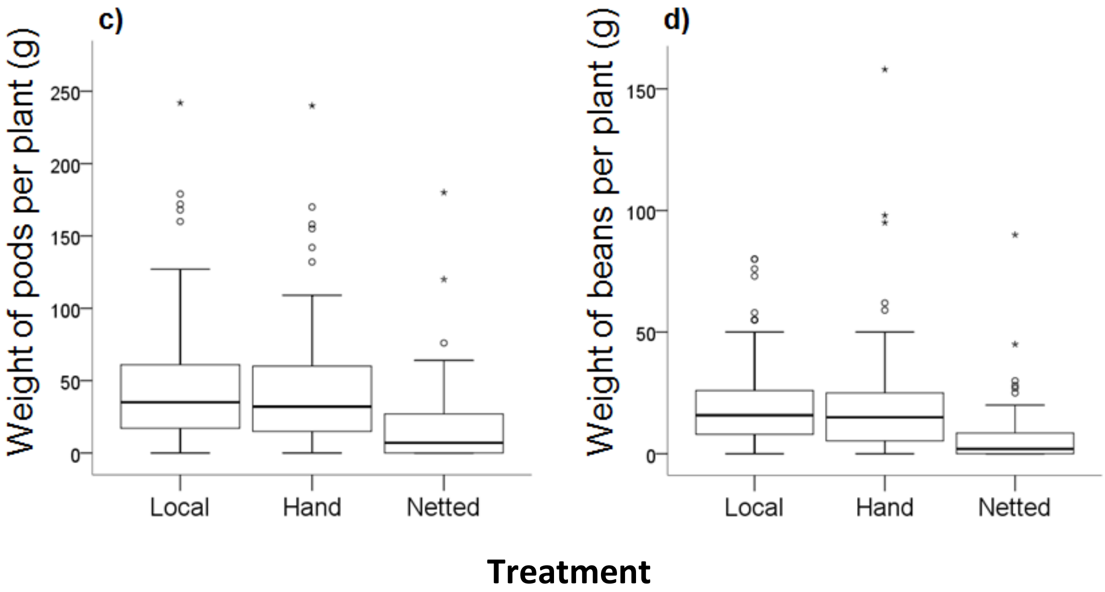
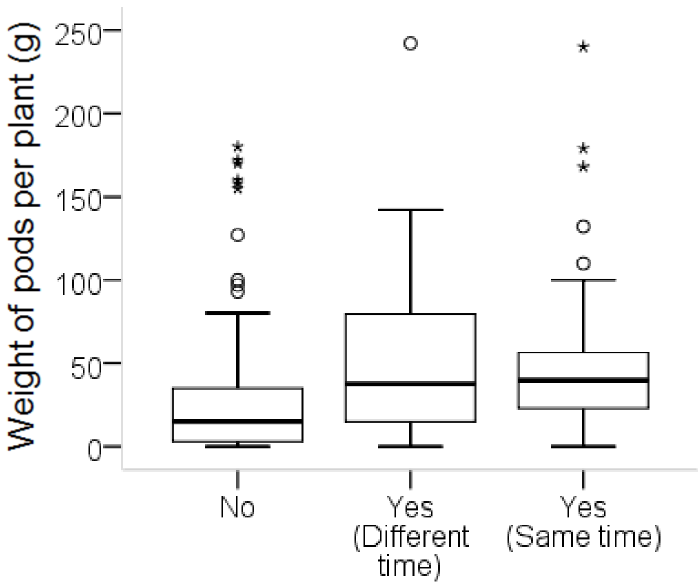


Figure 7 (continued): c) weight of pods, d) weight of beans produced by experimental plants in 2014, compared across Treatment Categories. The difference between treatments was highly significant in all four cases ($p<0.001$) and post hoc tests revealed 'local pollinated' yields were significantly different from 'netted' but not from 'hand pollinated'.



Were more *V. faba* grown in addition to the experimental plants?

Figure 8: Weight (in g) of pods produced by experimental plants, according to whether additional broad beans were grown at the same time at the same site, and whether flowering overlapped with the experimental plants.

3.4.2. 2014 cross-pollination vs. tripping results

Pods and beans were successfully harvested from the plants under both hand pollination treatments (tripped or cross-pollinated). There was no significant difference found between any of the yield measurements comparing tripped plants with cross-pollinated plants (number of pods: $\chi^2_1 = 0.005$, $p = 0.942$; number of beans: $\chi^2_1 = 0.006$, $p = 0.938$; weight of pods: $\chi^2_1 = 0.006$, $p = 0.936$; weight of beans: $\chi^2_1 = 0.035$, $p = 0.851$). For this variety of *V. faba*, both methods of hand pollination seem equally effective.

3.4.3. 2015 project methods

Modifications for 2015

The main modifications to the protocol for 2015 involved simplification of the hand pollination method, and a change to the level of detail in the additional observations volunteers were asked to make (insect visitors and robbing). Although the casual recording of insect visitors did not elicit confusion from volunteers, no analysis was possible of the returns, as they were mostly either too general (e.g. “flies”, “bees”), or not appropriate (e.g. “slugs”, “spiders”). Participants also did not record robbing yes / no frequently, and of those that did, responses were often accompanied by notes of uncertainty. These data were also unable to be analysed.

In accordance with the findings in Section 2.4.2. above – that there was no difference found between the hand pollination yields of beans that were cross-pollinated or only ‘tripped’ – the hand pollination method for the beans was simplified to tripping the flowers, and the instructions updated appropriately. Some volunteers still required clarification of the method, but individual email responses directing to specific web content solved the problems.

The adjustment of the ‘Hadopot’ size to 3L from 1.5L resulted in fewer reports of plants drying out. In addition, the garden fleece replacement for insect netting was acceptable and volunteers appeared to be able to purchase this easily; feedback did not indicate that the use of fleece was a problem.

The modifications to the protocol in 2015 were successful in improving the methodology and the ease of carrying out the experiment.

Modifications to the plants included

Following the investigation of other suitable plants for this protocol, the ‘rat tailed’ radish *Raphanus sativus* was added into the experiment in 2015. Details of this addition, results and conclusion are detailed in Chapter 4.

3.4.4. 2015 results

Completion rates and cost-effectiveness

Of the initial 515 participants in the 2015 run of *Bees ‘n Beans* there were 115 successful data returns, where pods and beans were harvested from the plants. An additional 67 participants were actively engaged with the project, notifying the group that their experiment had failed or filling in the feedback survey, giving an engagement rate of 35% (182/515) and completion rate of 22% (an improvement on the 14.5% of 2014). Again, participation was biased towards the south of England, and there was a better return rate from Scottish sites than in 2014 (Figure 9).

Most returns were from individual gardens (104/115), with four allotments, two communal gardens and five ‘other’. Gardens were mostly small, with 60 sites (52%) under 200 square metres in area.

Excluding staff time, the project cost £1857 to run in 2015; with most of that cost taken up by printing (£433.80), postage (£500), larger pots (£366), seeds (£287) and membership of the SurveyMonkey website (£200) for online collection of responses. Equating to £16.15 per set of useable data in 2015, compared to £31 per set from 2014; this is more cost-effective.

Pollination treatment results

The data was analysed in SPSS 22, using Generalised Linear Models (GLMs), with count data analysed using negative binomial errors. For weight, square root transformation was applied to the data to better fit the assumptions of the GLM, and analysed using linear errors. Post-hoc pairwise comparison was done through the GLM interface, with local pollination dummy coded as the reference group. Treatment type; garden size (m); latitude; location type (e.g. individual garden); and if extra beans were grown were included as main effects along with relevant interaction terms (against treatment); model simplification was via stepwise removal of non-significant factors.

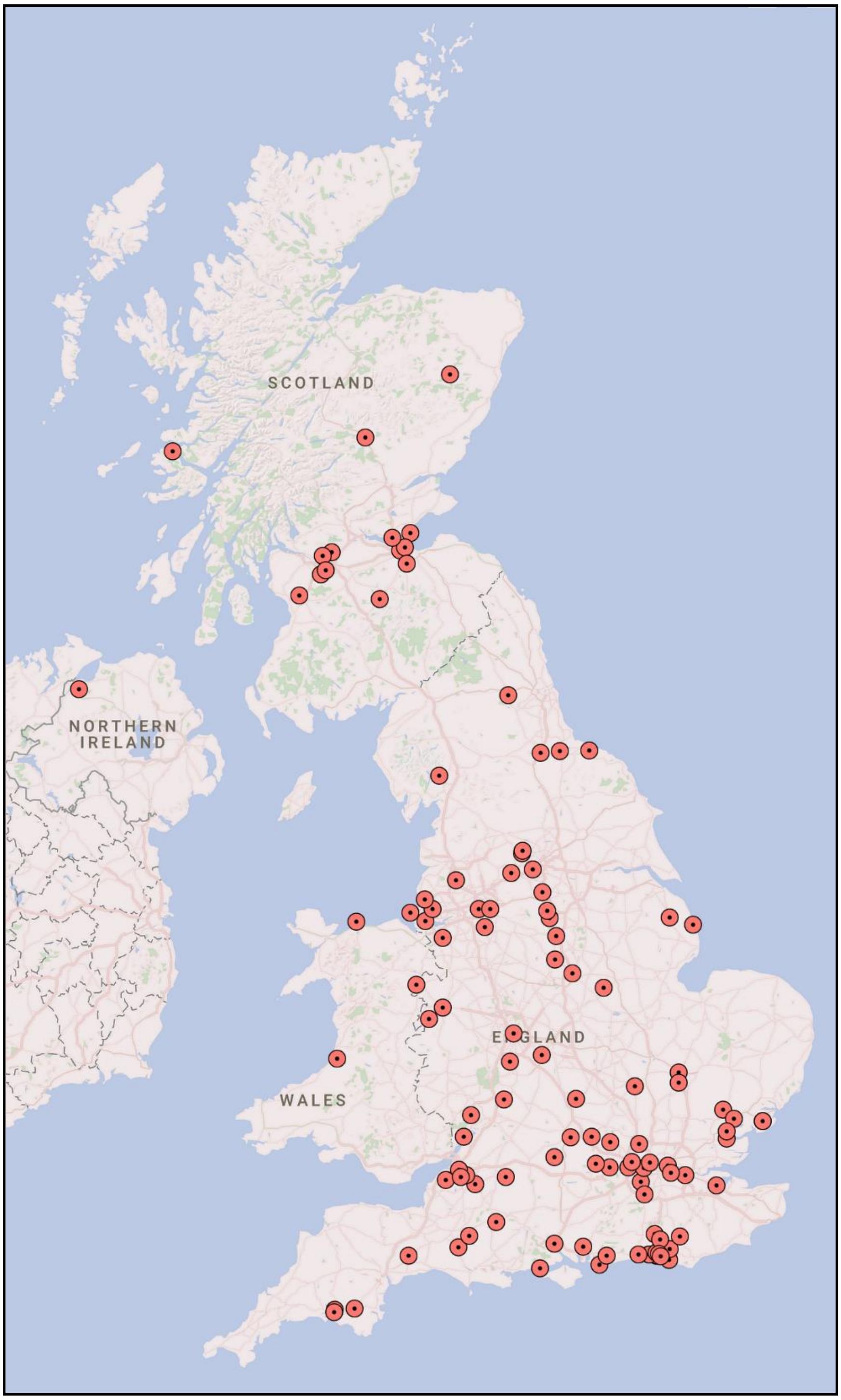


Figure 9: Location of completed returns (n=115) from *Bees 'n Beans 2015*

Analysis of results showed that only the treatment applied (netted, local, or hand-pollinated) was a significant factor influencing the total number of pods (χ^2_2 = 70.4, p = <0.001) or number of beans (χ^2_2 = 94.1, p = <0.001) produced by the experimental plants (Figure 10a & 10b). The total weight of pods produced by each experimental plant was significantly influenced by treatment (χ^2_2 = 20.1, p = <0.001), and also by the site aspect (χ^2_8 = 27.3, p = <0.001; Figure 10c). Total weight of beans produced by the experimental plants was also significantly influenced by treatment, with netting greatly reducing the weight of beans (χ^2_2 = 22.1, p = <0.001; Figure 10d); and by site aspect, with South-facing sites producing heavier crops (χ^2_8 = 25.7, p = <0.001).

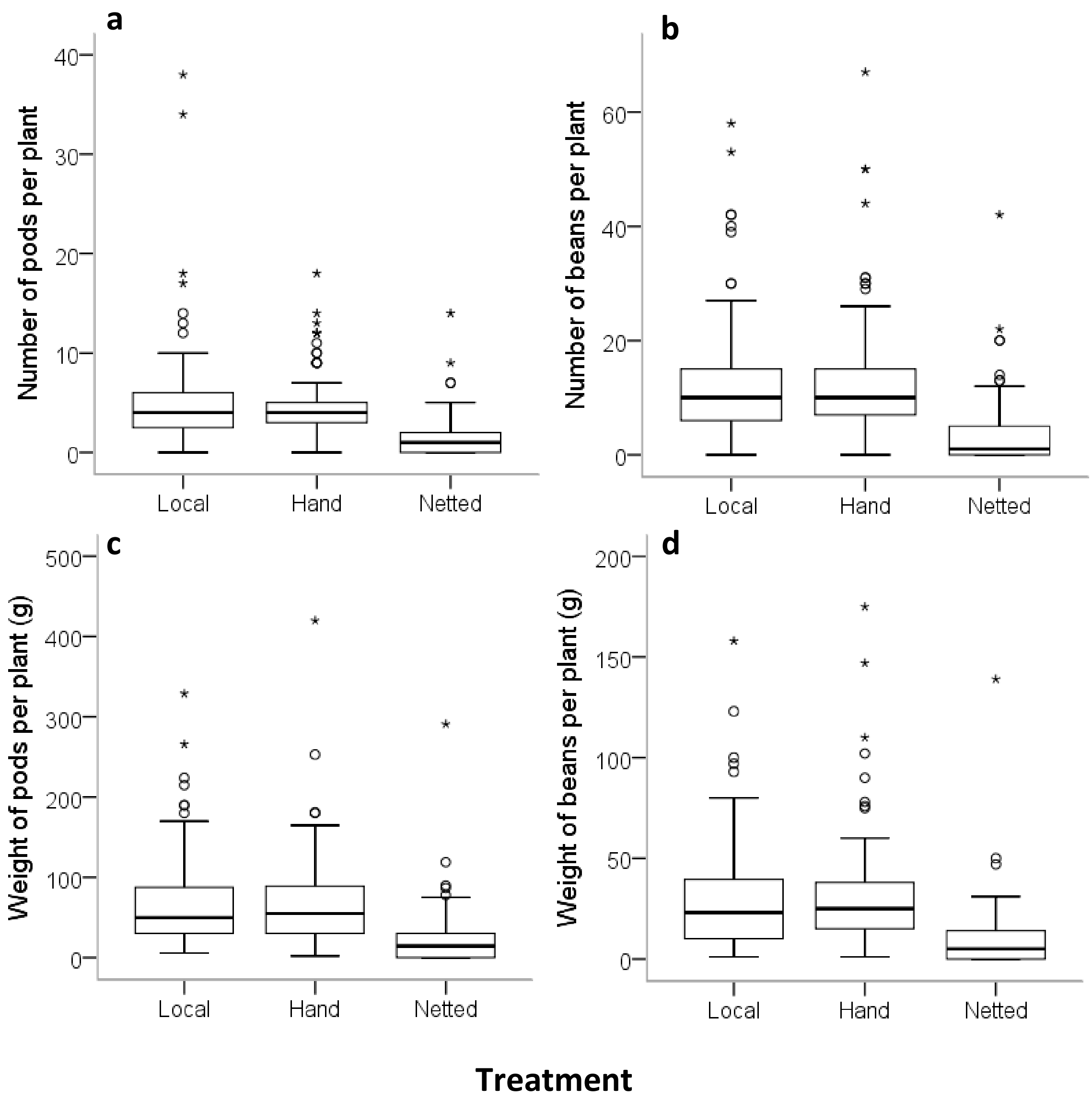


Figure 10: Number of pods (a), number of beans (b), weight of pods (c), and weight of beans (d) produced by experimental plants in 2015, compared across Treatment categories. The difference between treatments was highly significant in all four cases (p<0.001) and post hoc tests revealed 'local pollinated' yields were significantly different from 'netted' but not from 'hand pollinated'.

Post-hoc pairwise comparison through the GLM interface, with local pollination dummy coded as the reference group, showed the same effect of treatment on all yield measures. Netted plants produced significantly fewer pods (χ^2_1 = 58.8, p = <0.001), fewer beans (χ^2_1 = 66.7, p = 0.001), a lower total weight of pods (χ^2_1 = 17.1, p = 0.001), and a lower total weight of beans (χ^2_1 = 14.6, p = <0.001) than the local pollinated plants. Hand pollinated plants did not produce significantly different numbers of pods (χ^2_1= 0.800, p = 0.371); numbers of beans (χ^2_1= 0.006, p = 0.937); total weights of pods (χ^2_1= <0.001, p = 0.997); or total weight of beans (χ^2_1 = 1.107, p = 0.293) to the local pollinated plants.

There was no difference between the average weight of the individual beans produced by the local pollinated plants and beans from either the netted plants (χ^2_1=1.49, p=0.222) or the hand-pollinated plants (χ^2_1=1.28, p=0.257).

3.4.5. 2016 methods

Modifications for 2016

The main change for the 2016 protocol was requesting that participants carry out two versions of the experiment: one with the three bean plants grown in 3L pots, the other with three bean plants grown in the garden soil (thoroughly dug over before planting).

Throughout both 2014 and to a much lesser extent in 2015, volunteers reported plants drying out and some suggested that non-experimental beans that they grew in the ground did not experience the same problems. In addition volunteers had reported that the beans yields from spare plants were greater in the soil, and asked if they could plant experimental beans in the garden soil. In order to show that feedback was considered the protocol was extended to cover the garden soil in addition to the containers.

The project kits did not contain 'Hadopots' in 2016, instead requiring participants to provide their own 3L pots as the experimental containers. This was altered both for economic and logistical reasons. The cost of the Hadopots was relatively expensive and it was not clear how full the volunteers filled the pots on-site. It was postulated that as long as the same size of pot was used for all plants (the advice being 3L), variation should not be much increased.

3.4.6. 2016 results

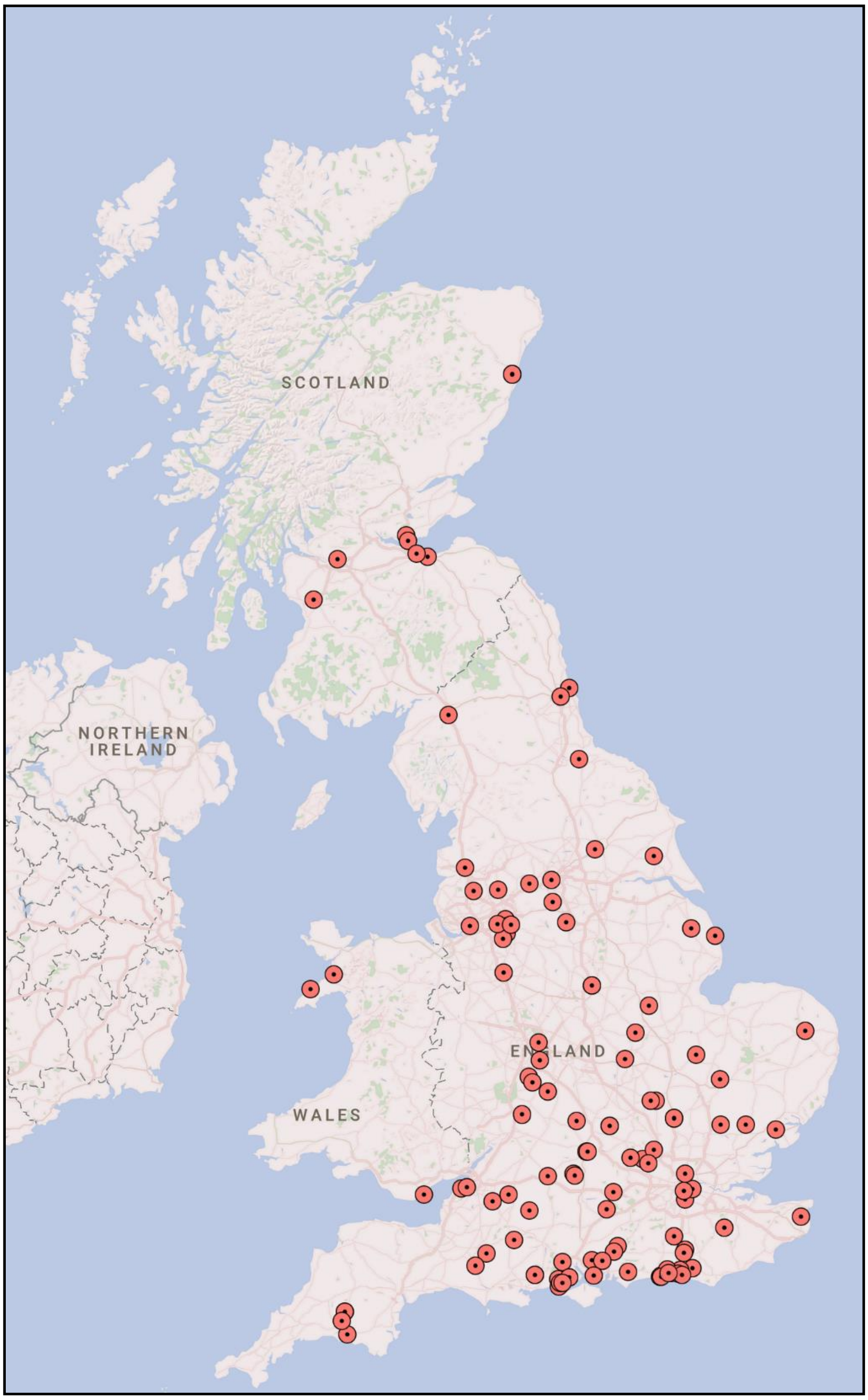


Figure 11: Location of completed returns (n=114) from *Bees 'n Beans* 2016.

Completion rates and cost-effectiveness

Of the initial 408 participants in the 2016 run of *Bees 'n Beans* there were 114 successful bean returns, where both pods and beans were harvested from the plants

(Figure 11). An additional 55 participants were actively engaged with the project, notifying the group that their experiment had failed but expressing continued interest in the project, giving an engagement rate of 41% (169/408) and completion rate of 28%, representing an improvement on the 22% of 2015.

Most returns were from individual gardens (93/114), with 13 allotments, one communal garden and seven ‘other’ (including roofs and balconies). Sites were on average a bit larger this year, with 50% of sites (57) 200 square metres or under in area; 27% (31) 201 – 600 square metres; and 23% (26) over 601m^2.

Excluding staff time, the project cost £1256 to run in 2016; with most of that cost taken up by printing (£345.2), postage (£300), seeds (£346) and membership of the SurveyMonkey website (£229) for online collection of responses. Equating to £11.02 per set of useable data in 2016; compared to £16.15 per set in 2015, and £31 per set from 2014, this was more cost-effective.

Garden vs. container growing

110 participants returned data from garden beans, and 113 from potted beans (4 people only grew potted beans, and 1 only did the garden beans). There were more *successful* returns of the potted bean data (97 results, 86%), than the garden bean data (83 results, 75%), although comparison with Fischer’s Exact Test gave $p = 0.062$; not significant, but potentially trending towards greater success rate with the container beans.

There was no observed difference in the amount of slug / snail damage experienced between plants in different positions, based on *reported* incidents of damage. This was both for experiments that failed entirely ($p = 0.762$, Table 5) and those that were able to produce results despite damage ($p = 0.36$, Table 6); there was no difference in the amount of damage incurred by experimental plants in either location. Overall, 37% (42/114) of returned experiments were damaged by slugs in some way, with a further 12 experiments noted as failing as a result of slugs but without returning data (47% overall damaged).

Table 5: Number of volunteer experiments reported as failed in 2016, and how many of those were slug damaged.

Failed experiments	Failed mainly due to slugs	Other main reason
Container	6	11
Garden	13	18

Table 6: Number of volunteer experiments in 2016 who reported slug damage to the plants.

Damaged experiments	Damaged by slugs	No reported slug damage
Container	26	87
Garden	32	78

Pollination treatment results

The data was analysed in SPSS 23, using Generalised Linear Models (GLMs), with count data analysed using negative binomial errors. For weight data, a square root transformation was applied to the data to better fit the assumptions of the GLM, and analysed using linear errors. Post-hoc pairwise comparison was done through the GLM interface, with local pollination dummy coded as the reference group. Treatment type; garden size (m); latitude; location type (e.g. individual garden); and if extra beans were grown were included as main effects along with relevant interaction terms (against Treatment); model simplification was via stepwise removal of non-significant factors.

Comparison between the garden beans and the potted beans ('type') showed that the garden plants produced significantly more pods than the pot beans ($\chi^2_1 = 5.04$, p = 0.025); although the effect of Treatment (netted, local or hand pollinated) was also significant and much larger ($\chi^2_2 = 117.5$, p = <0.001; Figure 12a). Netted plants produced significantly fewer pods than the local pollinated plants ($\chi^2_1 = 101.4$, p = <0.001), and there was no difference between number of pods produced by the local and hand pollination plants ($\chi^2_1 = 0.232$, p = 0.63). There was no interaction between Treatment and type, suggesting that the effect of the Treatment on pod number is unaffected by how the plants are grown.

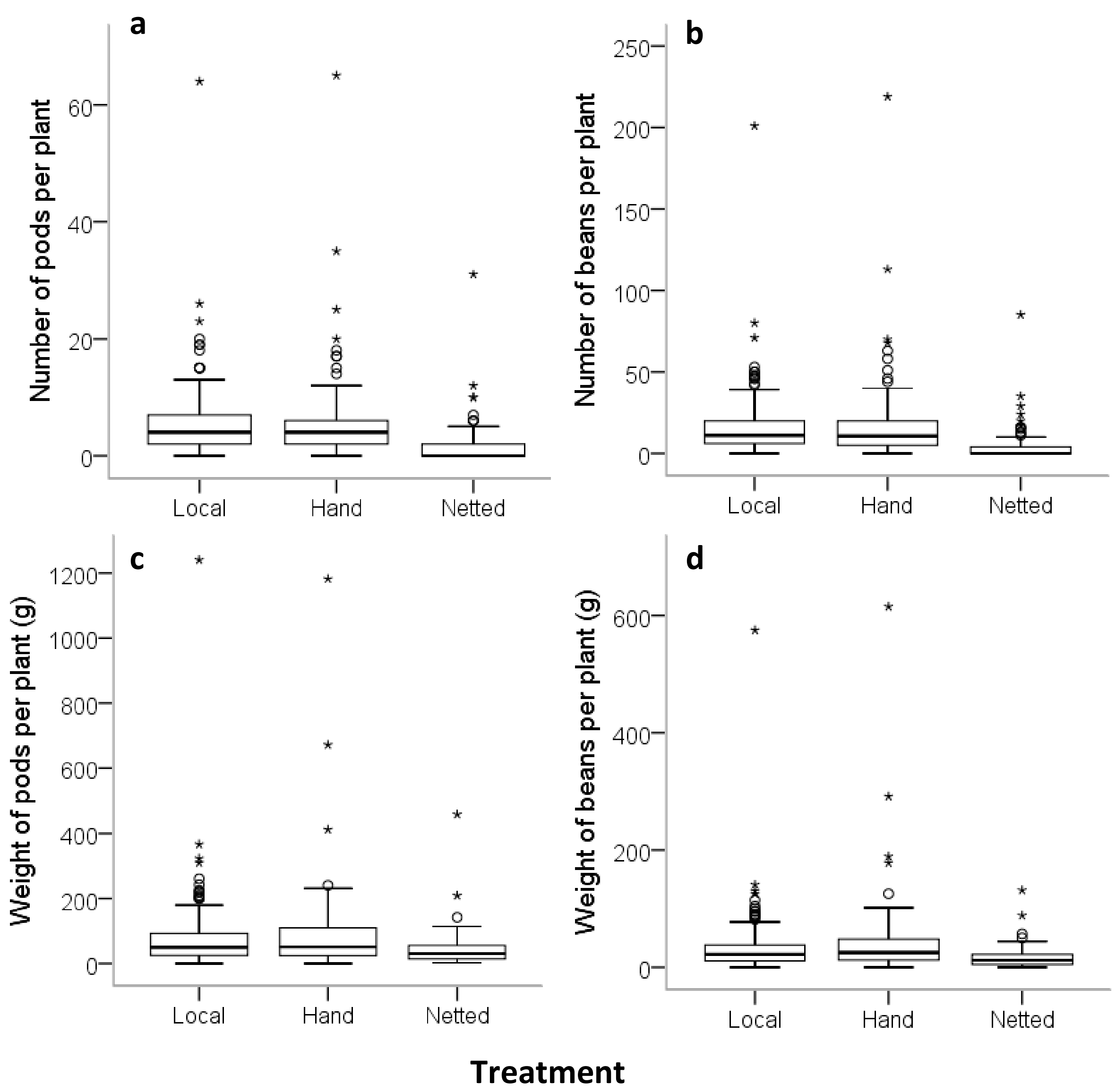


Figure 12: Number of pods (a), number of beans (b), weight of pods (c), and weight of beans (d) produced by experimental plants in 2016, compared across Treatment categories. The difference between treatments was significant in all four cases and post hoc tests revealed 'local pollinated' yields were significantly different from 'netted' but not from 'hand pollinated'.

Aspect was also significant (χ^2_8 = 20.2, p = 0.01), with south-facing sites producing more pods; and more pods were also produced by plants where the participant was growing other broad beans at different times to the experimental plants (χ^2_2 = 12.1, p = 0.002). Neither of these had an interaction with the Treatment type.

The number of beans produced was not influenced by whether the plants were in pots or the garden soil, and there were no interactions between any of the factors included in the model. Treatment significantly affected this measure (χ^2_2 = 178.2, p = <0.001;

Figure 12b), with netted plants producing fewer beans than local plants (χ^2_1 = 145.7, p = <0.001), but with no difference between the number of beans produced by local and hand pollinated plants (χ^2_1 = 0.003, p = 0.956). Aspect also influenced the number of beans produced (χ^2_8 = 26.0, p = 0.001), with West and North-facing gardens producing fewer beans; and so did whether the participant was growing broad beans in addition to the experimental plants, with additional plants grown at different times associated with greater numbers of pods per plant (χ^2_2 = 20.9, p = <0.001).

The weight of the pods produced was not affected by whether the plants were in pots or the garden soil, and there were no interactions between any of the factors included in the model. Treatment did have an effect on the weight of pods, but it seems quite weak (χ^2_2 = 7.40, p = 0.025; Figure 12c), with pods from netted plants lighter (χ^2_1 = 5.68, p = 0.017) than those from the local plants, and no difference between the weights from the local and hand pollinated plants (χ^2_1 = 0.166, p = 0.684). Also significant trends, but without interaction with treatment category were: aspect (χ^2_8 = 20.5, p = 0.009), again with West and East facing gardens producing a lower weight of pods than South-facing sites; latitude, with more southern locations producing greater weights of pods (χ^2_1 = 5.71, p = 0.017); and a greater weight of pods produced by participants who were growing additional broad beans at a different time to the experimental plants (χ^2_2 = 23.0, p = <0.001).

The weight of the beans produced was not affected by whether the plants were in pots or the garden soil, and there were no interactions between any of the factors included in the model. Treatment had an effect on the weight of beans (χ^2_2 = 13.9, p = 0.001; Figure 12d), with beans from netted plants lighter (χ^2_1 = 8.93, p = 0.003) than those from the local plants, and no difference between the weights from the local and hand pollinated plants (χ^2_1 = 1.14, p = 0.285). Southern facing sites produced a heavier weight of beans (χ^2_8 = 27.6, p = 0.001), as did those where participants were growing additional broad beans at a different time to the experimental plants (χ^2_2 = 16.1, p = <0.001).

3.4.7. Across all three years

Completion rates and cost-effectiveness

The number of initial participants varied across the three years of the project, with 2014 having the largest sign-up (551 people). However, the completion (successful returns) and engagement (unsuccessful return, but active contact with project) rates improved substantially with each year (Figure 13), and as a result of improvements to the protocol and these improved rates, the cost per usable unit of data was a third in 2016 what it was in 2014 (Figure 14).

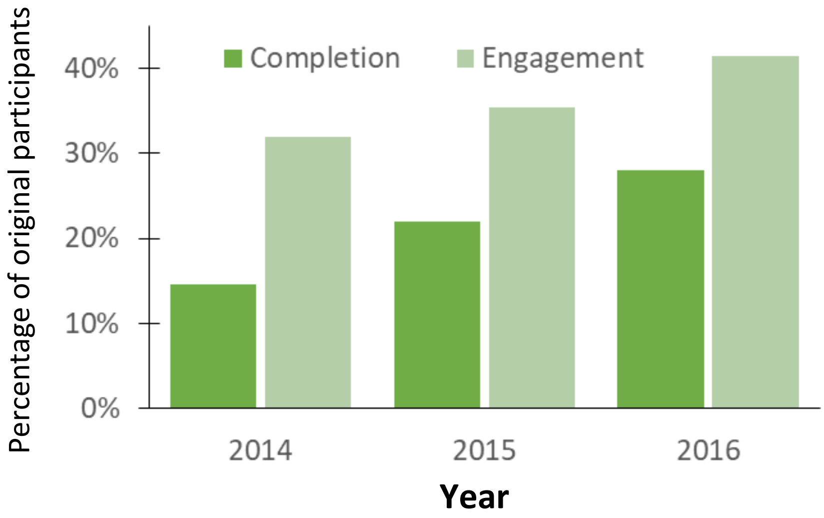


Figure 13: Completion and engagement rates across the three years of *Bees 'n Beans*. 'Completion' = returned a dataset. 'Engagement' = Completion + those in active contact with the project, even if their project failed.

Figure 14: Cost per usable data return from all three years of the *Bees 'n Beans* project, based on total project materials cost / usable returns.

In addition, while we only have site *type* data for the completed / returned data, it is possible to (very roughly) compare the number of gardens and allotments that returned data. Some estimates are available for the overall stock of these site types in the UK, with an estimated 330,000 allotments (Crouch & Ward, 1997) and 12.6 million gardens (the number of gardens from Davies *et al.*'s 2009 review that took part in wildlife gardening of some form). Thus we might expect roughly 3% of site returns to be from allotments. Considering the *Bees 'n Beans* sites that were either gardens or allotments (other categories were rare), 4.69% of returns in 2014 were from allotments, 3.7% of returns in 2015 were from allotments, and 12.26% of returns in 2016 were from allotments.

Pollination treatments and environmental effects

All three years of data were combined into one set, with 'year' as a new categorical ordinal variable. Treatment, year, aspect and latitude were included as main effects in the models. Only interactions terms including the treatment factor were included, since effects that have no interaction with treatment are affecting all three bean plants on a site in the same way regardless of the different pollination received; to not over-complicate the model.

Treatment

There was no interaction between 'Treatment' and 'year' for any of the measures of pollination taken: effects of applying treatments was the same across all three years.

The 'Treatment' factor had by far the greatest influence on the numbers of pods (χ^2_2 =167.1, p = <0.001) and beans produced by the experimental plants (χ^2_2 = 225.8, p = <0.001). Netted plants produced significantly fewer pods (χ^2_1 = 149.3, p = <0.001) and beans (χ^2_1 = 188.2, p = <0.001) than local plants; and there was no difference in number of pods (χ^2_1 = 2.41, p = 0.121) or beans (χ^2_1 = 0.768, p = 0.375) produced by local compared to hand pollinated plants. Treatment showed no interaction with any other factor in regard to the total number of pods and beans produced.

The average number of beans per pod showed a similar pattern, although a smaller effect, with Treatment significantly influencing the average number of beans per pod (χ^2_2 = 8.61, p = 0.013); netted plants averaged fewer beans per pod than local plants

(χ^2_1 = 8.67, p = 0.003), and there was no difference between the average beans per pod in local compared to hand pollinated plants (χ^2_1 = 1.31, p = 0.252). There was a significant interaction between Treatment and latitude (χ^2_2 = 8.02, p = 0.018) but only for netted plants, with those from lower (warmer) latitudes averaging slightly more beans per pod than netted plants from higher latitudes (χ^2_1 = 8.02, p = 0.005).

The total weight of pods and beans per plant was significantly affected by Treatment (pods: χ^2_2 = 29.7, p = <0.001; beans: χ^2_2 = 41.8, p = <0.001), with netted plants producing a lower weight of pods (χ^2_1 = 26.4, p = <0.001) and beans (χ^2_1 = 33.0, p = <0.001) than the local plants; and no difference between local and hand pollinated plants for either total pod weight (χ^2_1 = 0.161, p = 0.688) or total bean weight (χ^2_1 = 0.170, p = 0.680).

There was no effect of Treatment on the average weight of pods or beans produced.

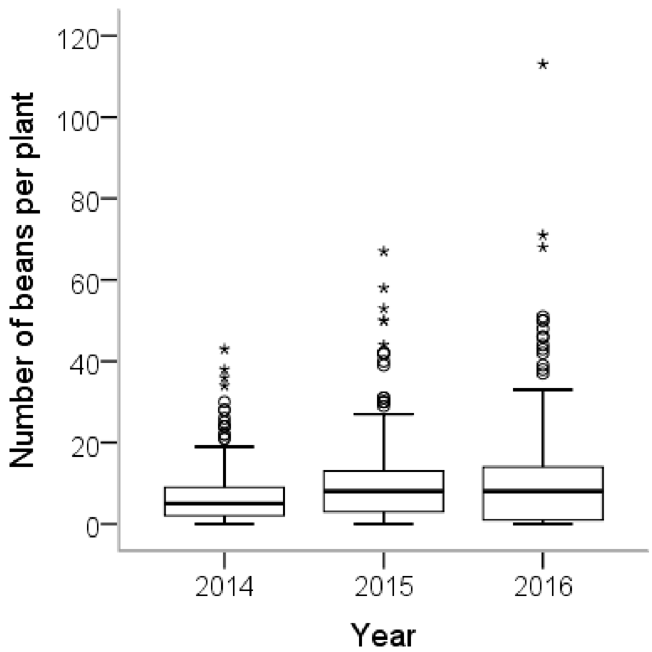


Figure 15: Number of beans produced by the experimental plants over the three years of *Bees 'n Beans.*

Year

The total number of pods per plant was unaffected by the year the experiment was performed in, but the total number of beans per plant was affected (χ^2_2 = 13.8, p = 0.001; Figure 15). 2015 and 2016 plants produced more beans than those from 2014 (χ^2_1 = 11.0, p = 0.001; and χ^2_1 = 11.6, p = 0.001, respectively); and there was no difference in the number of beans produced per plant between 2015 and 2016 (χ^2_1 = 0.064, p = 0.800).

Year also had a significant effect on the total weight of pods (χ^2_2 = 21.6, p = <0.001) and beans (χ^2_2 = 18.4, p = <0.001) produced by the experimental plants. Experiments carried out in 2014 produced a lower overall weight of pods than those from 2015 (χ^2_1 = 16.7, p = <0.001) or 2016 (χ^2_1 = 18.5, p = <0.001), as well as a lower overall weight of beans than those from 2015 (χ^2_1 = 12.1, p = 0.001), or 2016 (χ^2_1 = 17.0, p = <0.001); there was no difference between 2015 and 2016 in the total weight of pods (χ^2_1 = 0.419, p = 0.517) or beans (χ^2_1 = 1.11, p = 0.293) per plant.

There was no effect of year on the average weight of pods or beans produced.

Aspect

South-facing sites tended to produced more beans per plant (χ^2_7 = 15.8, p = 0.027), heavier weights of pods (χ^2_7 = 23.4, p = 0.001), and heavier beans (χ^2_7 = 24.8, p = 0.001). There was no interaction between the aspect of the experimental sites and the Treatment categories; aspect affected all plants on site equally.

Geographical variation

Sub-dividing the 2014-2016 *Bees 'n Beans* data down to UK regions (SPSS GLM on the counts of pods and beans, with negative binomial errors and 'Region' added as a main effect) did not show any areas of pollination deficit compared to the national level; there were no regions where counts of either pods or beans were consistently higher for the hand pollination treatment than the local pollination treatment. There was no significant interaction between Region and Treatment (χ^2_9 = 2.76, p = 0.973), or main effect of Region (χ^2_9 = 13.9, p = 0.127) on the number of pods produced; nor any significant interaction between Region and Treatment (χ^2_9 = 3.53, p = 0.939), nor main effect of Region (χ^2_1 = 7.10, p = 0.627) on the number of beans produced.

The detailed analysis is provided in Appendix A.7.

3.5. Discussion

The overall aims of this study were: to use these plants to test whether citizen science methodology can be used to quantify pollination services in urban gardens at a national scale; and if any current deficit in pollination can be detected in the UK using this method. Long-tongued bumblebees such as *B. hortorum* are the most effective pollinators of *V. faba* flowers (Kendall & Smith, 1975; Stoddard & Bond, 1987), therefore if there were an inadequate population of these bees in a given geographical area then a pollination deficit in the beans should be observable. Over the three years of the study (2014 to 2016), a large dataset from domestic gardens across a large geographical area covering the UK was obtained, and the potential usefulness of this citizen science method was assessed under real-garden conditions.

3.5.1. Detection of pollination deficit

No deficit in UK pollination provision was detected by the *Bees 'n Beans* projects 2014 – 2016. Local pollination yield results showed no difference to the maximum-pollination hand pollinated control, and both were significantly different to the yields obtained from netted controls. If the *V. faba* plant yields were unaffected by pollination actions, then the yields from both pollinated treatments would be expected to be the same as those from the excluded plant. This indicates that pollination services for *V. faba* are currently not limiting in gardens or allotments in the UK; at least not over the time period of the project, and when only small numbers of plants are grown per site (i.e. under normal garden conditions). This suggests that the populations of long-tongued bees in the experimental areas are sufficient for the provision of the pollination service required there.

It is possible that pollination is not a limiting factor for *V. faba* in garden sites; the sites are quite small, the plants were not densely clustered, and pollinator populations may be higher in urban areas compared to farmland (Owen, 1991; Goulson *et al.,* 2002; Osborne *et al.,* 2008; Ahrné *et al.,* 2009; Goulson *et al.,* 2010; Samnegård *et al.,* 2011). The protocol cannot detect pollination *surplus*, only whether or not there is limitation, and so it cannot reveal how close an area may be to entering a pollination deficit. Contining data collection over multiple years would allow for trends to be tracked and sporadic local deficits would be expected to precede broader national patterns.

The major significant factor affecting all measurements of bean yield was the treatment applied: excluding pollinators from access to the bean flowers resulted in significantly lower measures of yield than those from plants which had received pollination effort (either hand pollinated, or provided by the local insects). This is the same pattern shown by Garratt *et al.* (2014) in agricultural field-manipulations of *V. faba*, and by earlier work by Free in crop fields (Free, 1966). However, Free & Williams (1976) showed an improvement of yield with hand-pollination compared to local pollination, which neither our results nor those of Garratt *et al.* (2014) indicated; although the hand pollination did not seem to be *worse* than the local, suggesting that the method does not damage the hand pollinated flowers.

If a *V. faba* plant produced a pod or bean, they seem to be approximately the same weight regardless of the treatment applied to that plant, or whether it likely resulted from cross- or self- pollination (more likely in local, or hand pollination, respectively). This suggests that the yield measures in *Bees 'n Beans* are good indicators that a pollination event has occurred, thus that the pollination service has been provided.

Several other factors showed an influence on yield measurements. Pods and beans harvested later in the growing season were lighter than earlier harvests, likely because the pods had started to dry out, although this showed no effect on the numbers of either produced. In addition, more southerly (latitude) and south-facing (aspect) sites produced greater yields; again this was a common effect for all treatments.

In 2014 and 2016 a greater weight of pods was associated with whether or not the site was growing additional *V. faba* plants: sites *without* additional bean plants (at any time of the year) produced lighter pods. More bean plants may attract more pollinators to the site, but since no evidence for pollinator limitation was found this seems unlikely to be the explanation. This effect was seen when considering all plants in an experimental site, *including* the netted control, so it seems likely that participants who were already experienced at growing *V. faba* varieties, and thus had their own extra plants on site, were better at avoiding or compensating for any horticultural problems that arose during the study. This raises the possibility that the gardening experience of the participants may have a direct effect on results. More experienced gardeners will be more aware of plant health and watering requirements in changing weather conditions which may then improve the weight of pods produced; however this seems to apply equally across all pollination treatments on a site.

Detailed observation of flower visitors, as undertaken by Garratt *et al.* (2014), could provide more detail about the effectiveness of each pollination action; and protocols like the Great Sunflower Project (Oberhauser & LeBuhn, 2012) provide more specific information about the insects populations present and infer surplus pollinators that way. The *Bees 'n Beans* methodology was not designed for these types of observation, and there is a risk of losing volunteer engagement with inclusion of additional, more complex tasks requiring more time investment (West *et al.,* 2015) – but a combination of methods would produce better overall data, so the pairing of this pollination-only methodology with more observational studies will be considered later (Chapter 7).

3.5.2. Outcomes of methodology variations.

Modifications made to the methodology for *Bees 'n Beans* over the three years were generally successful, either by improving the robustness of the protocol, allowing for streamlining and improved rates of return. The hand pollination method of 'tripping' is simple to explain, and does not require especially delicate manipulations of the flower. While this method may increase the proportion of self- versus cross-pollinated seed in the resulting set beans, and thus the levels of auto-fertility likely in the next generation (Drayner, 1959; Rowlands, 1960; Bond & Pope, 1987), this is not a concern in regards to the *Bees 'n Beans* study. Production of beans and pods in response to a 'pollination event' did not differ between the hand and local pollinated plants, suggesting that self-pollination via mechanical action is as likely to produce a pod / bean as crossing by pollen transfer, at least in this variety. Were this protocol implemented at a larger scale, fresh seed from the same suppliers should be used each year, to ensure that the proportion of hybrid and inbred plants is the same for all participants in that year.

In terms of site positioning, while a small increase in the number of beans produced by plants grown directly in the soil was observed, indicating that soil-grown plants may be slightly healthier, the experiences of the 2016 study suggest that growing the beans in containers is still the most practical methodology for a citizen science programme.

Plants in pots can be temporarily moved if jeopardised by changes in garden conditions such as extreme weather events (‘hail’ having been reported a number of times during the study, for example), or to remove them from the reach of pests (e.g. moving to a table during the night to help combat slug attack). Being able to position pots in more accessible places than at ground-level also allows for volunteers with reduced mobility or dexterity to be able to carry out the experimental manipulations more easily; since a notable proportion of citizen scientists in the UK are likely to be older people (Roy *et al.,* 2012; Church *et al.,* 2015), this needs to be taken into account.

The wet weather and warm winters of recent years is predicted to continue (Kendon *et al.,* 2015), so the issues encountered with slugs and snails are also likely to recur. Nearly half (47%) of engaged participants in 2016 reported damage to, or complete loss of plants as a result of mollusc grazing, and feedback from all years highlighted this damage as a common and disheartening occurrence, particularly when it led to volunteers being unable to complete the project who were actively enaged. A modification to the methodology for any further use of *Bees ‘n Beans* should therefore include a length of copper tape to encircle each experimental pot to deter slugs (Schüder *et al.,* 2003). This would be an additional material cost but would not add much to the postage cost; wholesale sources could be sought for larger-scale projects.

Another methodology addition (reported in Appendix A.4.) is the use of sequential counting. Once a bean pod starts to develop it is easily identified. The flowers develop sequentially up the stem, so that new flowers are above those already pollinated. Once the flowering has finished and hand pollination is no longer required, pods can be counted once a week. As these are distinctive enough to not require manually interacting with the plant, and large enough for volunteers to be able to easily see, sequential counts could be undertaken. Most of these pods will go on to maturity unless damaged by pests or environmental events and – as shown in Section 3.4.6. – once a pod has formed it is likely to be similar to all other pods. Including a sequential count should improve the returns by making sure that at least *pod number* data is collected from all plants that successfully received their full pollination treatment, even if the plants or pods themselves are lost before the full harvest can occur.

The final modification to take in to account is the targeting of participant recruitment. The low poor return rate of 14.5% in 2014 (despite rapid sign-up) is not outside the rates typically found in citizen science projects in West *et al.*'s 2015 review (varying widely between 10% – 50% for volunteer projects), but meant that the first year of *Bees 'n Beans* was expensive in terms of data collection, at £31 per return. More focused recruitment on a specified social group is known to improve return rates of questionnaires / surveys (Crawford, 1997; Aldridge, 2001), and a similar effect was seen with the more-targeted recruitment to the *Bees 'n Beans* projects used between 2014 and 2016. Rate of return and engagement rates improved (with cost per data return down to £11 in 2016), suggesting that the modifications were successful.

In 2014 the project was advertised on social and local media plus personal ecological contacts and the first 550 people who volunteered for the project were accepted (who had a UK postcode). Recruitment questions were simply postcode and name, without requiring participants to anything other than some outside space, and the ability to purchase some compost. The 2015 protocol modified this, asking volunteers to provide netting, and to indicate if they were willing to try growing the additional plant as well. The intention in 2015 was to prioritise volunteers who would be able to grow both plants, and none were included who could not provide netting. The advertising for 2015 targeted both those who had indicated interest in 2014 (minus contacts who had dropped out for lack of interest) and new volunteers, this time with additional efforts to utilise conservation, ecology and bee related groups or gardening-related hashtags and mailing lists. The same approach was taken in 2016, with the additional requirement for volunteers to provide their own pots, which would likely further target people who already have some interest in gardening.

Overall numbers of volunteers declined over the three year period, but the rates of engagement *with* those volunteers, and the successful returns recorded, increased substantially. The proportion of sites that were allotments also increased (even with the rough calculation of an expected ~3% of sites as allotments, the 12% seen in 2016 is an increase on both this prediction and the previous years); since allotment holders are most often active vegetable growers they may have been additionally targeted. While focusing on gardeners in particular will add some bias to the demographics of the resulting volunteer pool, it does mean that the project is more likely to get data back. A larger-scale project based on this method would be advised to work with partner organisations who already have access to pools of potential volunteers. The *Bees 'n Beans* project was able to work with members of the Women's Institute, Ness Botanic Gardens and 33 schools in the Brighton & Hove area, for example, and forming UK working partnerships with similar groups would be highly recommended.

3.5.3. Use of *"Bees 'n Beans"* as a monitoring scheme

While *Bees 'n Beans* did not detect a pollination deficit, the results still suggest that it *could* do so (a final recommended form of the protocol will be discussed in Chapter 7), and that the method would be suitable for application to other plants that are pollinated by different groups of insects (alternative phytometers are discussed further in Chapter 4). The other aim of this work was to determine if an experiment to directly monitor pollination was suitable for use as a widespread citizen science project – and that does indeed seem to be the case. It is both possible and practical to recruit volunteers to conduct this style of experiment, gathering data on geographical scales that would be vastly more costly to achieve employing professionals alone (Dickinson *et al.,* 2010; Mackechnie *et al.,* 2011).

This project is thus of great potential importance when considered alongside the ongoing development of the National Pollinator Strategy (NPS), and the focus on evidence-based conservation practice in the UK (Dicks *et al.,* 2013; DEFRA 2014; Vanbergen *et al.,* 2014). The NPS proposed to assess potential provision of pollination services by surveying for pollinating species themselves. Direct measures of pollination are mentioned as a potential element but are not in the initial plan. The effectiveness of citizen science schemes in engaging a population of recorders on a large scale when established can be seen by the engagement success shown in the Great Sunflower Project (Oberhauser & LeBuhn, 2012), and the Urban Pollination Project (Potter & LeBuhn, 2015). The success *Bees 'n Beans* participation demonstrates that citizen scientists can produce data from experimental projects, and supports the inclusion of such schemes in further development of the monitoring strategy. Continuation of such data collection over multiple years would allow for trends to be tracked.

For *Bees 'n Beans*, the project methodology and rationale seems to be attractive to participants from a variety of backgrounds. Over the course of the study, the protocol was carried out in private homes, schools, gardening groups and botanical gardens, amongst others. Improvements to the instructions and method made over the three years, based on feedback from participants, appears to have had a positive effect on the completion / engagement rates shown in Figure 14. Forty-one percent of volunteers actively engaging with the project, even if they were not able to contribute results, is a good percentage – return rates for citizen science projects in various scientific fields generally ranging between 10-50% (Roy *et al.,* 2012b; West *et al.,* 2015; Sauermann & Franzoni, 2015) – and with the addition of sequential counting to the methodology, it should be possible to maximise returns from the engaged volunteers.

This was the only then-current UK surveillance project to ask for participants to complete a manipulation experiment, with most citizen science projects focused around primarily-observational methods (Carvell *et al.,* 2016). The material cost per unit of data decreased across the three years, down to £11 per return in 2016. More targeted recruitment, aimed specifically at those with gardening experience, a wider publicity campaign, and economies of scale on larger numbers would bring this cost per data set down further, if the methodology were adopted at a larger scale.

The cost per unit does not include the staff time for handing, data curation and analysis, because this work was carried out as part of PhD research. Alternative methods of funding, for both materials and staff time, would have be to sourced for any further development of the project, such as-seeking partnership arrangements with appropriate NGOs or other organisations.

In addition the protocol could readily be transferred to use other plants dependent on different pollinator guilds (see Chapter 4 for exploration of options), and with targeted recruitment of farmers or those living in rural areas it could be extended to assess rural pollination services. I therefore suggest that this protocol could form a basis for a large-scale, long-term, cost-effective monitoring scheme, addressing an urgent and well-recognized need for systematic data collection on pollination service provision.

Appendix A: Supplemental projects for *Bees 'n Beans*

A.1. Introduction

During the 2014-2016 field seasons, six smaller projects occurred alongside the 'main' *Bees 'n Beans* projects. These smaller pieces of work represented either exploratory experiments or analyses to investigate improvements or alternatives to ongoing methods, or were separate strands of work within the overall theme. This Appendix considers these projects in more detail, rather than crowd the associated main sections.

A.1.1. Appendix sections

1) Introduction.
2) Winter berries for birds (2014).
3) Ideal container size for growing experimental *Vicia faba* plants (2014-15).
4) Sequential counting of *V. faba* beans (2016).
5) Companion planting for *V. faba* beans (2016).
6) School Spaces – piloting pollination projects in UK schools (2015).
7) Regional analysis of *Bees 'n Beans* data 2014 – 2016.

A.2. Winter berries for birds: assessment of pollination received by common berry-producing plants in UK urban green spaces.

A.2.1. Introduction

Crops for human consumption are not the only urban plants to need pollination by insects. Berry-producing trees and shrubs – varieties deliberately planted as garden hedging or for other ornamental purposes, as well as wild plants – also have need pollination (Jacobs *et al.,* 2009), and the fruits that they produce represent an important food source for overwintering birds (Gibb, 1948; Snow & Snow, 1988; British Trust for Ornithology, 2012). Birds are a very visible element of urban biodiversity and are valued charismatic organisms in their own right (Chamberlain *et al.,* 2009; Jones 2011; Wei *et al.,* 2016). Interacting with or encountering wild birds is an important way of engaging with the natural world for many people (McKinney, 2002; Adams 2005; Jones, 2011; Galbraith *et al.,* 2014); the most common conservation action in the majority of UK gardens is supplemental feeding of birds (Chamberlain *et al.,* 2004, 2009; Gaston *et al.,* 2007; Fuller *et al.,* 2008).

There are a number of high profile long-running surveillance schemes focused around garden birds in the UK, including the Big Garden Bird Watch run by the Royal Society for the Protection of Birds (RSPB) and the British Trust for Ornithology (BTO), which engages with >400,000 volunteers annually to count birds visiting their gardens (www.rspb.org.uk/birdwatch); similarly, the BTO's Garden Bird Feeding Survey (https://www.bto.org/volunteer-surveys/gbfs) records birds using garden feeders.

Recent work by the BTO 'Birds and garden berries' study used volunteer observations to examine three elements of the relationship between garden birds and winter berries: berry availability through the winter months in gardens, how quickly berries were removed from the plants, and which birds took berries (http://www.bto.org/volunteer-surveys/gbw/about/background/projects/berries). This complements older observational work such as the seminal text 'Bird and Berries' by Snow (1988), and the earlier work by Gibb (1948) who collated observations from across the country on observed forage preferences of waxwings. Hawthorn berries were the main focus of birds until late January, changing around February to primarily rosehips, cotoneaster, and *Pyracantha* berries. These are all plants that occur frequently in UK gardens (Royal Horticultural Society, 2011; Armitage *et al.,* 2016), as well as hedgerows (Jacobs *et al.,* 2009).

These plants require pollination to some degree to produce fruit, birds will then eat the fruit, and the human population values interactions with those birds. In this case, provision of pollination is acting as a 'support' to a more direct ecosystem service of 'wildlife encounters' / 'wild species diversity' or similar (Costanza *et al.,* 1997; Wallace 2007; Haines-Young & Potschin, 2013). This is a less direct example of urban ecosystem service provision than crop production, but illustrates the multiples levels that consideration of ecosystem services can take (Fu *et al.,* 2011).

There is considerable overlap between advice lists of garden plants suggested to support birds (British Trust for Ornithology, 2012), and those for supporting pollinators (Natural England, 2007; Royal Horticultural Society, 2011; Garbuzov & Ratnieks, 2014b), with examples including Elder (*Sambucus nigra*), *Mahonia* species, and Honeysuckle (*Lonicera periclymenon*). However, demonstrating a link between these two ecosystem services is less clear. Does improved pollination of berry bushes improve winter forage availability for birds?

This project aimed to investigate the connection, and thus be able to provide recommendations for synergies in 'wildlife' gardening strategies.

A.2.2. Plant species

Plants were selected that were present on the Sussex campus, and which could have the exclusion method described below applied during the flowering period in spring / summer 2014. Two native bushes, more common to hedgerows, and two widespread garden introductions, were selected:

1) Common Hawthorn – *Crataegus monogyna*
2) Wall Cotoneaster – *Cotoneaster horizontalis*
3) Common Ivy – *Hedera helix*
4) Firethorn – *Pyracantha spp*. Exact variety unknown, but several of the same species were present within the experiment site.

Hawthorn

Hawthorn is common in hedgerows and woodland edges around the Sussex campus site. A self-incompatible native shrub, it shows little fruit set without pollination (Jacobs *et al.,* 2009). Hawthorn pollen is immature immediately after the flowers open, with anthers visibly pink and darkening as the pollen matures (Clapham *et al.,* 1989). Donor flowers will therefore be needed for cross-pollination.

Cotoneaster

Cotoneaster bushes are often recommended as a good plant to support birds due to extensive production of berries, which are particularly attractive to thrushes and finches (Snow & Snow, 1988; Corbet & Westgarth-Smith, 1992; British Trust for Ornithology, 2012). Several varieties of Cotoneaster are found on the Sussex campus site. *Cotoneaster horizontalis* was selected as the experimental plant, because it is both a garden shrub and also widely invasive in countryside areas (CABI, 2016a), making it a widespread resource. While *Cotoneaster* species are known to be partly apomictic (Pilkington, 2011), they do set seed and hybridise after cross-pollination action from bees (Randall *et al.,* 1996), and many other members of the Rosaceae show improvements in seed or berry numbers with cross pollination (Corbet *et al.,* 1991), thus this species was considered potentially suitable for the exclusion experiment. *C. horizontalis* has been listed on Schedule 9 of the Wildlife and Countryside Act since 2010 (Pilkington, 2011), but it is not illegal to offer it for sale for use in private gardens as the restriction present within the Act relates to causing the plant to grow 'in the wild'.

The pollen produced by *C. horizontalis* flowers is easily accessible and can be collected with a paint brush to allow for cross-pollinating.

Common ivy

Fruit-set in ivy has been shown to be significantly influenced by pollinator action, and reduced by exclusion using mesh bags (Jacobs *et al.,* 2009). Flowering usually occurs from September and the fruits ripen in March or April as the weather is warming, however individual plants may ripen fruit sequentially over a period of a few weeks. The flowers are attractive to a wide variety of pollinators, including wasps, bristly flies, honeybees and hoverflies (Garbuzov and Ratnieks, 2013; Jacobs *et al.,* 2010). Similarly, the berries are available for a long period of time and thus attractive to many bird species capable of eating them (Snow and Snow, 1988).

Pyracantha species

Another common garden shrub, planted for similar reasons to Cotoneaster varieties (although not considered to be invasive). Pyracantha is self-fertile but requires pollination to some degree, as insufficient pollination is known to be a problem for setting of ornamental berries (Royal Horticultural Society, 2014).

A.2.3. Method

The four species of berry bushes were assessed for their pollination requirement over the flowering season of 2014, using an exclusion method similar to that of Jacobs *et al.,*'s hedgerow studies (Jacobs *et al.,* 2010, 2009). Three treatments (netted, hand pollinated with cross-pollination, and left for local pollination alone) were applied to marked branches of the experimental bushes. Since pollen viability declines over time, and can thus impact on the success of hand cross-pollination (Stone *et al.,* 1995), pollen for hand pollination was collected from nearby flowers of the same species within the hour. Bagging was carried out using insect exclusion netting (‘Insect Mesh Woven Fine Netting’, manufactured by Intermas Group; INTERMAS NETS S.A., Ronda Collsabadell Barcelona, España), as this was moderately stiff and was possible to bend into the required shape, without touching the flowers, and secure in place.

Ten plants each of cotoneaster, hawthorn and ivy were selected on the Sussex campus sites at the start of April 2014. The locations of these plants are shown in Figure 1 below. For the *Pyracantha* experiment, four additional sites were located within private gardens in Brighton (belonging to local volunteers taking part in the *Bees ‘n Beans* experiment), because only one stand of *Pyracantha* bushes was found within the campus site. Since the additional bushes were in private gardens with restricted access, on these four sites the exclusion (netted) stems were compared only with local (open) treatments, with two replicates per site. Ivy flowers much later in the year, so stands of appropriate plants were identified and marked in April alongside the other plants, but treatments were not applied until August.

Experimental plants and inflorescences were selected before flowers opened; branches and inflorescences were then marked with labelled strips of dark orange tape at the base of the branches so that the colour would not interfere with insect attraction to any flowers. Inflorescences with 20-60 buds were chosen (depending on the species), and netted before the flowers opened. Electrical tape and staples were used to secure the necks of the mesh bags to prevent access by crawling insects. Sites were labelled as experimental areas, and all sites were photographed at each stage.

Once flowering was complete, all experimental branches were netted to protect ripening fruit. Mature fruit was counted, and fruit set compared between treatments. Analysis of the data was done in SPSS 23, using Generalised Linear models; negative binomial errors were used for analysing the count data; proportions of flower set were arcsin transformed to better fit linear errors.

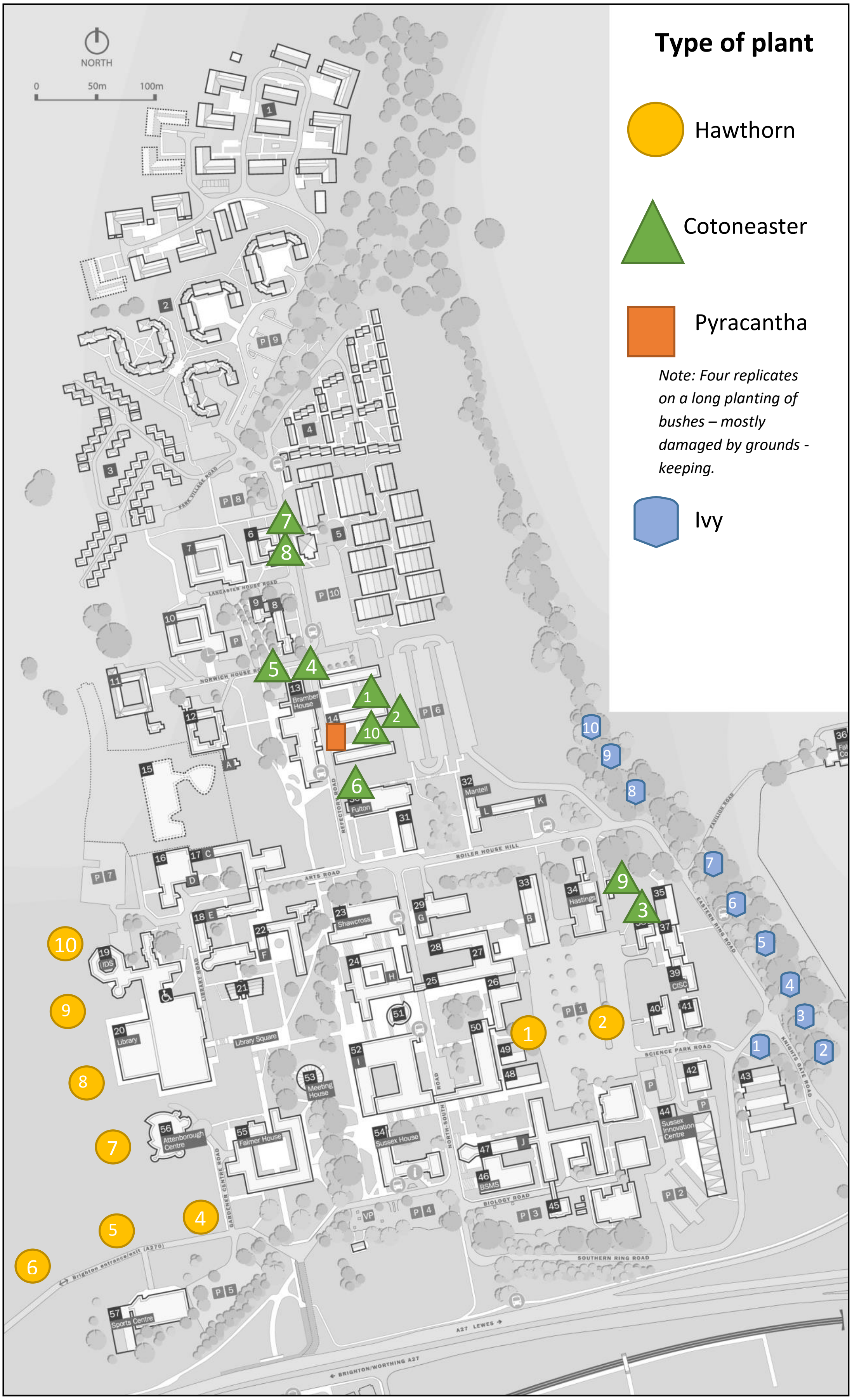


Figure 1: Locations of campus sites for hawthorn, cotoneaster, *Pyracantha* and ivy bushes.

A.2.4. Results

Although results were obtained from this study, this project was subject to a number of problems during the experimental period that were beyond the control of the investigator. The University Estates department were informed of the experiments and arrangements made, but grounds-keeping activities and re-development on the Campus resulted in some sites being compromised with bag removal and loss of labelling, and the loss of some entire sites.

Hawthorn

For the proportion of flowers that set fruit, both site of plant and treatment applied were significant factors (site: χ^2_9 = 164.9, p = <0.001; treatment: χ^2_2 = 35.9, p = <0.001, Figure 2). Both the local (χ^2_1 =17.1, p = <0.001) and hand pollinated flowers (χ^2_1 = 33.9, p = <0.001) set significantly more fruit than the netted control. There was no significant difference between the proportion of fruit set by local and hand pollinated branches (χ^2_1 = 2.85, p = 0.92).

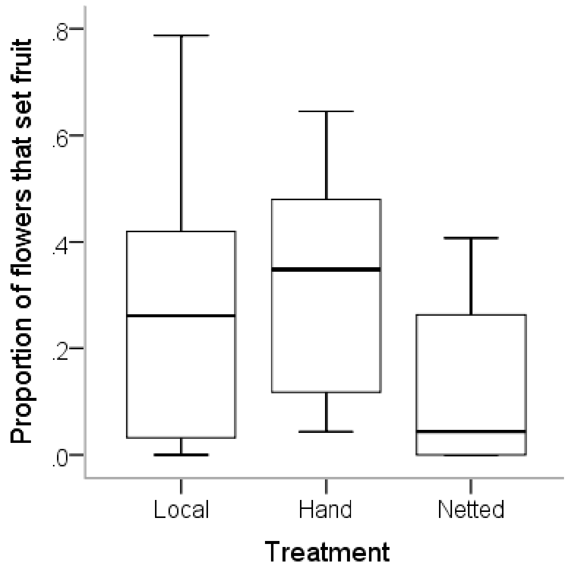


Figure 2: Proportion of hawthorn flowers that set immature fruit under different treatments in 2014.

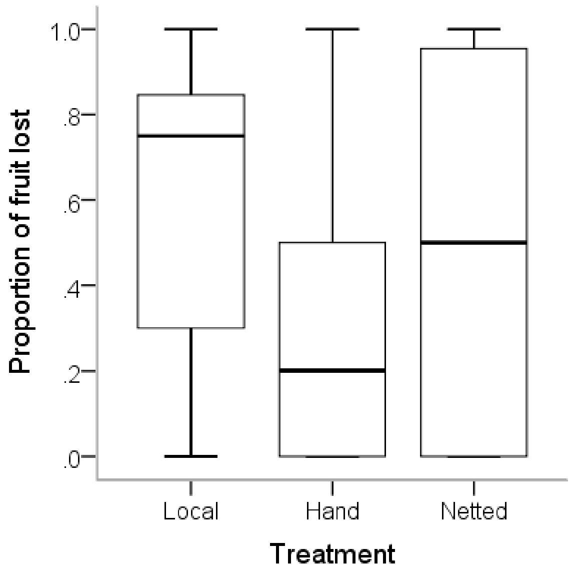


Figure 3: Proportion of immature fruit that were lost from the hawthorn plants under different treatments in 2014.

The proportion of immature fruit that did not mature was significantly affected by site (χ^2_9 = 82.9, p = <0.001), as well as by treatment (χ^2_2 = 9.42, p = 0.009, Figure 3). There was no significant different between local and netted treatments (χ^2_1 = 0.806, p = 0.369), but the proportion of immature fruit that failed was significantly less on hand pollinated branches than on local pollinated ones (χ^2_1 = 9.13, p = 0.003).

For the number of mature fruit produced by the experimental branches, only treatment applied showed a significant effect ($\chi^2_2 = 9.23$, p = 0.01, Figure 4), with hand pollinated branches producing significantly more fruits than the netted branches ($\chi^2_1 = 8.46$, p = 0.004; and local branches ($\chi^2_1 = 4.03$, p = 0.045). There was no difference in the fruit production between netted and local pollinated branches ($\chi^2_1 = 1.07$, p = 0.300).

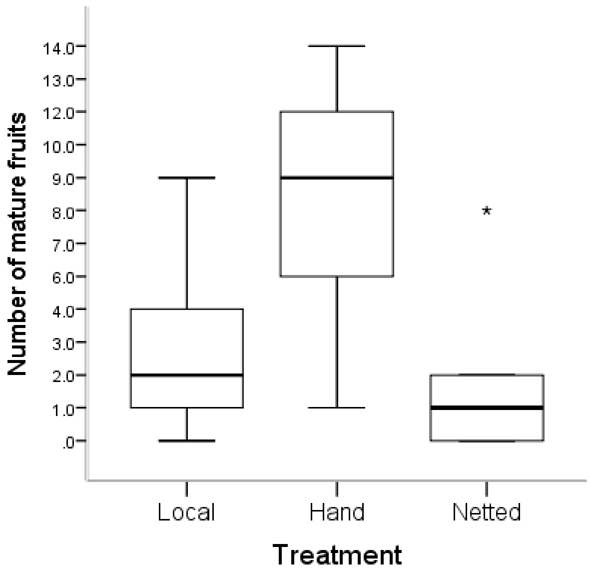


Figure 4: Number of mature hawthorn fruit produced under different treatments in 2014.

Cotoneaster

Four out of the ten cotoneaster plants were destroyed by grounds-keeping activities. One site became a car-park expansion, three more were lost due to hedge-trimming.

The remaining five sites, despite being visually similar, reacted so differently to the treatments that statistical comparison was not possible (Table 1). Replicates within the same large stand of bushes were similar, but between sites it became clear that these plants were actually different varieties.

The bushes were very heavily visited by honeybees and bumblebees whenever hand pollinating was being carried out. However, most of the bushes showed a very poor fruit-set of the locally-pollinated flowers, even with this observed high level of pollinator activity. In general, the level of fruit-set in the hand pollinated branches seemed to be more than the local or the excluded branches.

Table 1: Final number of mature fruit and percentage of original flowers that set fruit in cotoneaster plants; each plant with one of three pollination treatments applied to different branches.

Site	Treatment	Mature fruits	Fruit set
C1	Hand	20	68.97%
	Local	0	0.00%
	Netted	1	7.14%
C2	Hand	19	95.00%
	Local	7	28.00%
	Netted	0	0.00%
C3	Hand	lost	lost
	Local	lost	lost
	Netted	lost	lost
C4	Hand	25	100.00%
	Local	14	82.61%
	Netted	10	78.26%
C5	Hand	1	42.86%
	Local	0	0.00%
	Netted	0	0.00%
C6	Hand	lost	lost
	Local	lost	lost
	Netted	lost	lost
C7	Hand	16	64.00%
	Local	0	0.00%
	Netted	0	0.00%
C8	Hand	lost	lost
	Local	lost	lost
	Netted	lost	lost
C9	Hand	6	83.33%
	Local	6	60.00%
	Netted	lost	lost
C10	Hand	lost	lost
	Local	lost	lost
	Netted	lost	lost

Pyracantha

The *Pyracantha* bushes on campus were destroyed by groundskeeping action before harvesting could begin, and thus no result could be recorded.

One of the private domestic garden sites withdrew from the project due to personal reasons. The remaining three garden sites showed a low level of flower set (Table 2), but with only three replicates, little can be said with any confidence. One site, which had three bushes of the same age within the same area, found that only one of the three bushes produced any fruit at all, despite all other conditions being identical.

As with the cotoneaster, pollinator visitation of the plants was observed to be high, but did not seem to result in much fruit set.

Table 2: Final number of mature fruit and percentage of original flowers that set fruit in *Pyracantha* plants; each plant with branches either netted or exposed to local pollination.

Site	Treatment	Flowers	Mature fruits
G1	Local	75	6
	Netted	60	2
G2	Local	75	20
	Netted	61	5
	Local	80	23
	Netted	63	14
G3	Local	24	4
	Netted	24	7

Ivy

Ivy sites suffered heavy damage from animals (holes chewed in bags, bags removed) and grounds-keeping activities, and the experiment could not continue.

A.2.5. Discussion

Hawthorn

Hawthorn has a requirement for insect pollination, shown by the reduction in fruit production on branches with insects excluded; it also showed evidence of pollination limitation on the campus sites. While the proportion of flowers that set fruit was very similar between the local and hand pollinated treatments, the hand pollinated fruits were more successful in going on to maturity, with local and netted branches losing more immature fruit. This suggests that while the local pollination being provided to hawthorn was sufficient for fruit set to begin, the hand pollination may have delivered an improved *quality* of pollination, perhaps by delivering more pollen or reducing the proportion of geitonogamy (Wilcock & Neiland, 2002; Aizen & Harder, 2007). This is supported by the findings of Jacobs *et al.,* (2009) who demonstrated that fruiting success in hawthorn was limited by insect exclusion and improved by hand cross-pollination, compared to local effort alone.

Hawthorn typically flowers between March and June, with one of its common names: 'May Tree' indicating where the majority of this flowering is expected (Snow & Snow, 1988; Clapham *et al.,* 1989). The hawthorn on the campus site was flowering in early April, probably because Brighton is a very Southerly site with a warm climate (Met Office, 2016) and hawthorn is quite common in the experimental area (Figure 1). There are honeybee hives on the campus, and honeybees are an important pollinator of hawthorn (García & Chacoff, 2007). However it is possible that the pollination limitation shown by these bushes is in part due to an abundance of forage in the local area (those specific bee hives have been shown to have short foraging distances in spring, suggesting abundant local resources [Couvillon *et al.,* 2014; Garbuzov *et al.,* 2015]), and the bushes themselves may be flowering earlier than when populations of many other wild pollinators are typically flying.

When grown in gardens, hawthorn fruit set could suffer from pollination limitation in a similar way, with flowering ornamental plants perhaps distracting pollination activity away from the hawthorn. However, another risk for garden grown bushes is a high level of geitonogamy, leading to immature fruit loss, if there are no other hawthorn plants nearby for cross pollination. Thus, if planting hawthorn to support birds, the presence of other hawthorn bushes in the local area should be taken into account, considering at least the surrounding 500m in light of Garbuzov *et al.,*'s (2015) findings that urban honeybees forage in relatively small areas. If there are no other obvious hawthorn plants, the advice would be to plant two bushes in the same garden to improve the likelihood of cross pollination and correspondingly-improved fruit set.

Cotoneaster

Hand pollination seemed to increase the proportion of flowers that set fruit, ranging between 64 – 100%, and the netted exclusions did seem to greatly reduce the proportion of fruits set (0 – 7%) suggesting that insect pollination is required for berry development in the cotoneaster. However, the response to local pollination varied considerably, with three out of six sites setting no fruit at all, and three sites ranging between 28 – 83%. Yet pollinator activity was observed to be high on all the plants during the experiment, including honeybees and bumblebees, and individuals were observed foraging for both pollen and nectar at all sites, despite the differences in local pollination response. This supports the advice that these are good plants for provisioning local pollinator populations (Royal Horticultural Society, 2011; Garbuzov & Ratnieks, 2014b). However, the comparatively low fruit set on local pollinated plants also suggests that, at least for those varieties of cotoneaster, pollinator activity is high but not necessarily effective.

Pyracantha

The observation that three same-age *Pyracantha* bushes present in the same garden produced very different numbers of berries, despite co-flowering, suggests the plant may have more complicated fruit-set requirements than pollen limitation alone. Lack of other resources could lead to abortion of set fruit, or *Pyracantha* species may be affected by alternate bearing, where a plant produces an irregular crop load from year to year unrelated to pollination provision; this has been well-documented in other Roseaceae, particularly apples (Monselise & Goldschmidt, 1982).

Ivy

Ivy is known to provide significant quantities of pollen and nectar to insects during autumn (Jacobs *et al.,* 2010; Garbuzov & Ratnieks, 2013), and its berry provision is important for birds. Other work has shown a significant decrease in fruit set with insect exclusion (Jacobs *et al.,* 2009). Since ivy only flowers when mature (Doorenbos, 1965), if ivy is to have value for pollinator support as well as berry provision, stands in domestic settings should be maintained appropriately to allow the plants to reach that developmental stage (Gray, 2013).

Conclusions

This project aimed to investigate the link between winter forage for birds and the pollination requirements of the bushes that provide such. While the experiment suffered considerable setbacks, and will not be continued further into this PhD, some conclusions can be drawn.

Hawthorn was demonstrated to be reliant on insect pollination, and showed pollination limitation; thus efforts to improve hawthorn pollination would improve the resulting yields of berries. Determining which insects are the primarily pollinators of hawthorn, and if there are site-scale manipulations that would boost local populations of those insects, is an area to be developed. Immediate advice would be to ensure that there is cross-pollination available for deliberately planted bushes in garden environments.

Cotoneaster, while showing no clear link between the pollination experienced by the plants and the berry results, was utilised substantially by the bees present on the campus site. Advice in relation to this species would be: to determine when the most appropriate time to trim the bushes, to allow both flowering and berry development to complete. For ivy and *Pyracantha*, this project was not able to add anything else to the available scientific literature. However ivy is often considered to be an invasive pest (Lockton, 2009; Marrs *et al.,* 2010), so clear advice needs to be available for gardeners purchasing ivy to grow for berry provision, or about how to deal with existing stands.

The loss of experiments due to grounds-keeping activity highlighted the problems associated with carrying out research in public or semi-public greenspaces. The bushes in private gardens were kept in good condition and this illustrates the benefits of a citizen science approach, although some volunteer drop out will inevitably occur due to unforeseen circumstances.

A.3. Ideal container size for experimental *Vicia faba* plants (2014-15).

A.3.1. Introduction

The *Bees 'n Beans* experiment run in 2014 supplied participants with foldable 1.5L plastic pots to grow their *Vicia faba* broad bean plants in. Feedback at the end of the project indicated that these pots were prone to drying out, stressing the plants and increasing the risk of the experiment failing due to plant death. Before the 2015 run of the project, a small supplementary study was carried out to examine the health of bean plants grown in different sized pots, and determine what size was the most practical for including in the *Bees 'n Beans* kits.

A.3.2. Methods

V. faba seeds were germinated on damp tissue paper, to ensure that all seeds used in the experiment were viable. When the beans had sprouted, starting to produce a seedling stem and roots, they were planted 2cm deep in pots of fresh Levington M2 compost (supplied by Fargro Ltd, Vinery Fields, Arundel Road, Arundel, West Sussex, BN18 9PY). Five pots each of 1.5L, 2L, 3L and 5L were used, with 2x sprouting beans planted per pot; when the growing plants had reached 5cm in height, the weaker of the pair was removed. The resulting plants were kept in an unheated greenhouse and watered twice a week, in accordance with the *Bees 'n Beans* protocol.

Observations of the plants were taken weekly for nine weeks (10 weeks from sowing, including one week for sprouting the beans); the categories are listed in Table 3 below. The flower counts were used to determine if the total number of flowers formed by the plants varied in the different pot sizes.

Table 3: The different observations that were taken in order to assess the health of *V. faba* plants in 2014.

Count of…	Number of developing, unopened flowers Number of open flowers Number of gone-over flowers Number of bunches of flowers present on the plants (cumulative) Plant height (cms)
Measure…	Soil shrinkage (decreased mm from filled top of pot)

A.3.3. Results

Number of flowers

Figure 5 shows the cumulative total number of flowers on plants in different pot sizes in the last three weeks of the experiment. The larger pot sizes (3L and 5L) seem to result in a greater number of flowers than the smaller sizes (1.5L or 2L). One-way ANOVA of total flowers compared to pot size category was not significant ($F(3,8) = 3.59$, $p = 0.066$), but with post-hoc Tukey HSD test showing $p = 0.060$ ($M = 21.3$) difference between 2L and 3L pots, it may have been if more plants had been included in the comparison.

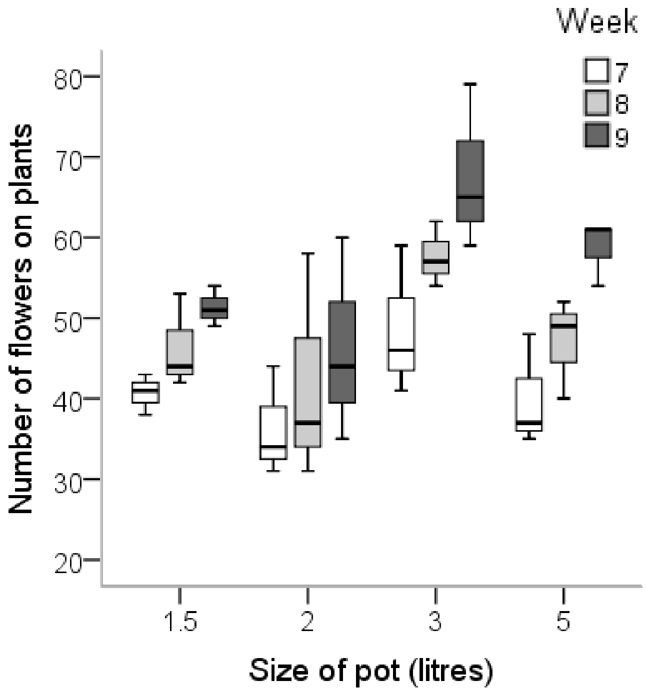


Figure 5: Cumulative total number of flowers per bean plant, counted weekly. Shown by the volume of the pot they were grown in.

Number of flower bunches

There was no significant difference shown by one-way ANOVA between the total number of flower bunches produced by the plants in different pot sizes ($F(3,8) = 0.134$, $p = 0.937$).

Plant height

There was no significant difference shown by one-way ANOVA between the final heights of the plants in different pot sizes ($F(3,8) = 1.23$, $p = 0.396$).

Soil shrinkage

No soil shrinkage was observed in the 3L and 5L pots. Both 1.5 and 2L pots all showed soil shrinkage of roughly 1cm from the top filled level; these pots also visibly dried out more often than the larger pot sizes.

A.3.4. Conclusion

Physical characteristics (height, flowers) of the plants did not differ significantly between the different pot sizes; although there seemed to be a trend for a greater number of flowers in the larger pots, it was not significant. The *V. faba* plants grown in 1.5L pots during 2014 should therefore be comparable to any later repeats that use larger pot sizes.

Soil in the 3L and 5L pots did not shrink or dry out, so even through the plants themselves were extremely similar across all sizes, larger pots make it easier to maintain a constant environment for the experiment. Drying out was a noted problem in 2014, so it was decided that subsequent runs of the experiment would use one of these larger sizes. Since 5L pots would need over three times the amount of soil as used in 2014, take up a lot more space, and there seems no difference between the 5L and 3L pot plants, 3L pots were included in the 2015-16 runs of *Bees 'n Beans*.

A.4. Sequential counting of *V. faba* pods

A.4.1. Introduction

During the three years of the *Bees 'n Beans* project, damage to plants from pests and environmental factors, such as changes in the weather, were major reasons for still-engaged participants withdrawing from the project. Attempts to limit these impacts (advising on pest control methods, detailed instructions and providing personal advice when approached) were somewhat successful, as was increasing the size of the pots used. However, particularly due to the warm UK winters in 2014-2016, damage from slugs and snails to experimental plants was a common problem (Buglife, 2016); this was discouraging for volunteers as well as detrimental to the project as a whole.

Another potential solution to this problem was examined in 2016, testing the use of sequential counting of set flowers. While the default *Bees 'n Beans* protocol requires participants to harvest all pods at the same time, counting and weighing mature beans and pods (Birkin & Goulson, 2015), the results of that three-year study suggest that weight of beans and pods may be more affected by the growing conditions experienced by the maturing fruit than by the pollination received (Section 3.5.). Therefore, keeping a record of the ongoing number of pods formed should provide at least a comparable 'number of pods' value, even if the plant itself is subsequently lost before full mature harvest.

A.4.2. Methods

In May 2016, 40 beans of 'The Sutton' dwarf variety of *V. faba* (supplied by Sutton Seeds, http://suttons.co.uk) were planted in individual root trainer modules (supplied by Tildenet Ltd, Journal House, Bristol, BS3 5RJ), transplanted into 3L pots when the plants were 10cm high, and moved outside. 22 plants were included in the study, each watered twice a week.

Sequential counting began in July when flowering started and continued for four weeks. Once a week, evidence of pod development was recorded, with any pods assigned a number based on where they had formed on the plant (flower clusters numbered in their position 'up' the plant, to avoid double-counting the beans). All bean pods were picked a week after flowering had finished, to allow any pods that were going to set to do so.

This study had a shorter timeframe than the *Bees 'n Beans* project, which estimates eight-to-nine weeks of applying the experimental treatments. This was partly because the beans were grown later in the year than the *Bees 'n Beans* project, and all in the same geographical location, whereas the main project instructions needed to be applicable throughout the UK, with northerly areas requiring a longer period of time than southern ones.

Results were analysed in SPSS 23, using Generalized Estimating Equations with Poisson errors; the number of set pods (of any size) as the response variable (count data) and the week number as the explanatory factor (categorical, ordinal).

A.4.3. Results

The number of pods increased significantly over the experimental period (χ^2_2 = 8.86, p = 0.012; Figure 6). Numbers increased until the third week of counting, with no significant change between the third and final (harvest) count (χ^2_1 = 0.148, p = 0.700). Maturing of pods is shown in Figure 7: while there was no difference in the number of pods between the third and final week, the pods present continued to get larger.

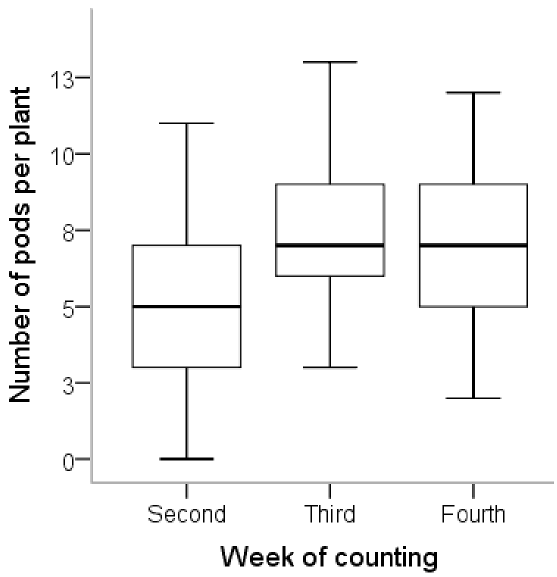


Figure 6: Numbers of pods per plant over the month of sequential counting. First week is not included since no pods were set yet.

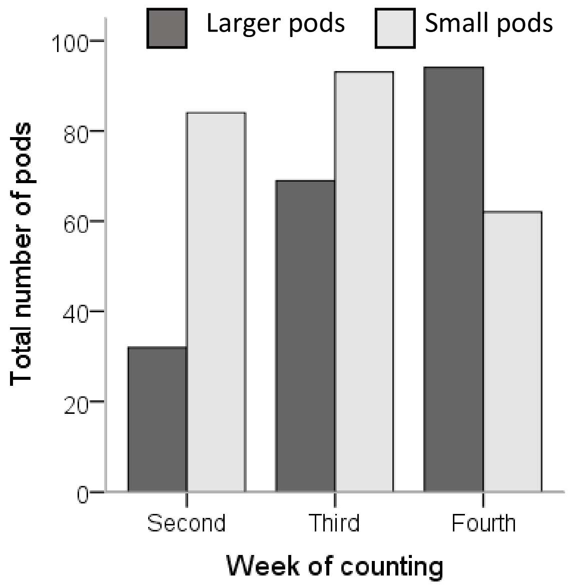


Figure 7: Total number of large and small pods over the month of sequential counting. First week is not included since no pods were set

A.4.4. Conclusion

The number of pods produced by the plants did not change significantly in the latter part of the project, although the size of those pods continued to increase. It would therefore be possible to include sequential counting in any further repeats of the Bees 'n Beans protocol, to ensure that some data could be returned even if plants were lost later as a result of pests. Volunteers would need to count the number of pods formed for at least the last month of the project, ideally throughout the whole flowering period. This may be more difficult for bagged plants, depending on the type of netting used, and may require the method of netting to be re-examined so it would be easier for bags to be opened and counted without introducing exposure to pollinators. Modifications to the recording sheets would need to provide somewhere for these results to be recorded.

A.5. Companion planting for *V. faba*

A.5.1. Introduction

Companion planting is a gardening technique that endeavours to protect or support one type of plant by growing a different species nearby (Franck, 1983). Deterrence of pests is a common rationale for these actions, using companions that produce compounds which have allelopathic effects on herbivores (Finch & Collier, 2012; Corbu *et al.,* 2014), but the idea of growing flowering plants to support pollinator populations for other nearby crops also fits under these criteria and is included in the idea of 'wildlife friendly' gardening (Loram *et al.,* 2008; Garbuzov & Ratnieks, 2014b). In 2015-16, the effects of co-planting tomatoes with 'pollinator friendly' plants were tested, both in more controlled conditions and within garden environments (Chapter 5), to examine if this sort of companion planting improved yields of tomato fruit as a result of 'magnet' effects drawing more pollinators into the area (Thomson, 1978; Laverty, 1992).

Both tomatoes and *Vicia faba* broad beans are pollinated primarily by bumblebees (Free, 1966; Banda & Paxton, 1990; Morandin *et al.,* 2001), and bumblebees in particular tend to be capable of switching their 'major' and a 'minor' flower of focus when foraging (Heinrich, 1979; Gegear & Laverty, 1998). Broad beans are used as the phytometer plant in the *Bees 'n Beans* projects, and the instructions do not restrict where in the garden participants are to place their experimental plants. If *Vicia faba* shows an effect of 'bee-friendly' companion planting on yields, then the instructions may need to be modified to take into account garden positioning.

This additional experiment was done in the summer of 2016 to indicate if effects of companion planting needed to be considered in more detail for further *Bees 'n Beans* recommendations.

Companion plants were selected based on the RHS 'Perfect for Pollinators' list, and what was seasonally available at the time of the experiment. The same variety of *Ageratum houstonianum* 'Blue Danube' plants were used as in the 2015 tomato study – since these plants did seem to be observationally attractive to pollinators, even if no effect was ultimately seen on the tomato yields – and in addition *Antirrhinum pendula*

('Snapdragons') were included. *Antirrhinum* flowers are also pollinated by bumblebees, requiring mechanical effort to open the flowers in a similar way to *V. faba* (Delaplane *et al.,* 2000), and produce large amounts of scent to attract bees (Dudareva *et al.,* 2000). These replaced 'Busy Lizzies' (*Impatiens walleriana*) from the tomato protocol, as the intention of this study was to see if *V. faba* pollination was helped or hindered by co-flowering attractive plants, so a more 'bee friendly' flower was included.

A.5.2. Methods

Thirty *V. faba* seeds were planted in May 2016 in individual 0.5L pots of 'Levington' multipurpose compost; plants were transplanted into larger 1.5L pots once they reached 5cm in height and grown on until 10cm tall before acclimating to outdoor conditions. Weak plants were discarded.

Companion plants were purchased as plug plants from Thompson and Morgan (http://www.thompson-morgan.com), repotted into 1.5L pots and grown on until the start of the experiment.

Twenty experimental planters were set up in June, each 40 cm x 30 cm x 20 cm (24 L) filled with 20 L of fresh Levington 'multipurpose' compost. Three *V. faba* plants were planted in a line down one side of each planter and companion plants down the other side, in the arrangement shown in Figure 8:

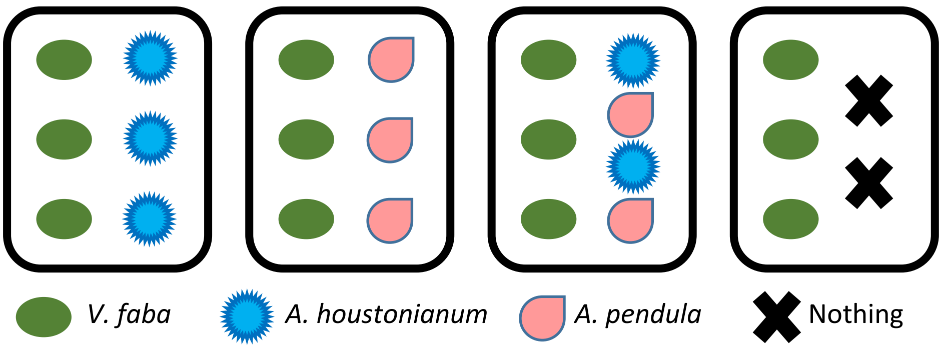


Figure 8: Arrangement of plants for each companion planting experimental group.

Each experimental group was positioned four metres apart, at least four metres away from any other flowering plants; with individual planters within a group two metres apart from each other. Plants were watered twice a week and maintained for ten weeks, as per the *Bees 'n Beans* instructions. When pods began to form, planters were fed with Levington '*Tomotorite*' liquid feed once a week according to packet instructions (20ml concentrate in 4.5 litres water). Companion plants were dead-headed as required to encourage continued flowering.

After ten weeks, the beans were harvested and counts of pods and beans, as well as their weights, were recorded. The data was analysed in SPSS 23 using Generalised Linear Models; negative-binomial errors with log link were used for count data; the square root of weights was taken to better fit linear errors. Number of beans per pod, per plant, and weight of beans per plant were used as response variables. Experimental group (the group of planters shown in Figure 8 above) and type of companion plant were fitted to initial models as main effects with interaction, simplification was done via stepwise removal of non-significant factors.

A.5.3. Results

There was no significant difference between any of the measures of yield for beans (Figure 9 and 10), associated with the different companion-planting regimes.

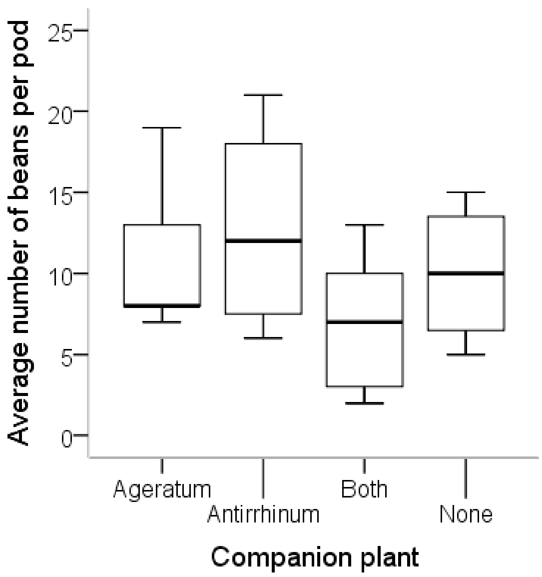


Figure 9: Average number of beans per pod, associated with the different companion plants.

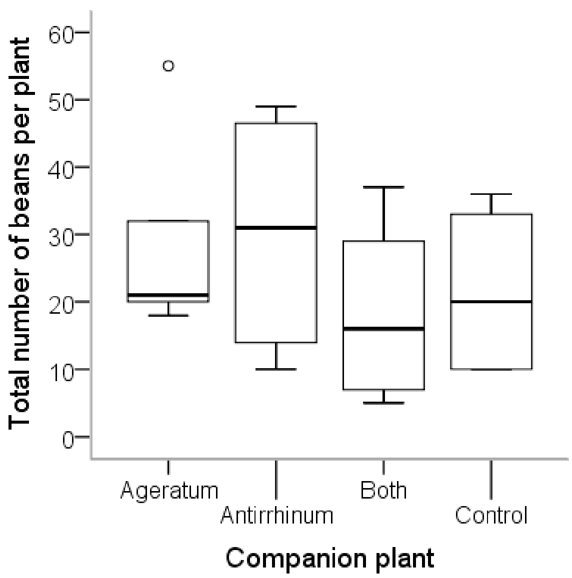


Figure 10: Total number of beans per plant, associated with the different companion plants.

A.5.4. Conclusions

The pollination service received by the bean plants seemed to be the same regardless of the companion planting type used, including the ‘bee-friendly’ plants compared to the empty control. Either the bean flowers are not pollination limited, and the pollinator density in the experimental area is sufficient for all of the flowers; or possibly the bean flowers are more attractive to pollinators than the ornamental plants around them. Either way, for the purposes of the *Bees ‘n Beans* experiment, this suggests that the experimental plants in participants’ gardens are not likely to be strongly affected by their positioning in regard to flower beds or other vegetables. There is no need to modify the instructions with a positioning requirement, other than to keep all experimental plants in the same environmental conditions (such as sun and shade).

A.6. School Spaces – piloting pollination projects in UK schools.

A.6.1. Introduction

Contact with the participants during *Bees 'n Beans* in 2014 indicated that the project had been taken on by science classes in six schools, as well as by some home-schooling families and extracurricular educational groups such as Scout troops, in addition to volunteers with young children. Recruitment for the 2015 version of the project focused more specifically on recruiting people with existing gardening experience, but it was also decided that the potential for this project to be specifically packaged for use as part of science education should be examined. As part of a possible monitoring schemes for UK pollination, involving schools in a longer-term project could be beneficial for both, as monitoring schemes require repeated data collection to observe trends (ideally from the same sites over time) and schools have an ongoing requirement to teach ecological subjects in a similar manner each year.

The protocol could be used to fit in Keystage 2 and 3 of the National Curriculum in England (Department for Education, 2013, 2014), to provide practical, visible demonstration of pollination interactions and to provide suitable flowers for observations of insect visitors. This fits in particular with the focus in Keystage 2 to understand about plant life cycles, and the role that insects and other invertebrates play in plant pollination (Sc2 3d); and the importance of plant reproduction to human food security (considered in Keystage 3), as well as forming a basis for practical work – including discussion of the need for replication and randomisation of treatment applications.

Partnerships with schools have been greatly successful in citizen science studies in recent years, with the recent UK Big Bumblebee Discovery project (sponsored by EDF Energy) receiving 26,868 bumblebee sighting records from 13,000 primary school children in 2014 and demonstrating the usefulness of focal plant observations; along with the importance of expert verification of those data (Roy *et al.,* 2016). Similarly, the RSPB's 'Big Birdwatch' projects include provision of educational resources to fit into the national curriculum (Royal Society for the Protection of Birds, 2017); and Buglife's 'Bee Lines' project has expanded to include packs and information to get primarily schools specifically engaged (Buglife, 2017b). These are primarily survey-style projects, but the ongoing work by Polli:Nation with 260 UK schools (Polli:Nation, 2015); and Pocock & Evans' (2014) 'Conker-tree science' project, looking at the spread of Horse Chestnut leaf miner; also demonstrate success in engaging school groups with more hypothesis-driven citizen science methodology.

Bees 'n Beans was presented at the Association for Science Educators (ASE) conference at the University of Reading on January 9th 2015 (http://www.ase.org.uk/conferences/events/2015/01/07/1391), to seek input from teachers involved in science education. Following this conference and feedback from volunteers who had used the project in an educational capacity in 2014, a schools-specific version of the protocol was developed for use in 2015.

A.6.2. Methods

The methods used were mostly identical to those of *Bees 'n Beans* 2015 (section 3.3.), with participants growing *V. faba* and *Raphanus sativus* plants under the three-level pollination treatment: bagged, hand pollinated, local pollinated. Instruction sheets were modified for schools, to provide easy to follow instructions and a separate, detailed reasoning provided for each section to allow teachers to incorporate the concepts into their own lesson planning.

The only methodological variation was that the schools' version started in mid-March rather than April, in order to better fit the project growing season into the typical UK school year, with the six-week summer holiday expected to start in late July. Participant schools were sent multiple packs of seeds, depending on how many repeats they indicated would be completed on-site. A specific sub-section to the LJBees project website was added for the 'School Spaces' blog, hosting pictures provided by participant schools and answering questions (http://www.ljbees.org.uk/schools).

Recruitment to the project was done using contacts obtained from the ASE conference, schools that had taken part in *Bees 'n Beans* 2014, the University of Sussex's existing schools outreach contacts and the social media employed for *Bees 'n Beans.*

A.6.3. Results

Thirty-three UK schools were signed up to the project. Setting up and planting stages were successful based on feedback, but some common problems occurred over the course of the project:

1) Ill-health of staff. Five schools had to withdraw from the project because the teacher who was overseeing the experiment was taken ill, and their replacement did not maintain the plants.
2) Timing mismatch. Because of the cold spring in 2015, even though the schools' bean plants were planted earlier, they were delayed compared to the plants used in 2014. This meant that the experimental stages fell during exam times or holidays, particularly the summer holidays.
3) Damage to plants from groundskeeping staff.
4) Staff finding that they could not dedicate sufficient time to the experiment.
5) One member of staff retired mid-year and the replacement did not continue with the experiment.

Fourteen sets of data were returned (42%, comparable to a completion rate of 41% for the *Bees 'n Beans* study in 2016), with most (8/14) of these from sites where only one repeat had been done on the school site. This was not enough to undertake a separate analysis, and since the delay in plant growth that occurred due to weather meant that the school project had progressed alongside the larger *Bees 'n Beans* study, the data was incorporated into that overall dataset for 2015.

However, despite these problems the project was well-received by the participants, with teachers generally notifying the project team when problems arose. The protocol and the learning aims provided on the website were commended as being a useful tool for ecology teaching.

A.6.4. Conclusion

The most common shared problem experienced by participant schools was the field season for *Bees 'n Beans* intersecting badly with term times. While the project was praised for its compatibility with science educational aims, in terms of the level of detail and accessibility for different age groups to take part, the flowering times were a drawback and led to several teachers taking the beans home to record final results during the summer holidays. There is still a potential synergy available between schools' needs to teach each new year of students similar information, and the requirement for monitoring to have repeated measures, but the current main *Bees 'n Beans* methodology would require some changes.

A possible solution to the timing problem would be to have a schools' version starting in September, with beans planted in the autumn for an early spring start. This would require the plants to be maintained for much longer, and means that the results would not be directly comparable to those collected during the April-planted project.

An autumn variation on *Bees 'n Beans* is a potential addition to any longer-term monitoring scheme, as it would allow the project to assess pollination provision earlier in the year with the same variety of plants, and a schools' pack may be better suited to inclusion in that modification. Schools could also use the sequential counting of pods (Appendix A.4.) to record on going pollination events, which would allow for additional collection of results and add immediate interest for the students.

Problems caused by ill health of staff members is not a predictable effect, however, if the project were more commonly used then more robust provision for dealing with unexpected changes of staff would likely buffer this; similarly, damage from ground staff or maintenance work is less likely for familiar experimental setups.

A.7. Regional analysis of *Bees 'n Beans* data 2014 – 2016

A.7.1. Introduction and rationale

Many existing biodiversity surveillance schemes present their data in the form of long-term trends for the whole of the UK and also broken down by geographical region, in order to give a more detailed picture of the status of their focal taxa throughout the country. The UK Butterfly Monitoring Scheme (UKBMS) produces trends for England, Scotland, Wales and Northern Ireland (Brereton *et al.,* 2016); and the British Trust for Ornithology's Breeding Bird Survey (BBS) produces country-level trends, as well as population trends in the English regions (Harris *et al.,* 2016).

Since drivers of change for biodiversity often vary geographically (Weber *et al.,* 2004; Westphal *et al.,* 2006; Magurran *et al.,* 2010), and analyses based at a level that is too broad may miss important changes in metapopulation effects (Hanski, 1999; Tscharntke & Brandl, 2004), it is important to be able to display and analyse data at an appropriate scale. For more mobile organisms that scale can be large, but for insects it may be much smaller (Blackburn & Gaston, 1994) and thus the most useful scale to consider insect-mediated pollination will vary with the type of pollinator being considered. Honeybees can potentially forage over 12km from their colonies, although urban populations in particular may find sufficient resources within the urban habitat matrix without moving out into surrounding rural environments (Garbuzov *et al.,* 2015). Wild bee species are much more varied in their observed or predicted foraging distances, ranging from a few kilometres to a few hundred metres (correlated positively with body size) (Greenleaf *et al.,* 2007; Osborne *et al.,* 2008; Zurbuchen *et al.,* 2010). The most common UK long-tongued bumblebee pollinator of *V. faba* is *Bombus pascuorum, which* has a foraging range of approximately 1km (Westphal *et al.,* 2006).

Given that the average garden area in the UK is under 200 square metres (Loram *et al.,* 2007; Davies *et al.,* 2009; see also the results sections above for *Bees 'n Beans*), the foraging ranges of long-tongued bumblebees are likely to overlap many gardens, so any pollination deficit detected would represent a potential loss of bees within a larger area than any individual site. Aggregation of the results from domestic gardens to larger scale categories would be needed to enable this type of project to be used as a monitoring scheme – low pollination in one garden may be as a result of individual garden management, but low pollination recorded in multiple gardens within the same larger area would suggest a wider shortfall in bees numbers. If volunteers were numerous enough, aggregation of data into 1km squares (similar to the UK BMS / BBS schemes) would also allow a better match to habitat datasets such as the Countryside Survey, for mapping of service provision (Medcalf *et al.,* 2014). Other environmental characteristics, such as temperature and rainfall, could be recorded by volunteers or acquired from other datasets e.g. the Meteorological Office (Met Office, 2017).

The total number of successful returns received during the three years of *Bees 'n Beans* was 309 (80 in 2014, 115 in 2015, 114 in 2016), which allows an assessment to be made of *overall* presence of pollination deficit per year, but means that drawing any robust conclusions of smaller-scale provision is currently difficult, due to few repeats being available in each geographical area. However, it is possible to demonstrate how regional deficits *could* be identified within a wider scheme, using the Bees 'n Beans data, and a similar approach to that used in public health monitoring.

In the UK, incidences of infectious diseases are reported by doctors to Public Health England and average case numbers plus rates per population are produced at national, regional and county / local authority level (Public Health England, 2017). If incidence rates at any of these levels show a change compared to the usual baseline, this can be identified and specific effort focused on that geographical area to determine reasons for the change. A similar approach could be taken for pollination monitoring, showing the direction of regional and national trends, or allowing the identification of any sudden sharp declines. More detailed investigation can then be undertaken into the causes of abrupt changes, or on areas where trends continue to decline compared to national stabilisation (or improvements). Mapping pollination provision alongside environmental factors and landscape characteristics can be used to identify some causes of decline such as unusually harsh weather (Medcalf *et al.,* 2014); and areas of deficit can be further targeted with focused transects and standardised observations such as those suggested by LeBuhn *et al.* (2003) to directly explore changes in the insect population.

Since site postcode data were collected from *Bees 'n Beans* volunteers, it is possible to divide the national picture down into more local areas (e.g. county, local authority, postcode sector). Data could be analysed at any level, but enough samples are needed to ensure that those results are meaningful. Due to the numbers of successful returns, it was decided to examine these data at a regional level, to make sure that there would be enough repeats per category to have sufficient power.

A.7.2. Methods

Statistical analysis was done with general linear models (GLM) performed in SPSS 23. Total count of pod numbers per plant, and total counts of beans per plant were used as the response variables, using negative binomial errors. For both counts, Year of experiment, UK region and Treatment categories were fitted to the model as main effects, initially including all 2-way interactions and the 3-way interaction, with model simplification via stepwise removal of non-significant interactions and factors. Post-hoc testing was done via the SPSS GLM interface.

Regions were based on the former Government Offices of Regions (GOR) of England, still used by the UK Office for National Statistics (Office for National Statistics, 2017); Wales; Northern Ireland; and Scotland divided into Northern and Southern Scotland (where Northern Scotland is primarily the Highlands).

Ten of the thirteen UK regions had more than five data returns per treatment, per year during the three years of *Bees 'n Beans*. For years where a Region had received fewer than five returns in *one* treatment, but had enough in the others, that Region was also included in the analysis, which provided enough data to undertake an initial analysis at a sub-national level.

A.7.3. Results

Number of pods

There were no interactions present in the simplified model. The Treatment category had by far the most significant effect on the number of pods produced by the plants (χ^2_2 = 158, p = <0.001), with post hoc test showing that this was mostly due to the much lower number of pods produced by netted plants (χ^2_1 = 138, p = <0.001); no significant difference was shown between the number of pods produced by the local and hand pollinated plants (χ^2_1 = 1.52, p = 0.218). This is in line with the analysis of national data in section 3.4.5. Since the netted data was so different to the local and hand pollinated counts, the analysis was then split by treatment, looking at the netted data alone, and the two pollinated treatments together.

GLM analysis of the netted data alone, with region and year as fixed factors, showed no interaction (χ^2_{17} = 15.1, p = 0.588), and no effect of Year (χ^2_2 = 1.54, p = 0.463) or Region (χ^2_9 = 9.91, p = 0.358) on the number of pods produced (Figure 1).

GLM analysis of the local and hand pollinated data, with Region, Year, and Treatment as fixed factors, showed only an effect of Year on the total count of pods per plant (χ^2_2 = 7.42, p = 0.024). 2014 counts of pods were significantly lower than those for 2016 (χ^2_1 = 5.88, p = 0.015), and there was no difference between 2015 and 2016 counts (χ^2_1 = 0.016, p = 0.898). There was no significant interaction between Region and Treatment (χ^2_9 = 3.53, p = 0.939), nor from Treatment (χ^2_1 = 1.32, p = 0.252), or Region (χ^2_1 = 7.10, p = 0.627) on the number of pods (Figure 2).

Between 2014 and 2016 there were no regions where the hand pollination pod counts were consistently higher than the local pollination pod counts.

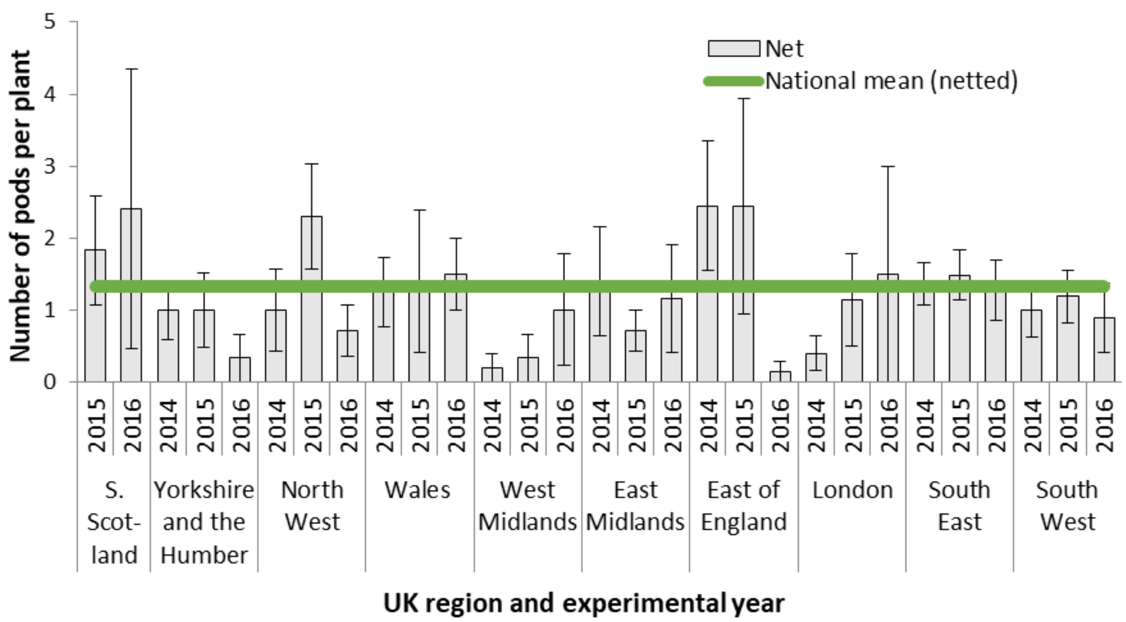


Figure 1: Average number of pods per **netted** *V. faba* plant, by UK region ± SE (10 / *13 UK regions returned sufficient data for inclusion)*. The national UK mean of pods per netted plant is also shown.

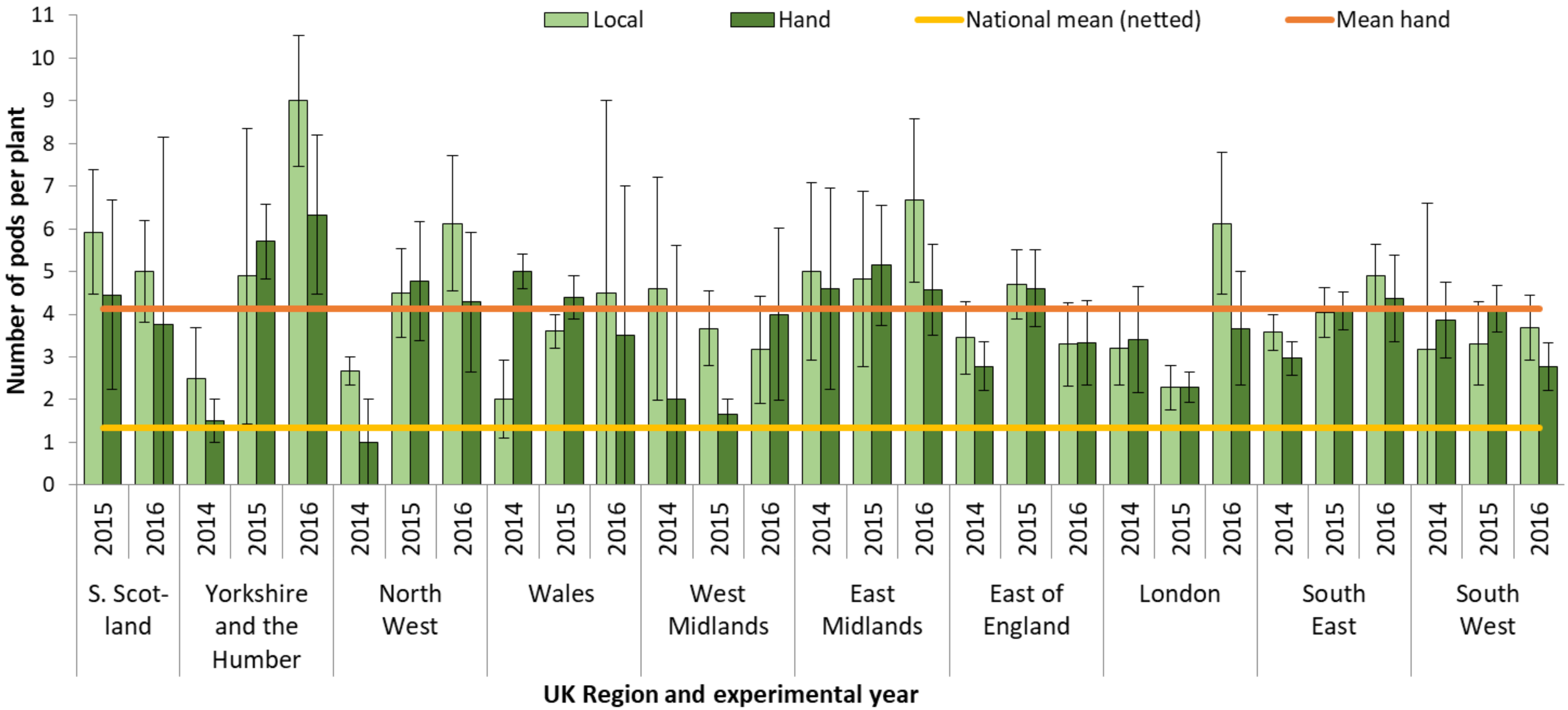


Figure 2: Average number of pods per *V. faba* plant, by UK region and treatment type (local pollinated and hand pollinated) ± SE. 10 / 13 UK regions returned sufficient data for inclusion. The national UK mean of pods per hand pollinated and netted plants are also shown (there was no significant difference shown between the local and hand pollinated plants, so only the two 'control' treatment national averages are shown, for comparison).

Number of beans

There were no interactions present in the simplified model. Similar to the pods data above, the Treatment category had by far the most significant effect on the number of beans produced by the plants (χ^2_2 = 243.8, p = <0.001), and post hoc test showed that this was mostly due to the much lower number of beans produced by netted plants (χ^2_1 = 199.0, p = <0.001); no significant difference was shown between the number of pods produced by the local and hand pollinated plants (χ^2_1 = 0.357, p = 0.550). Again, this is in line with the analysis of national data. Since the netted data was so different to the local and hand pollinated counts, the regional analysis of bean numbers was then split by treatment, looking at the netted data alone, and the two pollinated treatments together.

GLM analysis of the local and hand pollinated data, with Region, Year, and Treatment as fixed factors, showed only an effect of Year on the total count of beans per plant (χ^2_2 = 15.6, p = <0.001). 2014 counts of beans were significantly lower than those for 2016 (χ^2_1 = 14.7, p = <0.001), and there was no difference between 2015 and 2016 counts (χ^2_1 = 1.20, p = 0.274). There was no significant interaction between Region and Treatment (χ^2_9 = 2.76, p = 0.973), nor from Treatment (χ^2_1 = 0.325, p = 0.569), or Region (χ^2_9 = 13.9, p = 0.127) on the number of pods (Figure 3).

Between 2014 and 2016 there were no regions where the hand pollination bean seed counts were consistently higher than the local pollination bean seed counts.

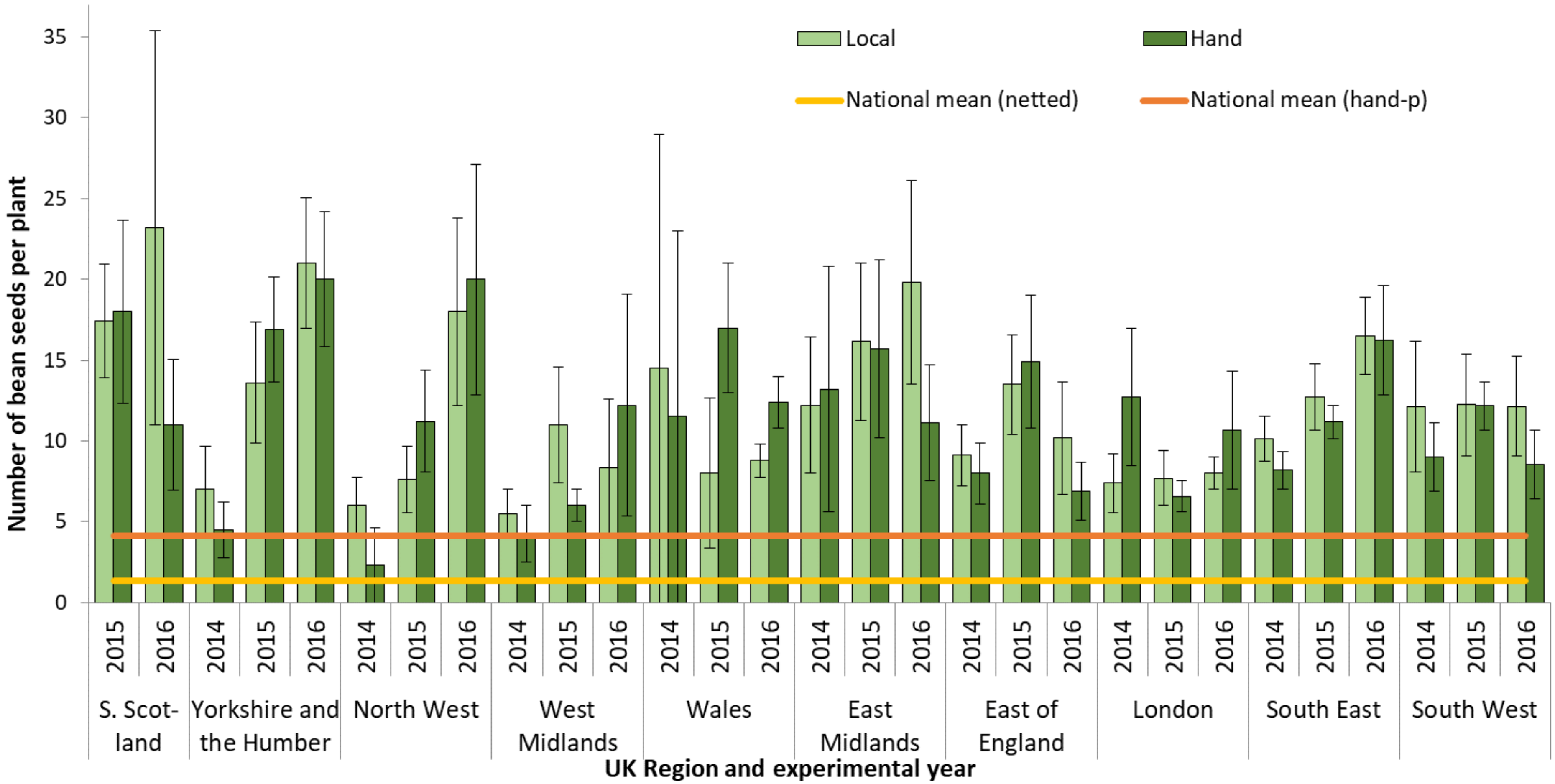


Figure 3: Average number of bean seeds produced per *V. faba* plant, by UK region and treatment type (local pollinated and hand pollinated) ± SE. 10 / 13 UK regions returned sufficient data for inclusion. The national UK mean of pods per hand pollinated and netted plants are also shown (there was no significant difference shown between the local and hand pollinated plants, so only the two 'control' treatment national averages are shown, for comparison).

A.7.3. Discussion

Regional analysis supports the overall conclusion in 3.5. that no deficit was detected in UK pollination of *V. faba*, at least for plants grown in gardens, in relatively small numbers. Where local and hand pollination levels are similar, differences in the average number of pods and beans produced are most likely to be due to environmental conditions (either good or bad).

While the analysis at regional level still covers fairly large geographical areas, it seems that this approach would work as a basis of a pollination 'alert' from a *Bees 'n Beans* type of surveillance scheme. Displaying the data on maps, nationally and regionally, using GIS methods such as those employed by Haines-Young & Potschin, (2013) and Medcalf *et al.,* (2014) could be used to show emerging patterns and how they are distributed across the country.

A national average calculated from more than three years of data would need to be developed, as well as baseline averages for all regions separately. This is to take environmental variation into account, since some areas of the UK may be environmentally poor for growing *V. faba*; meaning that lower base levels of yield in those areas compared to a national average may not necessarily indicate poor pollination – but a decline compared to the *regional* average might. Similarly, comparing changes in the pollinated treatments to the netted treatments could suggest reasons behind declines. For example, a 'local' value that is very similar to the 'netted' value indicates poor pollination in the area, but a *very* low 'local' value (or constantly zero) suggests that the local plants are dying or failing, rather than the low return being as a result of a loss of pollination. The presence of a pollinator-transmitted disease, such as a rust or powdery mildew (Batra & Batra, 1985; Agrios, 2004), could cause such a pattern, where the netted plant would not be affected due to exclusion of insects.

There are potential pitfalls associated with using a geographic approach to identify 'problem' areas. Analysis of data solely at a high level when there is an abundance of samples may mask much smaller areas where there is a specific problem, which would be recognised at a more local level. Conversely a very low level analysis of only local data may have insufficient information to be able to draw robust conclusions – which are particularly important if the analysis is intended to target more involved (and more expensive) monitoring. Thus, this need for sufficient coverage of results at an appropriate granularity would need to be built in to any monitoring system, including methods to target recruitment effort at comparatively ‘recorder deficient’ areas.

Chapter 4: Beyond Beans – monitoring the wider pollinator guild.

4.1. The requirement for extending the functional traits present in monitoring phytometers.

Pollination by animals – particularly by insects – is a vital ecosystem service for crops and wild plants worldwide (Corbet *et al.,* 1991; Delaplane *et al.,* 2000; Klein *et al.,* 2007), estimated to be worth between $112 to $200 billion annually (Costanza *et al.,* 1997; Kremen *et al.,* 2007), with agricultural pollination alone estimated as worth €153 billion a year (Gallai *et al.,* 2009). Thus, the evidence for ongoing declines in the populations of these key invertebrates is extremely concerning (Butchart *et al.,* 2010; Potts *et al.,* 2010; Vanbergen & Insect Pollinators Initiative, 2013), with knock-on potential impacts on biodiversity and human wellbeing (Haines-Young & Potschin, 2010; Sala *et al.,* 2012; Ellis *et al.,* 2015).

Conservation interventions to support pollinator populations – either specifically or as part of a broader biodiversity approach – have received recent increased political and public investment in response to evidence of those declines, at multiple scales (CBD Secretariat, 2010; Breeze *et al.,* 2012; Dicks, 2013; DEFRA, 2014). Some successes in slowing bee population declines has been demonstrated (Carvalheiro *et al.,* 2013; Gammans, 2013), but the majority of effort is ongoing and there is therefore a need for robust baseline and monitoring data about pollinator populations (Dicks *et al.,* 2013; Vanbergen *et al.,* 2014; Garratt *et al.,* 2014; Carvell *et al.,* 2016).

Most existing monitoring schemes are observational in nature (Bell *et al.,* 2008; Roy *et al.,* 2012a; Gardiner *et al.,* 2012), often using volunteers to record sightings of focal species either on a systematic or ad hoc basis (Westphal *et al.,* 2008; Gardiner *et al.,* 2012; Pocock & Evans, 2014; Dennis *et al.,* 2016; Roy *et al.,* 2016). The UK is currently developing national pollinator strategies which emphasise the use of such citizen science methods to collect data on pollinators and pollination provision (Scottish Government, 2013; Welsh Government, 2013a; DEFRA, 2014). Work completed as part of this PhD examined a proposed citizen science method for monitoring pollination in gardens, using a simple manipulation experiment carried out by volunteers on a focal plant: *Vicia faba*, the Broad Bean (Birkin & Goulson, 2015). The pollination requirements of *V. faba* are well understood, and cultivars of this plant are a commonly-used experimental plant in pollination studies (Free, 1966; Kendall and Smith, 1975).

However, the majority of pollination service to *V. faba* is known to be provided by long-tongued bumblebees (*Bombus pascuorum* and *Bombus hortorum* in particular [D. Goulson, 2003]), with much of the interaction with other bee species limited to robbing actions with much lower pollination service efficacy (Kendall and Smith, 1975). While these bumblebees represent common components of the pollinator guild, focusing pollination measures on only *V. faba* is likely to miss aspects of the overall service contribution provided by other bee species as well as other types of pollinator; flies, for example, have no notable interaction with broad bean flowers (Garratt *et al.,* 2014). A more complete assessment of the wider pollination service would include that provided by at least some of these other species.

There is also the issue of temporal coverage. Optimal conditions for *V. faba* growth is 15-20°C, especially during the reproductive phases of flower and pod development (Department of Environment and Primary Industries, 1994), so in the UK it tends to flower in May and June (depending on sowing date and weather conditions). Met Office data shows that these temperatures are regularly exceeded in England and Wales during later summer months, although Scotland does tend to remain cooler (Met Office, 2012). Temperatures are likely to be higher in many urban areas due to heat island effects (Wilby & Perry, 2006). To cover as much of the flowering season as possible, plants that flower later and have warmer optimal growth requirements should be included.

This chapter considers refinements and possible expansion of the *Bees 'n Beans* style protocol to improve the temporal and functional trait coverage of the proposed monitoring scheme (Birkin & Goulson, 2015; further detailed in Chapter 3 of this thesis) which were carried out in parallel to the *Bees ‘n Beans* project development.

Selection of the initial suite of potential phytometer plants (4.2.) used the same criteria as for *Bees*, leading to identification of the two plants used in 2014 in-house trials (4.3.), and refinement of the method for field trial in 2015 (4.4.), followed by discussion of the outcome and drawbacks found. Building on this, the 2015-16 project (4.5.) examined the use of a non-crop species, with testing of phytometer options in 2015 before the 2016 citizen science study, based on and reported akin to the *Bees 'n Beans* project. Future options for incorporation of this species and methodological variant in wider pollination surveillance are then presented.

4.2. 2014: Identifying potential phytometers

4.2.1. Selecting plants

V. faba was used as the phytometer (plant grown under controlled conditions to measure a response; in this case bean / pod yields) for *Bees 'n Beans*, and was selected accordance with the following criteria:

1. Reliant on pollination.
2. Easy to grow, from seed.
3. Quick to flower / annual.
4. Compact grow habit.
5. Attractive.

(See Chapter 3 for more detail about these categories.)

For an expanded protocol, plants were sought that were primarily pollinated by insects other than long-tongued bumblebees. Tomatoes, for example, were excluded despite fitting many of the criteria and being used in pollination studies elsewhere (Potter & LeBuhn, 2015), because they are pollinated by many of the same subset of the pollinator guild as broad beans, while being less reliable to grow. The use of tomatoes as a citizen science plant is considered further in Chapter 5.

In 2014, after review of the literature, eight species were selected to trial for the experiment. Table 2 summaries the suitability of each species against the selection criteria above.

Table 2(i): Beyond Beans experimental plant list, against selection criteria from Section 6.2.1.

Species	Reliant on pollination	Easy to grow seed	Fast flowers / annual	Compact	Attractive	Known pollinators	Problems
Sunflowers *Helianthus annuus* *Variety:* 'Dwarf Yellow Spray''	Yes. (Parker, 1981; Degrandi-Hoffman & Chambers, 2006; Greenleaf & Kremen, 2006b)	Yes	Yes	Yes Dwarf varieties are available.	Yes	Highly attractive to most pollinators. Wild bees and honeybees known to be important pollinators, potentially with synergistic effects when both present in an area (Greenleaf & Kremen, 2006b)	Flowers are very attractive, so may get pollinated in favour of other local plants; may not give a good representation of the local pollinator effort unless it is *very* low.
Coriander *Coriandrum sativum*	Pollination is via wind and insect action, with cross-pollination from insect transfer known to increase yield of seeds (Koul *et al.,* 1989; Chaudhary & Singh, 2011).	Yes	Yes	Yes	Yes	Widely visited by many insects, known to be popular with flies and honeybees (Chaudhary & Singh, 2011).	The flowers are much smaller than those of *V. faba* and therefore while hand-pollination for maximum yield may be *possible*, it might be tricky to use in a very simple citizen science protocol.

Table 2(ii): Beyond Beans experimental plant list, against selection criteria from Section 6.2.1.

Species	Reliant on pollination	Easy to grow seed	Fast flowers / annual	Compact	Attractive	Known pollinators	Problems
Fennel *Foeniculum vulgare*	*Plants are self-compatible, protoandrous, and improvements in yield with better pollination (wind & insect) shown* (Gross *et al.,* 2008).	Yes	While not an annual, fennel will flower and set seed in its first year.	Possibly. Plants can get large, but unlikely in first year.	Yes	Widely visited by many insects, with flies a potentially important pollinator.	Plants may be much larger than ideal for this experiment, although if they do not reach this size in the first year and do still set seed, then this may not be a problem.
Buckwheat *Fagopyrum esculentum*	An obligate cross-pollinating crop because of its sporophytic self-incompatibility system (Adhikari & Campbell, 1998).	Yes	Can flower as little as three weeks after planting.	Yes	???	Honeybees, but a significant potential contribution from other insect groups has been shown, and it is suggested that small, non-honeybee insects have the potential to maintain half of the yield of buckwheat in areas where there are few honeybees (Taki *et al.,* 2009, 2010).	These plants might be tricky to cross-pollinate manually due to the two types of flower they produce. Seeds will be ripening on lower flowers while higher up ones are still in bloom; it might be difficult to get a standardised time for harvest, without losing seeds.

Table 2(iii): Beyond Beans experimental plant list, against selection criteria from Section 6.2.1.

Species	Reliant on pollination	Easy to grow seed	Fast flowers / annual	Compact	Attractive	Known pollinators	Problems
Field poppy *Papaver rhoeas*	Field poppies are self-incompatible (McNaughton & Harper, 1960; Wheeler *et al.,* 2009) and require insect pollination.	??	Yes	Yes	Yes	Generally attractive to pollinators.	Unsure how reliable seed head / seed measurements will be.
Cornflower *Centaurea cyanea*	Yes	Yes	Yes	Yes	Yes	Honeybees and bumblebees; native pollinators.	Might be difficult to grow from seed.
Garlic chives *Allium tuberosum*	Yes	Yes	Probably	Yes	Yes	Generally attractive to pollinators.	Might not flower well in the first year.
Radish *Raphanus sativus*	Yes The variety used was the 'Rat Tail Radish' heirloom variety, grown for its seed pods – and these *do* need pollinating.	Yes	Yes	Yes	Yes	Flies; generally attractive to pollinators (Sampson, 1957; Steffan-Dewenter & Tscharntke, 1999).	Small flowers may be difficult to hand-pollinate. Vulnerable to pests if being left long enough to seed.

4.2.2. Growing plants

Of the eight plant species listed in Table 2, only the literature available for sunflowers (*Helianthus annuus*) and coriander (*Coriandrum sativum*) provided sufficient evidence of their pollination requirements to justify application of the full three treatments (excluded, local pollination and hand pollination). The other plants were grown with the intention of comparing just local and exclusion (netted) treatments, to see how easy they were to grow, and whether there was a sufficient difference between netted plants and open pollination plants to suggest they would be useful in this methodology. However after the radish (*Raphanus sativus*) plants grew extremely well, it was added to the full-treatment group, using extra plants to make up the pollinating spares. Table 3 shows the numbers of each species planted.

Table 3: Number of plants of each species grown for the 2014 comparison study.

Plant	Open	Cross	Netted	Spare / extras
Sunflower	15	15	15	15
Coriander	15	15	15	15
Fennel	10	-	10	10
Buckwheat	10	-	10	10
Cornflower	10	-	10	10
Garlic chive	10	-	10	10
Poppy	10	-	10	10
Radish	10	10	10	10
Total plants:	**310**			

Coriander, sunflower, buckwheat, and field poppy seeds were supplied by Thompson and Morgan (http://www.thompson-morgan.com). Garlic chives, fennel and radish seeds were supplied by Sutton Seeds (http://www.suttons.co.uk). Cornflower seeds were supplied by Mr. Fothergill's Seeds Limited (www.mr-fothergills.co.uk).

The aim was to grow enough plants to provide for ten or fifteen replicates of each species, depending on how confident the initial assumption of suitability was. So for sunflowers, radishes and coriander, which were the plants that best fitted the criteria and thus included the hand pollination treatment, this meant four mature plants per replicate (one a spare for pollen provision); for the other plant species that were to use exclusion and local treatments only, this meant two mature plants per replicate.

To be a suitable phytometer, it must be possible to sow and grow the plants to usable maturity in one field season. Seeds for all species were planted in April 2014 in the Sussex campus greenhouses. All seeds were sown in accordance with packet instructions, in seed trays using Levington M2 compost (manufactured by Everris; West Rd, Ipswich) and kept adequately watered.

Seedlings were thinned as required, and transplanted into 1.5L pots when young plants were large enough to handle without causing damage, which varied slightly by species. Plants were staked using garden canes as necessary to provide support.

4.2.3. Results: Successfully-grown experimental plants.

The study was completed successfully with the radish plants (‘rat tailed’ radish heritage variety), and sunflowers ('Dwarf Yellow Spray'). The other plants either proved difficult to germinate, grow on, or were not suitable for the experimental manipulations required (the coriander plants in particular were very inconsistent and easily damaged), the reasons for unsuitability are detailed in Table 4 below.

Table 4: Reasons for removal of potential phytometer plants from the experiment in 2014.

Plant	Reason for unsuitability
Coriander	Plants very slender, growth habits not standard, and *very* prone to damage even in a greenhouse environment. Unlikely to be suitable for netting in a garden environment, or handling by volunteers for hand pollination.
Fennel	Grew well, but did not produce flowers in the time required.
Buckwheat	The plants bolted easily. Plant were very slender, they fell over easily and tended to snap under their own weight. Not suitable for handling.
Cornflower	Only three of the plants flowered in time; low rate of germination.
Garlic chive	Difficulty establishing, and none of the plants flowered in time.
Poppy	Very low germination. One flower produced.

Sunflowers germinated well and the seedlings were easy to grow under greenhouse conditions (Figure 1a and 1b). They required staking for support and the plants reached the expected height of approximately 50cm. Each plant produced one large flower, and then some subsequent smaller flower heads, although these secondary flowers were much smaller and in most cases did not open.

Figure 1: a) Mature (flowering) dwarf sunflower; b) Sunflower netted before petal open, to exclude pollinators; c) Radish flower spike, showing multiple small four-petal flowers; d) radish plants before flowering, supported by cane in the greenhouse.

Radishes germinated well and grew easily in the greenhouse conditions (Figure 1c and 1d). While the plant leaves were quite brittle, and slightly irritating to touch, they seemed to survive damage well and when the flower spike was produced it was obvious.

4.3. 2014: Applying the pollination method.

Pollination service was to be measured directly by comparing yields produced under exclusion and supplemental hand pollination treatments, to those from plants that received local pollination action (Birkin & Goulson, 2015; Carvell *et al.,* 2016). The treatments used are summarised in Table 5 below, and were applied randomly to the experimental plants.

Table 5: The pollination treatments used in the *Beyond Beans* protocol.

Treatment group name	**Treatment applied**
Netted	Plant covered in netting or horticultural fleece to exclude pollinators
Local Pollinated	Plant allowed to be pollinated by the local pollinators
Hand pollinated	Plant allowed to be pollinated by the local pollinators and pollination supplemented by hand pollination every two days

4.3.1. Sunflowers

The plant

An annual in the family Asteraceae, the large characteristic heads consist of many individual flowers which mature into seeds. Pollination is required for seed set (Degrandi-Hoffman & Chambers, 2006; Greenleaf & Kremen, 2006; Parker, 1981). The open flowers are known to be attractive to wild bees and honeybees, potentially with synergistic pollination effects when both present in an area (Greenleaf & Kremen, 2006b). Sunflowers are used as the focal plant for the Great Sunflower Project in the USA (Oberhauser & LeBuhn, 2012), so have existing usage within citizen science projects, although these flowers are used as a platform for observation of visiting pollinating insects rather than pollination measured directly.

Method

Sunflower plants were grown in accordance with the method in 4.2.2., using the variety 'Dwarf Yellow Spray'; as a compact dwarf plant suitable for container growing. Fifteen replicates were distributed around the Sussex campus, with three plants per treatment (and a spare for fresh pollen). Due to the size of the plants, netting of the control plant was achieved by fixing a tube of insect-proof mesh (of 0.75mm x 0.75mm mesh size) around the whole plant, folded under the base and around the supporting cane to exclude pollinators ('Insect Mesh Woven Fine Netting', manufactured by Intermas Group; INTERMAS NETS S.A., Ronda Collsabadell Barcelona, España).

Hand pollination was performed by transferring fresh pollen (from a spare plant) to the open flowers in the experimental flower head using a soft muslin cloth; the cloth was moved in a gentle, inward-spiral to minimise loss of pollen. This was done twice a week, at or around midday during the flowering period, in dry weather.

When flowering had finished (in early September 2014; approximately 20 weeks after planting), the sunflower heads were left to develop and dry out on the plant. Once the back of the flower heads had turned brown and dry they were removed and transferred to marked trays in a warm greenhouse to dry completely. Only the first, main flower formed by each plant was included in the next stage of the experiments, as not all of the plants produced additional flowers, and in those that did many of the secondary heads did not open properly and were very small.

The number of seeds were counted; divided into categories of 'mature' seeds, which were dark and hard; and 'immature' seeds, which were softer, lighter and smaller. Seeds were weighed using an electronic balance.

Statistical analysis was carried out in SPSS 22, using Generalised Linear Models (GLM) to compare the yield measurements (number and weight of seeds), with 'Treatment' as the explanatory factor. Weights of seeds were analysed with normal errors; seed numbers were analysed with negative binomial errors with a log link.

Results

Of the original 15 experimental repeats, 11 produced usable results; four repeats were destroyed by mice.

Table 6: Total number of sunflower seeds and average weight of one seed from 2014 (n=11).

Treatment	Total number of seeds	Average weight of a seed (g)
Local	3407	0.260
Hand pollinated	3512	0.257
Netted	1532	0.375

Significantly more seeds were produced by the local pollinated plants than by the netted plants ($\chi^2_1 = 675$, p = <0.001). No difference shown between the number of seeds produced by the local pollinated and the hand pollinated plants ($\chi^2_1 = 1.60$, p = 0.207); shown in Figure 2a.

The total weights of seeds from individual flower heads ranged between 9.59g and 2.48g. The total weight of seeds produced by both the hand pollinated ($\chi^2_1 = 60.4$, p = <0.001) and local ($\chi^2_1 = 58.8$, p = <0.001) plants were significantly heavier than from the netted control (Figure 2b).

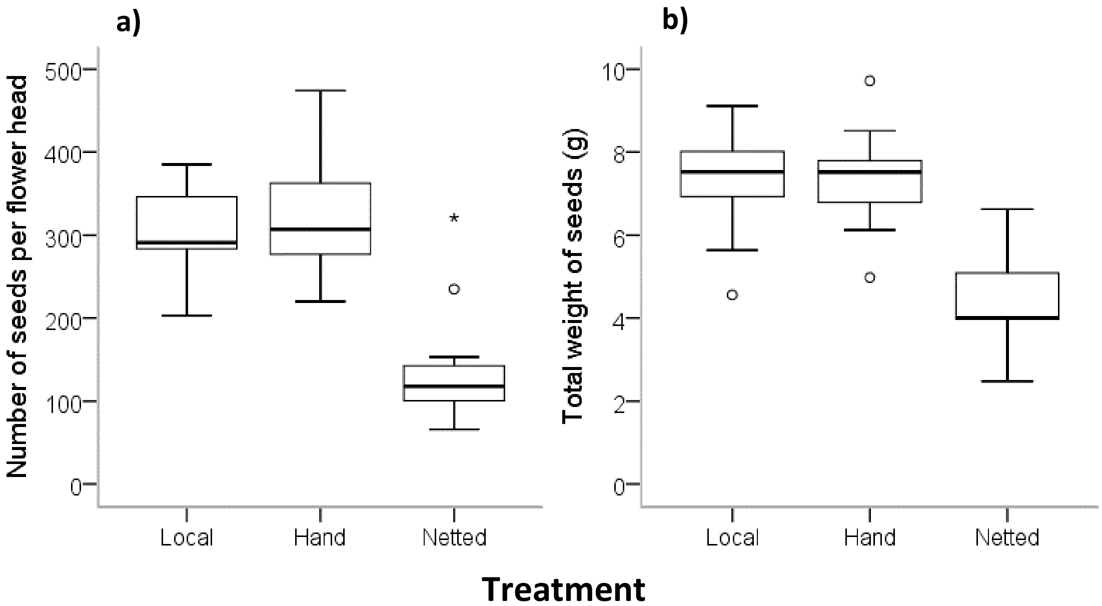


Figure 2: a) Number of mature seeds per flower head of sunflowers; b) total weight of mature seeds per flower head of sunflowers; under each pollination treatment in 2014.

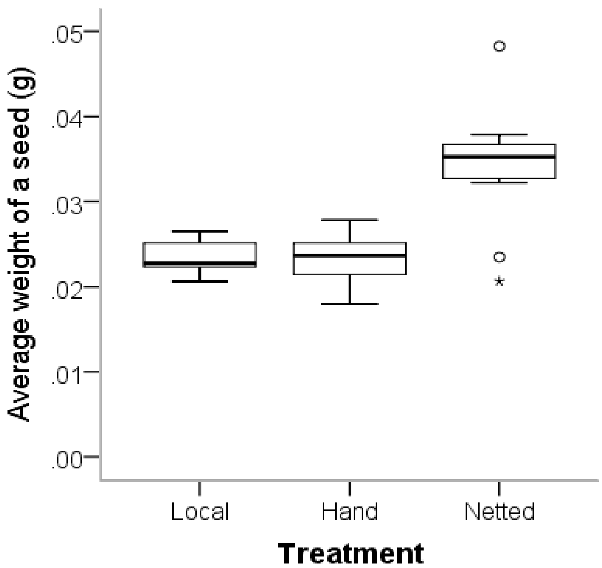


Figure 3: Average weight of one mature seed from the sunflower heads under each pollination treatment in 2014.

However, the average weight of a mature seed produced by the netted plants was significantly higher than the average weight of a seed produced by either the local ($\chi^2_1 = 29.8$, p = <0.001) or hand pollinated flowers ($\chi^2_1 = 31.1$, p = <0.001; Figure 3).

Problems encountered during experiment

Compared to *V. faba*, counting the sunflower seeds was laborious, time consuming, and required a much higher level of manual dexterity and visual acuity. Some darker seeds were very soft, thus difficult to assign to a category. Sunflower plants visibly suffered from slug and snail damage; in addition, the extra 'spare' plants kept in the greenhouses suffered from spider mites, although this was not observed outside.

Discussion

Sunflowers do show an effect of netting treatments, which suggests that they may be suitable for a pollination phytometer. No pollination limitation was found for these flowers on the Sussex University campus sites in 2014, since the hand pollinated and local results were not significantly different. The positioning of the sites was near to the on-campus hives, so honeybees in particular, as well as hoverflies and bumblebees were present, thus it is likely that the open flowers received adequate pollination.

Interestingly, and different to the pattern seen in *V. faba*, the level of pollination received by the plants did seem to show an effect on the average weight of the individual seeds produced, with mature seeds from netted plants much heavier, even though there were fewer of them produced overall. This may be because the plants have fewer viable seeds to invest resources into, due to low levels of self-fertility.

However, while sunflowers seem to be a potentially useful phytometer in a scientific setting, the experience of carrying out the study in 2014 suggests that these plants would not make a good addition to a citizen science protocol. Growing the plants is simple, but they suffer from slug damage like *V. faba* and have a lower tolerance for frosts. Frosts and chills are still likely early on in the season (particularly in the north of the UK), potentially increasing the time that plants would have to be kept inside volunteers' homes. Applying the treatments does not require more manual dexterity than the 'tripping' method for *V. faba* but counting the resulting seeds does, both in terms of extracting the seeds in the first place and sorting them when the flower head is disassembled. Flowers must be dried, taken apart and protected from mice, adding at least one more step to the process and making the counting procedure less attractive and accessible to volunteers. Determining whether a smaller or softer seed should count as 'mature' or not was also considered to be a potential source of confusion and frustration for volunteers.

In addition, the total weights of seeds recorded was very small, with less than 10g of seeds recorded from the largest heads. Volunteers from *Bees 'n Beans* (taken to be a reasonable representation of the population likely to continue to be interested in such a project) returned weight recordings for beans in whole grams and ounces in many cases (Chapter 3), because domestic weighing equipment does not generally weigh less than one gram accurately. With a mature bean averaging about 7g, potentially equivalent to an entire flower head's worth of mature sunflower seeds, this suggests that the margin of error for weights in sunflowers would be far higher.

4.3.2. Radishes

The plant

A fast-sprouting Brassicaceae most commonly grown as a root crop, although the flowers and seed pods of *Raphanus sativus* are also edible. The variety used in this study is primarily grown for its seed pods rather than its root, and is commonly known as the 'rat tailed' radish.

Radish flowers are perfect but self-incompatible (Sampson, 1957), so require insect-mediated pollination in order to set seeds. The flowers have four petals, obvious yellow pollen and a clear stigma (Figure 4a and 4b), so should be suitable for hand pollination with a small paintbrush. Pollination of radish flowers has been shown to be preferentially by smaller pollinators, such as solitary bees and hoverflies, possibly as a result of both bumblebee preference for deep flowers that offer a large nectar reward, and mechanical issues for larger bee species in remaining on the flowers to access them (Corbet *et al.,* 1995; Steffan-Dewenter & Tscharntke, 1999). This would make *R. sativus* a good companion for the bumblebee-focused *V. faba* in a wider monitoring scheme, as it would encompass pollination services from a greater section of the local pollinator guild.

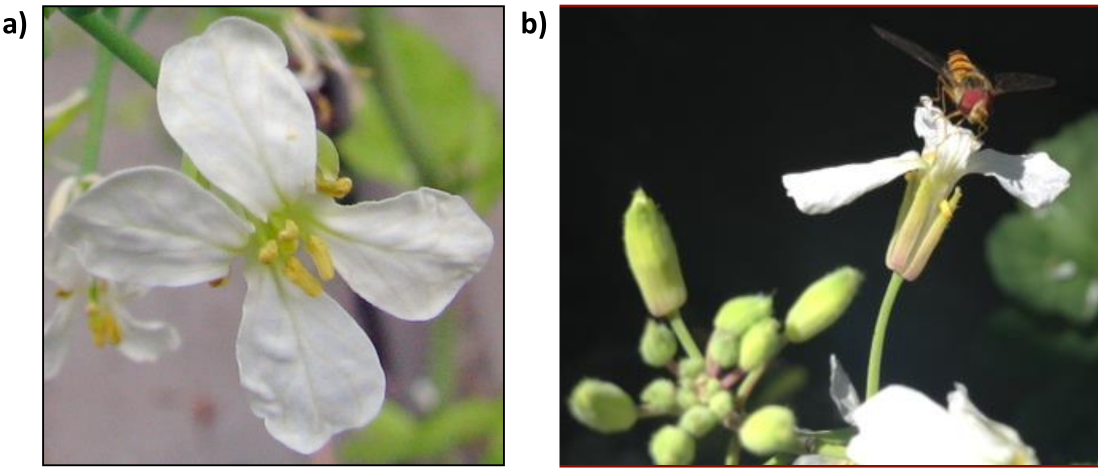


Figure 4: a) Radish flower, showing the yellow pollen and stigma in the centre; b) Radish flower with hoverfly (photograph by Leila Simpson, 2014).

Method

Plants were grown in accordance with the method in 4.2.2. Eleven repeats in total were put out around the Sussex campus (germination of seeds was so successful that there were enough spare plants to add an additional repeat), with three plants per treatment and a spare for fresh pollen.

Since radishes produce a tall flower spike which reaches ~1.5m height, netting of the plants was done by attaching a tall tube of insect-proof mesh (mesh size 0.75mm x 0.75mm) around the flower spike, fixed to the supporting garden cane. This was raised weekly as the experiment progressed. Three plants were covered with a soft net fabric rather than harder plastic mesh, to see which was a better method to use with this growth habit.

Hand pollination was performed by transferring fresh pollen from a spare plant to the open flowers, using a fine paintbrush. This was done twice a week at or around midday during the flowering period, in dry weather. Seed pods were left to develop on the plant, in accordance with the *Bees 'n Beans* style protocol, and all pods from all plants were harvested 16 weeks after sowing the seeds.

Pods were counted and weighed, then cut open and the number of seeds counted (see Figure 5). As the radish seeds are so small, and were in different stages of development, no attempt was made to weigh the seeds.

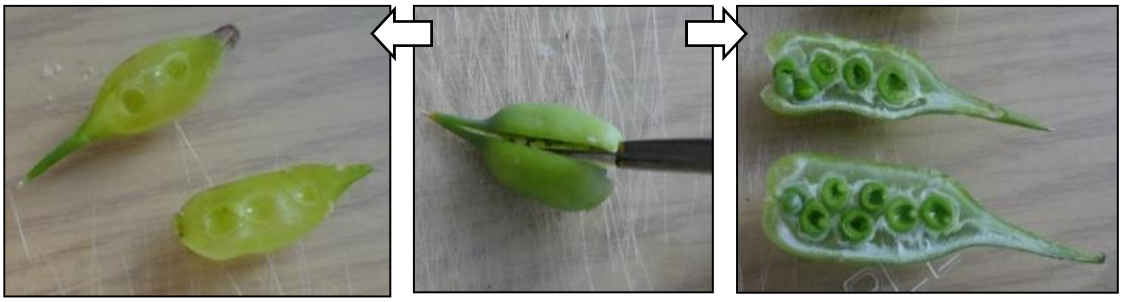


Figure 5: Examples of seeds in *R. sativus* pods. These are easy to count individual seeds (right), and clear from early on in pod development (left).

Statistical analysis was carried out in SPSS 22, using Generalised Linear Models (GLM) to compare the yield measurements (number and weight of pods, and number of seeds), with 'Treatment' as the explanatory factor. Weights of pods and average number of beans per pod were analysed with normal errors; pod and seed counts were analysed with negative binomial errors with a log link. Post-hoc comparisons were carried out through the SPSS GLM interface.

Results

There was a significant effect of the pollination Treatment received on all counts of pollination activity: total pod number ($\chi^2_2 = 12.1$, p = 0.002; Figure 6a); total seed number ($\chi^2_2 = 25.8$, p = <0.001; Figure 6b); average number of seeds per pod, $\chi^2_2 = 37.7$, p = <0.001; Figure 6c). For all of these measures, the netted plant count was significantly lower than the local pollinated plant (total pod number, $\chi^2_1 = 11.6$, p = 0.001; total seed number $\chi^2_1 = 22.4$, p = <0.001; average number of seeds per pod, $\chi^2_1 = 15.8$, p = <0.001).

Neither the total number of pods ($\chi^2_1 = 1.16$, p = 0.282) nor the total number of seeds ($\chi^2_1 = 0.064$, p = 0.801) differed between the local and the hand pollination treatment. However, the average number of seeds per pod was significantly higher in the hand pollinated treatments than the local pollinated treatments ($\chi^2_1 = 4.27$, p = 0.039).

Both total and average weight of pods produced by netted plants were lower than those produced by the local plants (total weight, $\chi^2_1 = 50.4$, p = <0.001, Figure 6d; average weight, $\chi^2_1 = 14.1$, p = <0.001); there was no difference in total weight or average weight between local and hand pollinated pods (total weight, $\chi^2_1 = 1.55$, p = 0.213; average weight, $\chi^2_1 = 1.11$, p = 0.293).

The number of seeds per pod appears to be determined in very early stages of pod development. Some older pods that were more developed (e.g. tougher, drier) were found that only had a few seeds in, whereas some of the younger pods were observed to have ~7 (as well as small ones that had only 1 or 2, and large ones with 7+). Radish seeds are easy to see with the naked eye as the pod is cut open.

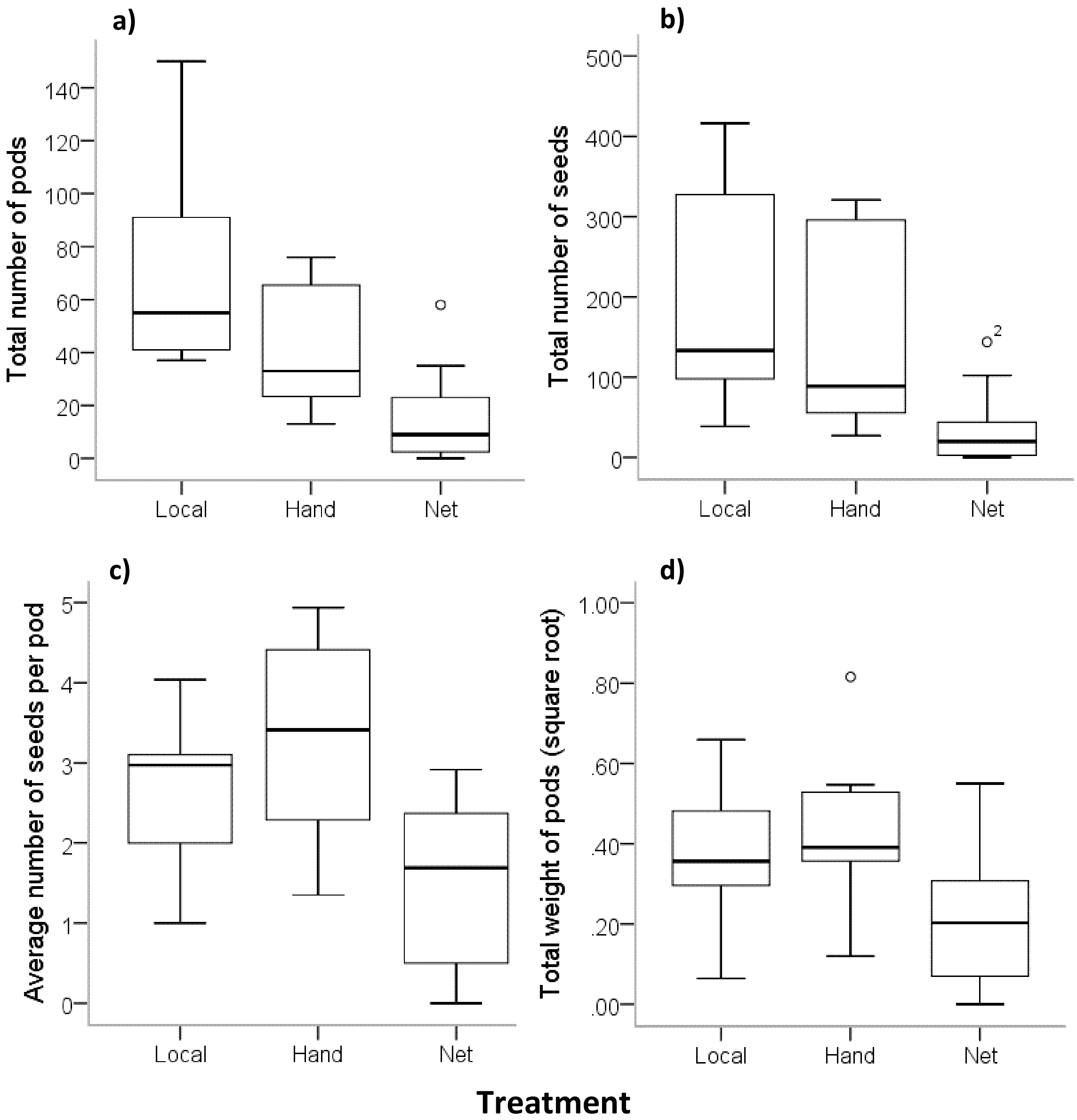


Figure 6: a) Number of pods per radish plant; b) Total number of seeds per plant; c) Average number of seeds per pod; d) Total weight of pods per plant; under each pollination treatment in 2014.

Quantified observations of the insect visitors to the radish flowers were not carried out as part of the protocol, but ad hoc observations of the plants in situ on site recorded a variety of potential pollinator species in attendance; these include: *Episyrphus* *balteatus* (marmalade hoverfly), *Scaeva pyrastri* (pied hoverfly), other bristly flies (not identified), *Apis mellifera* (honeybee), pollen beetles (various species, not identified), other small flies / wasps (not identified to species). Hoverfly larvae were also commonly observed hunting on the radish plants.

Problems encountered during experiment

Plants were quite brittle, with leaves prone to snapping, but this did not seem to be particularly problematic; by the time the flower spike started, the large root base built up kept plants anchored into the pot. Additional staking would be needed if plants grew taller, and using the stiffer mesh to exclude pollinators could potentially snap stems when moving it up the plants. This was not a problem when soft net was used.

Pieris rapae ('Small White' butterfly) larvae were found on the plants during the early stages of the project, and *Pieris brassicae* ("Large White") the later few weeks; in both cases the larvae were clearly visible and easy to remove by hand. The netted plants seemed prone to weevils building up in the net, but not to any obvious detriment.

Discussion

Radishes do show an effect of the exclusion treatments, so could be used as a pollination phytometer.

The higher average number of seeds per pod in the hand pollinated plants suggests that the local plants may be experiencing a limitation on their pollination provision on the Sussex campus, at least compared to the maximum control. However, there was no difference in the *overall* totals of pods and seeds produced by the two open treatments. In addition the hand-pollinated plants finished flowering faster than the local plants; while the netted flowers remained open considerably longer than either. This suggests that while the hand pollinated plants were receiving better pollination (potentially in terms of greater pollen loads delivered by direct brush transfer) and setting more seeds earlier in the experiment, a resource limit is being reached at that point, preventing more pods or seeds being produced. The local plants seem to also be reaching this limit, but it takes longer to do so.

All experimental plants were completely harvested at the same time, to follow the '*Beans 'n Beans*' protocol. Plants left in situ were observed to produce more flowers after pods had been removed, however, so it is possible that a sequential count would show more difference in total yields between hand pollinated and local plants, although it would be difficult to standardise in a citizen science protocol.

It was possible to count seed number easily when the pods were the advised size and ripeness for consumption (i.e. 'the width of a pencil', according to the Sutton's seeds website at http://www.suttons.co.uk). If participants were growing these plants for a citizen science protocol, they could be reasonably expected to harvest the pods once a week (or once a fortnight), and be able to record the counts and seeds while still having access to an edible crop. Accurate weighing of a few handfuls of light seed pods is likely to be a problem, considering the that normal electronic domestic scales generally weigh at one gram intervals, but pod counts do not have this limitation.

R. sativus fulfils the phytometer plant criteria proposed for use in a citizen science pollination protocol: responding appropriately to the experimental methodology, visited by a range of insect pollinators, and presenting as an interesting / attractive plant that should be easy for participants to grow. The mature plants seemed to be resistant to slug damage due to the slightly spiky and rough surfaces of the leaves, and recovered from both wilting in hot conditions, and temporary flooding due to flash rainstorms on-site. It was therefore decided to include *R. sativus* in the 2015 run of *Bees 'n Beans*.

4.4. 2015: Radish trial – 'Rolling out Radishes'

4.4.1. Volunteer recruitment

The 2015 run of *Bees 'n Beans* included *R. sativus* as a second plant. Recruitment of volunteers took place alongside that for the bean project, using the Beans 'n Bees web site (http://ljbees.org.uk), project twitter account (www.twitter.com/ljbees), and the Sussex University news website (http://www.sussex.ac.uk/broadcast/read/29334), as well the new Sussex University 'Buzz Club initiative (http://thebuzzclub.uk). Potential volunteers were asked to indicate if they would be willing to try growing this additional plant; just the beans; or just the radishes.

This modification was to ascertain if the radishes grew successfully in domestic gardens; if the plants were manageable as part of the protocol; and if the results demonstrated that *R. sativus* would be a suitable UK phytometer.

4.4.2. Modifications to project packs

Project packs for 2015 contained 20 radish seeds in addition to the broad bean seeds, and ten 3L '*Hadopots*', to be split between the two experiments.

4.4.3. Methods

504 volunteers (out of 515 total) agreed to grow the radish plants. Participants were required to germinate all seeds provided in the pack, in accordance with the detailed instructions provided (Appendix A).

Seeds were planted indoors, in commercial compost (or well-rotted garden compost), with four seeds per pot spaced out evenly, 1cm deep and well-watered. Once the seedlings had sprouted and were ~5cm tall, the smaller plants from each pot were removed, and the remaining plant grown on indoors until over 10cm high.

The radish plants produced large leaves and a flower spike from the centre of the leaf rosette approximately eight weeks after planting (shown in Figure 7a). This spike grows rapidly, and at this stage plants required a support cane adding, and the experimental treatments applying. As with the main *Bees 'n Beans* protocol, these treatments were: netted (pollinators excluded), local pollinated and hand pollinated (Figure 7b and 7c). A spare radish plant was retained to provide pollen for the hand pollination treatment. Volunteers were instructed to carry out hand pollination twice a week during the flowering period, and advised to use long enough stakes and enough fleece on the netted plant to allow the plant to grow substantially.

Harvesting of the radish pods was sequential, with volunteers picking and counting all 'pencil width' pods once every two weeks, starting as soon as the first pods reached maturity. This was to ensure that there was standardisation in picking, since part of the rationale was to determine if there was a difference between sequential picking and harvesting all pods at once (as was done in the 2014 in-house investigation).

Picked pods were cut open, the seed numbers within counted and recorded along with the harvest date. Volunteers were requested to harvest pods from all plants at the same time, which meant that the nets needed to be untied and retied if there were any pods present. Participants were not required to weigh the pods. The experiment finished when no further pods were formed, or at the end of September 2015.

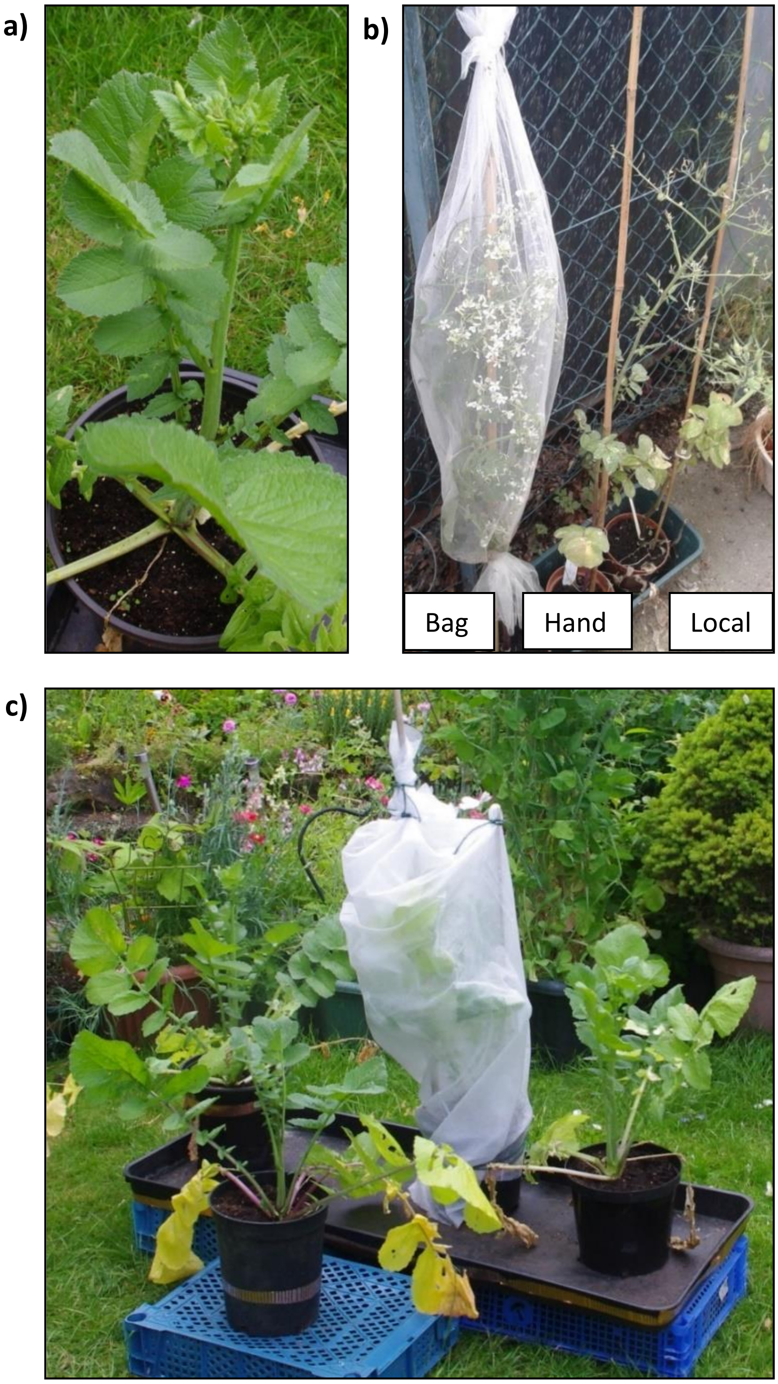


Figure 7: a) Flower spike forming. b) Radish experimental set-up instructions. c) *In situ* experimental set up.

Data was analysed in SPSS 22 using Generalised Linear Models (GLMs) and linear errors. Post-hoc pairwise comparisons were done through the GLM interface, with local pollination dummy coded as the reference group. Treatment type; site (each garden); garden size (m^2); site type type (e.g. individual garden, allotment); were included as main effects along with relevant interaction terms (against Treatment); model simplification was done via stepwise removal of non-significant factors.

4.4.4. Results

Pollination treatments

Of the initial 504 participants who indicated that they would be able to grow the radish plants, 36 usable sets of data were returned (7%; Figure 8).

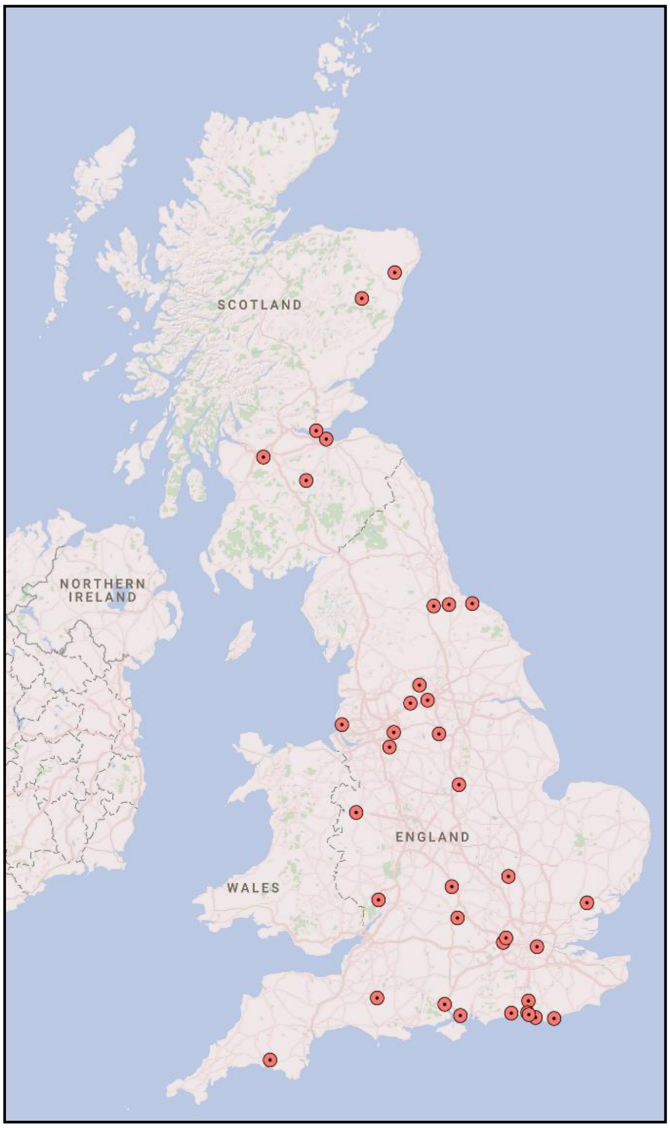


Figure 8: Location of completed radish plant returns (n=36) from *Bees 'n Beans* 2015.

Two further datasets were returned, but had to be removed from the analysis due to unusually high number of pods / seeds. In one of these sites, in addition to providing the numbers the volunteer reported that their hand pollinated plant had grown massively more than their other plants, producing 732 pods – seven times the number of pods than the average of open plants. In the other site, only the local plant survived but the return recorded 3,313 pods and 16,252 seeds from that plant alone.

Only the Treatment applied (netted, local, or hand-pollinated) was a significant factor influencing the total number of pods ($\chi^2_2 = 17.4$, p = <0.001) or total number of seeds ($\chi^2_2 = 18.8$, p = <0.001); none of the other factors had an influence.

There was no significant difference between local and hand pollinated plants in terms of the total number of pods produced ($\chi^2_1 = 0.018$, p = 0.893), the total number of seeds ($\chi^2_1 = 0.081$, p = 0.776), or the average number of seeds per pod ($\chi^2_1 = 1.34$, p = 0.247; Figure 9). Average seeds per pod ranged from zero to seven. The total number of pods ($\chi^2_1 = 13.6$, p = <0.001), total seeds ($\chi^2_1 = 15.2$, p = <0.001), and average seeds per pod ($\chi^2_1 = 22.9$, p = <0.001, Figure 9) were significantly lower from the netted plants compared to the local plants.

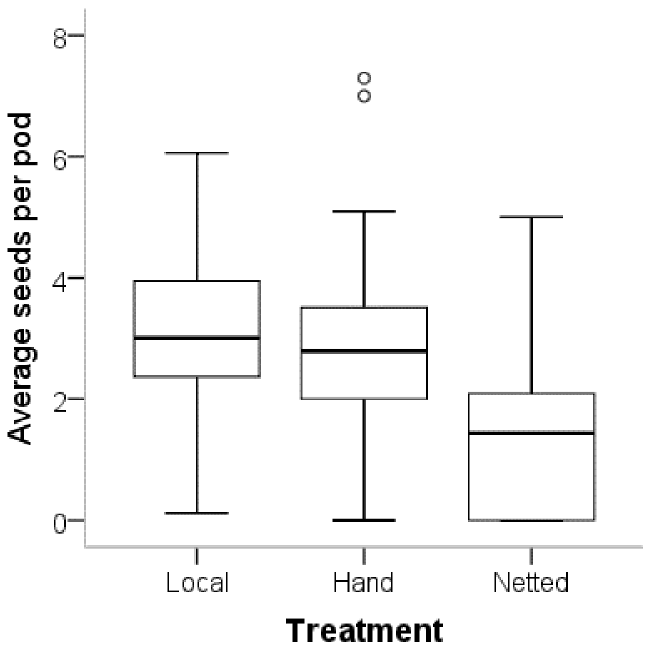


Figure 9: Average number of seeds per pod, by treatment type, in the 2015 radish plants.

Problems reported by participants

Problems were reported by participants during all stages of the experiment. Seedling establishment was an issue, with the radishes much less reliable in germinating and growing on to large plants than the beans. When plants did grow, the timing of flower spikes appearing and then flowering was a lot more variable than the timing of bean flowers opening. This resulted in sites without three plants flowering at the same time (even if multiples were grown). Mature plants also displayed much more variation in growth form than expected, with some plants producing very few flowers, and some becoming extremely large. Volunteers also reported more damage from slugs and other early pests than had seemed to happen on the campus sites in 2014.

4.4.5. Discussion

The similarity between the local and hand pollinated measures suggest that there was no pollination deficit detected in this study, although the numbers of results returned were small: 36, compared to 115 successful returns for beans in the same year. The effect of hand pollination in the 2014 pilot study – increasing average number of seeds per pod – was not seen this year.

Overall, the radishes performed much worse than expected as experimental plants. Few volunteers were able to successfully complete the experiment, even those who were able to do the *Bees 'n Beans* project without issue. 7% of total participants submitting a return is poor even in light of the wide variation seen in citizen science studies generally (10% – 50%, reviewed by West *et al.* [2015]). The radishes were not as reliable as the *V. faba* in regard to growing the number of plants needed for the experiment, and there seems to be a far greater degree of variation between the mature plants even before treatment was added. The fragility of the flower spikes was a problem in real-garden environments, with plants prone to snapping in windy conditions even when staked. The small flower size and comparative dexterity needed to transfer pollen also presented problems to some older volunteers.

These radishes *do* work as a phytometer, and would be a candidate plant for experiments run by researchers with access to sufficient greenhouse space to grow enough suitable plants and to maintain them in situ. Unfortunately, they are not as suitable for a citizen science based project, and were not included in any follow on work, or the 2016 *Bees 'n Beans* run.

4.5. 2015-16: Non-crop phytometers – aesthetic alternatives.

Six of the eight species of alternative phytometer examined in 2014 were selected from common UK garden *crop* plants, with a requirement for insect pollination in order to set fruit / seed included as the first category. This means that if that plant was being grown, a pollination requirement was associated with the *reason* it was grown i.e. for the harvest. Two plants were also considered that did not have this requirement: poppies, which have edible seeds but tend to be grown for display; and cornflowers, which are an ornamental plant. Both proved to be unsatisfactory (Table 4) and were not considered further.

However, as the citizen science projects progressed, it became clear that having a plant that was reliably easy to grow and to manage was more important to this type of study than requiring that the final output be edible. Maintaining engagement with volunteers is vital to the success of such projects and failed plants are very discouraging. Modifications were therefore made to the original criteria to widen the search; these are given below, with the modifications in bold:

1) Reliant on pollination to set seed or fruit, **even if that is not why the plant is typically cultivated**.
2) Easy to grow, **send to sites, and maintain – and ideally pest resistant**.
3) Quick to flower / annual.
4) Compact growth habit.
5) Attractive.

With these modified criteria in mind, an assessment of the flowering plants present in typical UK gardens was undertaken in spring and summer 2015. The list of garden species used was based on the 'Growing Towns' survey (Chapter 2). *Allium* species were thus identified as another potential phytometer.

4.5.1. Pilot study – which allium?

Introduction

In the UK several common garden crop plants are members of the *Allium* genus, including leeks, onions and chives. Many more ornamental varieties are also available, grown for their large spherical umbels of brightly-coloured flowers (Figure 10). Alliums are typically propagated from bulbs, which could present an advantage for citizen science use as volunteers may have less trouble getting a bulb to sprout than a seed. However it does mean that postage costs would be higher than for seeds.

Pollination of allium flowers is primarily via insect action, with little wind-pollination due to the stickiness of allium pollen grains (Erickson & Gabelman, 1956; Ockendon & Gates, 1976). The individual flowers within a flower head are perfect, but self-pollination is comparatively rare because the anthers mature and shed pollen before the stigma is receptive. All flowers in an umbel do not ripen simultaneously, opening over about 30 days, with most open in the second week (Ashworth & Whealy, 2012). Hand pollination is possible within the flower head, using a cloth or soft brush in a similar method to that used for sunflowers in 4.3.1.

Typically allium seed pods remain attached to the dried flower head until ripening, when the pods break open and scatter the seed. Theoretically it should be possible to apply the protocol of excluding pollinators / hand pollinating / local pollination to allium plants, if an appropriate variety that is easy to handle and to count is identified.

a) b) c)

Figure 10: Ornamental alliums*;* a) Flower head; b) Ripening seed pods still attached; c) Ripe seed pods opened to show black seeds.

Method

Observations were carried out over summer 2015 on the *Allium* species present in a domestic garden in Nottingham, to examine the characteristics of some of the varieties already growing, and their suitability for inclusion in a citizen science project. The six species already present on site for these observations were:

- 2x 'Globemaster' – *Allium giganteum*
- 2x 'Round-headed garlic' – *Allium sphaerocephalon*
- 4x 'Star of Persia' – *Allium christophii*
- 4x 'Blue-flowered garlic' – *Allium caeruleum*
- 6x 'Purple Sensation' – *Allium hollandicum*

The site was south-facing, and the alliums growing mixed in soil beds with other flowering plants. As observations began after flowering had already started in the plants, and due to the small numbers involved, it was not possible to net any of the flowers to compare for pollinator-exclusion.

Flower heads were removed in early July, with the following parameters recorded:

- Count of flower heads
- Count of unripe pods (those that did not show signs of opening to release seed)
- Count of ripe pods (those that showed signs of opening to release seed)
- Seed numbers from ripe and unripe pods (either by extracting ripe seeds from open pods, or cutting into unripe pods using a scalpel)

The flower heads were also checked to see if they:

- Retained all flower spikes after flowering had finished
- Retained all seed pods, or lost them over time

Results and discussion

Of the plants observed (summarised in Table 7 below), *Allium hollandicum* 'Purple sensation' presented as the most suitable for use as a phytometer. This variety was robust in the garden, maintaining a strong stem and producing a single umbel of reasonably consistent size. The appearance or quality of the umbel was also not affected by heavy rain. Additionally *A. hollandicum* did not lose the individual flower spikes from the umbel even when the heads were removed and put in a box to dry out.

Table 7: Allium species tested at the field site garden, for suitability as a phytometer plant.

Allium	Number of flower stalks in umbel	Number of shrivelled flowers	Number of ripe seed pods	Number of ripe seeds	Average number of ripe seeds per pod	Notes
giganteum	221	82	139	412	2.96	Very tall plants (>1m) requiring staking; large flower heads ~18cm across, difficult to net. Expensive bulbs (£18.50 for 10).
giganteum	231	29	202	570	2.82	
sphaerocephalon	69	15	54	139	2.57	Did not lose stalks; only 2 plants, possibly worth further investigation.
sphaerocephalon	102	97	5	5	1.00	
caeruleum	80	21	59	101	1.71	Spindly stalks; flower heads inconsistent shapes; no standard number of heads per plant.
caeruleum	92	13	79	201	2.54	
caeruleum	123	29	94	139	1.48	
caeruleum	236	114	122	221	1.81	
hollandicum	196	64	132	299	2.27	Suitable (see below)
hollandicum	383	80	303	704	2.32	
hollandicum	195	47	148	302	2.04	
hollandicum	227	61	166	394	2.37	
hollandicum	425	128	297	771	2.60	
hollandicum	447	108	339	1024	3.02	
christopii	Lost stalks with shrivelled flowers, and also dropped seed from pods sporadically, therefore these were not counted.					

Each *A. hollandicum* plant produced one flower head, averaging 312 flower stalks per head. Volunteers would have to be willing to count this number of stalks, and separate them into full seed pods and failed flowers. This is similar to the number of seed pods produced by the trialled *R. sativus* in the 2015 run of *Bees 'n Beans* (4.4), and feedback during that project suggested that volunteers are willing to count this many seed pods. Additionally because the dried flower heads can be stored and counted over time, not all the counting has to be done in one session.

However, with an average of 582 seeds in the pods from one umbel, ranging between 299 and 1024, and the removal and counting of each seed requiring the fiddly use of a sharp knife, counting of the individual seeds themselves may not be an appropriate task for a citizen science protocol. There were 2-3 seeds per pod and no empty pods recorded, so it would be possible to estimate the seed number from the count of pods. The *A. hollandicum* plants were therefore used in 2016 alongside the *Bees 'n Beans* family of projects.

4.5.2. 'All About Alliums' – citizen science study

Run in 2015-16 in collaboration with the University of Sussex' '*Buzz Club'* initiative, this project used *A. hollandicum* ('Purple Sensation') to assess pollination service provision in urban gardens. Another supplemental study was performed alongside this main project, examining further potential alternative allium plants not covered by the pilot study in 4.5.1. These were done at the same time because this was the last field season of this PhD funding, and from the previous experience with the radishes and bean plants it is clear that these phytometers need to be trialled in real-garden situations to determine their usefulness in those settings.

Recruitment of volunteers occurred in October 2015, using direct contact with Buzz Club members and with previous volunteers from the *Bees 'n Beans* project family who had indicated interest in the projects and remained strongly engaged.

All About Alliums

Figure 11: 'All About Alliums' logo used for the project in 2016.

Method

Project packs sent out to volunteers in October 2015 contained five bulbs and an instruction sheet (Appendix B); bulbs were sourced from J Parker (Dutch Bulbs Ltd, 14 Hadfield Street, Old Trafford, Manchester, M16 9FG). Compost or soil, appropriate sized pots (at least 18cm deep), and a light bag of garden fleece was provided by the volunteers themselves. Bulbs were planted as soon as they arrived and the plants maintained somewhere sheltered until May-June 2016, when flower spikes were produced and the experimental phase began.

Flower spikes were supported by a garden cane. This is not always required when growing the plants in soil in a domestic garden, but to ensure that experimental plants in pots did not snap, this was included as a step.

Participants selected the three most similar plants, matched for height and size as closely as possible. The treatments were assigned at random when the capsule over the first umbel began to split (instructions on randomising, and explanation for the need for it, were sent by email). All three flowers did not have to be open at the start to assign treatments, since there would still be a period of synchronous flowering if a spike had been produced. The treatments applied were: local pollinated (left alone), hand pollinated, and netted.

Hand pollination of the flower heads was performed using a either a soft brush (e.g. paintbrush, shaving brush, makeup brush) or piece of muslin cloth. Starting at the bottom of the flower ball, the flowers were gently brushed to dislodge pollen, moving in a spiral motion up the umbel to distribute pollen across receptive stigma. This was performed every two days, for four weeks. Netting of the plants excluded insects with garden fleece. Step by step instructions were provided, with photographs, before the treatments were applied (Figure 12).

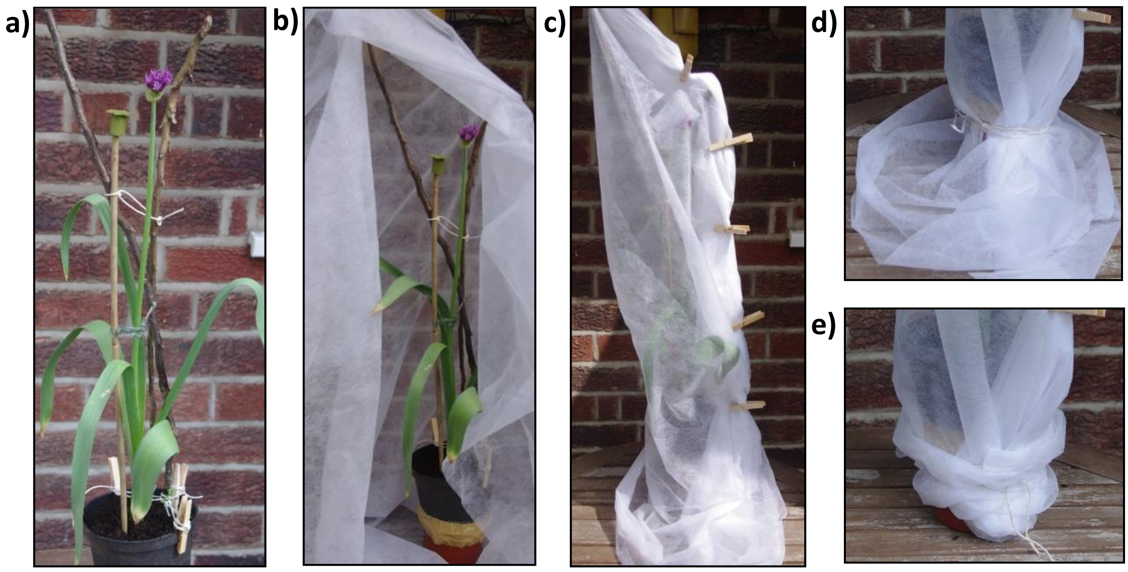


Figure 12: How to exclude insects from an *Allium* plant; instructions from 2016.
a) – c), how to apply the bag over the plant; d) – e), how to seal it at the base.

The plants were kept adequately watered as the seed pods developed. The number of seed pods and unpollinated flower stalks were ready for counting in late July. The difference between a seed pod and a dried stalk is very clear, and illustrated in Figure 13 below.

Figure 13: Seed pods and stalks from an allium umbel. Left to right: Large pods; medium pods; small pods; shrivelled pods / failed stalks.

Participants recorded the number of dry stalks with shrivelled flowers, and the number of seed pods, divided into large / medium / small categories according to the examples given below. Seed pods may have been green, yellow or brown, depending on how dry they were. The volunteers were asked to inform the researcher if their experiment failed, and to provide information on why this had occurred (regardless of the reason).

Final results were recorded using an online version of the recording sheet (using http://surveymonkey.com). Part of the results form asked questions to characterise the conditions the alliums were grown in and elicit further feedback (Appendix B).

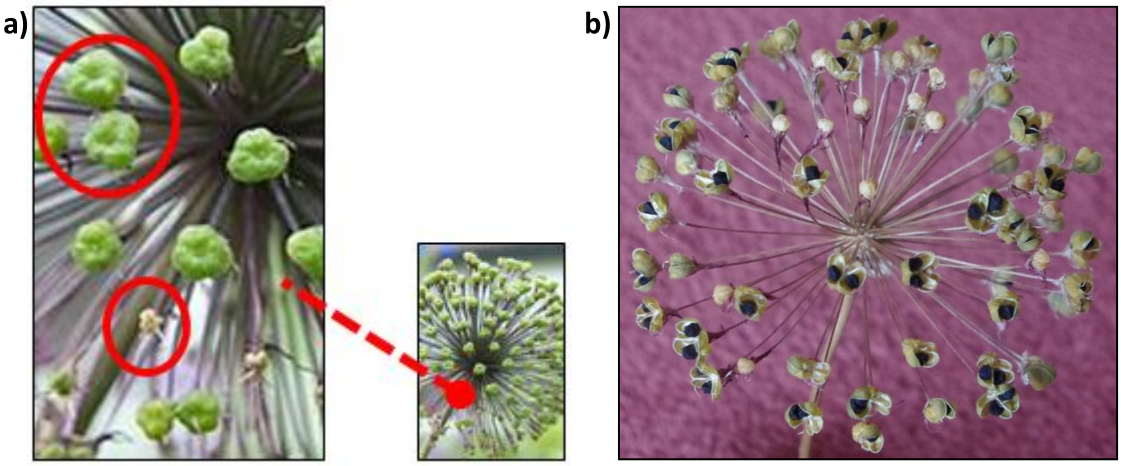


Figure 14: *A. hollandicum* a) seed pods and unpollinated stalks; b) dried / open seed pods.

Other varieties

The varieties of allium examined in 2015 as potential phytometers were those that were already present on the garden site. When ordering the 'Purple Sensation' bulbs for the citizen science study, two other varieties were identified as inexpensive and meriting further investigation, due to flowering at different times in the summer and potentially covering more of the growing season. These were: *Allium nigram*, a white allium that flowers in late June; and *Allium spherocephalon*, a purple allium that flowers in July-August. The latter had been noted as possibly worth further study in 2015.

Thirty bulbs of each were planted in 1.5L pots and maintained in the Sussex greenhouses, to be moved outside in groups of three and tested with the same treatments used for *A. hollandicum*.

In addition to these, 'garlic chives' (*Allium tuberosum*) were propagated in the garden site. A white allium that flowers in September, this had been included in the 2014 test of potential phytometers, but growing from seed within the year had proved unreliable. However, established plants present on the garden site were grown on in 2014-15, and propagated by dividing and separating existing patches, so there were enough plants to undertake the alliums protocol in 2016. Since chives do not grow as a single flower head and set of leaves, four planters of chives were maintained and the treatments and observations applied to the flower stalks produced. One umbel was netted per planter, and one was hand pollinated; all other heads were locally pollinated.

Statistical analysis

Statistical analysis was carried out in SPSS 23, using Generalised Linear Models (GLM) to compare the yield measurements (number of pods, and number of flower stalks) between treatments, and between different environmental conditions. As both measures are count data and contain a lot of zeroes, negative binomial errors with a log link were used for the GLMs. Flower heads that had fewer than 40 stalks were removed from the data before analysis, since these were heads that were reported as having had gone rotten or been eaten by pests; flower heads with >40 stalks were considered to be a viable result, because these were heads that produced large (well-pollinated) pods, just with lower numbers of flower stalks.

From the data returns, for analysis of *A. hollandicum* ‘large’ and ‘medium’ pods were added together to count the number of well-pollinated flowers. The difference between these larger pods and the small or shrivelled pods is much more distinct than the visual difference between a ‘large’ and a ‘medium’ pod, so it was decided to group these and not second-guess participants. ‘Small’ and ‘shrivelled’ were also combined, as they were poorly pollinated.

The initial model was fitted with the main effects: Treatment (netted, hand pollinated, or local pollinated) nested within each garden ‘Site’; Site (each garden); Garden size (m^2); site type (e.g. individual garden, allotment); volume of the pot that the bulb was planted in; position of allium experiment compared to other plants (Table 8); and amount of sun received by each experimental group (Table 9). Relevant interaction terms (against treatment) were included, and model simplification was done via stepwise removal of non-significant factors.

Table 8: Garden position of the experimental *Alliums* in relation to other plants in 2016.

Position
In with other flowers (in a flower bed, or surrounded by potted flowers)
Separate to other flowers (on a patio, path or lawn, etc), but within 1m
Separate to other flowers (on a patio, path or lawn, etc), more than a metre away
Completely separate to other flowers (up by the bins, along the side of the house, etc)
In with vegetables / fruit (in a vegetable bed, or surrounded by potted vegetables)

Table 9: Amount of sun received by the experimental *Alliums* in 2016.

Amount of sun received
Sunny position all day
Sun in the morning, shade in the afternoon
Shade in the morning, sun in the afternoon
Full shade ***(No alliums were grown in this position)***

Results

All About Alliums – A. hollandicum (Purple Sensation) results:

60% of participants returned usable data (31/52; Figure 14); plus 5 repeats undertaken around the Sussex campus, so n = 36. Three of the 31 participants did not have three mature flowering plants to use, so they performed only netted and local treatments.

Figure 14: Location of completed *Allium* plant returns (n=31) from *All About Alliums*, 2016.

There were no significant differences between the total number of flower stalks per head between Treatments (Figure 15a), or between Sites. All *Allium* produced very similar sized flower heads. The proportion of flowers that set pods was significantly affected by Treatment (Figure 15b), $\chi^2_2 = 43.7$, p = <0.001), with a much smaller proportion of the individual flowers from netted plants forming pods compared to the local plants ($\chi^2_1 = 34.4$, p = <0.001); there was no difference between the local and hand pollinated plants ($\chi^2_1 = 0.005$, p = 0.942). Since the number of mature pods per flower head were so much less ($\chi^2_1 = 128.6$, p = <0.001) from the netted control plants than either of the open treatments, netted data was removed from further analysis. With 'Treatment' nested within 'Site', there was no significant difference between the number of pods produced by the local and hand pollinated plants ($\chi^2_{23} = 16.8$, p = 0.848; Figure 16); or between sites ($\chi^2_{25} = 29.8$, p = 0.232).

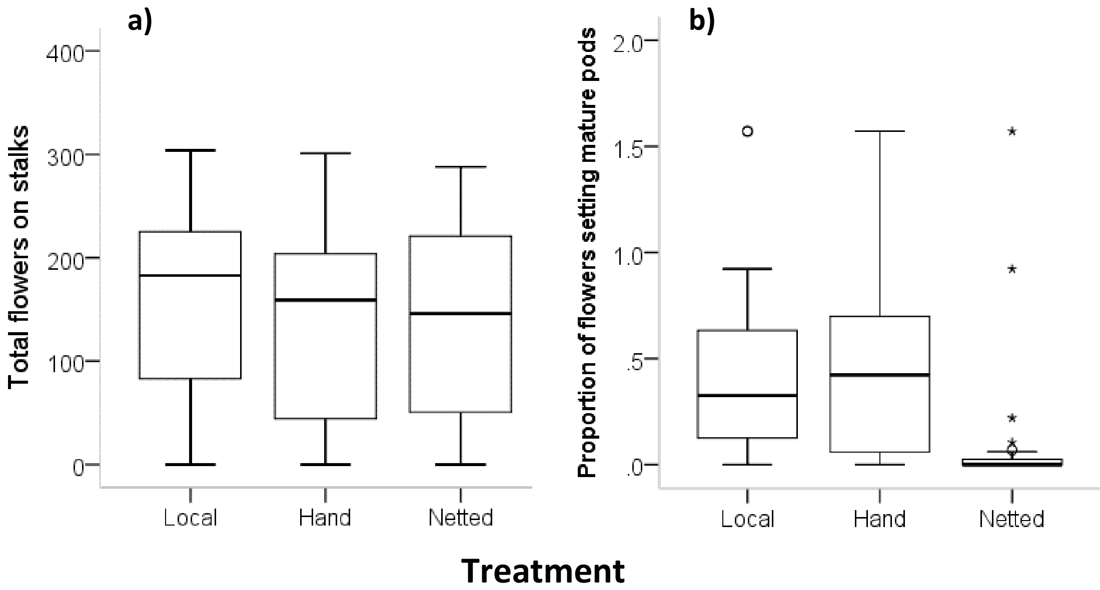


Figure 15: a) Total flower stalks on umbel heads, and b) Arcsin proportion of flowers that went on to form pods, by treatment.

When looking at the effects of the environmental conditions (position and amount of sun received; Table 8 and 9) recorded by the project participants, and the plant's suitability for use in citizen science, the five campus repeats were not included as they had not taken place in a domestic garden; so n = 31. Since the 'netted' treatment had such a strong effect on the number of pods produced, only the open treatments were compared between sites.

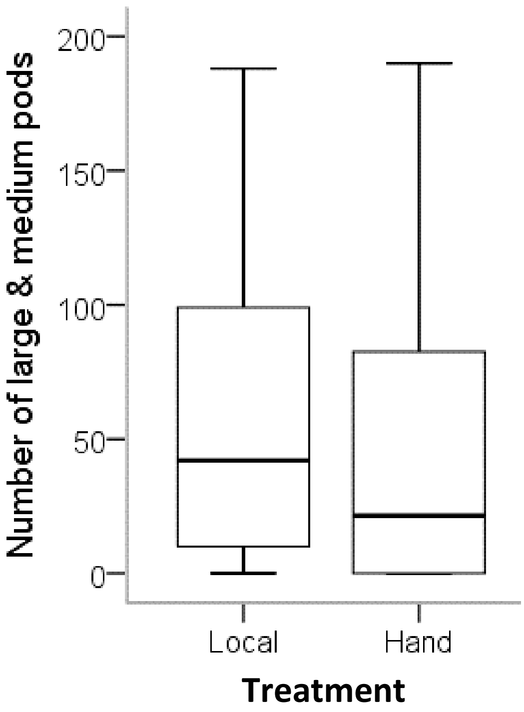


Figure 16: Number of mature (large and medium) pods set per flower head, by treatment.

Neither of the environmental conditions (Figure 17, amount of sun; and 18, garden position) correlated with any significant difference in the number of pods produced by the plants.

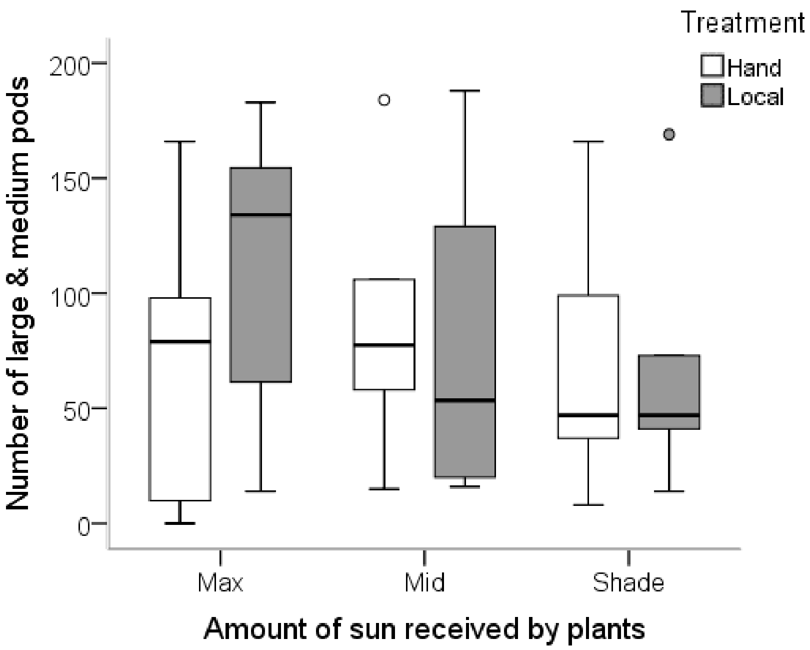


Figure 17: Number of mature pollinated pods produced by *Alliums* in 2016, by how much sun they received.

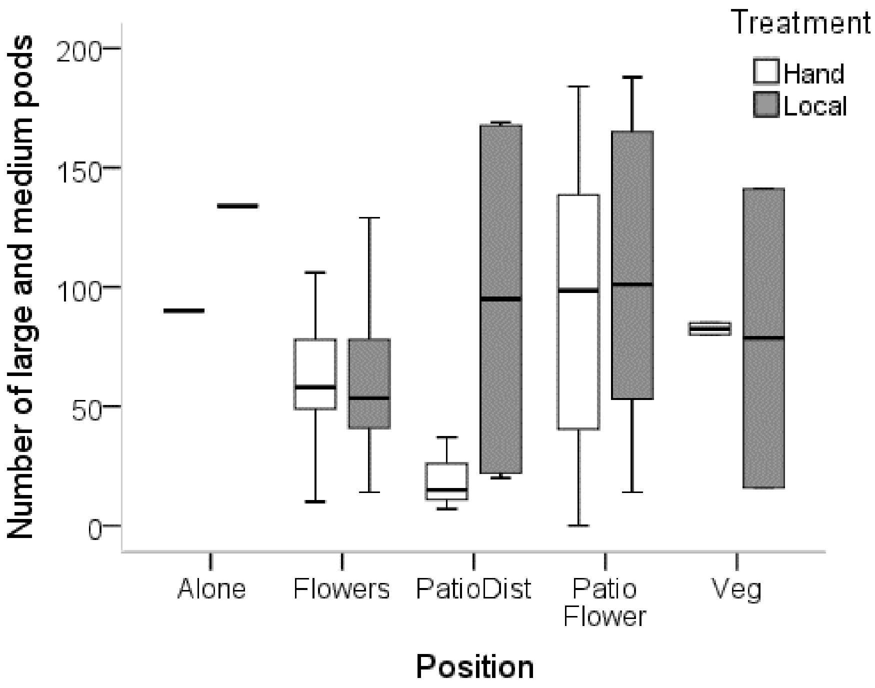


Figure 18: Number of mature pollinated pods produced by *Alliums* in 2016, by the garden position they were placed in.

Initial analysis showed a trend towards larger pot sizes used for the bulbs being linked to fewer pods, but as shown in Figure 19 this effect seemed to be caused by only two sites; when they were treated as outliers, pot volume was not correlated with any significant difference in the pod numbers produced by the plants.

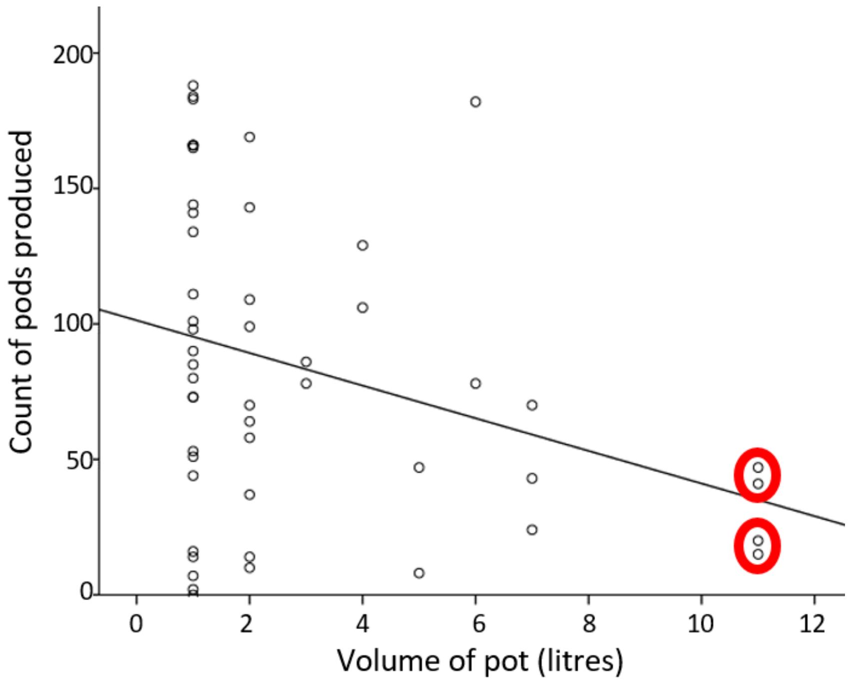


Figure 19: Number of *A. hollandicum* pods produced compared to size of pot used. The two outliers are highlighted in red; without these, there is no trend.

Feedback about the project from participants was generally positive. The 'Purple Sensation' plants were easy to grow, attractive, and while there was some confusion about exactly how to do the hand pollination, people managed it well. Additionally these alliums did not appear to be susceptible to aphid attack or to being eaten by slugs. They also coped well with the climatic conditions and were not reported as susceptible to drying out, or damaged if caught in heavy rain.

Alternative alliums

Allium nigram plants flowered approximately a month after *A. hollandicum,* produced large umbels, and the flower heads did not shed stalks. Pods were distinct and large enough to count. However, the plants did not produce flower stalks when grown in pots as reliably as *A. hollandicum* (only 11/30 plants produced flowers).

A. spherocephalon produced flower spikes in July, but the flowers did not open until late August, later than expected. The flower spikes grown in pots were very thin and tall. They requiring careful staking and were prone to bending and snapping. After flowering finished, the heads were difficult to count because the pods were much smaller and distinguishing pods size was complex and time consuming; taking up to 45 minutes per flower head. Additionally, although the finished flowers did not fall off the plant but shrivelled and curled back, compacting the entire dried head, which was overall much more difficult to handle.

Garlic chives

The protocol seems to be suitable for *A. tuberosum* in the same way as *A. hollanicum,* with no interactions present in the GLM, and netting the heads significantly affecting the number of pods set (χ^2_2 = 4.62, p = 0.099; Figure 20a). Netted flower heads produced fewer pods than local pollinated heads (χ^2_1 = 4.57, p = 0.033), with no difference between the number of pods produced by open flowers in any of the garden positions (χ^2_1 = 0.054, p = 0.694; Figure 20b).

The garlic chives were still producing flower heads into September, and producing seed pods into November. Observations of insect visitors to the flowers suggest that hoverflies and smaller bee species are common visitors to these flowers.

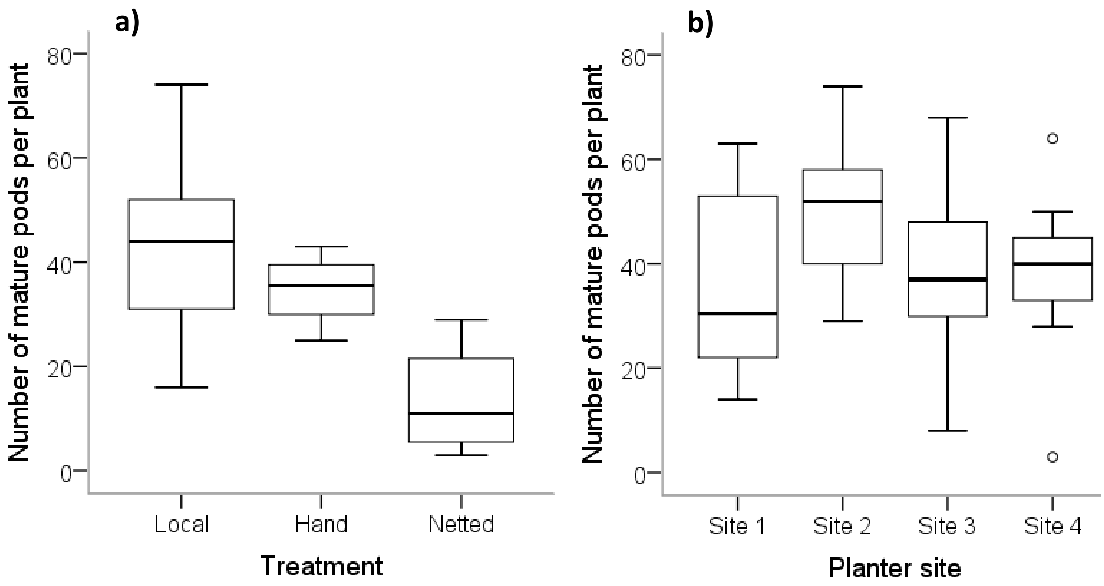


Figure 20: a) Total number of mature pods formed by *A. tuberosum* plants under different treatments; b) Number of mature pods formed by *A. tuberosum* plants in the different planters on the garden site.

Discussion

The similarity in pollination measures of hand- and local- treated alliums (*A. hollandicum*) suggest that either the local pollination effort is just as effective as the hand pollination – so there is no deficit to be detected – or that the hand pollination method used is ineffective but undamaging, with both treatments therefore reciving the same level of effort from local bees. Observation of the plants on campus suggest that the former is more likely, as the flower heads on the hand pollination treatment finished flowering and formed seed pods sooner than those on the local plants. Whether this is due to the plants reaching a maximum required level of pollination or a different resource limitation, the hand pollinated plants seem to reach it first. There also seems to be no difference in the behaviour of the alliums grown in different garden conditions, suggesting that they would be appropriate to use in different types of garden.

Further development of an allium version of the protocol would benefit from performing a hand pollination comparison, similar to that from Chapter 3 of this thesis: completely separating some plants from local pollinators in an excluded greenhouse, to compare isolated hand-only pollination with the supplemental hand pollination currently used, to make sure that the method is indeed effective. Comparison of the flower heads produced from the same bulbs in multiple years would also need to be done, to determine if each successive run would require fresh bulbs, or if volunteers could be asked to maintain a set of experimental alliums.

In order to keep the investigation straightforward in this initial stage there was no requirement in the citizen science protocol for volunteers to undertake any form of sequential counting, or record when in the experimental period each flower head had finished. Thus a further project using *A. hollandicum* plants would benefit from including an ongoing measure of pollination as well as the final totals (similar to the method discussed in Appendix A of Chapter 3). Since there are considerably more individual flowers in an allium umbel than on a bean plant, and pods are much smaller, sequential counts of developing pods may be impractical for citizen scientists but possible in a field centre(s). However, it would be possible to ask volunteers to keep a note of roughly what percentage of flowers were closed, open or gone over within the umbel, and the dates of those records. It would also be possible to ask volunteers to count the number of pods present on a series of sequential dates.

Since neither of the open pollinated *A. hollandicum* showed a deficit in the service they received, it could be that the flowers are sufficiently attractive that they will receive their maximum pollination even with a lower population of pollinators present in the area, which was also a concern in 4.3.1. when considering sunflowers. As the *A. hollandicum* umbels are large, they could provide an observation platform for insect visitors similar to the Great Sunflower project (Oberhauser & LeBuhn, 2012); since the alliums seem more likely than the beans to attract pollinators during a short observation period, they would be more suitable for that kind of citizen science protocol. The multiple flowers per head also means that any visitors are likely to remain on the umbel for long enough for identification to be attempted, and photographs taken – either for verification by the project team (Bonter & Cooper, 2012; Deguines *et al.,* 2012; Gardiner *et al.,* 2012), or by an existing organisation such as iRecord or iSpot (http://www.brc.ac.uk/irecord; http://www.ispotnature.org) that can provide experienced checking.

The *A. hollandicum* plants had a better rate of data return than the *V. faba* plants in Chapter 3 – 60% compared to 40% – and seem to fulfil the phytometer role well, both in terms of application of the treatments, and practical characteristics during the experiment, including good resistance to pests and being easy and attractive to grow. While this was a much smaller study than *Bees 'n Beans*, with participants who had already shown themselves committed to these projects in some way, it suggests that the alliums would be an appropriate plant for inclusion in a monitoring programme based on this design.

Most of the participants in the experiment did have three plants flowering at the same time but to ensure that number in a future study, it would be better to send ten bulbs, which would increase the costs per return substantially – particularly if new bulbs needed to be sent every year. Recruitment would thus be best focused on volunteers who are already committed to citizen science schemes, from the project or partner organisations, as they are the most likely to successfully return data.

Since the plants are reliable and interesting, and because the pods set quickly and obviously (if they are going to), *A. hollandicum* would also be appropriate for inclusion in a schools project. The bulbs could be planted, grown and pods counted within one academic year – started in September and finishing before the standard UK summer holiday. Bulbs left outside in large enough pots could be left during interim school holidays without coming to harm in respect of watering or slug attack. The protocol could be used to fit in Keystage 2 and 3 of the National Curriculum in England (Department for Education, 2013, 2014), to demonstrate pollination interactions, and to provide suitable flowers for observations of insect visitors as part of practical work.

Alternative alliums

Neither *A. nigram* nor *A. sphaerocephalon* presented a good alternative for *A. hollandicum* as a citizen science phytometer. The garlic chives (*A. tuberosum)* are potentially useful as a companion to *A. hollandicum*, because they flower much later and would allow for assessment of the pollination service provision that occurs later in the summer; particularly in regard to hoverflies, where several very common species see later-summer population peaks due to immigration from Europe (Stubbs & Falk, 2002; Graham-Taylor *et al.,* 2009). However, these plants did not grow easily from seed, do not form bulbs, and require being established to be used appropriately. If garlic chives were to be included in a monitoring programme, pots of plants would need to be grown (or bought) and distributed to participants, requiring central location(s) for pick up, or much more expensive postal costs. This might be suitable for partnership with an organisation with centres around the UK for distribution, such as local Wildlife Trusts or botanic gardens.

Appendix A: *Rolling out Radishes* instructions.

The instructions for *Rolling out Radishes* in 2015 were included with the *Bees 'n Beans* protocol. This Appendix only includes the sections of the 2015 protocol that refers to the radish plants.

Rolling out Radishes

Thank you for taking part in Bees 'n Beans! This project will use a simple experiment to look at how much pollination is happening in urban green space. In 2015 we will use **Broad Beans** and **'Rat-tailed' Radish** plants in the experiment.

'Rat tailed' Radishes produce much smaller flowers than broad beans, and are mostly pollinated by small bees and hoverflies (bumblebees are too large, and tend to fall off). A single plant cannot pollinate itself, but the pollen is bright and obvious, and easily transferred between plants by an insect, or paint brush. Seed pods are edible, raw or cooked, and taste lightly of radish.

Project Kit

The kit for this project should contain:

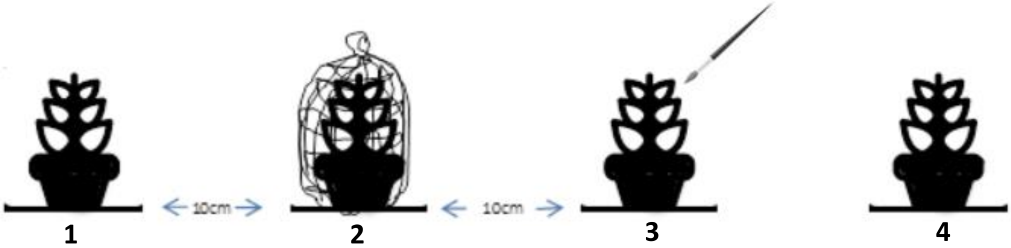
- 20 dried 'rat tailed' radish seeds
- 5x 3L folding pots
- Recording sheet & instructions

You will need to supply sticks to support the plants, garden fleece and the compost. Well-rotted garden compost or a commercial multi-purpose mix is fine, as long as all pots have the same.

The Project Plan

This project is to start in early **April 2015**. The plants are quite hardy, and this start time should miss all but the latest of frosts. The experimental plants will be:

1) Local plant – this plant is to be left alone, to let the local pollinators have access the flowers.
2) Netted plant – this plant will be covered in a light garden fleece to keep pollinators out.
3) Hand-pollinated plant – this plant will be pollinated by you (**details below**).
4) Spare plant – for getting extra pollen to use in hand-pollinating.



GROWING – RAT TAILED RADISHES

The radish experiment needs at least **four mature plants**. The kit contains 20 seeds (at least) and five pots for the radishes, so four radish seeds can be put into **each** pot.

Step 1 – Fill the pots with compost leaving about 1cm of space at the top to make watering easier. Push four radish seeds into the soil/compost in a square in the middle of the pot - about 1cm deep and about 3cm apart. Cover seeds with soil/compost.

Step 2 – Water well. Keep the pots indoors on a warm windowsill (or greenhouse, or conservatory) to give the plants a better start than going outside right away. If you do not have any such space, somewhere sheltered in the garden will do as long as frosts have finished.

Step 3 – When the plants begin to sprout (after around four weeks) when they are about 5cm high, carefully remove the smaller plants from each pot and grow on the remaining plant. You can keep growing the spare plants separately if you like; they are not needed for the experiment.

Step 4 – Plants should be moved outside when they are over 10cm high and the leaves are hairy. If these young plants were grown in the house, let them gradually get used to the outdoors by using a cold-frame, cloche or a porch and try to avoid any forecasted frosts. Plants should be kept 10cm apart, all with the same amount of shade, distance to other flowering plants, and amount of shelter. Keep the plants in trays to help with watering.

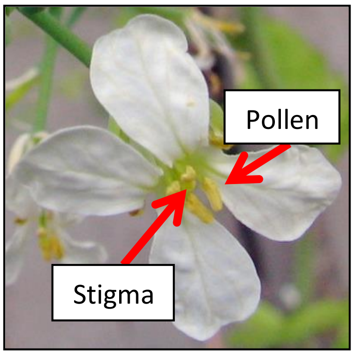
The plants need to be watered **twice a week** unless it is particularly warm, or the leaves begin to wilt (if so, water *all* plants at the same time). The radish plants will produce a flower spike after about **8 weeks**, and will need gently tying onto a supporting cane or stick so they do not snap. Small four-petal flowers will begin to open on the flower spike, which will continue to grow taller (to about a metre and a half) and the flowers spread out. The experiment starts when flowering does.

EXPERIMENTING – RAT TAILED RADISHES

You will need **four mature plants**. Don't worry if there are not many flowers open to begin with. One plant is spare, to provide pollen (Plant 4). Apply the treatments to the others as shown below (the order they line up in does not matter):

1. **Local plant**
2. **Netted plant**

- Gather the net/fleece around the supporting cane, leaving space to grow. The flower spike will grow quite tall, so be ready to move the net up.
- Gather the net/fleece around the stem of the flower spike and the cane, above the leaves, and tie it loosely. Water directly onto the pot.



3. **Hand-pollinated plant**

- Using a small paint brush, gather the bright yellow pollen from flowers on the spare plant (shown to the right). This should come off easily.
- Brush the collected pollen onto the stigma of open flowers on the hand pollination plant, **twice a week**.

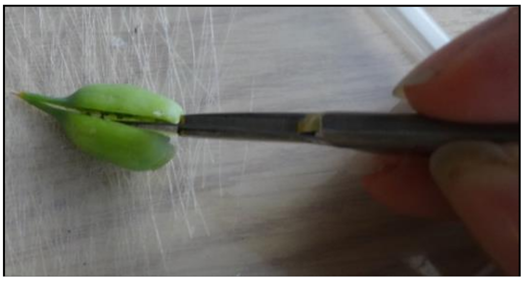
HARVESTING – RAT TAILED RADISHES

The radish seed pods are ready to harvest when they are about the width of a pencil. The first pods may be ready to harvest as little as **9 weeks** after flowering.

Removing the pods will encourage the plant to produce more flowers, so it is important that this is done consistently for **all** plants at the same time, **including the bagged plant** (Plant 2).

Seed pods that are big enough to harvest (pencil width or more) should be taken from all plants, **once every two weeks**.

The number of seeds per pod, per plant should be recorded on the provided recording form. Seeds can be counted by cutting open the pods, as follows:



Cut open pod, using sharp knife or scalpel

→ Count seeds

Seeds vary in how developed they are within the pods (shown on the right), but should be easy to count.

One the recording sheet provided, please note:

- The **date** of each harvest.
- The **number of pods** harvested per plant.
- The **number of seeds** harvested per plant.

This will allow us to compare the success of each treatment crop, and give a measure of how well the local insect pollinators are doing in helping pollinate the plants.

There will be a web form to return the data, or you can post the recording sheet to us. If you have any further questions, please do contact me either by email (L.Birkin@sussex.ac.uk), or by phone (01273 678509).

Appendix B: All About Alliums instructions.

A copy of the instructions for participants in the *All About Alliums* project. Recording sheets and photographs of the stages as they occurred (particularly seed pods) were sent out during 2016, since this was the first year this had been done and I initially had no 'stage' photographs.

All About Alliums

Thank you for taking part in 'All about Alliums', the latest garden pollination study from the Buzz Club and the University of Sussex. This project involves carrying out a simple experiment, aiming to see if we can use allium flowers to measure the amount of pollination that is happening in urban gardens – in order to see how healthy the pollinator community is there.

We will use the **'Purple Sensation'** variety of allium, which are grown from bulbs. They form a large, spherical flower head made up of many individual flowers, pollinated by a variety of insects, including honeybees and flies.

It is possible to record how well the flower heads are pollinated because it is easy to count which flowers have been visited, as they produce a green seed pod, and because the flowers that are *not* pollinated leave behind an obvious dried brown spike with a shrivelled flower.

A flowering allium.

Green seed pods.

A dried allium seed head.

The Project Plan

The project will start in 2015, with the bulbs being planted before the end of November, and will flower in summer (May / June) 2016. The pollination study will occur during the flowering period.

Project Kit

The kit for this project should contain:

- **Five 'Purple Sensation' allium bulbs**
- **Instructions**

The results recording form will be sent by email in spring of 2016.

Various (at least) 20cm deep pots.

You will need to supply **five pots** at least **18cm deep** (it is important that they are *deep* pots, as the roots grow straight down); sticks/canes to support the plants, 1m square of garden fleece, and compost. Well-rotted garden compost, bulb compost or a commercial multi-purpose mix is fine, as long as all pots have the same. **Do not** use extra manure, as alliums do not like it!

Planting The alliums

The planting phase starts in October-November 2015, to allow the bulbs to flower in May / June 2016. You will need **three** flowering plants for the allium experiment. The kit contains five bulbs to help to get three plants flowering at the same time.

1) Using a slightly moist compost, half fill each pot. Compost should be dark and moist to touch but not too wet, or the bulbs can rot.

2) Place one allium bulb in each pot, with the remains of last year's roots pointing downwards. The top of the bulb is slightly pointed. You can mix in a bit of grit or broken dry egg shell under each bulb to help the drainage if your compost is quite dense.

3) Cover the bulbs with compost up to the top of the pot.

Please keep a note of the date the bulbs were planted.

4) Keep the potted bulbs in a sheltered spot or cold greenhouse in winter. Cover the pots with mesh or a lid to keep out squirrels / mice. Unless the compost gets very dry, do not routinely water while the bulbs grow roots over winter to prevent them rotting.

Growing the alliums

The bulbs will grow quickly in the spring and produce curled green leaves, before the flowering spike. When leaves start to grow the plants should be gradually allowed to get used to the main outdoors, if they have been kept inside. The pots will need to be watered but well drained, so **do not** stand the pots in a tray that will keep water.

To help stop squirrels etc. from damaging young shoots use a protective loose fleece cover or some sticks to protect the plants. If you want to use a control method like slug pellets to discourage pests, that is fine – it just needs to be done the same for all the plants.

Flower heads should appear in mid-spring, when the experimental stage can start; we will keep you posted on progress with updated instructions in 2016. The flower spikes will reach 70-90cm, so a stick placed in the pot to support the flowering shoot will help to keep the stem straight while growing (*as shown to the right by a model*).

EXPERIMENTING

For the experiment – You need **three** plants that are about to flower at the same time. The treatments will be applied as shown below;

1) Local plant – this plant is to be left alone, to let the local pollinators have access to the flowers.
2) Netted plant – this plant will be covered in a light garden fleece to keep pollinators out.
3) Hand-pollinated plant – this plant will be pollinated by you.

Any extra plants you have grown are spare / backup; leave alone like the 'local plant'.

SETTING UP THE TREATMENTS

How to net a plant to keep out pollinators

Shown to the right, with a tennis ball as a 'flower'. We will send out further pictures as they become available in 2016.

1) Place a second cane in the pot, which is longer than the top of the flower spike by about 20-30 cm.

2) Wrap the fleece around the flower head, the new cane, the stem and the old cane.

3) Tie the fleece with string above and below the flower head (and both sticks). It is important that no insects can crawl up the stick so use tape to secure the fleece at the bottom if necessary.

This pot may become unstable due to the fleece, and may need to be weighed down with stones or placed in another larger, heavier pot to prevent it blowing over.

How to hand pollinate alliums

This needs to be done **twice a week** when the flower head is open. The flowers in the flower head mature at different times, so this needs to be done for **four weeks**.

You will need either a soft camel-hair brush (e.g. paintbrush, shaving brush, makeup brush) or piece of muslin cloth. Starting at the bottom of the flower ball, the flowers should be **gently** brushed to release pollen, moving in a spiral motion upwards so any dislodged pollen is swept up the flower ball rather than lost. This will spread pollen to the receptive flowers above, and pollinate the allium.

A video of this will be made available in 2016.

HARVESTING THE ALLIUMS

The experiment has finished when all the flowers on the flower heads have gone over. A finished flower head will have (shown on the right):

- Shrivelled flowers or flower stalks where flowers have dropped off.
- Unripe seed pods – a green colour.
- Ripe seeds pods – brown colour, black seeds inside.

The number of ripe seeds will depend on how long it takes for all the flower heads to go over – so do not worry if you only have unripe green pods!

All three plants should be harvested **at the same time**. The flower heads can be kept e.g. in a tupperware box, and the seed pods / stalks counted over a period of time – you do not have to count them all at once.

RESULTS TO RECORD

The results will allow us to compare the success of each treatment, and give a measure of how well the local insect pollinators are doing in helping to pollinate the plants. Recording sheets will be sent out in 2016. You will need to record:

- The date of planting bulbs
- The date of treatment allocation
- The date of flowering starting
- The date of harvesting and counting
- The **number of unripe (green) ripe pods** harvested per plant.
- The **number of ripe (open) pods** harvested per plant.
- The **number of unpollinated spikes / dried flowers** present on the seed head.

We will not **require** you to count the number of seeds per pod. You **can** count seeds if you would like to, and we can use the data, but this is fiddly and requires a sharp knife to cut open the small seed pods. It is entirely **optional**.

Results can be returned online, or posted to the team; links and address will be provided on the results form itself.

Flower visitors *(optional)*

Alliums are very attractive to a wide range of insects. If you would like to keep a record of any insects that you see visiting the plants, a section will be provided on the recording form to get that information back to us as well. We have not provided a specific identification guide with the project documents, but there are resources online for identification if you would like to have a go: www.nhm.ac.uk/nature-online/life/insects-spiders/identification-guides-and-keys is a good place to start.

Chapter 5: Vegetable-bedfellows – companion planting for pollinators and garden crop yields.

5.1. Introduction

Urban agriculture is a notable component of city life worldwide, with between 15-20% of global food production occurring in areas that can be classified as 'urban' (Armar-Klemesu, 2000). These crops make important contributions to dietary quality, public health and food security (Smit *et al.,* 1996), as well as reducing pressure on rural environments and their associated biodiversity (Smith *et al.,* 2006). Many of the fruits and vegetables typically grown in urban spaces are of comparatively high commercial value (Mougeot, 1999) and benefit from some level of insect-mediated pollination (Carreck & Williams, 1998; Klein *et al.,* 2007; Breeze *et al.,* 2011). Despite this reliance, there is ongoing uncertainty over the adequacy and reliability of pollination provision in urban areas (Matteson & Langellotto, 2009). There have been few studies of cropping in urban environments, although fruit set in urban trees was shown by Hausmann *et al.* (2015) to be greatly increased with higher numbers of wild bee visits, and pollination from wild bees has been shown to significantly increase the yields of tomatoes grown in San Francisco gardens (Potter & LeBuhn, 2015).

Most urban agriculture occurs in relatively small areas of land, such as gardens and allotments (Mougeot, 1999). It has been suggested that there is considerable scope for improving the yields achieved in small-scale farming by 'ecological intensification' – enhancement of useful biodiversity to provide more ecosystem services, such as pest control and pollination (Garibaldi *et al.,* 2016), and this may be applicable to gardens as well. In rural areas, biodiversity improvement is usually achieved through agri-environment schemes, including restoration of areas of native wildflowers and favourable management of border features, such as hedges (Goulson, 2003a; Pywell *et al.,* 2005; Abrol 2011; Staley *et al.,* 2012), and variations on these methods can also be applied in urban spaces.

The presence of co-flowering plants has been shown to facilitate pollination in some less attractive (Feldman *et al.,* 2004; Ghazoul, 2006) or even deceptive plant species (Johnson *et al.,* 2003) through 'magnet' effects (Thomson, 1978; Laverty, 1992). Diverse floral displays potentially benefit rare species of plant in particular, through the attraction of more abundant and diverse pollinators to the area (Laverty, 1992; Cussans *et al.,* 2010), as well as supporting more-generalist species. It is less certain whether planting with wildflowers is significantly better for supporting local biodiversity than planting with non-native but rewarding species (Matteson & Langellotto, 2011; Pardee & Philpott, 2014; Salisbury *et al.,* 2015), where the size and consistency of the floral display through the spring and summer may be more important (Owen, 1991; Stelzer *et al.,* 2010; Matteson & Langellotto, 2012; Wojcik, 2012).

Bees show a high level of flower constancy (Grant, 1950); many species can switch this preference relatively easily (Laverty, 1994) and are not restrained to a single type of flower. Bumblebees especially show a tendency to have both a 'major' and a 'minor' flower of focus when foraging (Heinrich, 1979; Gegear & Laverty, 1998). However, it is also possible that flowers offering little reward, or that require specific complex handling, may find pollinators distracted away by displays of more easily-accessed, co-occurring blooms (Free, 1993; Bartomeus & Winfree, 2011).

Better pollination – meaning either more complete or higher levels of cross-pollination – could be of great value to urban agricultural efforts. Links between improved yields and greater seed set within fruit has been documented in many crops (Roldán & Guerra-Sanz, 2006; Holzschuh *et al.,* 2012; Garratt *et al.,* 2014), in addition to improved *quality* of the seed that is set. Recent examples of this have been shown in blueberries, where heavier fruit are produced after greater flower exposure to visiting bees (Javorek & Mackenzie, 2009; Isaacs & Kirk, 2010); in strawberries, where better pollination provision to the crop increased weight and size of the fruit but not achene number (Roselino & Santos, 2009); and in tomatoes, where bumblebee pollination has been shown to improve the flavour of fruit, compared to artificial wand-pollination (Hogendoorn *et al.,* 2010).

The projects discussed in this chapter investigated the use of pollinator-supporting companion planting, intended to improve the yields from garden tomato crops. With increasing recognition of the importance of urban gardens in biodiversity protection and green infrastructure (Davies *et al.,* 2009; Goddard *et al.,* 2010; Cameron *et al.,* 2012), and recent guidance for gardeners focusing on wildlife-friendly methods and plant choices (Gaston *et al.,* 2007; Garbuzov & Ratnieks, 2014b), it is important to be able to target efforts appropriately to increase uptake of such advice. Gardeners who are already invested in the idea of wildlife gardening for the sake of the wildlife may be interested in essentially 'bonus' effects of their actions. Gardeners who are less driven by ideological motives could be encouraged to act by showing demonstrable benefits to their horticultural success – and thus emphasising and strengthening the connection between conservation and 'real life' outcomes.

This chapter details two variations on the theme of companion planting. Section 5.2. considers a 2015 project that examined the effect of co-planting crop plants with ornamental companions, each of which differed in their likely attractiveness to pollinating bees. The first project used isolated planters in otherwise flower-deficient areas; whereas the follow-on in 2016 (5.3.) considered placement of those crops in real-garden conditions, where the potential for distraction or facilitation is likely to differ.

5.2. Plastic not-fantastic: the effects of 'bee friendly' companion flowers on tomato yields.

"Modern, intensively bred, annual bedding plants such as busy-lizzies and petunias provide no food for insects – so your garden might just as well be filled with plastic flowers." (Goulson, 2010b)

Many of the ornamental plants that are popular in domestic gardens and civic planting schemes are varieties that have been bred intensively for dramatic colours, larger size of flowers, or extra sets of petals, with the result that the pollen and nectar that was accessible in the original species is no longer available, or is significantly decreased (Comba *et al.,* 1999; Goulson, 2006). Could these intensively-bred bedding plants act as useful ‘magnets’ for pollinators around less-showy flowers, or is their presence of no more impact than planting plastic flowers? Conversely, might the presence of co-occurring ‘bee friendly’ flowers prove distracting to pollinators, drawing them away from the target crop?

Biodiversity improvement in garden environments sometimes takes the form of companion planting, where ornamental plants are deliberately grown near to crops to improve yields and growing conditions (Franck, 1983). Generally the rationale behind the co-planting choices relate to pest control (Finch & Collier, 2012; Corbu *et al.,* 2014), or environmental regulation such as providing shade (Tscharntke *et al.,* 2011), or desalination (Albaho & Green, 2000). In recent years many advice lists have become available in the gardening media about how to select ‘pollinator friendly’ plants for companion planting choices, to improve pollinator populations and pollination services. Although there is considerable variation within these lists in terms of how plants have been selected for inclusion, they do provide an accessible starting point for gardeners looking to support their pollinator populations (Garbuzov & Ratnieks, 2014b).

The aim of this study was to examine the pollination received by a phytometer (a plant grown under controlled conditions to measure a response; in this case seed / fruit yields), to assess if it is enhanced or reduced when in the presence of co-flowering companion plants offering high or low rewards. Tomato plants (*Solanum lycopersicum*) were chosen for use in this study because the flowers are easily counted, pollinated flowers quickly become obvious, and the netted truss (excluding pollinators) can be on the same plant as open-pollinated trusses. The flowers do not offer a nectar reward and pollen from tomato flowers is generally only accessible to bees that are capable of using ‘buzz pollination’ to sonicate the flower to eject its pollen (Free, 1993); *Apis* bees do not do this, so insect-pollination of tomatoes is mostly by non-*Apis* bees, often bumblebees (Free & Williams, 1977; Banda & Paxton, 1990). In addition, the flowering period of *S. lycopersicum* is in the UK summer, which coincides with a wide selection of commercially-available flowering plants to use as the companions.

5.2.1. Methods

A high reward 'attractive' plant was chosen from the Royal Horticultural Society's 'Perfect for Pollinators' list (Royal Horticultural Society, 2011). The effects of co-flowering of the attractive plant were compared to: i) those of annual bedding plants which are *not* specifically marketed as 'pollinator friendly'; ii) tomatoes grown with no companion plants at all; iii) tomatoes grown surrounded by colourful plastic 'flowers'. Pollinator exclusion was performed on trusses of flowers on each tomato plant, as a within-plant control. Measured response variables were the number of fruit set, fruit weight and seed number recorded from the resulting harvest; compared between treatments.

Study sites

To reduce any influence of other nearby floral resources or distractions, the experimental sites were locations with no, or very few, concurrently-flowering plants in situ (the effects of more typical garden-style planting were investigated in Section 5.3.). For this study, and as part of the University of Sussex's ongoing schools outreach programme, school yards / car parks around Brighton were sought as placement sites in July 2015. These areas fitted the requirements for study sites as they contained few other flowering plants, and because they were empty (owing to summer holidays) during the experimental period, meaning there was little or no pedestrian or vehicular access occurring.

Schools were recruited by email contact with science teachers or heads of department, a preliminary visit was then made to each to ensure that the site would be suitable, and further explain the project requirements. Four schools were able to provide an appropriate site and access during the project time frame (Appendix A), with arrangements made in cooperation with site managers and on-site staff for access and safety restrictions. Appropriate risk assessments were completed for each site. In addition, an area on the University of Sussex campus was included as a fifth site, which had the same characteristics as the car parks, to allow for closer monitoring of the experimental setup.

Study plants

Cherry tomato (*Solanum lycopersicum*) was used as the experimental crop plant, using a similar method to that described by Potter & LeBuhn (2015). These plants are annual, benefit from insect-mediated pollination, and are typically flowering during July (Free, 1993; Morandin *et al.,* 2001). The 'Gardener's Delight' variety of cherry tomato was used, because it is suitable for container growing and is a very popular choice for UK gardeners.

Tomato seeds (supplied by Thompson and Morgan, Ipswich, Suffolk, UK. IP8 3BU) were initially propagated in small pots in a temperature-controlled greenhouse (20^{o}C). Seedlings were separated and potted on as they developed, resulting in 83 plants, each grown in individual 1.5L pots. These were managed as 'bush' plants by removing the growing tips at the top of the plant when they reached 1m in height, to encourage side shoot development, as is common with this variety of tomato. The plants were ready to use when the second truss of flowers was produced.

The companion plants were ordered as plug plants (from Thompson and Morgan); potted on into 1L pots on arrival, grown on and then acclimated to outdoor conditions for two weeks before the experiment started. The compost used was Levington M2 (supplied by Fargro Ltd, Vinery Fields, Arundel Road, Arundel, West Sussex, BN18 9PY) and the same batch of compost was used for growing and potting on all plants. The companion plants were chosen as follows:

1) The **high value** 'bee friendly' plant – Ageratum 'Blue Danube' (*Ageratum houstonianum*) a RHS' 'Perfect for Pollinators' plant (Royal Horticultural Society, 2011).
2) The '**low value**' plants – Busy Lizzies 'Divine' (*Impatiens walleriana*); a common bedding plant with large colourful flowers, but little nectar or pollen available for bees.
3) The **plastic flowers** – Plastic ovals, 9cm x 5cm, painted pink and blue ('Pacific Blue' and 'Fluorescent Pink' *PlastiKote* spray [Valspar Paint, 675 Eskdale Road, Wokingham. RG41 5TS]). These colours were also used in another ongoing Sussex pan trap study, and are known to be attractive to pollinators. Paint was applied two weeks before the experiment to allow all solvent to evaporate.
4) **Control** – a tomato plant with nothing surrounding it.

Experimental design

Tomato plants used for the study were selected once there were at least two trusses of flowers present on the plants, with only one or two flowers per truss open or about to open. Trusses were marked with coloured plastic twist-ties further down the stem, so they could easily be identified at later stages. Any tomato flowers that were already open before the plants were delivered to the sites were removed with small scissors and the starting number of flowers per truss, per plant was recorded.

The experimental group setup at each site consisted of four 40cm x 30cm x 20cm (24L) vegetable planters, filled with 20L of fresh compost mixed with 5g / litre '*Westland* Water-Saving Gel' crystals (Glowcroft Ltd, Needham Market, Suffolk), to reduce the risk of plants drying out in the summer weather. All sites had two blocks, consisting of two sets of four planters in total (Figure 1).

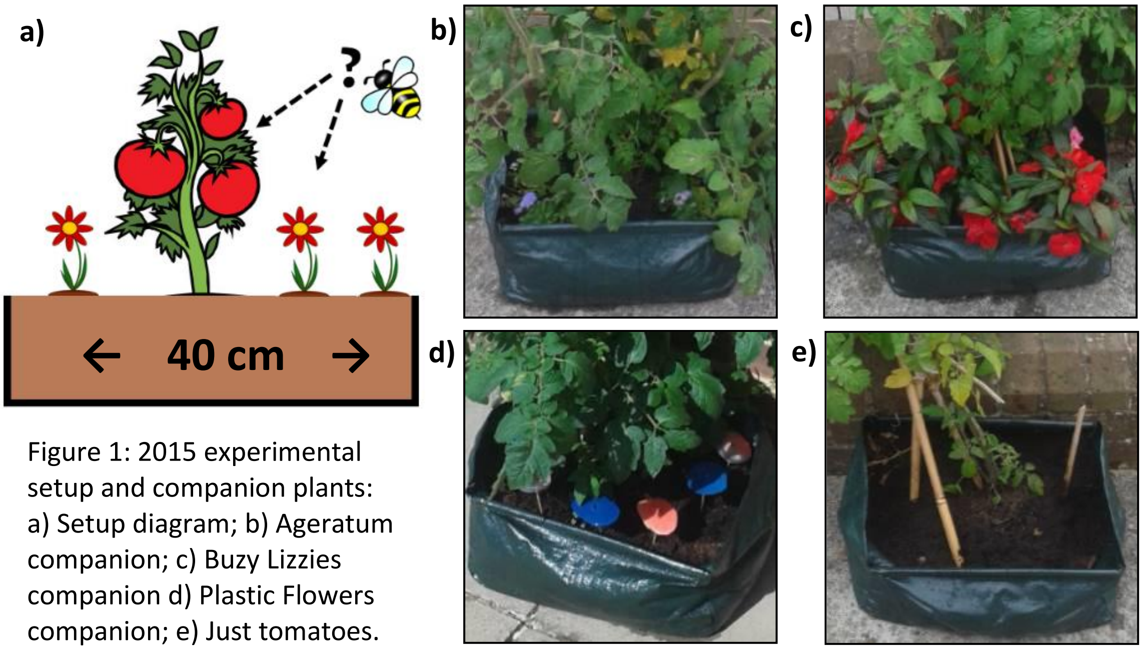


Figure 1: 2015 experimental setup and companion plants: a) Setup diagram; b) Ageratum companion; c) Buzy Lizzies companion d) Plastic Flowers companion; e) Just tomatoes.

Each planter contained one tomato plant and one of the four companion treatments detailed above. Companion plants were placed around the sides of the containers before transport to sites and the tomato plants were added on-site, since they were easier to transport undamaged in the smaller pots. All plants on a site were delivered at the same time. On arrival, tomato plants were transplanted into the larger planters containing the compost and companions, and placed into a randomly allocated position. Experimental planters were situated 4m apart, regardless of block allocation.

Flowering plants were on-site for four weeks between 29/07/2015 and 28/08/2015 (the exact dates of delivery and removal were different for each site, due to transport requirements and school opening times), watered at least once a week (more if the weather conditions required it), and removed at the end of that time. No additional fertiliser was added to the planters during the four weeks on site.

Tomato flowers exhibit a degree of self-fertilization (Morandin *et al.,* 2001), which is increased when plants are exposed to movement by the wind (Free, 1993). To quantify the extent of self-pollination experienced on these sites, each tomato had at least two 'open' trusses, with no treatment; and two 'netted' trusses, which were covered in a small tulle bag with mesh of <0.5 mm. A third truss was potentially added to each treatment, on each plant, depending on how well they grew at the site.

Counts of the number of flowers present on marked trusses were conducted once a week, and the number of set tomatoes were recorded. Observations of pollinator activity on the tomato flowers and the surrounding plants were taken; recording all visitations in 15 minute time periods during biweekly watering visits to the sites. It was not possible to carry out long observations as three of the four sites were primary schools, so even during holidays staff were required to be on site to allow access.

Flower numbers per truss proved difficult to standardise, unlike Potter & LeBuhn's (2015) experience; the tomato plants in this study produced trusses that varied from six to 14 flowers, and damage to the plants due to being exposed to wind and other environmental effects prevented standard numbers from being maintained. Instead, the flower numbers on each marked truss were counted during site visits, so that loss of flowers and percentage set of tomatoes could be compared.

When returned to Sussex, all plants were moved into a greenhouse, including those from the campus sites. Any further trusses of flowers other than the marked ones were removed, and any new growing shoots were removed to prevent them growing further. All plants received the same watering regime and were fed once a week with Levington *'Tomatorite'* tomato food (to packet instructions) while fruit was developing, to ensure adequate nutrient provision.

Tomatoes were harvested when fully ripe, or if it was necessary to remove them from the plant due to eventual onset of blight, or plant death from other sources (one plant was run over in the car park prior to being brought back, and did not recover). Harvested tomatoes were weighed on electronic balances in the laboratory and their colour/degree of ripeness recorded.

Tomatoes were cut open so the seeds could be separated and counted. All seeds from all harvested tomatoes were counted, with mature and immature seeds scored separately.

a) **b)**

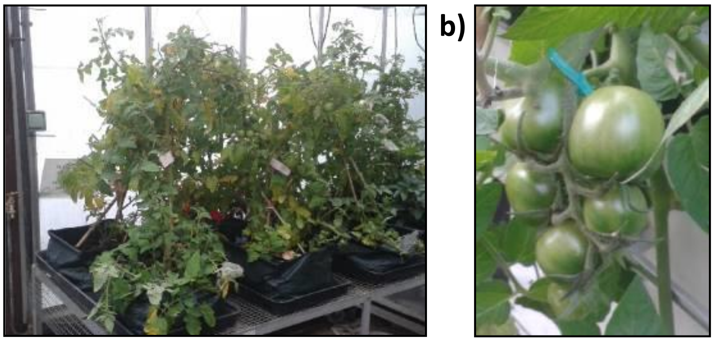


Figure 2: Tomato plants returned to the Sussex greenhouses.
a) Trimmed and maintained. b) Developing fruit.

Statistical analysis

Statistical analysis was carried out in SPSS 22, using Generalised Linear Models (GLMs) to compare the flower set, seed numbers, and weight for each treatment.

For weight, a square root transformation was applied to the data to better fit the assumptions of the GLM, and analysed using linear errors. For seed number (count) data, negative binomial errors were used. For flower set, the inverse sine of the proportion of flowers that set tomatoes was used as the response variable, and analysed using linear errors. In all GLMs the initial model was fitted with: treatment (netted/open), companion plant type, site (which school), and block nested within site, as main effects and relevant interaction terms, with model simplification via stepwise removal of non-significant factors. Post hoc pairwise comparisons were obtained through the SPSS GLM interface, with dummy-coding of categorical explanatory variables performed automatically by the SPSS software.

5.2.2. Results

Measurements taken from the experimental sites and plants are given in Table 1(a-d). Treatment (netted or open) had a significant influence on all response variables, with netted trusses setting fewer tomatoes (χ^2_1 = 9.24, p = 0.002), producing fewer mature seeds (χ^2_1 = 4.95, p = 0.026), and producing lighter tomatoes (χ^2_1 = 10.1, p = 0.001). Overall, 61.1% of open flowers went on to set tomatoes, compared to 49.2% of netted flowers. There were no significant interactions in this or the subsequent models.

There were also significant environmental effects on all measures, with 'site' affecting flower set (χ^2_4 = 44.1, p = < 0.001), mature seed number (χ^2_4 = 34.32, p = < 0.001) and tomato weight (χ^2_4 = 82.3, p = < 0.001), with lower yields at the campus site likely due to an outbreak of blight. Block effects were observed on flower set (χ^2_5 = 21.5, p = 0.001) and weight of tomatoes (χ^2_5 = 16.1, p = 0.007), but not on the number of mature seeds produced.

Table 1a: Summary results of *Ageratum* companion planted tomatoes from the five sites. Total numbers of tomatoes, weight of fruit, and total counts of seeds; from open-pollinated trusses or pollination-excluded trusses (netted).

a)	**Ageratum**							
	Total flowers		Total tomatoes		Total seeds		Total weight (g)	
Treatment / Site	Net	Open	Net	Open	Net	Open	Net	Open
BV	49	58	21	31	842	1276	223.89	390.9
Cam	38	46	16	20	193	444	83.21	93.65
Dav	30	24	27	21	874	1284	378.94	463.32
Nics	36	40	8	30	65	1133	13.55	238.68
Som	38	42	18	24	629	989	234.71	375.53

Table 1b: Summary results of Busy Lizzie companion planted tomatoes from the five sites. Total numbers of tomatoes, weight of fruit, and total counts of seeds; from open-pollinated trusses or pollination-excluded trusses (netted).

b)	**Busy Lizzie**							
	Total flowers		Total tomatoes		Total seeds		Total weight (g)	
Treatment / Site	Net	Open	Net	Open	Net	Open	Net	Open
BV	53	35	31	25	1424	1135	332.6	263.57
Cam	35	37	5	8	70	14	41.26	7.68
Dav	27	33	8	19	338	1111	87.52	301.36
Nics	19	30	13	14	607	256	207.61	120.66
Som	29	41	16	31	625	1761	163.91	478.31

Table 1c: Summary results of 'Plastic Flowers' companion planted tomatoes from the five sites. Total numbers of tomatoes, weight of fruit, and total counts of seeds; from open-pollinated trusses or pollination-excluded trusses (netted).

c)	**Plastic flowers**							
	Total flowers		Total tomatoes		Total seeds		Total weight (g)	
Treatment / Site	Net	Open	Net	Open	Net	Open	Net	Open
BV	39	46	29	29	739	1125	164.95	339.05
Cam	42	57	14	27	232	309	67.2	91.26
Dav	29	31	18	26	792	1501	219.66	436.85
Nics	31	40	18	26	666	989	211.13	257.35
Som	28	40	14	30	475	1850	146.47	437.06

Table 1d: Summary results of control, tomato-only plants from the five sites. Total numbers of tomatoes, weight of fruit, and total counts of seeds; from open-pollinated trusses or pollination-excluded trusses (netted).

d)	**Tomato only**							
	Total flowers		Total tomatoes		Total seeds		Total weight (g)	
Treatment / Site	Net	Open	Net	Open	Net	Open	Net	Open
BV	47	54	23	24	936	1171	277.9	319.51
Cam	41	48	6	15	40	313	26.11	81.52
Dav	39	43	23	27	1342	1542	305.17	410.07
Nics	46	36	26	25	497	626	132.13	295.17
Som	26	35	9	27	285	672	78.29	133.71

The companion planting showed no significant effect on the flower set (χ^2_3 = 3.98, p = 0.264) or mature seed number (χ^2_3 = 1.094, p = 0.779) but there was a significant difference in the weight of the tomatoes produced (χ^2_3 = 15.6, p = 0.001, Figure 3). Post-hoc pairwise comparisons through the GLM interface, with tomato-only dummy coded as the reference group, showed that the planters containing *Ageratum* plants produced significantly heavier tomatoes (χ^2_1 = 15.1, p = < 0.001), but there was no significant difference in weight of tomatoes between the tomato-only crop and the Busy Lizzie (χ^2_1 = 1.66, p = 0.198) or 'Plastic Flower' crop (χ^2_1 = 2.00, p = 0.157). There was no interaction with the treatment applied, with this effect found in association with *Ageratum* plants regardless of whether the tomato flowers were netted or not.

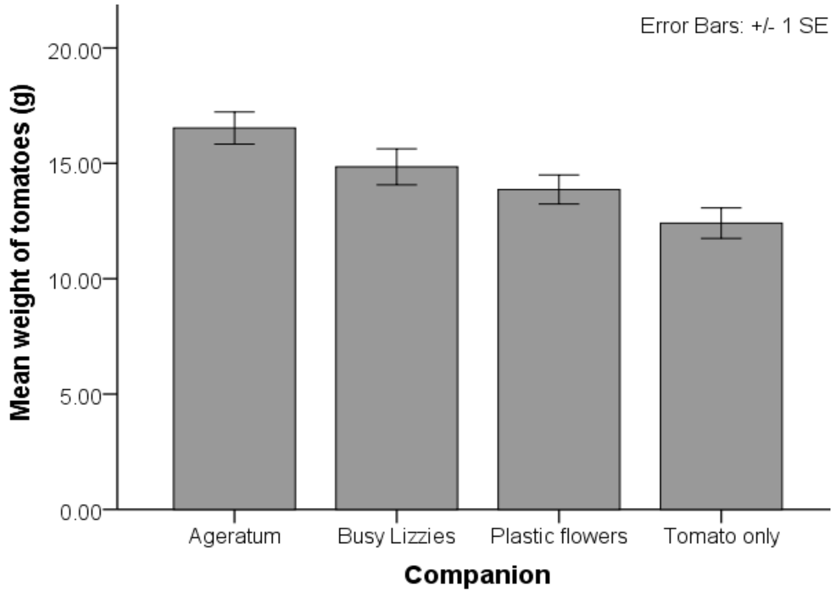


Figure 3: Mean weight in g (± SE) tomatoes grown under different companion planting treatments.

An additional observation made during the seed counting process was: that some of the final, very small tomatoes produced from the netted trusses had very few seeds, either mature or immature. This was markedly different from the tomatoes that had to be harvested early due to blight, which had the same sort of numbers of immature seeds present as the mature seeds found in the ripe fruit.

Observations of pollinator activity were taken during the project, but did not produce enough data for statistical analysis. Weather conditions during watering visits were frequently very windy, or raining, and pollinator activity was very low under those conditions. Due to the access restrictions to the sites observation frequency could not be increased to compensate for poor weather. Limited observations suggest that *A. houstonianum* was attractive to local pollinators on the campus sites, where bumblebees, honeybees and hoverflies would follow the plants around as they were being moved between greenhouses prior to the experiment – but this was not recorded systematically, nor the species involved identified.

5.2.3. Discussion

Seed numbers and flower set did not seem to be affected by the choice of companion plant in our experiment, only by the open or exclusion treatment. Although Potter & LeBuhn (2015) found an effect of pollination limitation on seed set in their study, Greenleaf & Kremen (2006) did not count seeds, and both used a different cultivar of cherry tomato (‘Sungold’). It is possible that the ‘Gardener’s Delight’ may produce roughly the same number of seeds per fruit as long as a certain threshold of pollination is met (which was exceeded by all open-pollinated flowers in our study, but not by the excluded ones). This is in line with Morandin *et al.*’s (2001) findings, which suggested that only 1-2 bee visits are necessary for complete seed set in tomato flowers.

The lower yield measurements recorded from pollinator-excluded tomatoes confirms that this variety does benefit from receiving insect pollination (Kearns & Inouye, 1993). Overall set of the open-pollination tomatoes at 61.1% was similar to the 66% found by Potter & LeBuhn (2015) and the 60% found by Greenleaf & Kremen (2006). While the latter suggest that 100% fruit set is not an appropriate maximum to expect in tomatoes, Morandin *et al.,* (2001) observed ~80% as typical with controlled high levels of exposure to bumblebees. Our results suggest that all tomato plants were receiving the same level of bee attention, and the presence of flowers beside the crop did not seem to act as a distraction to pollinators. There may well be room for improvement in fruit set, but these companion plants do not seem to contribute to that.

The one measure that did show a difference in association with a companion plant was weight. Tomato fruits were heavier from those plants surrounded with ‘bee friendly’ Ageratum, compared to the other treatments, despite identical watering and feeding regimes at all stages. This effect was not seen in association with the Busy Lizzies or brightly-coloured plastic controls. However, the lack of interaction of Ageratum planting with treatment category in the analysis casts doubt on the likelihood that these ‘attractive’ plants are facilitating the pollination of the tomatoes via a magnet species effect (Thomson, 1978; Laverty, 1992). If it were, an effect on the open tomatoes would be expected, but not on the netted controls. Growing Ageratum in companion does seem to have a positive impact on tomato weight, but this is unlikely to be influencing the *pollination*.

What is likely to be producing this effect? Busy Lizzies are a much larger plant with larger root systems than Ageratum, so it is unlikely to be a result of Ageratum roots breaking up or aerating the soil. The watering and feeding regime was the same for all plants, and the controls (with no competition for resources) produced the same weight tomatoes as the Busy Lizzies. It therefore seems most likely that the Ageratum plants are altering the chemical environment in the soil in ways beneficial to the tomatoes.

Ageratum houstonianum (of which 'Blue Danube' is a variety) is known to produce pyrrolizidine alkaloids (Wiedenfeld & Andrade-Cetto, 2001) which may be a deterrent against soil pests, particularly nematodes (Walker *et al.,* 1994; Thoden *et al.,* 2009). Extracts from the closely-related *Ageratum conyzovides* (an often-invasive species, also known as billy goat weed) have been used or considered for pest control for a wide range of invertebrates (Bouda *et al.,* 2001; Okunade 2002; Moreira *et al.,* 2007; Prakash *et al.,* 2008), so it is not unreasonable to assume that *A. houstonianum* exudates may have similar properties. However, there were few visible pest problems on the experimental tomato plants (other than blight); the growing compost used was new, and the plant roots were not examined for root knots or other signs of nematode activity because of this. So it is not possible to say for certain if Ageratum co-planting has a protective effect, but does suggest that any positive effect may be more to do with the 'traditional' reasons for companion planting than pollination augmentation.

5.3. 'Bee-friending' your garden – the effects of planting position in domestic gardens on tomato yields.

The first half of this work manipulated a floral display in an otherwise pollination 'neutral' area, but pollination and positioning in real-garden situations may present local pollinators with more complicated decisions. The foraging environment available to bumblebees in a garden setting is very different to the isolated experimental plant-companion blocks used in the previous study, with many different varieties of flower, and their rewards, available and varying in quality and accessibility over time. It is possible that the 'bee friendly' flowers used in 5.2. (*Ageratum houstonianum*) are simply not attractive to the species of bumblebees that primarily pollinate tomatoes, so the effect of their co-planting presence was no different to that of the low-reward plants. The lack of bee behaviour observations meant that it was not possible to determine whether bees visiting one sort of flower would also visit the other.

In real garden environments, the floral community is likely to be more diverse, particularly given the increased focus on 'wildlife friendly' gardening in recent years (Loram *et al.,* 2008; Davies *et al.,* 2009; Garbuzov & Ratnieks, 2014a). A greater variety of co-flowering plants may have different effects on the pollination environment experienced by garden crop plants than close-by planting of just one species. Bumblebees show a fairly high degree of consistency in their foraging choices, tending to switch to flowers with a similar structure to the original resource (Grant, 1950; Laverty, 1994; Gegear & Laverty, 1998), so a large number of other flowers that *do* provide a nectar reward, unlike tomatoes, may prove distracting. Alternatively, the maintenance of more constant floral displays in gardens all year round (even if a large proportion of this includes non-native species [Loram *et al.,* 2008; Salisbury *et al.,* 2015]) may keep local populations of bumblebees high, boosting the pollinators available to the crop plants during their flowering season, even if nothing is specialising on them (Comba *et al.,* 1999; Stelzer *et al.,* 2010; Salisbury *et al.,* 2015).

This study looked at pollination provision to tomato crop plants in real urban garden environments, comparing pollination levels in different parts of the garden. In addition, this second study allowed for testing of the use of 'Gardener's Delight' tomatoes in a citizen science protocol: assessing if volunteers could successfully handle the plant, and if the 'Gardeners Delight' is suitable as a phytometer in terms of its habit and manageability.

5.3.1. Methods

Site requirements

As access to the garden sites was required, both to deliver and collect the plants, recruitment of participants was focused on the Brighton and Hove area. Advertisements for volunteers began in April 2016, for a project start at the end of June. This was primarily through social media (using the 'LJBees' presence developed under the *Bees 'n Beans* work), an article in the June edition of the community magazine 'Preston Pages' delivered free to local households (http://www.prestonpages.com), and an interview on BBC Sussex / Surrey's 'Dig it!' radio programme on April 10th.

Gardens were sought that had the following characteristics (ideally all three, but just having the neutral area and the flowering area was enough to take part.)

1) A '*pollination neutral'* area such as decking, patio, or even the middle of a lawn. The exact type of space was not specified, although the plant for this position needed to be a minimum of 3m away from any flowering plants.
2) A *co-flowering* area, where the experimental plant would be surrounded by plants that were actively flowering during the duration of the project, such as within flowering borders, or surrounded by pots of flowering plants.
3) (Optional). A *vegetable growing* area, usually used for growing crop plants.

Figure 4: Representation of the three growing areas asked for, used in advertising.

In Brighton 22 volunteers were signed up for the project. Five more sites were included from the Sussex campus, with 'garden' parts selected based on flower-rich areas on the site (either decorative or experimental) and a nearby 'neutral' area for each e.g. a car park. This allowed the protocol to be observed on site.

In addition, a second group of five volunteers with suitable gardens was recruited in Nottingham from personal contacts, to test the protocol in cooler weather conditions than those commonly experienced in Brighton (which is amongst the sunniest places in the UK [Met Office, 2016]). The project was set up using identical methodology to the Brighton version, and site visits occurred at key stages (selection of experimental plants, treatment assignment, and delivery to sites). A volunteer co-ordinator looked after the day-to-day husbandry required for growing the initial plants, and after delivery all volunteers followed the same protocol as in Brighton.

Feedback was sought from all volunteers about their experience of the project.

Study plants

The same variety of cherry tomato (*Solanum lycopersicum,* 'Gardener's Delight') was used as in 5.2. Seeds were supplied by Thompson and Morgan (Ipswich, Suffolk, UK. IP8 3BU), and initially propagated in small pots in a greenhouse. On the Sussex campus plants were grown in grown in fresh Levington M2 compost mixed with 5g / litre '*Westland* Water-Saving Gel' crystals (Glowcroft Ltd, Needham Market, Suffolk). In Nottingham the compost was Levington Original Multi-purpose, as that was the one available from the local garden centre; the gel crystals were from the same batch.

Seeds were germinated in three batches in two temperature-controlled greenhouses (20^{o}C) in Brighton to ensure that sufficient plants were available at the start of the experiment, should be any problems during growing. In Nottingham two batches were germinated in two separate greenhouses to try to minimise disease or pest problems. Seedlings were separated and potted on as they developed, up to a maximum pot size of 3L. As is appropriate for the variety, these were managed as 'bush' plants by removing the growing tips at 1m in height, to encourage side shoot development.

Experimental design

Tomato plants used for the study were selected when there were at least two trusses of flowers present on the plants, with only one or two flowers per truss open or about to open. The first truss of flowers to develop was marked as the netted control for that plant, and enclosed in a 10cm x 12cm fine tulle bag with mesh of <0.5mm. The bag was large enough to allow for fruit development in situ. Subsequent trusses were not marked before the plants were delivered to the sites, but any flowers that opened before the plants were in place were removed.

Plants were grouped before delivery to be matched for growth habit (such as main stem number and size), so each group of plants taken to the experimental sites were as similar as possible to the others plants on that site. Plants were delivered personally by the researcher in Brighton and the co-ordinator in Nottingham. Within-site positions were randomly allocated on-site by a coin-flip. Photographs of each plant in position were taken upon delivery, as well as more detailed pictures of any surrounding or nearby plants that would be in flower during the experimental period.

Volunteers were given verbal direction backed up with a written instruction sheet (Appendix B) and required to keep the plants watered and in the same position, for four weeks. They were instructed not to remove side shoots (although this is a common practise when growing a 'bush' variety of tomato [Cockshull *et al.,* 2001]) because standardisation of the action could not be guaranteed, and also to keep the project leader (or co-ordinator in Nottingham) informed of any problems that arose.

After four weeks, the plants were collected and returned to the greenhouses, where they were curated. The numbers of trusses and flowers present were recorded, and all trusses with flowers that had finished were marked with coloured plastic twist ties. The truss with the largest tomatoes at this time was noted as being the first non-netted truss to develop. The nets were opened and removed carefully by cutting the mesh, leaving the base of the open net attached as a marker and causing minimal disruption to the truss. Any flowers which had not opened on the existing trusses were removed, along with any non-flowering side shoots, and any growing tips of the plants were pinched out.

In Brighton plants were maintained in the greenhouses until fruit matured, with counts taken weekly of the number of set flowers and maturing fruit. In Nottingham the greenhouses developed a severe infestation of aphids thus the decision was taken to grow the plants on outside in a sunny but sheltered position. The weather remained favourable during the growing on period, so apart from tying the plants to canes to keep them in position no further action was needed to secure the safety of the plants.

All plants received the same bi-weekly watering regime and were fed once a week with Levington 'Tomatorite' tomato food (to packet instructions) while fruit was developing, to ensure adequate nutrient provision.

Tomatoes were harvested when fully ripe, or if it was necessary to remove them from the plant due to eventual onset of blight, or plant death from other sources. All tomatoes from the netted truss and the first open flowering truss per plant were allowed to mature and picked when ripe, or were the first two tomatoes from all subsequent trusses.

Colour/degree of ripeness for the harvested tomatoes were recorded, and they were weighed (on electronic balances in the laboratory in Brighton, and electronic gram scales in Nottingham). Tomatoes were cut open so the seeds could be separated and counted. All seeds from all harvested tomatoes were counted, with mature and immature seeds scored separately.

Statistical analysis

Statistical analysis was carried out in SPSS 23, using Generalised Linear Models (GLMs) to compare the flower set, seed numbers, and weight of harvested tomatoes. For weight, a square root transformation was applied to the data to better fit the assumptions of the GLM, and analysed using linear errors. For seed number (count) data, negative binomial errors were used. For flower set, the inverse sine of the proportion of flowers that set tomatoes was used as the response variable, and analysed using linear errors.

In all analyses, the initial comparison was between the yield measurements from the netted control trusses, and the first open truss, as these were the first trusses to open on the plant and were *definitely* present in the same pollination environment on-site. Since the effect of netting in the 2015 experiment was so significant (5.2.2.), if this same result was shown again then the data from the netted trusses could be removed for the subsequent GLM, to allow for better sensitivity to any potential differences between positions.

For each GLM, the initial model was fitted with main effects of Site, and Position (near flowers / veg, or alone) nested within site; and relevant interaction terms, with model simplification via stepwise removal of non-significant factors. Post hoc pairwise comparisons were obtained through the SPSS GLM interface, with dummy-coding of categorical explanatory variables performed automatically by the SPSS software.

5.3.2a. Results – Brighton locations

In total 22 sites, plus five locations on the Sussex campus, were included in the study (Figure 5). Of the garden sites, five had all three location types (there were two more sites with vegetable beds, but these were lost to damage before collection); twenty of the sites did not contain a dedicated vegetable-growing area. Pollination neutral 'Alone' plants were recovered from 22 sites, producing 166 tomatoes in total; co-flowering 'Flower' plants were recovered from 25 sites, producing 170 tomatoes; vegetable bed 'Veg' plants were from 5 sites, producing 50 tomatoes.

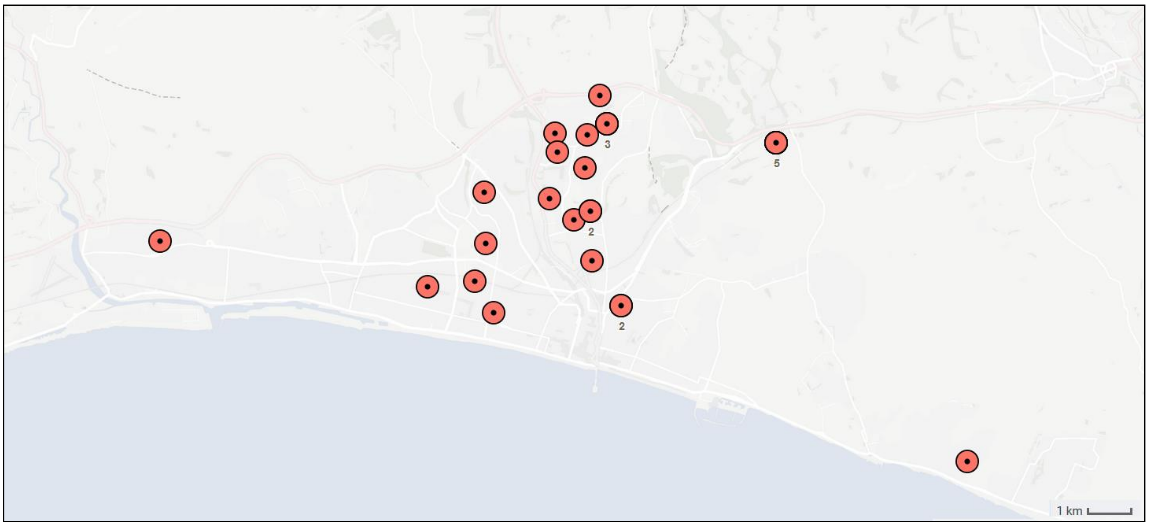


Figure 5: Location of gardens in Brighton & Hove that hosted tomato plants in 2016.

Netting significantly decreased the proportion of flowers that set tomatoes (χ^2_1 = 38.14, p = <0.001); the weight of those tomatoes (χ^2_1 = 14.04, p = <0.001); and the number of mature seeds that they contained χ^2_1 = 4.34, p = 0.037) compared to the first open truss on the plants (summaries in Table 2 and 3). Therefore, for further analysis, data from the netted trusses were separated from the open truss data.

Table 2: Results from open truss tomato plants grown in gardens in 2016; by position.

Open trusses	**Total flowers**	**Number set fruit**	**Proportion of flowers set**	**Mature seeds**	**Average seeds per tomato**	**Total weight of fruit (g)**	**Average tomato weight**
Flower	695	433	62.30%	9756	22.53	2200.12	5.08
Veg	138	93	67.39%	3230	34.73	960.74	10.33
Alone	578	340	58.82%	9433	27.74	2096.02	6.16

Table 3: Results from netted truss tomato plants grown in gardens in 2016; by position.

Netted trusses	Total flowers	Number set fruit	Proportion of flowers set	Mature seeds	Average seeds per tomato	Total weight of fruit (g)	Average tomato weight
Flower	171	63	36.84%	1640	26.03	406.49	6.45
Veg	31	7	22.58%	116	16.57	55.44	7.92
Alone	179	57	31.84%	1346	23.61	327.67	5.75

'Site' was significant in flower set and weight analyses; this is not surprising, as environmental conditions would have varied in different gardens. There was no significant effect of Location type (alone / flowers / veg) on the proportion of flowers that set tomatoes (Figure 6a), only the individual Site had an effect (χ^2_{25} = 62.5, p = <0.001), with no interactions. In terms of weight of tomatoes, both Site and Location (nested within Site) showed significant differences (χ^2_{25} = 182.2, p = <0.001; and χ^2_{26} = 147.0, p = <0.001, respectively). Comparison within Location shows that the significance is associated with plants grown near vegetables (Figure 6b), which produced heavier tomatoes (χ^2_{1} = 40.1, p = <0.001); while there was no difference between the weight of 'Alone' or 'Flower' tomatoes (χ^2_{1} = 0.575, p = 0.448).

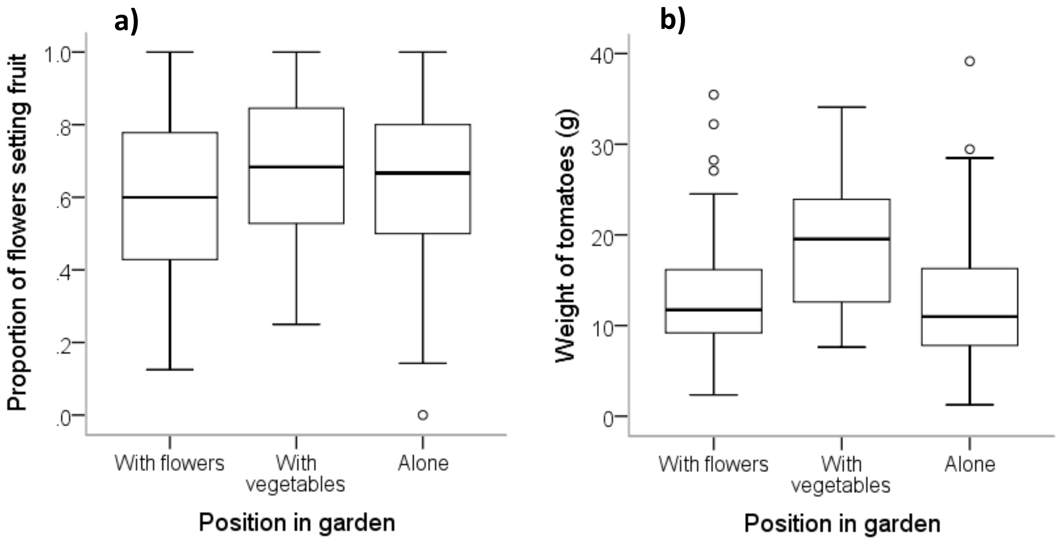


Figure 6: a) Proportion of tomato flowers that set fruit during the 2016 experiment;
b) Weight of individual tomatoes produced by the experimental plants in 2016, from open flower trusses; by position in garden.

The number of mature seeds in harvested tomatoes did not differ in relation to Site or Location (χ^2_{25} = 19.8, p = 0.758; χ^2_{26} = 11.2, p = 0.995, Figure 7; respectively).

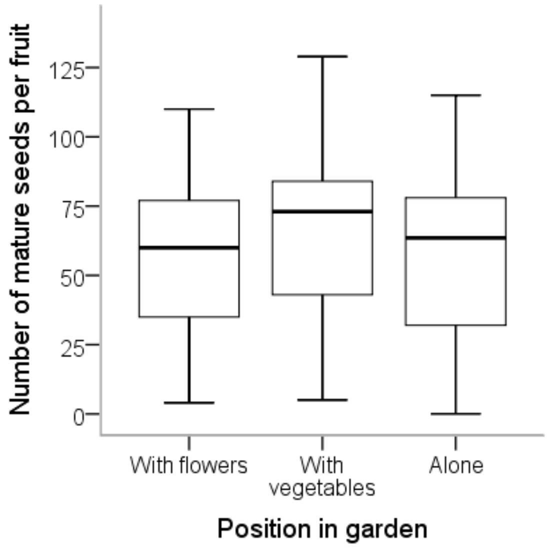


Figure 7: Number of mature seeds per fruit during the 2016 experiment, from open flower trusses; by position in garden.

5.3.2b. Results – Nottingham locations

Five sites were recruited in Nottingham, but in one site the plants failed due to drying out, thus only the data from four sites could be analysed.

Netting significantly decreased the proportion of flowers that set tomatoes ($\chi^2_1 = 8.42$, $p = 0.004$), and the number of mature seeds found in the harvested tomatoes ($\chi^2_1 = 10.8$, $p = 0.001$); so the 'netted' data was removed from further analysis for these two measures.

There was no effect of netting on the weight of the tomatoes from these sites ($\chi^2_1 = 2.02$, $p = 0.155$), so netted data was left in the overall analysis for weight.

In terms of flowers that set tomatoes, only 'Site' showed a significant effect ($\chi^2_3 = 16.6$, $p = 0.001$), again showing that different sites have varying conditions. There was no significant effect of either Site or Location on the number of mature seeds produced in harvested tomatoes, or their weight. The Nottingham-site tomatoes were effectively all the same, regardless of location or treatment.

5.3.2c. Results – both locations

All data together, including 'town' as a variable. In this section, 'Location' was nested within 'Town'.

In terms of flower set, the *netted* plants differed significantly by town (χ^2_1 = 10.0, p = 0.002), being lower at the Brighton sites than the Nottingham ones. This effect was not seen in regard to flower set when comparing the open trusses (χ^2_1 = 0.582, p = 0.445), so likely in some way relates to the nets themselves. There was no effect of garden location on the flower set of open trusses.

For weight of tomatoes, there was no effect of town on the netted weights; for open trusses, the Brighton tomatoes were heavier (χ^2_1 = 76.2, p = <0.001). There seemed to be an effect of Location, with the increased weight of Brighton 'Vegetable' plants not shown in Nottingham 'Vegetable' plants (χ^2_4 = 36.4, p = <0.001; Figure 8).

In terms of mature seeds, there was no effect of town on the netted counts (χ^2_1 = 0.425, p = 0.514); although Nottingham tomatoes seem to have more mature seeds in harvested fruit than the Brighton ones (χ^2_1 = 4.51, p = 0.034). There was no effect of 'Location' on the seed set.

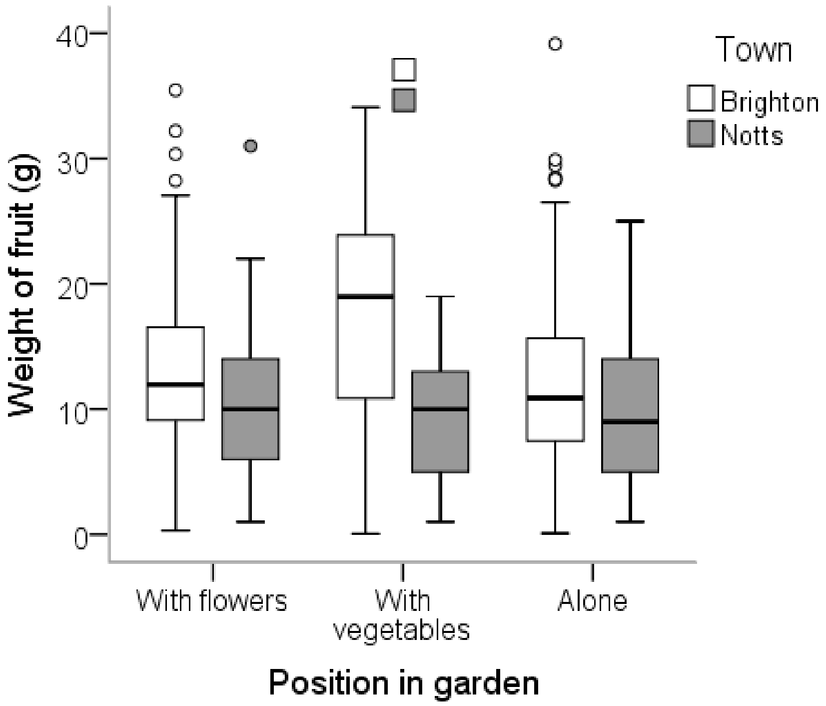


Figure 8: Weight of individual tomatoes produced by experimental plants in 2016, from open flower trusses; by town and position.

5.3.3. Discussion

The 61% open flower set was very similar to that observed in 2015 (61.1%), suggesting that the pollination provision in the 2016 gardens was similar to that experienced by tomato plants on the 2015 sites. Those sites had been selected to be pollination 'neutral' other than for the companion planters, so seeing the same pollination levels in real-garden environments suggests that positioning near to co-flowering ornamental plants does not detract pollination attention away from the tomatoes – although there was no indication that it enhances it either. Lower yields from netted trusses confirm that the plants did require insect pollination to successfully set tomatoes (Kearns & Inouye, 1993), but it seems that the open tomato flowers were all able to receive a fairly typical level of pollination effort (given Potter & LeBuhn [2015] found 66% set, and Greenleaf & Kremen [2006] 60%) regardless of their positioning on the sites. This is good news for domestic tomato growing, as it suggests a low chance of crop failure due to a lack of pollination – as long as pollinators are present, they seem likely to find the flowers, even if the plants can only be positioned in a fairly florally-poor area.

Potter & LeBuhn (2015) found that on their San Francisco sites, pollination correlated positively with floral resource density and proposed that this was due to increased abundance of bees; similar effects have been shown in other studies, for bumblebee species richness in particular (Goulson *et al.,* 2002; Matteson & Langellotto, 2012; Pardee & Philpott, 2014; Salisbury *et al.,* 2015; Foster *et al.,* 2016). While this effect was not seen in this study, both Brighton and the area of Nottingham where sites were located are primarily suburban, with large proportions of green space, so sufficient bees were likely present in the area for that level of pollination. Mismatch between landscape-level floral support for pollinators (Kohler *et al.,* 2008; Frankie *et al.,* 2009; Foster *et al.,* 2016) – including the maintenance of diversity over time as well as abundance of flowering plants in general (Hein *et al.,* 2006) – compared to the provision of pollination service in individual sites, is a noted concern for urban biodiversity planning (Cameron *et al.,* 2012; Pardee & Philpott, 2014). These results emphasise the importance of supporting pollinator populations over a wide area (Goddard *et al.,* 2010): bees can travel far (Chapman *et al.,* 2003) and might well be able to find tomato flowers regardless of where the plants are situated in a typical garden, but are unlikely to be primarily supported by resources in that area (Savard *et al.,* 2000; Tommasi *et al.,* 2004; Ahrné *et al.,* 2009; Matteson & Langellotto, 2010).

Difference in the harvested weights of netted tomatoes between each city is likely to do with how the plants were transported to the sites. Nets were added before transport, and the Brighton plants were carried to their sites on the bus; whereas Nottingham plants were transported by car. It is likely that movement of the nets during transport affected the Brighton plants, because they were in transit for longer. Differences in the open truss weights, with heavier tomatoes from Brighton plants, seems likely to be due to environmental conditions between the sites; probably due to Brighton being more southerly, and experiencing more sunlight than Nottingham.

Plants that received their pollination in vegetable-growing areas in Brighton produced heavier tomatoes than other garden positions. However, all plants were grown in the same volume of soil, from the same batch of compost, in the same sized pots; as well as receiving identical watering and feeding regimes when brought back from the sites, while tomatoes were actually developing. There was no difference shown between the 'Vegetable' sites in any other measures of yield; nor was this effect present in the Nottingham plants. This suggests that the greater average weight of tomatoes from the 'Vegetable' sites is likely to be co-incidental and an effect of small repeat numbers, since only four sites contained 'Vegetable' areas, compared to 22 sites without.

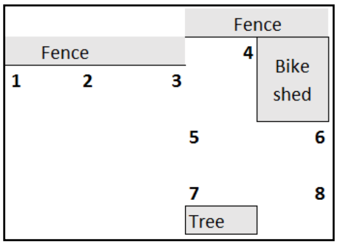
The 'Gardener's Delight' variety of tomato did seem to work as a citizen science plant, although blight damage was commonly reported. More variation was seen between tomato plants than between bean plants used previously; with the growing method also being more complicated and potentially less reliable for resulting in mature plants of similar habit. However, tomatoes are potentially more resilient than beans in terms of recovery from damage, as this variety readily produces side shoots. This poses an additional requirement for volunteers to remove shoots, and the need to keep doing this after plants are returned, but does mean that recovery from loss of flowers or damage to an experimental setup is possible. This variety is thus appropriate to use with similar methods to those of Potter & LeBuhn (2015), distributed from a central location, and using a tomato variety more suited to UK temperatures.

Appendix A – School site summaries

Four schools in Brighton & Hove offered their car parks / outside space for the project to use; these are detailed below.

St. Nicolas CE Primary School

Locks Hill, Portslade, Brighton BN41 2LA



Position of planters

Four plants were positioned along the car park wall / back fence. Plants were also tied to the fence for support. Four plants were positioned in a square around the concrete mesh area in front of the bike shed.


The car park fence, back fence and the bike shed on the St Nics site.

The plants around the concrete area were much more exposed, particularly as there were several weeks of strong wind and heavy rain over the course of the experiment. It proved difficult to keep them upright due to weather and the depth of the planters, but there was no serious damage. One of these planters was damaged by a vehicle running into it.

Brighton and Hove Sixth Form (BHSVC)

205 Dyke Rd, Brighton and Hove, Hove, East Sussex BN3 6EG

	Left	Right	
Fence	**1**	**5**	Wall
	2	**6**	
	3	**7**	
	4	**8**	

Position of planters

Two groups of four planters, set against the fence and wall respectively.


Tomato planters along the wall, and along the fence, on the BHVS site.

The group against the wall suffered considerably more with drying out, due to the slight overhang and prevailing wind direction, and did not remain upright; however there was no significant damage to the plants.

Davidgor Infant School

Somerhill Rd, Hove, East Sussex BN3 1RG

Fence	
1	**2**
3	**4**
5	**6**
	7
	8
	Gate

Position of planters

Eight planters arranged around a small courtyard, with plenty of support for the growing plants. There were bushes behind the surrounding fence, but they did not flower during the experimental period.

The courtyard area

Somerhill Junior School

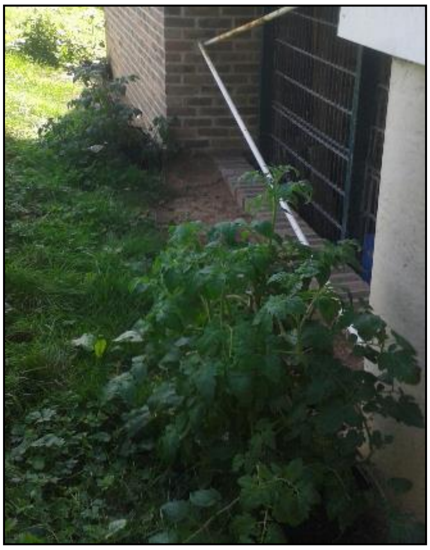
Somerhill Rd, Hove, East Sussex BN3 1RP

Car park	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**
	Hedges			Hedges				

Position of planters

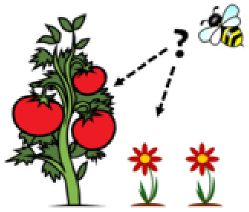
Eight planters were positioned in a line along the slope at the front of the site, which is grassy but not flower-rich. The surrounding surfaces were all impermeable (road, and roof).

Position 6 – 8



Position 4 - 5

Appendix B – Instructions for ‘bee-friending your garden’ 2016.



Bee-friending your garden

<u>Instructions for tomato-hosts</u>

Hi everyone!

Thanks again for agreeing to host some tomatoes for this summer experiment, looking at the effects of co-flowering on tomatoes in Real Garden Environments. Along with this sheet, you should have received your tomato plants, so here are a few quick reminders of what I need you to do with them.

<u>In the garden</u>

Hopefully I will have been able to help you set the plants up, but if this has not been possible, here are the steps to take.

1) Identify a ‘**pollination neutral**’ area of your garden. This should be a place where nothing / very little is flowering during the time you have the plants. So suitable places would include: decking, patio, up by the bins, against a wall, or even in the middle of a lawn.

   On the website we have suggested **3 metres** of non-flowering space around the plants, but if your garden is too small for that, don’t worry – just put them as far away from flowering plants as you can. We will measure how far they are and take that into account when looking at the results later.

2) Identify a ‘**flowering**’ area of your garden. Somewhere where there are lots of flowers in bloom during the experiment.

3) (optional) If you have a **vegetable patch**, separate to the flower beds.

I will bring you a tomato plant for each of those areas (two, unless you’ve told me you have a vegetable patch as well, in which case you will get three). There are mature plants in 3-litre pots and will either have started, or be about to start, flowering.

Each plant will have a **small mesh bag** over one set of flowers – this is the **control**, and should be left in place.

What you have to do then:

1) Put the plants in place in your garden, one in each of the above areas.
   (I will want to take a photograph of where they are – or you can – but this can be done at any time during the experiment.)

   It does not matter if you prefer to dig a hole for the pots, or sit them in trays, or rest them on the soil, as long as the plants **stay in their pots** (so I can take them away again without making big holes in your garden!).

2) Keep them well watered.

I will come and take the plants away again in August (they will be with you for four weeks). If you would like extra plants to replace them, just for you to keep, do let me know – because I am going to have a lot of spares!

Thank you again, and happy growing,

- Linda

Chapter 6: Using citizen science to monitor pollination services.

6.1. Introduction

The dividing line between interested amateur and professional scientist can be a fine one, particularly where the study of nature is concerned. The majority of well-respected historical information about wild species distribution and abundance has been recorded by naturalists, private hobbyists and generally-curious individuals who have tracked, twitched, tallied, illustrated, photographed and even stuffed their wildlife encounters over the last century (and before) (Pocock *et al.,* 2015). It is only relatively recently that 'professional' surveys have become common, and biological recording undertaken by volunteer schemes and societies still forms the underpinning backbone of ecological science, policy, and practice. For example, the UK National Biodiversity Network (NBN) Gateway holds 217 million species records collated from nearly 200 different schemes and surveys, most of which are primarily carried out by members of the public (NBN Secretariat, 2015).

Involvement of volunteers in science is the broad definition of 'citizen science' (Schmeller *et al.,* 2009; Silvertown 2009; Roy *et al.,* 2012a), and in recent decades there has been a substantial increase in the number of structured volunteer schemes that are developed and led by professional scientists, in addition to those run by community groups or interested societies (Theobald *et al.,* 2015). Several high-profile recent reports (Dickinson *et al.,* 2012; West *et al.,* 2015; Roy *et al.,* 2016) have examined the use of citizen science as a research tool; investigating participant motivations, demographics and the frameworks for running long-term studies (the *Bees 'n Beans* project publication [Birkin & Goulson, 2015] is referenced in both latter papers). They conclude that drawing on the observations and actions of a wide pool of potential observers offers opportunities for data collection on considerably larger spatial scales, and in far shorter periods of time, than a specialised professional group alone could achieve – which is especially relevant in ecology, where the phenological window for data collection may be short, and sites widely dispersed (Devictor *et al.,* 2010; Pocock *et al.,* 2014, 2017). This is hugely valuable economically; indeed, the 'in-kind' contribution of volunteers to UK biodiversity surveillance in 2007 was estimated to be worth over £20 million (Tweddle *et al.,* 2012).

In the UK, much of the monitoring of biodiversity status and trends – used to inform government and conservation initiatives – relies heavily on volunteer recording (Mackechnie *et al.,* 2011; Roy *et al.,* 2012b), particularly those used to derive the annual UK Biodiversity Indicators (DEFRA, 2017b). With an increasing policy focus on adopting ecosystem service approaches to ecological management, this need for working with citizen scientists will continue to intensify (Dickinson *et al.,* 2010; DEFRA, 2011). The majority of existing surveillance schemes are primarily observational, requiring participants to record occurrences or take measurements and report back; far fewer schemes require volunteers to undertake even simple manipulations or experiments (Dickinson *et al.,* 2010; Pocock & Evans, 2014; Carvell *et al.,* 2016).

The status and trends of pollinating insect populations, and the ecosystem service they provide, is an area of biodiversity surveillance that there has been considerable recent drive to improve (Dicks *et al.,* 2013; Carvell *et al.,* 2016), in light of the ongoing decline in UK bee populations (Breeze *et al.,* 2012; Dicks *et al.,* 2013; Goulson *et al.,* 2015). In response to this need, the National Pollinator Monitoring Strategy for England (DEFRA, 2014) set out a 10-year plan for supporting pollination, highlighting the current lack of long term standardised monitoring schemes for pollinators (wild bees and hoverflies in particular), and advocated using volunteers to collect data under instructions from professional scientists. This was followed by a report from Carvell *et al.,* (2016), which brought forward the development of a monitoring framework for agricultural crops. However, these recommendations focused specifically around using citizen science for the monitoring of pollinating insects themselves, whereas the projects undertaken in this PhD (and reported in preceding chapters) used a different approach: investigating methods of measuring the pollination *service* present, primarily in domestic gardens.

All of the projects within my PhD required some degree of volunteer participation. Three involved participants growing and manipulating focal plants, and taking standardised observations; two required participants to make measurements of their own pre-existing plants; two for project plants to be hosted and maintained but not to perform experimental manipulations or observations; and two were questionnaires (summarised in Table 1). All projects required recruitment and retention of participants, modification of methods based on feedback, handling emergent problems and questions, and ensuring that data was collected and returned appropriately.

Table 1: List of all the *Bees 'n Beans* family of projects, completed 2014-16, and the degree to which participants personally undertook experiments.

Project name	**Summary details**
Bees 'n Beans (Chapter 3)	Participants grew *Vicia faba* plants (seeds provided); were required to randomise pollination treatment application (netted for exclusion of bees, local pollination only, local pollination supplemented with hand pollination); maintained plants over the experimental period; and recorded counts and weights of resulting pods and beans. Primarily measuring service provision from long-tongued bumblebees, as the main pollinator of *V. faba*.
All About Alliums (Chapter 4) *Rolling out Radishes* (Chapter 4)	Focal plant pollination protocol, based on *Bees 'n Beans*. Radishes (*Raphanus sativus*) seeds, and *Allium hollandicum* bulbs were provided to participants, with the same pollination treatments as above. Pods (both plants) and seeds (radish only) were counted, but not weighed. These plants were used to measure pollination provision from the wider pollinator community, not only bumblebees.
Shopping in the garden (Chapter 2) *How much does your garden grow?* (Chapter 2)	The 'Garden shop calculators'. Both projects required volunteers to record and weigh the yields of their garden produce, submitting the results to the project via provided spreadsheets. In *Shopping in the garden*, volunteers did not receive produce 'valuation' until after submission; in *How much does your garden grow?* the provided spreadsheets automatically calculated values of produce as they were filled in.
Bee-friending your garden (Chapter 5)	Tomato plants delivered to participants' gardens, positioned in areas with: co-flowering plants, or no flowering plants, to examine effects of planting position on pollination received. Participants maintained plants (watering), but did not perform manipulations.
Plastic flowers? (Chapter 5)	Tomato plants surrounded by different companion plants (one specifically marketed as 'bee friendly', one not, one plastic, and nothing) to examine if co-planting affected pollination received. Plants provided by project and hosted in school car parks; no action needed by the school other than allowing access.
Growing towns (Chapter 2) *The Need for Bees* (Chapter 2)	Online questionnaire studies, asking participants about their garden characteristics, actions and planting choices in regard to pollinators. Requires answering questions about existing behaviour.

Since there are few other current projects which use *experimental* citizen science methods to collect data (Carvell *et al.,* 2016), this raised some interesting questions. Does the increased complexity of this type of project make it impractical to use in monitoring, or prohibitively confusing for volunteers? Do these methods add anything new to data collection, to make the investment of time required to run them worth the effort (Cohn, 2008)? Will volunteers stay engaged with the projects (Dickinson *et al.,* 2012)? Does involving members of the public also improve their understanding of the subject of the project (Cooper *et al.,* 2007)?

In order to address these questions, information on the practical application of my projects, as well as the perceptions/views of the volunteers involved, needed to be collected. Taking this approach from the beginning of the work also helped to i) maximise participant engagement with the study and adherence to the protocols; ii) provide early warnings of potential problems, allowing modifications to be made to the methodology immediately if required; and iii) elicit feedback to inform subsequent studies. To gain as much information as possible, individual feedback from participants (via email or telephone) was accepted at all stages of each study, and all projects specifically requested end-of-experiment feedback. Changes made to project protocols as a result of practical suggestions from feedback are covered in the previous Chapters 2 to 5, as part of the respective methodology sections.

A final questionnaire was sent out to all volunteers at the end of 2016 and this chapter will first consider those responses. Questions were asked about participants' motivations in taking part in the *Bees 'n Beans* family of project, their perceptions of both the work undertaken and their own understanding, and if taking part in these projects had led to change(s) in their behaviour. These results are compared with wider reviews of citizen science participation in the current literature, and in light of all feedback received over the three years. Finally, recommendations are provided on how to approach undertaking experimental citizen science – both in general and specifically in regard to pollinator services – based on my own 'lessons learned' as part of this PhD and current available guidelines.

6.2. Methods

The final questionnaire was developed during the field season of 2016, to consider the overall experiences and opinions of volunteers in regard to the projects, protocols and feedback; if their behaviour in regards to pollination and gardening had changed as a result of taking part in the projects; and their 'awareness' of conservation issues. The questionnaire was piloted by asking six volunteers (who had finished their experiment and lived locally) to complete the questions during a semi-structured review session, followed by discussion, to determine if the questions made sense to the intended audience and to ensure that suitable reply options had been provided. A complete list of the final questions used is included in Appendix A. The questionnaire was sent to participants who had been involved in any of the projects, in any of the years, and disseminated after all of the projects had finished so that none of the questions could influence the routine feedback, or garden practice mid-experiment.

Responses were anonymous, not asking for postcode information or other identifiers used in previous studies, and collected via an online form hosted by Survey Monkey (www.surveymonkey.com). While this did not allow for comparison of changes in perceptions of individuals across multiple years, it was considered preferable to keep participants anonymous so that they felt under less pressure to give 'correct' answers.

Invitations to participate in the 2016 questionnaire were issued by first collating the email addresses of all volunteers who had taken part in any of the studies listed in Table 1, regardless of what year(s) they had participated or the success / failure of their experiments. Any email addresses that had been shown as non-functioning from prior communications were excluded, as were email addresses that bounced back after dissemination of the questionnaire. A total of 1,000 volunteers were invited to take part.

6.3. Results of 2016 questionnaire

6.3.1. Recruitment to the projects

Of the 1,000 volunteers contacted, 162 completed the questionnaire (a 16% return rate), with 78% of participants (126) considering themselves to be either experienced or amateur gardeners (Table 2).

Table 2: How participants would classify their level of gardening and scientific experience. Multiple choices. n = 161.

Level of experience	Number	% of answers
Interested amateur gardener	77	48%
Experienced amateur gardener	52	32%
Professional scientist (current or retired)	23	14%
Just starting in the garden, or have a new interest in ecology.	15	9%
Experienced amateur scientist	9	6%
Professional gardener (current or retired)	6	4%
Professional ecologist (current or retired)	5	3%

Table 4: Which questionnaire projects were undertaken, 2014-2016. Multiple choices. n = 156. All projects were part of this PhD.

Sussex questionnaire projects completed	Number	% of answers
Only questionnaires or feedback sections associated with the project(s) I was involved with (e.g. the Bees ‘n Beans feedback sections)	98	63%
Need for Bees 2015	7	4%
Growing Towns 2014	2	1%
None	55	35%

Table 3: Which citizen science projects from the University of Sussex were taken part in, 2014-2016. Multiple choices. n = 162. **Bolded** projects were part of this PhD.

Sussex projects undertaken	Number	% of answers
Bees 'n Beans 2016	83	51%
Bees 'n Beans 2015	78	48%
Bees 'n Beans 2014	33	20%
Bee-friending your garden 2016	17	10%
All About Alliums 2016	14	9%
Hoverfly Lagoons 2016	14	9%
Pollinator Abundance Network (P.A.N.) 2015	13	8%
Pollinator Abundance Network (P.A.N.) 2016	12	7%
Garden shop calculator 2016	8	5%
Hoverfly Lagoons 2015	7	4%
Pollinator Abundance Network (P.A.N.) 2014	4	2%
Air B 'n Bee 2016	1	1%

After accounting for multiple responses, 90% of participants (145) had taken part in at least one of the *Bees 'n Beans* projects (Table 3). Twenty-seven people (19%) did both 2015 and 2016 *Bees 'n Beans*; six people (4%) did 2014 and 2015; and seven people took part in all three years (5%); this is compared to the overall percentages who took part in multiple years in Table 5. Twelve people did *Bee-friending* alone, five did *All About Alliums* only, and the majority of participants had not contributed to any questionnaire projects other than feedback forms (Table 4).

There was no single source of information that the majority of participants had used to find out about the citizen science projects. The most common individual category was '*recommended by friend or family*', and was responsible for a quarter of recruitments. After accounting for multiple responses, 77 people (57%) found out about the projects via an online source, and 57 people found out about it by a non-online source (43%), including personal recommendation (Table 6).

Table 5: The percentage of total participants in *Bees 'n Beans* projects who had taken part in multiple years, compared to the percentage of the final questionnaire respondents who had done so. For total participants, calculating percentages was done with n = the number of participants in the *final* year considered. E.g. 9% of participants in 2015 had also taken part in 2014; where 2015 n = 515. For 2016 n = 408. For the questionnaire n = 145; the number of respondents who had taken part in *Bees 'n Beans* in *any* year.

Years of participation	Total participants	% of overall total	Final questionnaire respondents	% of questionnaire respondents
2014 and 2015	44	9%	6	4%
2014 and 2016	22	5%	9	6%
2015 and 2016	87	21%	27	19%
2014, 2015, and 2016	11	3%	7	5%

Table 6: How did participants find out about the project(s) they took part in? More than one category could be chosen. n = 134.

Where did you find out about the project(s)?	Number	% of answers
Recommended by a friend/family/colleague	34	25%
Other web site	30	22%
Article or advert in a newspaper or magazine	26	19%
'Buzz Club' web site	18	13%
'LJBees' web site	10	7%
'LJBees' Twitter	10	7%
'Buzz Club' Twitter	7	5%
Other Twitter	6	4%
Approached by the project team	5	4%
Heard about on TV or radio	4	3%
Attended a presentation by the project team	2	1%
Attended an event by one of the project team	1	1%

There were common motivations for taking part, with a majority of participants having a general interest in ecology or conservation, and approximately half indicating that they had a specific interest in bees, or *'thought it would be fun'* (Table 7).

Table 7: Reasons for participation in citizen science projects.
More than one category could be chosen. n = 159.

Motivation for taking part in the project(s)	Number	% of answers
Interested in ecology or conservation generally	112	70%
Thought it would be fun	84	53%
Specific interest in bees	81	51%
I am a gardener looking to improve my garden for bees and other beneficial insects	70	44%
Interested in doing some 'practical science' related to my garden	66	42%
Have children that I wanted to do the experiments with	28	18%
Recommended by a friend / family / colleague	17	11%
I work in education and was looking for teaching aids	9	6%
I was asked by a member of the project team	3	2%

6.3.2. Perceptions after taking part

Over half of participants indicated that their level of interest in conservation and bees had not changed over the course of the projects, although about 30% reported that they now paid more attention to programmes and articles about bees than they had done before. There seems to have been a small increase in interest in conservation generally – and while two people noted more uncertainty, none of the participants had been discouraged entirely (Table 8).

There was little change in the number of conservation, or bee-themed events attended after taking part in the projects (Table 9); although the responses and more detailed comments provided in 'Other' suggest that a lack of events to attend, or a lack of awareness of anything occurring locally, was a common reason for this. One participant (a *Bees 'n Beans* volunteer) specifically reported that they had helped 'tired' bees with sugar water, and their daughter was now 'not afraid of bees anymore'.

There was little change in the frequency with which participants visited wildlife sites since being involved in the project (Table 10), nor in their membership of conservation groups (Table 11); however, the majority of volunteers indicated that they already visited wildlife sites, and a quarter were already members of conservation groups.

Table 8: Whether participants felt that taking part in citizen science projects had changed their level of interest in bees or conservation. More than one category could be chosen. n = 162.

Level of interest in bees or conservation	Number	% of answers
My interest level is about the same as before	91	56%
I have read more articles in books, magazines or on the internet about bees	52	32%
I now pay more attention to TV or radio programmes that are about bees	51	31%
I now pay more attention to TV or radio programmes that are about conservation in general	27	17%
I have read more articles in books, magazines or on the internet about conservation in general	27	17%
I am now more aware of local conservation activity	25	15%
I am more uncertain about these issues than I was before	2	1%
It has put me off	0	0%

Table 9: If participants had attended any bee or conservation events since being involved in citizen science projects. n = 160.

Events attended	Number	% of answers
No – I did not have the time to attend any events, but would like to have been able to	36	23%
No – there have not been any close enough to attend	37	23%
Other	30	19%
No – attending events is not of interest to me	25	16%
Attended a bee- or conservation-related activity / event	18	11%
Taken part in practical conservation or ecological work	10	6%
Been involved in organising a bee- or conservation-related activity or event	2	1%
Given a talk or presentation on bees or conservation	2	1%

Table 10: If participants had visited any wildlife sites since being involved in citizen science projects. n = 157.

Wildlife sites visited	Number	% of answers
Yes – but no more than I did before being involved with citizen science	95	61%
Yes – I have been to new places since being involved with citizen science	25	16%
No – I did not have the time to visit but would like to have been able to	22	14%
No – this is not of interest to me	8	5%
No – there are not any that are close enough to visit	7	4%

Table 11: If participants had joined any bee or conservation groups since being involved in citizen science projects. n = 159.

Groups joined	Number	% of answers
Not joined any groups	93	58.49%
I am already a member of a conservation group or forum and have not joined any more since being involved with citizen science	40	25.16%
I have joined internet forum(s) or other online group involved with bees or conservation	12	7.55%
I have joined a national group involved with bees or conservation	8	5.03%
I have joined a local group involved with bees or conservation	6	3.77%

6.3.3. Citizen science as a research tool

The majority of participants did not take part in any other citizen science projects alongside those from Sussex (119; 73% of responses). Of the other projects listed, the most common were Garden Birdwatch (15 people), and the UK Butterfly Monitoring Scheme (UKBMS) Butterfly Count (10 people). Most participants felt that their efforts in the Sussex projects had contributed to scientific research, although about a quarter were unsure how (Table 12), *yet al*most all participants felt that the feedback provided by the projects to volunteers was adequate (Table 13).

Table 12: If participants felt that they had contributed to scientific research by taking part in projects from Sussex. n = 161.

Did you feel you have contributed to research?	Number	% of answers
Yes	112	70%
No	10	6%
Unsure	39	24%

Table 13: If participants considered the existing level of project feedback adequate (summary results sent back where possible, publications linked to, and a named contact). n = 161

Was feedback adequate?	Number	% of answers
Yes	153	95%
No	8	5%

6.3.4. Moving forward

The majority of participants indicated that they were willing to take part in all of these projects types again (Table 14), with *Bees 'n Beans*-style experimental projects being the most popular, followed by questionnaires, and hosting plants. Only 10% indicated that they would not want to take part again, mostly due to difficultly combining specific experimental timeframes with lifestyle or employment; or changes in circumstances, such as relocation to a less unsuitable area, or health issues (Table 15).

Table 14: If participants were willing to take part in these types of projects again in the future. More than one category could be chosen. n = 162.

Would you take part again?	Number	% of answers
Yes – simple projects that include putting plants into control and experimental groups (e.g. like *Bees 'n Beans, All About Alliums*)	137	85%
Yes – answering questionnaires	104	64%
Yes – hosting plants provided by the team (e.g. like tomato plants)	101	62%
Yes – to set up simple apparatus and record observations (e.g. like hoverfly lagoons, bee hotels, P.A.N. project)	94	58%
No – please see next question.	17	10%

Table 15: Reasons given by participants who answered 'no' in Table 14, to why they were unlikely to take part in such projects again. n = 17.

Reason for no	Number	% of answers
My life style/job makes it difficult to keep track of tasks that need doing in specific time frames	8	28%
My life style/job is such that I am away a lot and cannot do tasks at specific times	4	14%
Holidays get in the way of the schedules	4	14%
I did not enjoy the practical projects	2	7%
My family lost interest	1	3%
Overall it is too time consuming	0	0%
Instructions are unclear, confusing or too complex	0	0%
Other (details given)	10	34%

The majority of volunteers had made some modification to their ornamental flower gardening habits (with 41% indicating they made *no* changes), but this was distributed across the categories. Greater awareness of, and willingness to buy, bee-friendly plants were the most common changes (Table 16). There were fewer changes listed in vegetable growing behaviour, with the majority reporting that they made no change –

although roughly a quarter of participants indicated a greater tolerance for the presence of flowering weeds near crops (Table 17).

Most participants had not increased interest in in local civic or community planting actions. Although about a third were more interested in council planting choices, fewer had contacted their local councils to enquire or comment (Table 17).

Table 16: If participants had made any changes to their **flower** gardening habits as a result of taking part in the citizen science projects. More than one category could be chosen. n = 160.

Changes made to **flower** gardening habits	Number	% of answers
I have not made any changes	66	41%
I look for 'bee friendly' plants and seeds when shopping	66	41%
I am more aware of what makes a 'bee friendly' plant	64	40%
I have used more 'bee friendly' plants in the flower garden	31	19%
I have stopped or reduced pesticide use	21	13%
I have made some other change to my flower gardening	9	6%
I have stopped using some plants that are not 'bee friendly'	5	3%

Table 17: If participants had made any changes to their **vegetable** gardening habits as a result of taking part in the citizen science projects. More than one category could be chosen. n = 158.

Changes made to **vegetable** gardening	Number	% of answers
I have not made any changes	96	61%
I tolerate flowering weeds more	43	27%
I have stopped or reduced pesticide use	25	16%
I have used more 'bee friendly' flowering plants in the vegetable garden.	20	13%
I have made some other change to my vegetable gardening.	6	4%

Table 18: If participants have taken any more interest in civic or community planting in their area, as a result of taking part in citizen science projects. More than one category could be chosen. n = 153.

Category	Number	% of answers
I have not taken any more interest in civic or community planting	82	54%
I have taken more notice of what the council have been planting in respect of 'bee friendly' plants	54	35%
I have taken more notice of other community planting in respect of 'bee friendly' plants	34	22%
I have contacted the council to ask about their planting/gardening policy	10	7%

6.3.5. Neonicotinoid awareness

Responses to this question showed that a high percentage of participants were aware of what a neonicotinoid is. Most of the detailed answers were correct, ranging from simply knowing it was 'a pesticide'; to 'pesticide harmful to bees', to very specific knowledge. Only one 'yes' answer was considered to be too vague to be correct i.e. *'Something to do with tobacco'.*

Table 19: If participants knew what a **neonicotinoid** was, without using the internet or other reference. n = 162.

Do you know what a neonicotinoid is?	Number	% of answers
Yes (please detail)	105	65%
No	41	25%
Not sure	16	10%

6.4. Discussion

Respondents to this final questionnaire had primarily undertaken *Bees 'n Beans* projects, and because the latter two years (2015-16) in particular made specific efforts to target recruitment towards gardeners, it is unsurprising that the majority of respondents identified themselves as such. Although the questionnaire return rate of 16% may be low, it seems that the responses are likely to be representative of the overall experiences of taking part in the projects. Rates of participation across multiple years shows a similar pattern for both the survey participants and the total *Bees 'n Beans* project volunteers: for example, in the 2016 *Bees* project, 21% of participants had also taken part in 2015, compared to the questionnaire responses, where 19% had taken part in *Bees* in both 2015 and 2016.

Comparatively few respondents had completed any of the purely 'questionnaire' projects (detailed in Chapter 2), and most people indicated that they were not involved in any *other* citizen science projects, although reported a high degree of interest in conservation and ecology generally, as well as a willingness to take part in further similar work. Even participation in 'at home' observational studies of birds and butterflies were uncommon, despite projects such as the RSPB's Big Garden Birdwatch and the UK BMS Garden Butterfly survey being amongst the most widespread citizen science initiatives ongoing in the UK (Roy *et al.,* 2012b; Pocock *et al.,* 2014).

This suggests that the population of potential volunteers for *experimental* citizen science studies such as *Bees 'n Beans* is different to that of people who are mostly interested in taking part in observation projects, and this may represent a good way to expand the proportion of the public who are actively engaged with conservation (Bonney *et al.,* 2016). Respondents strongly indicated that they felt their participation had contributed to research efforts, and that it was this type of project that was of the most interest to them for future participation. Not that observational studies were specifically rejected, but there seemed to be an overall preference for experimental-style projects amongst these volunteers.

The majority of recruitment for the projects was via various online sources (described in previous chapters), yet a quarter of participants reported that they became aware of the studies via family or friends, indicating that offline discussion and social promotion of engaging projects definitely occurs. A specific point raised in feedback for both *Bees n' Beans* and the garden shop calculators was the desire to be able to compare progress with others on a wider-project scale. Adding competitive comparison and other 'gamification' ('game playing') elements to citizen science projects has become increasingly common in recent years (Eveleigh *et al.,* 2013, and reviewed by Roy *et al.,* 2012b), and one of the main motivations indicated for taking part in the Sussex studies was that the projects seemed 'fun' as well as interesting. Enjoyment of the activity is a vital characteristic of successful public engagement actions, emphasised by both Pocock *et al.* (2014) and Dickinson *et al,* (2012), so the willingness of participants to enthuse about these projects to others is an encouraging outcome.

The ability to take part in these projects specifically from home seems to be an important part of their success. Despite indicating a pre-existing interest in conservation, there was little change in participants' reported visitations to wildlife sites, membership of conservation groups (about a quarter were already members of a group and indicated they had not sought out anything further), or attendance of bee- or conservation- events after the projects were complete. However, approximately 40% of respondents stated that they *had* altered their own private gardening behaviour, deliberately choosing and seeking out plants labelled 'bee-friendly'. This is higher than the 31% of gardeners found by Mew *et al.* (2003) to select plants specifically that are attractive to wildlife. While there is debate over exactly how useful labelling like 'bee friendly' is – both in terms of the actual attractiveness and provisioning potential of the plants themselves (Garbuzov & Ratnieks, 2014b; Garbuzov *et al.,* 2017), and the potential of other dangers such as pesticide content of commercially-grown flowers (Lentola *et al.,* 2017) – having 'at a glance' branding like that is useful for consumers (Wollaeger *et al.,* 2015). Since this is being used to make deliberately conservation-conscious purchasing decisions, more coordination between the horticultural industry and conservation professionals is required to ensure that such labelling is accurate and appropriate.

Given that there was a relatively high interest in bees / conservation in general amongst the respondents, it is likely that this group is already fairly willing to make changes in their behaviour to support these things, but it does still suggest that actively taking part in citizen science projects may prompt those changes to occur, as well as providing a source of trustworthy information to better inform their decision-making (Evans *et al.,* 2005).

In contrast to effects on ornamental planting, there was little change demonstrated in regard to vegetable (or fruit) growing behaviour. However as discussed in Chapter 5 (and similar to results found by Cussans *et al.* [2010]) if bees are present in an area they are likely to find and adequately pollinate flowering crops. Many common crop plants may provide reasonably good forage for bees as part of the overall garden vegetation, since flowering crops are selected for their fruit / seed production rather than aesthetics (Comba *et al.,* 1999) and must thus retain the ability to *attract* pollinators. There is some evidence to show this effect for *Vicia faba* and other leguminous crops (Brown *et al.,* 1992; Knight *et al.,* 2009; Dicks, 2014), although with garden sizes in the UK approximately averaging 170-190m^2 (Osborne, *et al.,* 2008; Davies *et al.,* 2009) and the flowering period of *V. faba* being approximately five weeks (Free, 1993; Osborne *et al.,* 1997), it is unlikely that even a very committed amateur gardener would be able to grow enough beans alone to influence nearby bee colony survival. Thus improving the ongoing bee-friendly nature of the garden as part of the urban habitat matrix (Cooper *et al.,* 2007) is probably more useful for conservation than specific changes to vegetable-growing habits.

There is scope here for recommendations for 'easy' (or even better, free) actions that could be taken to improve gardens for bees. Twenty-seven percent of survey respondents said they were now more tolerant of the presence of flowering weeds in their gardens, and 16% indicated they had reduced pesticide use. Both of these are actions that require *less* effort or expenditure rather than more (although may incur extra time cost, if e.g. pesticide has been replaced by hand-removal of insects or weeds), and the uptake suggests that there is appetite for this kind of modification (Thompson, 2011). Letting crucifers flower or leaving 'bolted' crops (such as coriander, rocket and radish) to flower are some examples that are similar in approach to tolerating flowering weeds, and could easily be included in post-project advice for wildlife gardening, helping volunteers to build on their efforts to support bees even after the results have been handed in.

About a third of participants reported that after taking part in the projects they had become more interested in bee conservation specifically, paying more attention to articles and other media relating to bees, and also to the planting choices made by their local councils. Few people indicated that they had attempted to contact their local authorities about local schemes, but enabling participants to more critically evaluate and understand the reasoning behind local planting choices is important in helping to relate conservation initiatives to 'real-world' outcomes, and may motivate them to engage more with local ecological decision-making in the future (Bonney *et al.,* 2016). Since a pre-existing interest in conservation was one of the prime motivations for taking part in this suite of projects – further illustrated in the questionnaire results by 65% of respondents correctly knowing what a neonicotinoid was, compared to the 43.4% found by Wollaeger *et al.* (2015) – raising interest levels still-further in a third of participants is a positive and encouraging outcome.

Overall, the responses given in this final questionnaire indicate that experimental-style citizen science projects can successfully increase interest in conservation of wildlife, as well as having great potential to provide useful and informative scientific data. This is particularly in regard to those aspects – such as pollinators – that are visibly present within participants' own gardens, and which allow for direct experience with the wildlife concerned. In these type of studies, actively performing an experiment seems to appeal to people who are not currently 'employed' as volunteers in more observation-based studies. These activities may be more easily shared and compared with friends or family members, and may also appeal to older gardeners by 'doing something useful' which is contributing to scientific research (Pocock *et al.,* 2014). In line with the findings of other recent experimental citizen science projects (Pocock & Evans, 2014; Foster *et al.,* 2016), I conclude that these hypothesis-driven programmes have the potential to be very valuable to ecological sciences – provided that the projects are robustly designed, transparent in their reasoning and information provision, and implemented with sensitivity to the requirements of volunteers.

6.5. Working from home: making use of citizen science.

There are a great deal of potential methods that could fit under the broad definition of 'citizen science' (Roy *et al.,* 2012b) even just within ecological sciences, and it is beyond the scope of this thesis to attempt to summarise such a large area. Nor do I intend to duplicate work done by recent publications which provide frameworks for identifying when, where, and what methods may or may not be appropriate for a given scheme. Tweddle *et al.* (2012)'s 'Guide to Citizen Science' provides a guide to designing and implementing projects, aimed at those already involved with citizen science; the Cornell Lab of Ornithology (2013) has an online 'Citizen Science Toolkit' (http://www.birds.cornell.edu/citscitoolkit/toolkit) which guides practitioners through the design of new projects (including how to avoid duplicating existing ones); and most recently Pocock *et al.*'s 2014 framework paper is presented in the form of a dichotomous key, annotated with specific case studies, to help users to decide if citizen science approaches are appropriate for their intended study, and where to start.

Once the decision to use citizen science methodology has been taken, further consideration needs to be given on how to recruit participants, how volunteers will collect and return data, and how the research team will maintain contact and keep volunteers engaged with the work. Modern developments in technology, particularly in terms of mobile devices and internet tools, has greatly expanded and strengthened the range of options available compared to historic data collection (August *et al.,* 2015). Easy recording of geographic information means that observations can be accurately located faster than ever before (Goodchild, 2007; Connors *et al.,* 2012); this type of data has been recently used successfully in tracking and responding to invasive species such as the Asian hornet *Vespa velutina* (DEFRA, 2017a). In particular, the availability of online portals and similar options for data submission makes getting results back from participants easier and faster, removing sources of error from copying out paper forms, as well as reducing postal costs and the risk of data being lost in delivery (Pocock *et al.,* 2015; NBN Secretariat, 2015). Social media and email also greatly facilitate maintaining contact with participants, updating information and answering questions.

Since there are so many ways to undertake citizen science, getting started can be daunting. The above frameworks and guides are extremely useful places to begin, and include summary case studies. To complement these pieces of work, the following sections will consider in detail the lessons learned across the three years of my PhD, my experience of designing and implementing citizen science projects, and will provide recommendations for approaching such work, both in general and specifically in respect to pollination services.

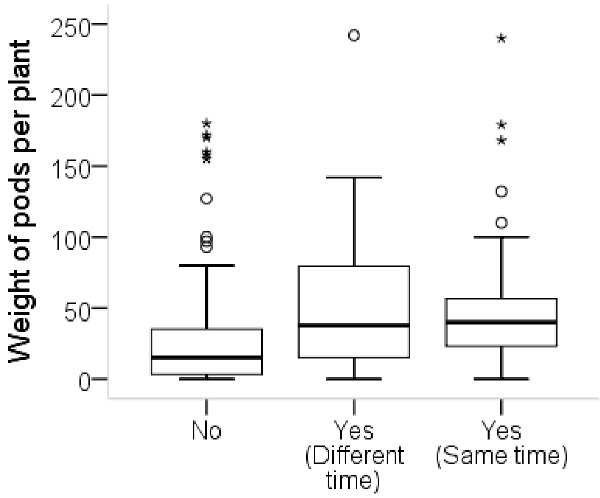
6.5.1. Recruitment

Experience of project recruitment 2014-2016

Raising awareness of any proposed project, and getting interested participants to sign up for it, is a fundamental step for citizen science studies, but requires careful consideration in order to maximise the value of the resulting data. For example, in the 2014 run of the *Bees 'n Beans* project, recruitment was not focused on any particular subdivision of the UK population, other than framing the project as mostly aimed at volunteers who did not live in a 'rural' area (although this was not strictly defined). As the first year of the project, this broad advertisement was chosen to judge overall interest in the project and with a view to including as many types of growing spaces as possible, given the variation present within 'urban' areas (Gaston *et al.,* 2005; Angold *et al.,* 2006). Potential participants were asked for no more than a name, email and postal address; recruitment ended once the required number of sign-ups had been achieved (550).

The advantage of this type of recruitment is that high numbers of registered participants can be achieved quickly (for *Bees 'n Beans* 2014 this took under two weeks); however, high initial sign up rates are often countered a low rates of retention and final data return (West *et al.,* 2015; Sauermann & Franzoni, 2015).

Feedback and discussion with participants during the 2014 run of the project indicated that people who already had some gardening experience were better able to maintain the experimental plants and handle emergent problems (such as pest control). This was further supported by analysis of the data returns, which showed higher yields associated with familiarity with growing the phytometer *V. faba* plants (reproduced in Figure 1); this was elucidated via a question on the data return form for 2014, asking if other beans in addition to the experimental plants were grown on site.



Were more *V. faba* grown in addition to the experimental plants?

Reproduced from Chapter 3, Figure 8.

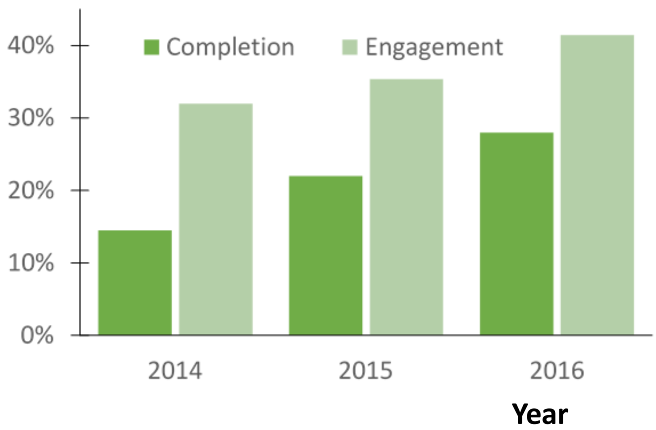
Weight (in g) of pods produced by experimental plants, and if additional beans were also grown.

The weight of pods (regardless of pollination treatment) was significantly higher on sites where additional *V. faba* were also grown (χ^2_3 = 10.5, p = 0.015) – indicating gardening experience was associated with success.

Figure 1: Gardening experience affected the yield of pods from the 2014 *Bees 'n Beans* plants.

In the two subsequent years an attempt was made to focus recruitment specifically onto those who already identified themselves as gardeners, and were therefore more likely to have existing equipment or expertise required to complete the project. This was done not by specifically excluding potential volunteers (by e.g. saying 'if you are not a gardener, do not take part in this study'), but by including more questions in the initial sign-up form, mentioning the need for specific equipment. For *Bees 'n Beans* 2015 and 2016, participants were asked if they would be able to supply their own garden fleece (or similar exclusion netting), and in addition in 2016 they were asked to supply 3L pots to grow the plants in. Priority for volunteers who could supply these items was noted on the form. When the appropriate number of suitable volunteers was reached, a bcc mass email confirming participation was sent before project packs were dispatched; anyone with a non-functioning email address was removed from the project, since it is vital to maintain contact with the group. It had been made clear in the recruitment call that not all volunteers would be selected, due to the need to ensure wide geographical coverage, so those not selected based on gardening ability or email failure would not feel 'rejected'.

A longer timeframe was given to cover recruitment in 2015 and 2016, allowing for a slower rate of sign up due to the additional requirements, although sufficient numbers were still recruited to be able to run the studies. These modifications resulted in greatly improved rates of return, and rates of 'engagement' (participants who specifically informed the project team if their experiment failed were considered to still be engaged with the project, even if they were unable to return results); summarised in Figure 2.



Reproduced from Chapter 3, Figure 13.

'Completion' = returned a dataset.

'Engagement' = Completion + those volunteers who remained in active contact with the project, even if they were unable to return data, and gave information on why this was.

Figure 2: Completion and engagement rates across the three years of *Bees 'n Beans*.

For the 2016, smaller-scale project pilot *All About Alliums*, volunteers were sought from those already engaged with citizen science work at Sussex University – either from the University 'Buzz Club' initiative (http://thebuzzclub.uk), or from those who had been successful in the *Bees 'n Beans* studies and indicated further interest in this work. Participants in *All About Alliums* were thus selected from a more targeted population, similar to Foster *et al.* (2016), who identified volunteers from Garden Organic – a UK charity promoting organic growing, who had already taken part in a bumblebee survey. Foster *et al.* achieved a return rate of 31% (similar to the first year of *Bees 'n Beans*), and *All About Alliums* had a data return rate of 60%; both are in line with the range of citizen science return rates found by West *et al.'s* 2015 review.

It is likely to be desirable to recruit participants from a specific targeted population if you are undertaking a more-experimental project. Large scale observational projects such as the Birdwatch, or ad hoc schemes which focus on getting people to record something they happen to have seen, can target the population broadly, but experimental projects are likely to need either pre-existing expertise or the willingness to develop it. For *Bees 'n Beans*, that turned out to be gardening skill (mostly the understanding of how to grow broad beans), and return rates were far greater when focusing on gardeners. Focusing effort on a more specific population also allows for better evaluation methods – if you have more idea about how many people you have advertised to (by counting attendance at and event or stall, or as typical of phone studies), then uptake rates and engagement rates are easier to estimate.

Recommendations for recruiting citizen scientists

1) How – and who – to recruit?

In the UK, the majority of people who take part in citizen sciences are older, middle-class and (predominantly) white (Roy *et al.,* 2012b), and a similar demographic pattern is found amongst those who 'grow their own' vegetables (Church *et al.,* 2015). Schools and organisations that work with young people are also common focal groups for recruitment to conservation work (Pocock & Evans, 2014; Polli:Nation, 2015; Buglife, 2017b; Royal Society for the Protection of Birds, 2017), since the overlap with educational aims is beneficial for both participants and organisers (Department for Education, 2014). This is the same pattern seen in the *Bees 'n Beans* project family, where retired people as well as parents and children were common participants.

It is likely that this 'typical' recruitment population would provide enough volunteers to carry out observations and experiments, for most projects. However, if there is a specific educational or awareness-raising component (Cooper *et al.,* 2007; Devictor *et al.,* 2010) then steps need to be taken to reach a wider population of participants, which will likely require more targeted effort (Nisbet & Scheufele, 2009). People who are not already somewhat engaged with conservation may not be as easy to access via online recruitment methods, and may require more time-consuming or hands-on recruitment methods (such as public events, focused on e.g. inner city community groups, or schools).

Accessibility of the project also needs to be taken in account. If your population of volunteers is likely to involve older or much younger people, then there may be limits to the experimental manipulations that they can reasonably be asked to carry out. In *Rolling out Radishes*, it transpired that the small radish flowers were considered difficult to see clearly and handle properly by some older volunteers (who contacted the project directly about this issue). Similarly, if recruitment is to be primarily via internet sources this could be missing a large proportion of potential participants, if they do not use social media. A solution is to consider print media in targeted areas as well (*Bee-friending your garden* was advertised in the project area via a local community magazine, with contact phone number included).

2) Be very clear about **what** volunteers need to do.

Recruitment to the project should be as specific as possible about what activities participants will need to do, and how much space will be taken up by the project set-up. Mock-ups of the proposed experiment, or examples from a pilot study or previous version can be very helpful in setting the scene. Describing any manipulations that will be required, beyond observation, is likely to reduce the initial uptake, but also reduces the drop-out rate (West *et al.,* 2015; and shown over the three years of *Bees 'n Beans*). Space for pictures is not usually a problem for online recruitment, but any printed advertisements will likely need to be succinct due to space restrictions, and the pertinent points must still be included. Ideally the advert in all media should refer interested parties to somewhere that more detailed information can be found, such as a project website.

Volunteers will be of all ages, abilities and educational levels (even if they might tend towards being older, there will still be a range – in *Bees ‘n Beans*, participants ranged from four to sixty-eight years old), and may not have English as a first language. Instructions must therefore be as straightforward as possible, avoiding jargon and colloquialisms (if something cannot be avoided, explain it clearly). Diagrams must be clearly labelled and infographics easy to understand – photographs of each methodical stage are encouraged, if possible, as this shows participants what it 'should' look like. *Bees 'n Beans* included a video of hand pollination, hosted on Youtube, to demonstrate how to perform the most complex element of the project. Draft instructions should be tested among colleagues and lay readers (e.g. willing family and friends; ideally those with a similar level of biological knowledge to the proposed recruitment population), particularly to help identify where extra clarity or more explanation is required.

3) Be explicit about **how long** participation in the project will take.

Volunteers might sign up faster to a project that is vague in timescale, but drop-out rates are likely to be high if e.g. a focal plant needs more frequent watering than predicted, or the project runs for longer than advised. It is also important to note if participants need to do anything specific at weekends, or during the day on weekdays.

If the duration of the project stages are unknown or variable, the best estimates possible should be given, and the uncertainty emphasised. The timings of school holidays, or common family holiday periods that may occur during the project's expected duration should be taken into account when planning start / end dates. One of the main problems faced by the 'Schools' variation of *Bees 'n Beans* (Chapter 3; Appendix A6), for example, was that due to poor weather, the *V. faba* plants were only ready for harvest during the summer holidays – meaning that the students who had been involved with maintaining the plants were not able to take part in recording results as they had then 'moved up' a year, or changed schools.

4) Be very clear about what **costs** participants will have.

Does the project require participants to provide any equipment? Soil, pots, canes and garden fleece were all required for the *Bees 'n Beans* projects (as well as the allium and radish variants), and this was made clear from the beginning. Does the data return method cost postage, or can it be done online? If not, consider supplying stamped addressed envelopes, and if that is not possible then let volunteers know the cost of postage before they sign up.

5) Explain **why** this data is being collected.

Feedback from all of the projects in this PhD indicated that participants were very interested in knowing where their data went, and what it was used for, or was planned to be used for. Feeling like they are contributing to 'real science' is an important potential motivator, and for citizen science in particular, the social element – being part of a 'group' working towards a task – is rewarding (Bell *et al.,* 2008; Roy *et al.,* 2012b). Participants are more likely to take part in a project a second time if they feel that their work is useful and appreciated (Wolcott *et al.,* 2008).

6.5.2. Communication

Recommendations for communications

Good communications need to be established from the beginning of any citizen science project; potential participants should be able to contact the project team for information as soon as the advertisement is open. Social aspects of volunteering are extremely important for retention of participants in voluntary schemes; this includes both the competitive and the collaborative aspects (Bell *et al.,* 2008; Roy *et al.,* 2012b), which enhance the feeling of being 'part' of a wider scheme and are acknowledged as important for attracting volunteers and retaining their interest (Cooper *et al.,* 2007; Pocock *et al.,* 2014). Communications before and during the experimental phases of the projects are a vital element of this, making participants feel valued by the project team, informed and confident about what they are being asked to do, and that they are actively contributing to something important.

1) Using appropriate language

Setting the right tone in communications is essential, needing to be friendly and informative, but still remain professional (Trench, 2006). An appropriate written tone of voice is important for clearly communicating information, and while a degree of informality can help keep a reader engaged this should not be overdone (Meyer, 2016). Colloquialisms and contractions (such as "isn't" rather than "is not") should be used carefully (Barrass, 2002); in moderation these contribute to a personal tone, and help to avoid coming across as distant, but communications still need to sound sincere. A similar situation applies to the use of emphatic punctuation or formatting, such as exclamation marks or italics – it is easy to come across as forced or overexcited. A good starting point is to limit exclamation points to one per email, and not to use them at all in experimental instructions; unless it is for emphasising hazards (Trask, 1997).

As discussed above, education levels and linguistic skills are likely to vary between participants. Instructions that are confusing or difficult to follow will put volunteers off, and over-use of 'jargon' terms risks making the project seem inaccessible. On the other hand, as discussed earlier, the 'science' element of these type of projects is attractive, so communications also need to avoid coming across as patronisingly simplistic. 'Citizen science' itself is potentially a jargon term, but it is useful to use to emphasise the difference between these sort of projects and less-active, *ad hoc* observational studies.

Small boxes inset into the text to **define specific terms** are a useful visual tool, allowing definitions of 'scientific' terms to be checked easily, without needing to read whole paragraphs again.

Care needs to be taken in the introduction of new, more -scientific terminology without seeming that the project will require volunteers to learn a lot of additional words. Each new scientific term or concept term needs to be clearly defined when it first appears, and it is important try to avoid bringing in too many too quickly.

Examples of the language used in *Bees 'n Beans* instructions and communications can be found in Chapter 7.

2) Clear instructions and branding.

Product branding is a key feature of marketing practice, and while research projects are not selling a product, there is still enough overlap with advertising requirements to draw parallels – particularly between the engagement of citizen science volunteers and supporters of charities. Investing in clear branding in the charitable sector improves volunteer / supporter engagement and loyalty (Dixon, 1997; Roe, 2015), and both are important characteristics of successful citizen science projects. Based on volunteer feedback and charity guidance, the following approaches are recommended for these type of projects:

i) Having a clear, eye-catching project ‘brand’ is advisable, particularly a logo. This gives a project a specific identity and reduces the likelihood of project paperwork being discarded by accident. Similarly, ensuring that posted project documents are printed professionally on good quality paper means that they will be distinct from ‘everyday’ papers, as well as robust enough to be used outside without being easily damaged.

ii) Project instruction sheets, recording forms and any other documentation (such as identification guides) should take into account the above recommendations about language use. It is also advisable to offer to have large-print versions available on request.

iii) Instructions should contain all the information that participants require to complete the project, including information about how to record / return results and predicted dates to do so.

iv) It is preferable to provide physical recording sheets for data collection, as these do not require participants to have access to a computer on-site, are more practical to take outside, and can be filled in by hand. Although the majority of volunteers will probably have access to the internet throughout the project, this cannot be guaranteed and some will participate ‘off line’; thus as far as possible, providing a complete package at the beginning maximises the chances of successful completion.

v) Pdfs of project documents should be available online for participants to download if posted documents are lost.

3) Ensuring an approachable and accessible project team

It is important that participants can contact the project leader/team with any questions or problems that arise during the experiment, and receive a prompt response. This is particularly vital in situations when the phenological window for observations may be narrow, or as part of protocols where live plants (or insects) are being maintained by participants – since a slow response to a problem may result in a dead plant and an experiment that fails for that volunteer. It also allows for issues that have been raised repeatedly to be addressed in relation to the whole project group (such as pest control problems) and follow-up advice to be sent to all volunteers.

Having multiple options for contacting the team facilitates accessibility. Social media accounts on different platforms (e.g. Twitter, Facebook, and websites) can be integrated; when combined with email mailing lists and phone lines, this means that information can be disseminated rapidly to those taking part. Dedicated email accounts for the project means that staff absence can be covered without the confusion of temporarily swapping of points of contact.

4) Ensuring regular contact with the volunteer group

It is essential to that participants feel part of the project, to maximise engagement and keep the dropout rate as low as possible (Cooper *et al.,* 2007). Regular contact with the mailing list of participants is important for this, but volunteers should not feel harassed or 'spammed' with unnecessary information. The *Bees 'n Beans* projects used the following:

i) Welcome emails. This confirms to volunteers that they are part of the project, and also provides a point for anyone uncertain to drop out of the project, enabling resources to be diverted to recruiting replacements.

ii) Specific emails just before critical stages of the experiment (for example: 'time to plant the beans', 'bean flowers will start opening around now, so the manipulation experiments have to start') serves to remind volunteers what they need to do, and allows the project leader/team to add in any extra information that has arisen in the meantime.

iii) In addition to critical stage reminders, email contact with volunteers should be sent approximately once a fortnight during the experimental period, and once a month in the build-up to it (or, e.g. during growing stages for phytometer plants). This frequency seems to be sufficient for retaining interest overall. These do not have to be long emails; ‘just checking in’, or providing short updates about the project and its planning is enough, and keeps the project profile high.

iv) The use of social media allows the project team to share wider information relevant to the work, such as facts about the taxa involved, or other interesting articles or events that are relevant to the area under study. As the volunteers need to actively choose to access this, it avoids the possibility of direct email information overload.

5) Data returns, feedback and security

Having multiple routes for participants to return their data improves the return rate (in their 2015 review, West *et al.* suggest that three methods of submission increased submission rates to 100%). For my PhD projects, the online returns were delivered via the “Surveymonkey” website (www.surveymonkey.com), with some recording sheets posted by volunteers who preferred to return data in that way. Throughout the projects, five major themes were identified as important to ensure that data were returned and collated successfully:

i) Ensure multiple methods of collection and data checking. The advantage with online returns is that the amount of input needed to be done by the project leader / team is reduced (not eliminated, since there were some postal returns) and the process is faster; however, it does not remove the requirement for curating the data to make sure that the correct information has been typed in, or contacting volunteers personally if potential errors are identified.

Postal returns need to be manually inputted, which adds time and another potential source of transcription error. However it is easier to view the data as a whole on a paper return and potential outliers can be queried with the relevant volunteer. Cross checking data against original returns is straightforward.

ii) Ensuring that adequate data security mechanisms are in place. Data security is an important aspect of research protocols that use citizen science (Pocock *et al.,* 2014), as some level of information about members of the public will be being collected. For my PhD projects, volunteers were asked to provide their name, postal address (plus postcode of experimental site, if different to postal address), and email address on the sign up form, as this enabled research material to be posted and contact arranged.

The sign up information included an assurance that personal data would not be shared with anyone outside of the University project team (myself, and designated laboratory-group helpers). Information in electronic form was kept secure by storing any personal data in password protected databases (Microsoft Excel; Survey Monkey website) on a password protected system (Survey Monkey website; University of Sussex intranet). On the data return forms, only postcode plus a further identifier (e.g. first name / surname) was required to be able to remove any duplicates from the online database.

Secure storage is required for paper returns, especially if they contain identifying information about participants; the level of security required will differ depending on the data requested and the organisations involved, and should be determined and arranged prior to any data collection.

Email addresses were kept confidential by using 'bcc' to avoid there being a huge list of identifiable email addresses emails at the top of updates. This meant that a) participants are only sharing their email address with the project team, b) it prevents 'reply all' problems, and c) allows the emails to feel more personalised (Wolcott *et al.,* 2008). A system such as 'mailmerge' can also be used to address bulk emails to volunteers individually.

iii) Analysis should be carried out on anonymised data. Postcodes were used for mapping locations of sites, and while these were hosted online and available to view, the website used (www.batchgeo.com) allows the user to set a zoom limit so individual streets and addresses cannot be easily identified.

iv) Feedback and comments *from* volunteers should be encouraged and accepted at any point during the project. Specific feedback after the project finishes should be sought while experience of participation is still fresh. Ideally, participants who withdraw before the end of the project (and inform the team of this) should be asked the same questions as those who complete, so sources of problems can be identified as early as possible.

Providing a feedback / comment section on the recording form also allows notes to be made during the experimental period, as well as keeping participants aware that they will be asked to provide some at the end of the project.

v) Feedback *to* volunteers should also occur over the course of the project (Pocock *et al.,* 2014); responding to questions or problems in a timely manner. Reassurance needs to be given that even a failed experiment is useful to know about, as it can indicate changes needed in the protocol for future experiments. This strategy helps to provide a better idea of engagement rates than participants just stopping communicating if the experiment fails. If possible, it is useful to provide appropriate information to participants about ongoing results. This allows volunteers to compare 'how they are doing' with others, and emphasises that their results are feeding into a larger body of data. However this should not compromise the experiment, so may only be appropriate for some designs of project; e.g. data on the number of returns would be possible (50% finished; only 20% to go, etc); and data from 'Garden shop calculator' (Chapter 2) style projects giving e.g. 'the average value of bee-pollinated harvest this month was…'. Results of ongoing analysis, such as 'low pollination service provision in this area of England' or 'very few of this species seen in Berkshire' may influence volunteers to alter their reporting behaviour or effort, so should not be shared.

6) Avoid asking for 'needlessly' repeated data.

An issue that came up during feedback received from the 2014-16 projects was that some participants who had taken part in multiple years – or multiple projects within the PhD or *Buzz Club* associated projects – questioned why they had to provide information again which had not changed since the previous year, or had already been provided to another project.

Garden characteristics (width x length, main aspect facing, etc); what type of green space they had; and typical planting habits were all queried, and the responses included 'same as last year', or 'told in other project' (a few people responded with 'don't you still have this?'). This suggests that asking for these basic data items again on sequential occasions risks distancing participants from the project, making them feel as though they are not being listened to, or are not being *remembered*, and thus reducing the social connection with the project team.

It is therefore recommended to ensure that there is a suitable database set up before any repeats of a multiple-year project, allowing returning volunteers to be matched with their already-provided information quickly. This can either be done manually, comparing provided names / email addresses / postcodes as identifiers, or by a web interface which allows volunteers to log in, or skip already-answered questions. The web based solution can be developed but may not be cost-effective for a few hundred volunteers, however for much larger schemes the time-saving may be worth the initial programming cost outlay.

6.5.3. Maintaining engagement and managing losses

Once participants are involved with a project, the goal is to keep them interested in order to complete the study. If the project is intended to take place over multiple years (as any project intending to produce meaningful trend data will need to), retaining participants across multiple years allows for more powerful statistical analysis (Fairweather, 1991; Legg & Nagy, 2006; Roos *et al.,* 2012). As discussed above, good communications are vital to this, but so is management of experimental failures. Projects that require the maintenance of living things are particularly prone to going wrong. Plants and insects die, get diseases, are eaten by pests, and so on. Some of the most common problems encountered during the *Bees 'n Beans* experimental projects were:

- Loss of plants to grazing pests (particularly slugs / snails).
- Loss of plants to adverse weather conditions (excessive heat, cold, rain and hail were all experienced).
- Loss of plants to accidental damage, such as falling off a table or being crushed by a misstep.

Less common (but interesting) problems included, but were not limited to:

- Plants crushed in process of attempted burglary (twice).
- Netting on bagged plants stolen by fox and badger cubs.
- Escaped herd of cattle destroyed the garden (volunteer returned the next year, however, and successfully submitted data).

The failure of a project, particularly where participants have had to look after plants for some months, can be very discouraging even if the reason for the loss was not the *fault* of the volunteer. Steps can be taken to limit the impact of plant losses, while still only asking for participants to manage a small workload, and by emphasising that even letting the team know that the project definitely failed is useful (since 'dead' will be handled quite differently in analysis than 'missing data' or 'nothing produced'), volunteers can still feel like they contributed to the work. Some solutions I used to mediate the effects of losses are as follows:

1) Have alternative methods clearly available, if possible.

In the *Bees 'n Beans* family of projects (including *All About Alliums* and *Rolling out Radishes*), participants were required to maintain three mature (flowering) plants under the experimental conditions. If any of these plants died, then there was still data that could be submitted, but it had to be made clear to volunteers that this was possible. Having alternative options included *in the instructions* from the beginning can reduce the likelihood of volunteers dropping out entirely due to a partial failure, or becoming discouraged.

For example, for *Bees 'n Beans*

- If the **bagged** plant died, then 'local' and 'hand pollinated' records could still be returned.
- If the **hand pollinated** plant died, then local and bagged could still be returned.
- Only if the **local** plant died was the experiment considered to have failed.

2) Consider sequential counting (or similar) to offset pest damage

Another option that came out of the three years of the *Bees 'n Beans* was the possibility of including a sequential count. The numbers of pods and / or seeds in these experiments seem to be the better indicator of pollination action than weights (see Chapter 3, 3.4.7; showing the average weights of pods and beans were unaffected by the treatment applied). A subsequent investigation of 'sequential counting' – where the number of beans that showed signs of development were counted during the experiment, as well as a total at the end (detailed in Chapter 3, Appendix 4) – suggested that this would allow at least some data to be recorded, even if the plants ended up failing before the end of the project.

This does add another layer of complexity to the experiment, requiring volunteers to mark pods that they have already counted (or to remember which ones they have counted, which is not advised as the only method), and identify potentially quite small pods. The small size of early developing pods in the *Alliums* (Chapter 4; 4.5.2) for example, means that a sequential count might be difficult for volunteers with less dexterity, or with eyesight issues. The practicality of using sequential counts in a project will be determined by the characteristics of the phytometer plant, and what data needs to be recorded.

6.5.4. Seek partnerships

Many of the citizen science projects currently underway in the UK and further afield are being undertaken by non-governmental bodies and interested amateur groups, and many of these involve collaboration between two or more organisations (NBN Secretariat, 2015). These are not always specifically conservation or ecology organisations, as partnership with a surveillance scheme may contribute to goals or company strategies (such as Waitrose's partnership with Earthwatch and Friends of the Earth: www.waitrose.com/content/waitrose/en/home/inspiration/about_waitrose/the_waitrose_way/butterfly-count.html). The *Bees 'n Beans* projects were designed, implemented, advertised and run by me, funded by my PhD stipend, but any longer-term project based on these methods would greatly benefit from partnership arrangements. These groups provide not only a good starting point of volunteers to recruit from (especially if the group already has some knowledge of the focal taxa; or has some pre-existing reason to be in the geographical area of interest), but are also likely to have their own media and communication channels already in place (Bell *et al.,* 2008); this is useful for starting the project, but also for disseminating the findings afterwards, given the importance of showing *how* volunteers' own involvement has directly contributed to science (Roy *et al.,* 2012).

Schools and other educational bodies can also be good to involve in citizen science projects (Pocock & Evans, 2014; Polli:Nation, 2015; Roy *et al.,* 2016). As a pollination-focused protocol, *Bees 'n Beans* could be used to provide practical, visible demonstration of pollination interactions, and to provide flowers for observations of insect visitors. This fits in with the focus in Keystage 2 to understand about plant life cycles, and the role that insects and other invertebrates play in plant pollination (Sc2 3d); and the importance of plant reproduction to human food security (considered in Keystage 3) (Department for Education 2013, 2014). However, as found in 2015 if projects are delayed due to weather they may fall afoul of term dates and then prove unsatisfactory, so any protocol for use in schools needs to be especially robust and provide alternative approaches in case problems occur.

Pursing partnerships from the start of a citizen science project allows the needs of the partners to be included in planning, and should involve collaboration at the planning stage (Reed, 2008), allowing it to be presented as a collaborative effort and thus benefit from existing goodwill towards the partner organisation. Making sure that participants feel valued and not disappointed by the experience is therefore essential for maintaining good partnership relations, and collecting good data.

6.6. Conclusions

Even with the recent rise in projects specifically positioned as being or using ‘citizen science’ (Silvertown, 2009; Roy *et al.,* 2012b; Theobald *et al.,* 2015), it is still relatively unusual for such projects to require active experimentation from their participants. However, there does seem to be great potential in these projects for data collection and public engagement with science. At the start of this chapter, several questions were raised about the practicality of utilising ‘experimental’ citizen science, and I conclude that – while there are valid concerns – it is both possible and practical to use these methods and minimise potential problems.

Structured experimental projects are likely to be more complicated than many purely observational studies; although bearing in mind that ‘observational’ covers a very wide variety of project types, from ad hoc schemes that only ask participants to record the presence of specific taxa or events, to full stratified sampling surveys which provide training and develop identification skills of participants over multiple years (Whittingham *et al.,* 2007; Harris *et al.,* 2016); but this does not seem to be prohibitively confusing for volunteers. Carvell *et al.* (2016) discussed the training of recorder groups to use bagging experiments, and the results from this PhD indicate that provided the experiment is well-designed and all instructions are clear, volunteers seem able to successfully complete this type of experiment. It is still preferable to recruit volunteers with experience of plant growing and manipulation (e.g. gardeners), but is not essential to do so.

Another concern is the cost of running citizen science projects, and whether the data collected is 'worth' the investment. Citizen science is not free, and although it is widely acknowledged as capable of providing data in a cost-efficient manner (Battersby & Greenwood, 2004; Bell *et al.,* 2008; Gardiner *et al.,* 2012) it is important to make sure during the design of the experiment that the aim and specific data collection methods are very clear; the reason for collecting this information does not duplicate existing work; and that citizen science is the most effective method to achieve this (Cohn, 2008; Tweddle *et al.,* 2012; Pocock *et al.,* 2014). Since domestic gardens represent a large part of urban green space (Gaston *et al.,* 2005; Loram *et al.,* 2007; Davies *et al.,* 2009), being able to collect data from these areas is important both for good geographical coverage, and as part of engagement activities. Accessing that number of private sites with a research team would be very expensive in staff time, arranging access and travel, assuming that the garden owners would be willing to provide access at all. Thus for urban ecology in particular, being able to get volunteers to record their own data is very economically advantageous.

Retention of participants and engagement during projects is an ongoing concern for citizen science schemes, especially those with intent to run for more than one year (Bell *et al.,* 2008; Dickinson *et al.,* 2012). Recruitment and retention are closely linked (Cooper *et al.,* 2007); there will be a natural attrition from the participant pool due to personal concerns such as health, or changes in circumstances (Wolcott *et al.,* 2008), as well as disengagement due to project failure, or waning interest. Targeting recruitment appropriately before the project starts and making sure that the time and effort requirements are clear should reduce this rate of loss, but there will always be a requirement for continuing strong communication with existing participants and the recruitment of new ones (Schmeller *et al.,* 2009), which needs to be built in during the design of the project. An advantage with citizen science is that volunteers who enjoy taking part in the project are likely to discuss it with their friends and family; I found that word-of-mouth recommendation was a notable way that volunteers found out about my projects, with similar behaviours observed by Evans *et al.* (2005) and Oberhauser & Prysby (2008).

Finally, does citizen science actually improve the understanding those citizens have, about the science they are involved with? The overall opinion seems to be positive, with caveats (Cooper *et al.,* 2007; Dickinson *et al.,* 2010; Roy *et al.,* 2012b; West *et al.,* 2015). A *purely* educational endeavour may not be best undertaken with 'citizen science' methods (Pocock *et al.,* 2014), but improving some element of volunteers' engagement with science is often a stated element of the work; be it through demonstration, explanation, or even demystification of what being a 'scientist' actually entails (Devictor *et al.,* 2010).

My projects showed an improvement amongst participants in their understanding and interest in pollination and bees, and also indicated that behavioural changes based on that knowledge were being made. However, it has to be accepted that there was already interest present in the research area within my volunteer pool, since effort had been made to recruit from populations who already had some applicable knowledge (gardeners). Improving understanding in members of the public who already have a grounding in the subject is likely to be comparatively easy / effective, compared to those with much less pre-existing knowledge (Evans *et al.,* 2005), but focusing strongly on recruiting from less already-invested demographics risks a poorer rate of return, and reduced accuracy of the actual data collection. An acceptable balance between engagement of new audiences and usefulness of final data needs to be determined for any project considering citizen science methods.

Appendix A: Questions from the final engagement questionnaire.

A list of the questions and multiple-choice responses from the 2016 engagement questionnaire.

Question	Response options
Would you consider yourself a...? *Tick all that apply.*	Professional ecologist (current or retired) Professional scientist (current or retired) Professional gardener (current or retired) Experienced amateur scientist Experienced amateur gardener Interested amateur gardener Just starting gardening, or have a new interest in ecology
Which University of Sussex projects have you taken part in? *Please tick all that apply.*	Bees 'n Beans 2016 Bees 'n Beans 2015 Bees 'n Beans 2014 Bee-friending your garden (companion planting for tomatoes) 2016 Garden shop calculator 2016 All About Alliums 2016 Air B 'n Bee 2016 Hoverfly Lagoons 2016 Hoverfly Lagoons 2015 Pollinator Abundance Network (P.A.N.) 2016 Pollinator Abundance Network (P.A.N.) 2015 Pollinator Abundance Network (P.A.N.) 2014
Which University of Sussex questionnaire studies have you completed previously? *Please tick all that apply.*	The Need for Bees 2015 Growing Towns 2014 Only questionnaires or feedback sections associated with the project(s) I was involved with (e.g. the Bees 'n Beans feedback sections) None
Where did you find out about the University of Sussex project(s) or questionnaires? *Please tick all that apply to all projects or questionnaires.*	'LJBees' web site 'LJBees' Twitter Buzz Club' web site Buzz Club' Twitter Other web site Other Twitter Approached by one of the project team Recommended by a friend/family/colleague Attended a presentation by one of the project team Attended an event by one of the project team Article or advert in a newspaper or magazine Heard about on TV or radio Other

Why did you take part in a University of Sussex project(s) / questionnaires? *Please tick all that apply.*	Interested in ecology or conservation generally Specifically interested in bees Have children that I wanted to do the experiments with I work in education and was looking for potential teaching aids Interested in doing some 'practical science' related to my garden I am a gardener looking to improve my garden for bees and other beneficial insects I was asked by a member of the project team Recommended by a friend/family/colleague Thought it would be fun Other
Do you feel that taking part in the citizen science project(s) / questionnaires has increased your general interest in bees or conservation? *Please tick all that apply*.	My interest level is about the same as before I now pay more attention to TV or radio programmes that are about bees I now pay more attention to TV or radio programmes that are about conservation in general I have read more articles in books, magazines or on the internet etc about bees I have read more articles in books, magazines or on the internet about conservation in general I am now more aware of conservation activity in my local area It has put me off I am more uncertain about these issues than I was before
Have you taken part in any bee or conservation events since being involved with the citizen science project(s)/questionnaire?	No – attending events is not of interest to me No – I did not have the time to attend any events, but would like to have been able to No – there have not been any close enough to my location to attend Attended a bee- or conservation-related activity or event Been involved in organising a bee- or conservation-related activity or event Given a talk or presentation on bees or conservation Taken part in practical outside conservation or ecological work
Have you visited any conservation or wildlife areas since being involved with the citizen science project(s)/questionnaire?	No – this is not of interest to me No – I did not have the time to visit but would like to have been able to No – there are not any that are close enough to visit Yes – but no more than I did before being involved with citizen science Yes – I have been to new places since being involved with citizen science

Have you joined any bee or conservation groups?	Not joined any groups I am already a member of a conservation group or forum and have not joined any more since being involved with citizen science I have joined a local group involved with bees or conservation I have joined a national group involved with bees or conservation I have joined internet forum(s) or other online group involved with bees or conservation
Are you taking part in any other citizen science projects (not run from Sussex)?	No Woodland Trust, Spring or Autumn watch The Big Bug Hunt Tea Bag Index UK Other
Do you feel that you have contributed to scientific research by taking part in a citizen science project(s)/questionnaire?	Yes No Unsure
If you took part in Sussex University projects, how did you find the different components? (ranking)	Clarity of the instructions that were provided Quality of equipment provided Quality of communications from the project team Accessibility of the project team (answering your questions and so on) Online resources Ease of performing experiments Ease of returning results
When possible, summaries of the results collected during these projects will be sent back to participants, as well as links to any publications listed on the project webpages, with a person named as a point of contact. *Do you find this a good level of feedback?*	Yes / no
Would you take part in these sort of projects again? (This does not mean that you *have* to take part, it is a measure of the type of project that you may feel comfortable in undertaking in the future.) *Please tick all that apply.*	Yes – simple projects that include putting plants into control and experimental groups (e.g. like Bees ‘n Beans, All About Alliums) Yes – hosting plants provided by the team (e.g. like tomato plants) Yes – to set up simple apparatus and record observations (e.g. like hoverfly lagoons, bee hotels, PAN project) Yes – answering questionnaires No – please see next question. Response Other (please specify)

Have you changed any aspects of your *flower* gardening as a result of joining the citizen science project(s)? *Please tick all that apply.*	I have not made any changes I am more aware of what makes a 'bee friendly' plant I look for 'bee friendly' plants and seeds when shopping I have used more 'bee friendly' plants in the flower garden – please give up to 3 examples below I have stopped using some plants that are not 'bee friendly' – please give up to 3 examples below I have stopped or reduced pesticide use I have made some other change to my flower gardening – please give details below Examples / details
Have you changed any aspects of your *vegetable* gardening as a result of joining the citizen science project(s)?	I have not made any changes I have used more 'bee friendly' flowering plants in the vegetable garden – please give up to 3 examples below I tolerate flowering weeds more I have stopped or reduced pesticide use I have made some other change to my flower gardening – please give details below Examples / details:
Have you taken more interest in civic /community planting in your area?	I have not taken any more interest in civic or community planting I have taken more notice of what the council have been planting in respect of 'bee friendly' plants I have taken more notice of other community planting in respect of 'bee friendly' plants I have contacted the council to ask about their planting/gardening policy
Without using the internet or other reference source please answer the following question: Do you know what a **neonicotinoid** is? *This is not a trick question, it is a measure of how successful communications from various groups to the general public have been, and your immediate knowledge level is really helpful in planning future work.*	No Not sure Yes (please detail)
Any other comments?	Open response

Chapter 7: Measuring pollination service provision – where to go from here.

7.1. Introduction

At the start of this PhD, a core aim was to assess the suitability of experimental citizen science approaches for monitoring pollination services in the UK, primarily in urban areas. The development and testing of proposed methodologies for such schemes was carried out over 2014-16, and is discussed in detail in Chapters 3 and 4; with an overall conclusion that the *Bees 'n Beans*-style project would be appropriate for use at a national scale. Chapter 6 discussed the use of that methodology by the participant citizen scientists, assessing their experiences and feedback of taking part, and this final chapter will consider the future of this work, in the light of both my own findings and concurrent developments in the field. In particular I will consider the recent findings and recommendations of Carvell *et al.* (2016), in their report to the UK Department for Environment, Food and Rural Affairs (Defra), Scottish Government and Welsh Government.

Populations of many insect species are declining (Allen-Wardell *et al.,* 1998; Biesmeijer *et al.,* 2006; Goulson *et al.,* 2008; Butchart *et al.,* 2010; Potts *et al.,* 2010; Breeze *et al.,* 2012), putting at risk the provision of pollination essential for the life cycles of wild plants and the yields of most cultivated crops. In England, the National Pollinator Strategy (NPS) sets out a 10-year plan for supporting pollination ecosystem services (DEFRA, 2014), with similar plans produced by the devolved administrations (Scottish Government, 2013; Welsh Government, 2013b), and these highlight the current lack of national long-term, standardised monitoring schemes for wild bees and hoverflies.

Carvell *et al.* (2016) propose a National Pollinator and Pollination Monitoring Framework (NPPMF) to assess changes in the status of insect pollinator populations, and to determine how pollination services to crops are changing over time. For pollinator *communities* this revolves around the use of fixed transect walks, pan traps and timed floral observations based on a stratified network of 1km squares. For assessment of pollination *service* delivery and deficits, they conclude that direct measures using exclusion and hand pollination methods represent the best method available, and that volunteer recorder groups can be trained to implement these procedures successfully. This PhD supports that potential, demonstrating several projects where volunteers were able to successfully perform a direct pollination experiment to collect data; these projects also seem to be valuable for outreach, potentially engaging with volunteer groups who are not currently involved with more-commonplace types of citizen science.

My projects have focused on pollination provision in urban and semi-urban environments rather than the rural settings where pollination research has tended to focus (Bates *et al.,* 2011; Hall *et al.,* 2017). While built-up environments represent only a small portion of the UK land area, the effect of their highly-managed green spaces on pollinator populations may be disproportionate to their size, potentially acting as refuges, reservoirs and corridors, particularly in otherwise intensive agricultural landscapes (Tommasi *et al.,* 2004; Ahrné *et al.,* 2009; Samnegård *et al.,* 2011; Baldock *et al.,* 2015). Urban areas are home to 80% of the UK's human population (Davies *et al.,* 2011), which presents a large pool of potential volunteers for recruitment to such projects, and for developing a more informed population – who are then more likely to undertake training or surveillance actions which involve more investment of time or travel (Forbes & Kendle, 1997; Cooper *et al.,* 2007; Bonney *et al.,* 2016).

The *Bees 'n Beans* projects carried out in 2014 – 2016 did not detect any pollination deficit experienced by *V. faba* in gardens; the focal urban habitats seem to currently be maintaining sufficient populations of long-tongued bumblebees to provide the required service. However, the yield results obtained suggest that the protocol would be capable of identifying a deficit if one occurred, and that such direct measures of pollination have the potential to work well as citizen science projects. Simply because (primarily) garden habitats are currently able to provide suitable pollination for a small number of *V. faba* plants does not mean that this will always be the case, nor that pollination provision for other garden and wild species is currently adequate. It is important to be able to monitor for changes in these populations, both for within-garden pollination requirements and for urban green spaces to play a potential role as refuges for insects from agricultural intensification – and a possible source of recolonization after restorations (Tommasi *et al.,* 2004; Kohler *et al.,* 2008; Samnegård *et al.,* 2011; Goulson *et al.,* 2012).

Thus, this last chapter outlines a final proposed form of *Bees 'n Beans*, incorporating all modifications from the original protocol, and any additions that are advised following the project analysis and evaluation – including the use of additional phytometer species and suggestions for other plants to use, or which would bear investigation. I consider the potential application of the *Bees* project(s) as part of a wider pollination monitoring scheme; how these methods could fit into alerts and long-term surveillance, and what other types of monitoring would need to be carried out in order to gather the most robust data possible on this service provision.

7.2. *Bees 'n Beans* going forward

7.2.1. The *Bees* protocol

The final *Bees 'n Beans* methodology remains as an exclusion / hand pollination experiment, requiring volunteers to grow (a minimum of) three *Vicia faba* plants, excluding pollinators from one with garden fleece (or other insect-proof netting), hand pollinating the second, and leaving the third to the pollination action of local bees. Plants should be a reliable dwarf variety that will remain available in seed catalogues ('The Sutton' is recommended). Plants should be grown in 3L pots of commercial compost (the same in all three), to give maximum flexibility in case the experimental set up needs to be moved to avoid damage from environmental conditions – particularly heavy rain / flooding – or as overnight protection from pest damage. Further modifications to the method used in 2014-16, based on feedback and additional experiments undertaken during that time, are small but should improve data return and plant survival.

The first is the use of **sequential counts** of bean pods. This was discussed in detail in Chapter 3 (Appendix 4) with little difference found between the count of developing pods compared to final harvested pods. Volunteers should make a note of the presence of any developing bean pods on all plants, either numbering them going up the plant (as flower trusses open, e.g. Truss 1 is the lowest, has 1 pod) or by marking the pod carefully with a waterproof pen, or twist tie, depending on participant preference and dexterity. Keeping this ongoing count would mean that even if the bean plants were damaged or died as a result of pests (slugs and snails in particular have shown to be a problem), participants could still return useful data.

Interestingly, while Carvell *et al,* (2016) also used *V. faba* as one of their experimental plants, their field cage exclusion manipulation showed no significant effect on the number of bean pods produced per plant, whereas in the *Bees* projects the netted plants consistently produced significantly fewer pods than the pollinated plants. I propose this is because of the varieties of *V. faba* used: Carvell *et al.*'s studies were on agricultural crops of 'field bean' (variety not specified), whereas the *Bees* projects use 'The Sutton'. Agricultural varieties of *V. faba* in particular have been selected for increased autofertility (Stoddard & Bond, 1987), but 'The Sutton' is a heritage variety (Sutton Seeds, 1925) and is less likely to have been deliberately bred for autofertility in the absence of insect pollination.

In addition, Carvell *et al.*'s hand pollination / exclusion comparison for *V. faba* did detect a large pollination deficit, with hand pollination resulting in significantly more pods initially set than the open treatment – but this did not follow into final yields, with *'resulting bean yield similar under all field pollination treatments'*. Since *V. faba* have been shown to display greater levels of autofertility on later trusses (Drayner, 1959; Stoddard & Bond, 1987), the plants may be compensating for low pollination with increased selfing later on, resulting in very similar final yields. The *Bees 'n Beans* methodology used in 2014-16 would not have been able to pick this effect up – if it occurs in 'The Sutton' – since all measures of yield were based on *final* yields. Thus, with sequential counting of set pods (particularly if the counts are dated) it may be possible to compared the rate of pod set in the hand pollination plants compared to the local plants, and improve the ability of the protocol to detect pollination deficits.

The second modification to the *Bees 'n Beans* protocol would be to include **adhesive copper tape** as part of the project packs, to be placed around each experimental pot to deter slugs (Schüder *et al.,* 2003). Nearly 47% of participants in 2016 reported damage from slugs / snails, and with warmer winters and damp summers likely to continue in the UK (Kendon *et al.,* 2015; Buglife, 2016), providing a pest control mechanism to compliment the routine advice is important for both data returns and participant retention.

An updated version of the *Bees 'n Beans* methodology is provided in Appendix A of this chapter, as the basis of any further development of this protocol.

7.2.2. Other direct measures of pollination

By using *V. faba* plants as the phytometer, *Bees 'n Beans* primarily assesses pollination by the long-tongued bumblebees (such as *Bombus hortorum)* that are capable of accessing bean flower nectaries (Kendall & Smith, 1975; Stoddard & Bond, 1987). Additional species of plants, associated with other insects, would need to be added to the protocol for a more complete assessment of UK pollination service provision. Chapter 4 details the results of my projects that looked into this, concluding that *Allium hollandicum* ('Purple Sensation') could be included since it is easy to grow, resistant to slugs and responds well to the exclusion / hand pollination treatment. However, it is possible that the allium flowers may also be highly attractive to *many* different types of pollinator, which could mean that that they would not be sensitive enough to declines in local populations of specific types of insect to be a good phytometer (since they may receive pollination in priority, even if insect numbers are unusually low).

Developing other phytometers is an important part of other follow-on work with *Bees 'n Beans*. These do not have to be *extremely* specific in their pollinator relationship, since the aim of the project is to assess pollination provision, and much of that service is likely to be provided by a range of more-generalist insects (Ghazoul, 2005), but covering a greater range of functional traits is desirable. Having a plant each for looking at shorter-tongued bees and hoverflies would give improved coverage of the pollinator guilds. Given the importance of the insect-pollinated Brassicaceae (especially *Brassica napus*, 'oilseed rape') in agriculture, including a plant from this family would be beneficial, particularly given their association with wild bees and hoverflies (Steffan-Dewenter & Tscharntke, 1999; Jauker *et al.,* 2012). The variety of radish *(Raphanus caudatus)* tested in Chapter 4 showed that brassicas can act as phytometer of this kind, but the specific plant itself proved unsuitable for citizen science methods (more difficult to grow from seed than anticipated; too variable in habit; hard to hand pollinate for older volunteers); finding a brassica that would more usable would be a helpful addition.

Another potential element of a citizen science protocol is to include plants that are already established in participants' gardens. Volunteers could be instructed to perform hand pollination / exclusion / local manipulations on these plants and report back the resulting fruit or pod set. While these would likely be different cultivars of any chosen species at different sites, if there was sufficient coverage (and all three manipulations are completed for each plant at each site), then this may be a suitable addition to the survey, with the extra advantage that if volunteers already have these plants, they presumably know how to grow / maintain them. Some considered examples are given below:

Garlic chives *(Allium tuberosum)*, which performed well in my exclusion tests and flower later in the summer than either *V. faba* or *A. hollandicum*, but were impractical to send out to volunteers as seeds because they do not form flowers in the first year. If pots of plants could be distributed from a central location (by a partner organisation, for example), or existing plants could be used, then this allium could be included to widen the diversity of pollinators covered. It may be particularly suitable in regard to hoverflies, where several very common species see late-summer population peaks due to immigration from Europe (Stubbs & Falk, 2002; Graham-Taylor *et al.,* 2009).

Foxgloves *(Digitalis spp.)* show very clearly when pollination has occurred, with large seed pods forming quickly, but do not flower until at least the second year of growing from plug plants, and even later from seeds. It would be easy for participants to count the number of pollinated flowers, even calculate the percentage-pollinated by comparing obvious large seed pods to shrivelled flowers. These plants are very attractive to bees, so a failure in pollination for foxgloves in a region would be a cause for concern, and could thus form part of a pollination service 'alert' system. A disadvantage is that foxgloves are primarily pollinated by the same long-tongued bees as *V. faba* (Broadbent & Bourke, 2012), which might duplicate effort – but if foxgloves are also present in a *Bees 'n Beans* garden that reports low pollination of the beans, comparison with existing foxgloves could be an indicator if this was due to bean plant failure, or pollination deficit.

A third potential species for this approach is **hawthorn** (*Crataegus spp.*), a hedgerow plant grown as a bush or tree in gardens (results of a pollination / exclusion experiment are discussed in Chapter 3, Appendix 2), which flowers early in spring and has been shown to be pollinated by honeybees and hoverflies (García & Chacoff, 2007). The first appearance of hawthorn flowers are part of the UK Phenology Network monitoring (Collinson & Sparks, 2008), and progressively earlier flowering of hawthorn has been linked to the effect of increasing global temperatures (Sparks & Smithers, 2002) so a deficit or declining trend in hawthorn pollination may suggest a phenological mismatch developing between pollinator emergence and the start of flowering (Hegland *et al.,* 2009; Kudo & Ida, 2013).

For urban environments in particular, it could also be worth investigating the use of *Mahonia spp.* These are introduced ornamental plants, noted as important nectar sources for winter-flying bumblebees and other pollinators (Stelzer *et al.,* 2010; Owen *et al.,* 2013). Mahonia are self-fertile but have some degree of insect pollination requirement (CABI, 2016b), and as a popular garden plant may be suitable for inclusion in a pollination monitoring scheme, although this would need to be tested.

7.2.3. Pollination alerts and regional mapping

All of these variations on the *Bees 'n Beans* protocol would produce data on the pollination service experienced by different phytometer plants throughout the UK, and all would be able to be located geographically fairly easily (e.g. by postcode). Changes in yields or flower pollination percentage could be compared against national and regional averages (and finer resolutions; see Chapter 3, Appendix 7 for discussion of potential geographical analysis for *Bees 'n Beans*), to identify areas where pollination deficits may have occurred, or where the trend in service provision is declining. With multiple plant species involved, this analysis would be more sensitive to declines in different components of the pollinator guild, and increase the likelihood of identifying areas of notable problems.

If measures for *all* included plants had declined in a given area at once, it would suggest that there had been an acute impact there, such as a drastic landscape change or shift in environmental conditions (severe flooding, or pollution events, for example). If only certain plant types were affected, then it implies that some species of pollinator were being affected differently – for example, if plants that are more favoured by generalists and hoverflies (alliums) displayed no deficit, but *V. faba* (and foxgloves, potentially) did, then that indicates a problem for long-tongued bees.

Other existing datasets could be incorporated within a geographical approach, such as rainfall data and climate maps (Haines-Young & Potschin, 2013; Medcalf *et al.,* 2014). Lower levels of pollination everywhere would be expected during a wet, cold year; short-term declines under those circumstances would perhaps not be concerning, but a visible decline in an area that is otherwise environmentally similar to stable regions would suggest the need for closer study. The exact timescale within which 'problem' areas could be identified would have to be determined after development of baseline values of pollination provision for all included plants, at appropriate geographical scales.

Both the temporal and geographical level at which change can- or is desirable to be able to be- detected is likely to vary by pollinator, due to the natural variation in insect populations, and the challenges of developing appropriate trends and analysis for biodiversity data more generally (Swaay *et al.,* 2008; Magurran *et al.,* 2010). The *Bees 'n Beans* data showed no deficit present in the UK during the three years of its run – in gardens, with a small number of plants, and in relation to the pollination service from long-tongued bees – and no regional differences were found. It was, however, a relatively small dataset, clustered in the south of England and with no existing baseline to compare to. This does not invalidate the conclusions, but for a national monitoring scheme care must be taken to design the protocol and the volunteer recruitment to ensure sufficient statistical power to detect changes.

7.3. Complementary schemes

As a surveillance scheme, *Bees 'n Beans* (and expanded versions of the protocol) assesses the *direct* provision of pollination to the phytometer plants. The more specialised the relationship between that plant and its pollinators is, then the more confidently the assertion can be made that a decline in the pollination of that plant is likely to be related to a decline in its specific pollinators (Biesmeijer *et al.,* 2006; Potts *et al.,* 2010). For the *V. faba* plants, pollination is provided mostly by long-tongued bumblebees, but the protocol provides no way of identifying *which* long-tongued bees provide that service (or which are declining, if a deficit is identified).

While space was provided on the recording sheets for *Bees 'n Beans* participants to attempt identification of any insects that they observed visiting their bean plants, the data returned was of very low quality (most was of the level of 'a fly', 'a bee', or even 'slugs'). Analysis of feedback in Chapter 6 suggests that the volunteers drawn to the *Bees 'n Beans* project(s) were – while interested in bees generally – primarily gardeners; good at growing plants but with a relatively low level of insect taxonomy knowledge. Responses also suggested that the *Bees 'n Beans* participants were not heavily involved with other citizen science schemes, which are generally more observational in nature (Dickinson *et al.,* 2012; Pocock & Evans, 2014), so attempting to get these volunteers to perform identification recording may not be effective – or appropriate.

However, most existing biodiversity surveys and schemes are already based around recording specific species, and the proposed development of robust national monitoring for pollinators includes a large amount of this. Carvell *et al.,'s* proposed NPPMF presents: *"a standardised protocol designed to be implemented by one person on one day (with four repeat site visits per year) . . . [including] a combination of water-filled pan traps, fixed transect walks and timed floral observations*" as well as discussion of the use of volunteers to perform exclusion / manipulation experiments within agricultural sites. The *Bees 'n Beans* direct pollination monitoring would be complementary to this work, covering the more urban areas that are not the focus of the NPPMF, and extension of the identification protocols into urban sites would allow the pollination service monitoring to be put into context of the species and trends present in those areas. Full discussion of the use of pollinator species surveys is beyond the scope of this thesis, and would represent unnecessary repetition of Carvell *et al.*'s work (as well as that of the Urban Pollinators Project [Baldock *et al.,* 2015]), but the next section will briefly consider those three proposed methods in relation to the *Bees* projects and participants.

7.3.1. Pan trapping

The use of pan traps to sample insect species richness is a common passive sampling method used in biodiversity studies, and is considered to be an important part of systematic monitoring of bees and other pollinators (LeBuhn *et al.,* 2003; Westphal *et al.,* 2008; Carvell *et al.,* 2016). In 2014, the UK Pollinator Abundance Network (P.A.N.) project was piloted at the University of Sussex, also running in 2015 and 2016, to examine the efficacy of the use of pan traps by citizen scientist volunteers (http://thebuzzclub.uk/Pollinator_Abundance_Network.php). While this work was not undertaken as part of my PhD, *Bees 'n Beans* project contacts were used as an initial starting point for recruitment, and the sister project *All About Alliums* (Chapter 4) was carried out under the Sussex 'Buzz Club' initiative; of which P.A.N. was the inaugural project.

In terms of citizen science, particularly in private gardens, the use of pan trapping requires a slightly different approach to recruitment than the *Bees 'n Beans* projects. This is primarily due to the destructive nature of the sampling. While repeated sampling with pan traps has been shown not to damage insect populations (Gezon *et al.,* 2015), feedback from potential participants indicated that a project which required killing insects was considered distasteful by some, and induced squeamishness in others. The need to handle samples of dead insects and the high postage costs of sending back pots of liquid for professional identification were also noted as unattractive to some potential volunteers (the latter is potentially mitigated for participants by providing postage costs via the project, but this increases the cost to organisers). There is also a potentially large cost in time and resources needed to provide specialist identification of the pan trap samples. However, the P.A.N. project *did* get volunteers who were willing to take part, and those that did tended to return samples

(R. Fowler, *personal communication.*). While care would need to be taken in the approach to recruitment for pan trap sampling in gardens as part of a wider scheme, this supports the viability of the option – assuming that sufficient expertise (and time) was built into the project for identifying the returned samples.

7.3.2. Fixed transects and timed flower observations

Fixed transects, particularly of the lengths most commonly used in insect monitoring (ranging from 25m long, to 2-4km for the 'Beewalks' / UK Butterfly Monitoring Scheme; [Tommasi *et al.,* 2004; Westphal *et al.,* 2008; Brereton *et al.,* 2016; Bumblebee Conservation Trust, 2016]) may be impractical to carry out in individual UK domestic gardens, which average 170-190m^2 in area (Osborne *et al.,* 2008; Davies *et al.,* 2009). Transects in green public spaces are more practical (Baldock *et al.,* 2015), since they are larger and would not need to get permission from multiple owners, unlike a transect going through several gardens.

Timed observations at focal flower species are proposed by Carvell *et al.* (2016) as a component of a wider citizen science scheme, and I agree that this is a necessary element in garden-based studies, both for data collection and for raising the taxonomic skill level of participants overall. However, rather than relying on volunteers to already be growing a specific set of plants, *A. hollandicum* bulbs could be provided either as part of a full *Bees*-style allium project, or in a manner more akin to the Great Sunflower Project in America (https://www.greatsunflower.org; Oberhauser & LeBuhn, 2012) – where participants are encouraged to grow sunflowers and monitor the insect visitors to the plants. Sunflowers were examined as a potential phytometer in Chapter 4, but I would suggest alliums as a better choice in the UK due to their pest resistance and ease of growing. The flower head of *A. hollandicum* is large and attractive to pollinators; it also consists of many small flowers that make up the 'ball', so insect visitors are likely to spend some time there, moving from flower to flower. This gives a good platform for identification, and for photographs to allow for expert verification, which improves the quality of data collected in this manner (Gardiner *et al.,* 2012; Roy *et al.,* 2016). Concerns about the allium flowers being 'too' attractive for measuring pollination deficits are considerably less important if the plants are specifically being grown as an observation platform.

7.4. Conclusion

The conclusions of my PhD overall – that it is both possible and practical to assess the provision of pollination services via experimental citizen science methods – is supported by, and compliments, recent developments in conservation science and UK policy, and the data collection that has informed those changes. The *Bees 'n Beans* methodology developed is suitable for direct monitoring of pollination provision in gardens, and for producing trends and potential alerts at larger geographic scales, if undertaken with wide enough coverage to ensure sufficient statistical power. There is considerable scope for expansion of the basic project with additional phytometer plants, for better assessment of the service provided by other sections of the pollinator guild.

This style of project also has considerable value for scientific outreach and public engagement, since it allows for personal experience and observation of pollination services in action in participants' own garden spaces. Even if the data collection element of the project were unsuccessful on an individual basis, as long as there is a focus on clear communication and transparent reasons behind the activities, taking part is able to produce an overall improvement in participant's understanding of pollination and the need to undertake monitoring. At national scale, a challenge for organising such a scheme would be to engage with large enough numbers of volunteers and maintain the level of interest over multiple years.; however the project seems capable of recruiting from sections of the population that are otherwise unengaged with current citizen science initiatives. This is encouraging, since this approach may help increase the capacity of citizen science engagement, and reduce the risk of overloading current volunteers.

Appendix A: Suggested basic protocol for *Bees 'n Beans* based projects

Bees 'n Beans Instructions

Thank you for taking part in Bees 'n Beans. This project will use a simple experiment to look at how much pollination is happening in urban green spaces. We couldn't run it without your support!

The Plant

Broad Beans are mostly pollinated by bumblebees. The flowers contain both male pollen and female stigma, and *can* pollinate themselves without pollen from another bean flower being brought in. But the pods are larger and contain more beans if the flower has been cross-pollinated, or even if insect visits have moved pollen within the flower – and it is this difference we are interested in.

Project Kit

The kit for this project should contain:

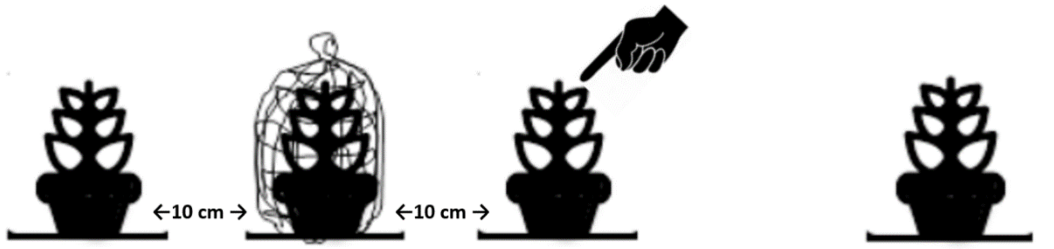
- 10 dried beans ("The Sutton" Dwarf bean)
- Copper tape to deter slugs
- Recording sheet & instructions

You will need to supply: **sticks** (or canes) to support the plants; **garden fleece** or other insect-proof netting; at least three **3-litre pots**; and **compost**. Well-rotted garden compost or a commercial multi-purpose mix is fine, as long as all pots have the same. You also need some smaller pots (at least 8cm deep) to germinate the seeds in, depending on how much space you have to grow on the young plants.

The Project Plan

This project is to start in **March [YEAR]**. Broad beans are quite hardy, and this start time should miss all but the latest of frosts. The set up for the plants is as follows:

1) Local plant – this plant is to be left alone, to let the local pollinators have access to the flowers.
2) Bagged plant – this plant will be covered in a light garden fleece to keep pollinators out.
3) Hand-pollinated plant – this plant will be pollinated by you (**details below**).
4) Spare plant(s) – in case of losses.



Plant 1 Local | Plant 2 Netted | Plant 3 Hand-pollinated | Spare plant(s)

Growing

You will need **three mature plants** in total for the experiment.

Step 1 – Fill ten smaller (approximately 8cm deep) germination pots with compost (or five pots with two beans per pot), leaving 1cm space at the top to help with watering. Make a hole a few cm deep in the soil and put a bean into each one. Fill with compost/soil and water well.

Step 2 – Keep the pots indoors on a warm windowsill (or greenhouse, or conservatory) to give the plants a better start than going outside right away. If you do not have any such space, use a sheltered place in the garden, as long as frosts have finished. The plants should appear after about four weeks. Transfer to larger pots as they grow.

If you put more than one seed per pot, either pull out the weaker seedling of the pair, or carefully split them into separate pots.

Step 3 – All plants should be moved outside when they reach about 10cm high. If these young plants were grown in the house, let them gradually get used to the outdoors by using a cold-frame, cloche or a porch. Try to avoid forecasted frosts.

When flower buds start to form, the plants are ready to use. You want three plants of about the same size, which have the same number of stems. Don't worry if there are not many flowers at first.

Experimenting

Wrap and stick the copper tape around the middle of each of the 3 Litre pots. Transfer each plant to a 3-litre pot and fill with compost. Position the pots outside, 10cm apart, and place in trays to help with watering. All pots should have the same amount of shade, distance to other flowering plants, and amount of shelter.

Before assigning treatments to the plants, you need to **randomise** them (this makes the analysis we do on your results more accurate on a whole-project scale). Two easy ways to do this are given below:

1) Write the treatment names on three separate pieces of paper (local, hand-pollinated, bagged,) and numbers 1 to 3 on three other pieces of paper. Shake them in a cup, and assign plants to treatments in the order you pick them out of each cup.

2) **(OR)** Using dice, assign treatments to each plant. So plant “one” will be <roll>. 1-2 = bag; 3-4 = local, 5-6 = hand pollinated, for example.

Apply the treatments as follows (pictures below):


Local


Netted plant


Hand pollinated

1. **Local plant**

This plant needs to be left open, protected from pests and kept watered.

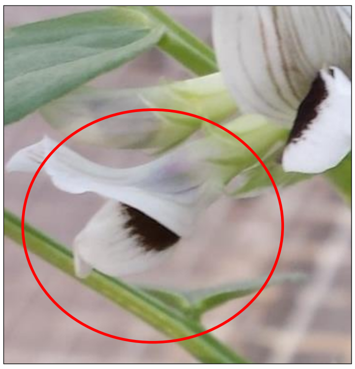
2. **Netted plant**

Make a tent from net or fleece to keep out pollinators. Gather the net/fleece around a supporting cane; tie in place. Use a couple of sticks around the base of the plant to keep the net away from the flowers. Fold the net/fleece underneath the pot, or gather and tie it securely around the base and stick. Watering can go through the net/fleece.

3. **Hand pollinated plant**

Hand pollinate twice a week.

Hand pollination method:


Step 1.
Find open flowers.
The black part should be visible.


Step 2.
Gently grip the top petals.
Gently grip the bottom petals.


Step 3.
Pull gently on the bottom petals, opening the flower
To show pollen.
Repeat x5 per flower.

Flowers will go dull, greyish and floppy after about a week. **Do not try** to hand pollinate flowers that have 'gone over' like this, as it might damage the flowers and cause them to fall off. **Do not** force flowers open – the petals should move easily. New flowers will open as old ones finish, opening in bunches up the plant as it grows. (See the **[project website]** for a hand pollination video.)

Counting the Pods

Bean flowers will continue to open for several weeks, with new flowers opening in clusters above the old ones. As a cluster finishes, you will start to see tiny green pods develop, where a large bean will eventually form.

Once a week during the experiment please count the **number of pods** of any size present on **all** plants (you may have to open the net on the excluded plant to do this).

The recording sheets have a section to put these counts, along with the date you did each one. If possible, please write down the counts like this:

Plant # Date: 0 + 1 + 0 + 2 (etc)

Where the first number is the pods on the *lowest* bunch of flowers, and the last is the highest up the plant. You can mark the beans you have counted before, if that helps (e.g. with a soft felt tip pen).

Please note that just a **total pods per plant** is fine, if keeping track of fading flower bunches does not work for you. (Missing a week due to holiday / etc is fine!)

Harvesting – Final counts

Bean pods should be ready for harvest **16 weeks** after sowing (or a bit later if you are further north).

All pods from all plants should be harvested **at the same time**, and recorded on the project recording sheets provided:

- **Number of pods** from each plant
- **Weight of pods** from each plant
- **Number of beans** from each plant
- **Weight of beans** from each plant

This will allow us to compare the success of each treatment crop, and give a measure of how well the local insect pollinators are doing in helping pollinate the plants.

Then send in the results!

There will be a web form to return the data at: **[web address for online return]**
Or you can post the recording sheet to us: **[address for postal return]**
If you have any further questions, anything is unclear or you have a problem with experiment, please do contact **[the project team]** either by email **[email]**, or by phone **[phone number]**.

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