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RESEARCH ARTICLE

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# Crop–pollinator interactions in urban and peri-urban farms in the United Kingdom

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**Societal Impact Statement**

Urban food production could contribute towards sustainable food provision and would also deliver benefits to biodiversity and the health of urban residents. Many crops rely on insect pollination, but urban pollinator populations are under-studied. In this study, crop–pollinator interactions and pollination quality were quantified in urban allotments in the United Kingdom. A diversity of insects was observed visiting the flowers of food crops, with squash, cucumber and fruit trees attracting the most flower visitors. However, strawberry plants pollinated naturally by insects produced lower quality fruit than those receiving supplemental hand-pollination. Urban crop pollination could therefore be improved through the provision of food and nesting habitats for insects.

**Summary**

- Growing food in and around cities could be a partial solution to sustainably increasing food production in an urbanised world. Recent studies have shown that small-scale urban farms can be as productive, if not more so, than large-scale conventional farms. However, the question of which insects visit fruit and vegetable crops in urban areas and whether there are sufficiently large and diverse populations to provide adequate pollination to food crops has been little explored.
- Here we quantified plant–pollinator visitation networks in urban allotments in the city of Brighton and Hove, UK, to determine which insect groups visit commonly grown fruit and vegetable crops. We also conducted pollinator deficit experiments to determine whether there are sufficient pollinators in urban allotments to adequately pollinate two commonly grown insect-pollinated crops, strawberries (Fragaria x ananassa) and runner beans (Phaseolus coccineus).
- A broad range of insect-pollinated fruit and vegetable crops were grown in allotments and were visited by a diversity of insects spanning many taxonomic groups. We found little evidence that runner bean crop yields were limited by a lack of pollination; however, open-pollinated strawberry plants produced more 'unmarketable' fruit suggesting there is potential for improving the delivery of pollination to strawberries grown in urban areas.

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- Our results suggest there are potential opportunities for expanding urban food production to the benefit of both people and biodiversity. We recommend that future work should also consider the effectiveness of different insect groups in pollinating the various crops grown in urban areas.



**KEYWORDS**

biodiversity, ecosystem services, food security, plant-arthropod interactions, plant–insect interactions, pollination, urban horticulture


## 1 | INTRODUCTION

One of the biggest challenges currently facing the world is how to sustainably produce enough food to meet the needs of a rapidly expanding human population. In addition to increasing food demands, the world is also experiencing large-scale migration away from rural areas where food is conventionally grown, and it is estimated that over two thirds of the world's population will live in urban areas by 2050 (United Nations, 2018). Could urban farming provide a partial solution to meet rising food needs and the shift in demands from rural to urban areas?

Global estimates suggest that there are currently 67 million ha of urban croplands, and that urban farms, which are particularly prevalent in East and South Asia and the Global North, may already account for approximately 5.9% of all cropped areas around the world (Thebo et al., 2014). Zezza and Tasciotti (2008) found that between 10% and 70% of urban households in 15 low- and middle-income countries they studied participated in agricultural activities. Extrapolation from these data suggests that over 260 million urban households may engage in food production around the world (Hamilton et al., 2014). Though urban farms tend to be small-scale and labour intensive, there is increasing evidence to suggest that small farms can be equally, if not more productive than large-scale industrial monocultures (Altieri, 2009; Edmondson et al., 2020; Grafius et al., 2020; Laughton, 2017). Farms smaller than 2 ha make up just 12% of global agricultural areas, yet produce 70% of food in Africa and Asia, demonstrating the importance of small farms to food security (Lowder et al., 2016). The smallest 2-ha farms in the United States have been shown to produce ~$15,000 USD/ha (~$2000 net), substantially more than the biggest farms, which averaged just $249 USD/ha ($52 net) (Altieri, 2009). Similarly, a recent study of UK organic farms <20 ha also found them to be as productive and financially viable as conventional larger farms, despite being significantly less reliant on subsidies (Laughton, 2017). In the urban context specifically, yields of small-scale organic farms and gardens in the city of Sydney, Australia, have been shown to be twice that of commercial vegetable farms, at 5.94 kg/m$^2$ (McDougall et al., 2019), and a similar case study of urban growers in the city of Brighton and Hove, UK, found that growers produced an average of 1 kg/m$^2$ fresh fruit and vegetables per year, with some growers producing as much as 9.68 kg/m$^2$ (Nicholls et al., 2020). This study only recorded the yields of crops requiring insect pollination and therefore likely represents a substantial underestimate of the productivity of urban farms in the United Kingdom.

Conventional, large-scale industrial farming systems are also one of the biggest drivers of environmental degradation, accounting for one fifth of all greenhouse gas emissions and resulting in soil erosion, freshwater pollution and biodiversity loss (Newbold et al., 2016; West et al., 2014). Crop yields in these systems are heavily dependent on synthetic inputs, which also contribute to environmental warming and pollution. In contrast, recent research suggests that urban growers tend to use fewer pesticides than conventional farmers (Nicholls et al., 2020) and that urban and peri-urban farms may offer substantial other benefits aside from food production, including protection from extreme climatic events (Drescher et al., 2006; Susca et al., 2011), carbon storage (Dobson, Crispo, et al. 2021), reduced air pollution (Lwasa et al., 2014), health and wellbeing benefits for growers (Clatworthy et al., 2013; Dobson, Reynolds, et al., 2021; Hawkins et al., 2013; Wakefield et al., 2007) and the creation of habitat to support biodiversity (Baldock et al., 2019; Lin et al., 2015; Quesada & MacGregor–Fors, 2010). Despite these benefits, countries such as the United Kingdom have seen steady losses of urban agricultural land since the peak of production in the 1950s, with a recent study of 10 urban areas in the United Kingdom reporting a mean decline in urban agricultural land per capita of 62% (Dobson et al., 2020). Demand for growing spaces is high, with half of English councils reporting an average wait time for an allotment of 18 months (ASPE, 2022). Loss of urban agricultural land was also shown to disproportionately affect areas of deprivation within UK cities, thereby impacting on people who may already be facing food insecurity (Dobson et al., 2020). Though such losses are often due to residential or industrial development, in some cases, former allotment land remains vacant or is repurposed into other green space uses such as playing fields, and the analysis by Dobson et al., 2020 suggests that three out of four UK cities studied would be able to meet current demand for urban growing space by restoring former allotments to their prior use.

All crop production is heavily reliant on the provision of ecosystem services, such as pollination, pest control and nutrient cycling. The provision of pollination by insects, for example, is estimated to be worth £200 billion to the global economy, and our reliance on insect-pollinated crops has been increasing (Aizen et al., 2008; Calderone, 2012; Eilers et al., 2011). Thanks to decades worth of agroecological research on this topic we now have a relatively good understanding of which insects pollinate conventional crops grown in rural areas, and the importance of insect diversity for both maximising yields and ensuring our food systems are resilient to fluctuating environmental conditions (Garibaldi et al., 2011, 2013; Senapathi et al., 2021). Yet the question of which

insects pollinate crops in urban areas and whether pollinator populations in cities are sufficiently large and diverse enough to meet the pollination needs of current urban food production, or its potential expansion to meet growing demands, has been little explored.

Urban farms, allotments and community gardens may themselves serve as hotspots for biodiversity in urban areas (Borysiak et al., 2017; Colding et al., 2006; Matthies et al., 2015). For example, a recent large-scale study conducted across four major cities in the United Kingdom showed that, compared with all other green spaces found in urban areas, including nature reserves, allotments had the highest abundance of bees, and increasing the area of this green space would provide the greatest potential benefit for plant–pollinator communities (Baldock et al. 2019). Another study found that bumblebee colonies in urban areas grew larger and produced more offspring compared with colonies in rural locations (Samuelson et al., 2018), and an experimental study comparing paired flower-rich sites in rural and urban areas across multiple European cities found pollination service delivery to be higher in urban sites, despite overall lower insect species richness (Theodorou et al., 2020). There has been little examination of plant–pollinator interactions specifically in the context of the pollination of flowering crop plants grown for consumption in an urban context however.

In this study, we quantified plant–insect visitation networks in urban allotments (a plot of land rented by an individual or community group for horticulture) in the city of Brighton and Hove, South-East England, UK, to determine which insect groups visit which commonly grown crops. We also conducted pollinator deficit experiments to determine whether there are sufficient pollinators in urban allotments to adequately pollinate two insect-pollinated crops, strawberries and runner beans. We address the following questions: (1) Which insects visit flowering fruit and vegetable crops grown in an urban area in the south of the United Kingdom? (2) Which flowering fruit and vegetable crops are most attractive to flower-visiting insects? (3) Are there sufficient insects in an urban city in the United Kingdom to provide adequate crop pollination? To address the final question, we provided supplemental hand-pollination to a subset of crops and compared the yield with open-pollinated (OP) plants receiving visits from insects alone. If a pollinator deficit exists, we expected those plants receiving supplemental pollination to exhibit higher yields.

## 2 | METHODS

### 2.1 | Plant–visitor surveys

The study was conducted in the city of Brighton and Hove, Southeast England, UK. Brighton has a population of 273,369 (UK census 2011) and according to the city allotment strategy published in 2014 (Brighton & Hove City Council and Brighton & Hove Allotment Federation, 2014), there are 6000 allotment growers (~2% population), farming 3100 plots over 37 allotment sites. In total, allotments cover an area of approximately 50 ha, and an unknown proportion of home gardens are also used to produce food in the city.

We obtained permission to visit and conduct pollinator surveys in 83 allotment plots and community growing spaces in Brighton and Hove in 2017 and 2018. Plots were distributed across nine allotment sites (3–11 plots per site) located in different regions of the city (Figure 1). Using QGIS software (v. 3.99.2) and the CORINE Land Cover (CLC) inventory (2018), we quantified the land cover categories (Table S1) in a 750-m radius from the centre of each allotment site (Figure S1). This radius was selected as it has previously been shown to have the greatest impact on flying insect abundance and richness in urban areas (Theodorou et al., 2017) and is within the foraging range of many pollinator species (Gathmann & Tscharntke, 2002; Greenleaf et al., 2007). The proportion of urban land was 0.81 on average ($SD$ ± 0.25), ranging from 0.28 to 1 (Table S2). The mean land use index, calculated as the proportion of urban cover minus the proportion of agricultural cover, ranged from −0.45 to 1 (Table S2, mean ± $SD$ = 0.64 ± 0.47). Two pollinator surveys per month were conducted between April and September, or for as long as a particular plot had insect-pollinated crops flowering. Surveys were conducted on sunny, dry and calm days, between the 10:00 a.m. and 3:00 p.m. For each flowering crop in a plot that we were surveying, we recorded the approximate number of plants using the following categories ($A = 1$–$3$, $B = 4$–$10$, $C = 11$–$20$, $D = 21$–$40$, $E = 41$–$60$, $F = 61$–$80$, $G = 81$–$100$, $H = 100+$) and estimated the average number of open flowers per plant by examining one or two individual plants per crop. In the case of large fruit trees, we observed one large branch and estimated the number of open flowers on that branch.

We then performed an instantaneous count of the number of pollinators of each type (*beetles*, *hoverflies*, *flies*, *butterflies/moths*, *bumblebees*, *honeybees*, *solitary bees* and *social wasps*) visiting the flowers of the crop. This was achieved by recording the numbers of pollinators observed when looking at individual flowers of a particular crop type one by one in sequence until all flowers had been observed (Levin et al., 1968, Vaissière et al., 2011). Honeybees and bumblebees were identified to species level.

### 2.2 | Pollination deficit experiment

In 2018, we conducted an experiment to test for a pollinator deficit in Brighton and Hove, using two crops commonly grown in urban allotments: strawberries (*Fragaria x ananassa*, *v*. Elsanta) and runner beans (*Phaseolus coccineus v*. Hestia).

### 2.3 | Plant care

We purchased 120 small strawberry plants from a local garden centre in late April 2018. Strawberry plants were housed outside and potted individually into 20-cm pots. Dwarf runner bean seeds were sown in trays in a glasshouse in late April 2018. Once bean seedlings were large enough to handle, we re-potted them into 30-cm pots, three seedlings per pot, and provided canes to support their growth. For both crops, the growing medium was multipurpose compost (Levington) mixed with fertiliser at the recommended rate (Miracle-Gro All

Purpose Plant Food). During flowering and fruiting, we fed plants once per fortnight with tomato feed (Levington Tomorite) at the recommended rate of 20 ml per 4.5-L water.

One week prior to the onset of flowering (strawberries mid-May, beans late-June), we placed two pots of size-matched strawberry plants and one pot of runner beans (containing three plants) in the plots of 30 allotment holders who had agreed to let us use their plots for the experiment. Plots were distributed across three allotment sites in Brighton and Hove (Figure 1, 10 plots/site, see Figure S1 and Tables S1 and S2 for more details regarding site location, size and surrounding landscape). The proportion of urban cover in the 750 m buffer surrounding each site ranged between 0.81 and 1. For beans, we randomly assigned the two most closely sized plants to the 'supplemental pollination' (SP) and 'open pollination' (OP) treatment. We assigned the third plant as the 'donor', which was used to provide pollen for the SP treatment. For strawberries, one of the two plants was randomly assigned to the SP treatment and one to the OP treatment. Sixty strawberry donor plants remained at the University of Sussex, and we collected the donor pollen from individual flowers using separate paintbrushes immediately prior to visiting an allotment site. Paintbrushes loaded with pollen were transported inside a 50-ml falcon tube containing ~2 g of silica beads to prevent the pollen from absorbing moisture during transport.

## 2.4 | Pollination treatment

From the onset of flowering, each allotment site was visited every 2–3 days. Plants were watered and fed according to the schedule described above, and pollination treatments were applied on each visit. At each plot, all open flowers on strawberry plants in the SP treatment received supplemental pollen from an individual paintbrush, meaning that each SP flower received pollen from a single donor flower. OP flowers were left untouched. After receiving the supplemental pollen, we marked the calyx of each open SP flower with a permanent marker pen as a record of the treatment. Occasionally flowers would open and senesce before we could apply the SP treatment; therefore, any unmarked flowers were removed from SP plants, as well as an equivalent number of flowers of a similar stage from the paired OP plant, where possible. Strawberry plants were left in situ at the allotment sites until they had finished flowering and were then returned to the University of Sussex campus greenhouses to allow the fruits to reach maturation, minimising the risk of predation.

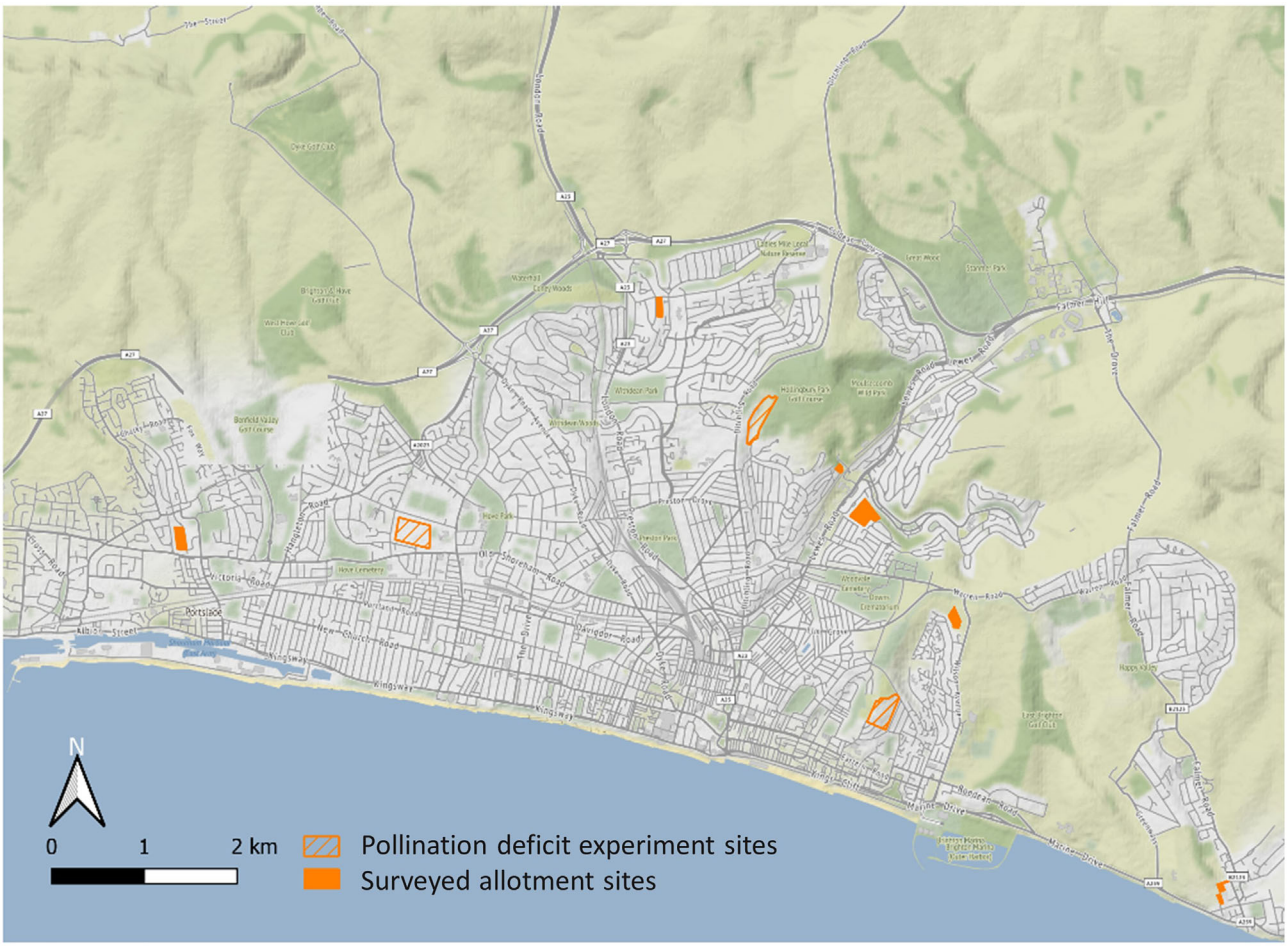



**FIGURE 1** Study location (a) the city of Brighton and Hove (black marker) in East Sussex (orange highlighted area), UK, and (b) the location of specific allotment sites that were surveyed for pollinators across the city ($n = 9$). Plots shaded with orange cross-hatching ($n = 3$) were also the location of the pollination deficit experiments. For further detail regarding site size and surrounding land cover, see Figure S1 and Tables S1 and S2.

Runner beans flower over a protracted period of up to 12 weeks and so providing SP over this entire period was not feasible. Therefore, beans were left in situ for a 4-week subset of the total flowering period. At each plot, all open flowers on the plant in the SP treatment received supplemental pollen from an individual flower from the donor plant, which was transferred using a paintbrush. The calyx of open flowers on both the SP and OP plant were then marked with permanent marker. Given that bean flowers typically only last 1 day, some flowers would open and senesce between our visits and before the SP treatment could be applied. Therefore, we removed all unmarked flowers from the SP and OP plants on each subsequent visit.

On the day of collection, prior to removal from the field site, all unmarked flowers of plants in the SP and OP condition were removed. Once plants were returned to the University of Sussex campus, they remained outside, and we continued to remove any unmarked flowers until all pods had been harvested. This was to avoid any resource shunting that may occur if there is indeed a pollination deficit and only a subset of flowers on SP plants received SP.

### 2.5 | Yield assessment

Both in the field and back on campus, strawberries and bean pods were harvested only once fully mature (strawberries = completely red, beans = pods ≥15 cm in length). We weighed each strawberry to the nearest mg using a precision balance (Sartorius 1419). We then used digital callipers to measure the length (calyx to tip) and diameter (measured at the widest point) of each strawberry. We assigned each strawberry a quality classification of 1–4 based on the methods of Klatt et al. (2014) and Hodgkiss et al. (2018). Each strawberry was then cut in half longitudinally, and we measured the sugar content of a drop of juice to the nearest 5% using a handheld refractometer. To assess the extent of achene fertilisation, we followed the methods of Hodgkiss et al. (2018). Briefly, one half of the strawberry was blended with 200 ml of water in a 1-L plastic beaker for 30 s, using a stick blender (Bosch, Germany). After 5 min of settling time, we counted the number of achenes that floated on the surface of the water (unfertilised) and those that sank to the bottom of the beaker (fertilised).

Due to the large number of beans harvested each day, pods were frozen at −20°C to maintain their freshness prior to assessment. We measured the length of the bean pods to the nearest millimetre and weighed the whole pod to the nearest milligram. We then counted and weighed the individual beans.

## 3 | DATA ANALYSIS

### 3.1 | Plant–visitor networks

Over two field seasons (2017–2018), we conducted 1160 surveys of insect-pollinated crops. For certain crops, we were only able to conduct a limited number of surveys, due to them being grown less frequently in the volunteers' plots that we surveyed. Therefore, to avoid having low sample numbers for certain crops, which may affect the estimation of network structure (Fründ et al., 2016), crop types were condensed into the following ten categories; apple (*Malinae* sp., apples and pears combined, $n = 54$ observations), broad bean (*Vicia faba*, $n = 68$ observations), cherry (*Prunus* sp., cherries and plums combined, $n = 31$), cucumber (*Cucumis sativus*, $n = 66$), currant (*Ribes* sp., redcurrant, whitecurrant, blackcurrant and gooseberries combined, $n = 60$), raspberry (*Rubus* sp., blackberries, raspberries and loganberries combined, $n = 235$), runner bean (*Phaseolus coccineus*, $n = 172$), squash (*Curcubita pepo*, courgette, squash and pumpkin combined, $n = 275$), strawberry (*Fragaria* × *ananassa*, $n = 86$), and tomato (*Solanum lycopersicum*, $n = 77$). Crops for which there were less than 15 surveys (aubergine, blueberry, physalis and peppers, $n = 36$) were excluded from the analyses ($n = 1124$ observations remaining), given that previous researchers have found that certain network metrics, such specialisation, can be underestimated where sampling effort is low (Fründ et al., 2016; Nielsen & Bascompte, 2007; Rivera-Hutinel et al., 2012) (Dataset S1).

We used non-metric multidimensional scaling (NMDS) based on the Bray–Curtis dissimilarity index (metaMDS function in the 'vegan' package [Oksanen, 2019] for R v. 4.1.2 [R Core Team, 2022]) to visualise the similarities in crop visitation between pollinator groups (Code S1). A stress value of 0.09 indicated that the ordination adequately represented the data (Ramette, 2007). With the niche.overlap.boot function in package 'EcoSimR' (Gotelli et al., 2015), we calculated Pianka's overlap index (Pianka, 1973) using a matrix containing total counts of insect pollinators observed visiting the 10 different crop types. The index ranges from 0 to 1, with increasing values indicating a higher overlap in visitation between pollinator groups. To determine if this overlap was significantly higher or lower than expected at random, we used the function niche_null_model to run 10,000 simulations with the randomisation function RA3, which reshuffles values within each pollinator group to generate a null distribution, which we then compared with observed values.

We then constructed a plant–visitor network from the matrix of insect pollinator counts using the 'bipartiteD3' package in R (Code S1). To standardise the values according to sampling effort, we followed the methods of Ballantyne et al. (2015, 2017) and calculated the visits by each insect group as a proportion of the total insect visits observed to a particular crop type. Only legitimate visits to crops were included. Honeybees or short-tongued bumblebees that were observed 'robbing' nectar from flowers (predominantly runner beans) during a visit were excluded from the plant–visitor analysis.

After visualising the network, we calculated the following network indices using the 'bipartite' package (Dormann, 2022). We used $H'_2$ to estimate the level of specialisation at the level of the network (Blüthgen et al., 2006). A score of zero equates to extreme generalisation and a score of one indicates perfect specialisation, that is, each pollinator group interacts with only one crop type. We also calculated the nestedness (weighted according to sample size) and evenness of interactions. Nestedness describes the relationship between generalist and specialist species in the network. When more specialist pollinators visit a subset of plants visited by more generalist pollinators, the network is nested (Dormann et al., 2009; Watts et al., 2016). We estimated the generality of the network, that is, the mean number of

partners that a plant or visitor interacts with, also weighted according to sample size (Bersier et al., 2002). At the insect/crop level, we measured the strength and specialisation (d′) of interactions. Given that network metrics can be affected by factors such as the number of species in the network and sampling effort (Blüthgen et al., 2006; Fründ et al., 2016; Vizentin-Bugoni et al., 2016), we calculated the means from 1000 null models using the Patefield algorithm (Patefield, 1981), which fixes the network size while shuffling interactions randomly. We then used *z*-scores ([observed value-null mean]/null standard error) to test for significant differences from the null model distribution (Dormann, 2022).

### 3.2 | Pollination deficit experiment

We used generalized linear mixed models (GLMM) with a Poisson distribution to test for differences in the total number of strawberries, bean pods and beans produced by plants in the open or supplemental pollination (SP) treatment in the pollination deficit experiment (Code S2). Linear mixed models (LMM) were used to test for differences in total fruit, pod and bean weight between plants in the two pollination treatments (Dataset S1). In all analyses, pollination treatment was included as a fixed effect, and allotment site and plant ID as nested random effects. To compare the diameter, length, fresh weight, Brix, water content and percentage of fertilised achenes between strawberries, and the length and weight of bean pods and beans, we used an LMM with allotment site and plant ID as nested random effects. To compare the proportion of fertilised versus unfertilised achenes in strawberries harvested from plants receiving open versus SP, we used a GLMM with a binomial error structure. Site, plant ID and fruit ID were included as nested random effects. A $\chi^2$ test was used to compare the frequencies of strawberries in each market class.

Where data failed to meet the assumptions of normality, a transformation was used prior to analysis. Total and individual strawberry weight was square root transformed, sugar content was log-transformed, and bean length data were transformed to the power of two. At the plant level, pod and bean weight still failed to meet normality assumptions and so a non-parametric Mann–Whitney test was used to compare between pollination treatments.

## 4 | RESULTS

### 4.1 | Plant–visitor networks

Over the two years of the study, we conducted a total of 1124 crop observations in 83 plots across nine allotment sites in the city of Brighton and Hove. Surveyed plots were a mixture of individual ($n = 76$) and community growing plots ($n = 5$). The number of observations per crop type, and the number of plants of each type observed at a particular plot were variable (Table S3), due to individual preferences in types and numbers of each crop grown by each plot holder.

We recorded a total of 1845 legitimate insect visits to flowering crops. Both the number of crop observations ($n = 352$), and the number of insects ($n = 523$) peaked in August (Figure 2); however, the number of insects recorded per crop observation was highest in May (mean ± *SD* = 1.89 ± 5.14), with the highest rate of insect visits per flower in June (0.26 ± 1.19). The lowest total number of insects (Figure 2) and mean number of insects per crop observation (0.99 ± 2.00) was recorded in September, at the end of growing season; however, the lowest mean number of visits per flower occurred in April (0.01 ± 0.03), at the beginning of the season.

A null model analysis of the plant–pollinator interaction network (Figure 3) showed significant differences between all indices of the observed and random interaction networks (Table S4). The observed visitation network was more specialised than the null model predictions, with a significantly higher $H'_2$ value; however, the network was still fairly generalised ($H'_2 = 0.339$) indicating that most pollinator groups interact with multiple crop types.

The network had a moderate level of nestedness (WNODF = 44.92) and was significantly less nested than the null model (Table S5). Interactions were quite evenly distributed (evenness = 0.775), significantly more so than the null model predictions (Table S5), suggesting that interactions were not dominated by a just a few pollinator groups. Visitor generality (i.e., the average number of crop types visited) was 5.647, and this was significantly higher than the null model predictions indicating that insect groups interacted with more crops than would be expected at random. In contrast, plant generality was 4.610, which was significantly lower than the null model prediction of 6.752, indicating that crops received visits from fewer insect groups than would be expected by chance.

The crop types for which the highest number of insect visits were recorded per observation were species from the Rosaceae (*Rubus* [raspberries, blackberries and loganberries], *Malinae* [apples and pears] and *Prunus* [cherries and plums]) family and *Cucurbita* genus (courgette, pumpkins and squash) families (Table S3), with flowers from the genus *Rubus* visited by insects from every group, *Malinae* by every group except wasps and the *Cucurbita* by every group except butterflies (Figure 3). Indeed, the Rosaceae species had the lowest specialisation in the visitation network, and the *Rubus* species had the highest species strength (Table S4). The lowest number of visitors was recorded during observations of tomato and broad bean crops.

Tomato flowers were only visited by two groups of insect, bumblebees and honeybees and had the second highest specialisation in the visitation network (d′ = 0.359), after cucumbers which were predominantly visited by beetles (d′ = 0.524). In contrast, broad bean crops received visits from all groups except butterflies (Figure 3). When controlling for the number of flowers surveyed per observation of each crop, the highest rate of visits was to plants from the Cucurbitaceae family (courgette, cucumbers, pumpkins and squash) (Table S3), driven predominantly by high numbers of pollen beetles (Figure 3), and the mean rate of flower visitation recorded for the Rosaceae species was in fact below that of strawberries (Table S3), which were visited predominantly by flies, and runner beans, which were visited predominantly by honeybees and bumblebees (Figure 3).

The observed pattern of crop visitation by different pollinator groups, which was visualised using NMDS (Figure 4), had significantly

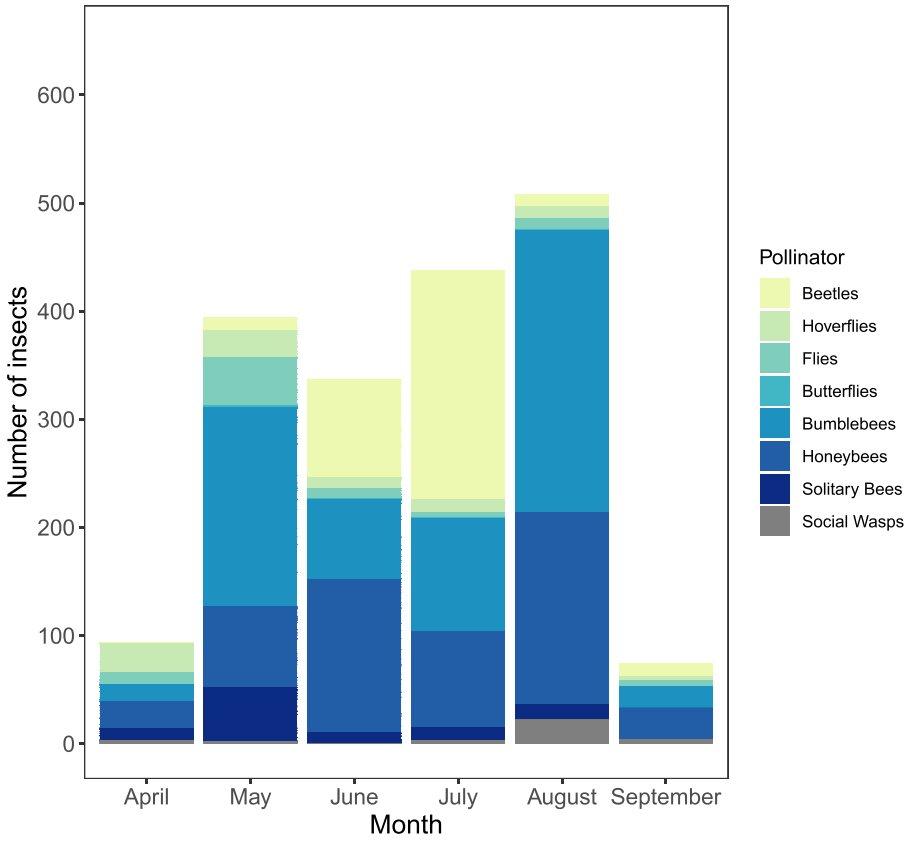



**FIGURE 2** Total number of insects of each pollinator category recorded per month of the growing season (data from both years of the study combined). In 2017 and 2018, two pollinator surveys (an instantaneous count of the number of pollinators of each broad taxonomic type) were conducted per month between April and September in 83 allotments and community growing spaces distributed across nine growing sites in the city of Brighton and Hove.

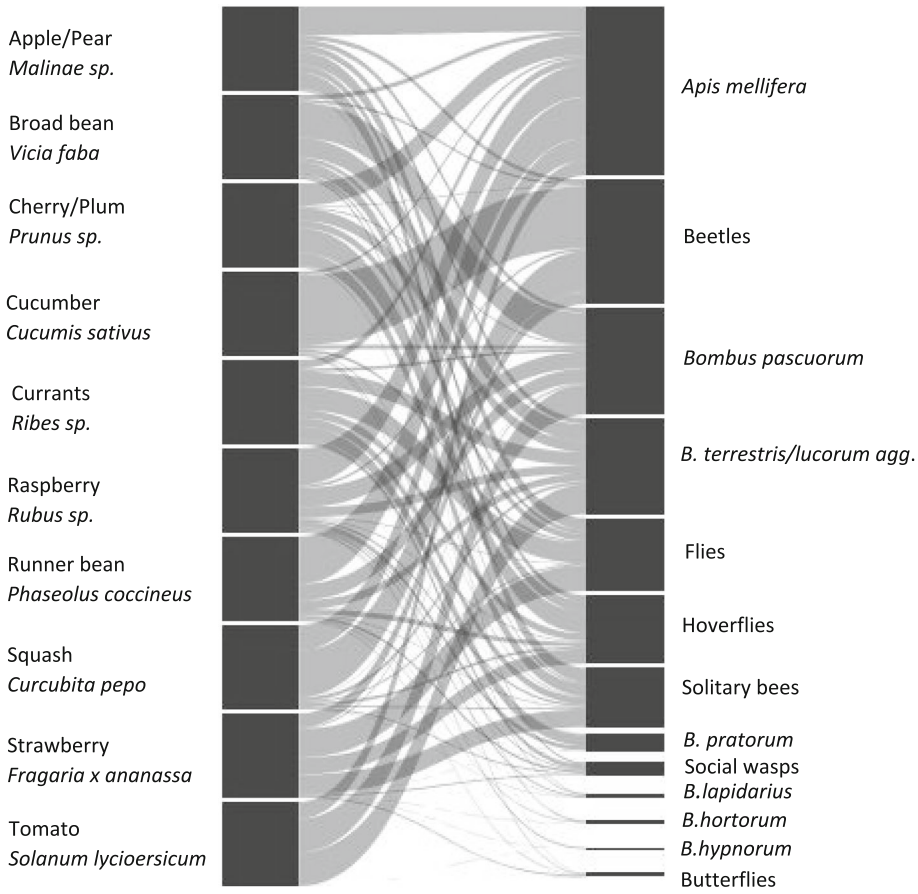



**FIGURE 3** Visitation network for insect-crop interactions ($n = 1845$ interactions). Over two growing seasons, we conducted 1124 observations of insect-pollinated crops in 83 allotments and community growing spaces distributed across nine growing sites in the city of Brighton and Hove. During each observation, we performed an instantaneous count of the number of pollinators of each broad taxonomic type. Honeybees and bumblebees were identified to species. Crop visits are standardised according to sampling effort by dividing the number of each insect type or species by the total number of insect visits to a particular crop to calculate the proportion of total visits. Only legitimate flower visits and data for crops where there are >5 observations are included in the analysis. For an interactive D3 (data driven document) version of this network, please visit online (https://bethbees.github.io/Nichollslab/Rspeciesnew.html).

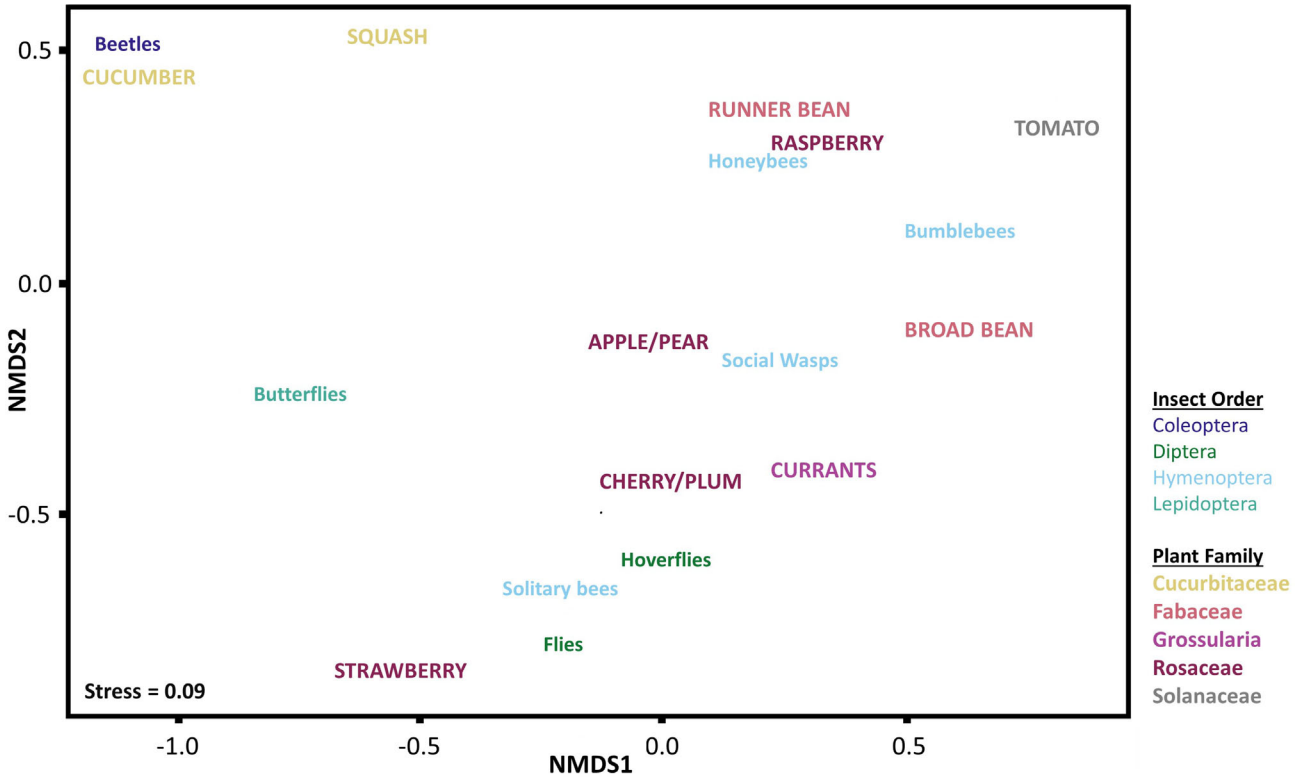



**FIGURE 4** Results of nonmetric multidimensional scaling (NMDS) run with a matrix of dissimilarities (Bray–Curtis) of the relative frequency of crop visitation by the different pollinator groups (stress = 0.09). The shorter the distance between insect pollinator taxonomic groups, the greater the overlap in crop types visited.

higher levels of overlap in visitation between pollinator groups than expected at random (Figure S2; observed mean = 0.580, Simulated mean = 0.380, standardised effect size = 5.228, $p < .001$). Values of Pianka's index of overlap between pollinator pairs ranged between 0.183 and 0.975 (Table S6), from completely different crop preferences to almost identical. The highest degree of overlap between crop preferences were observed for social bees (honeybees–bumblebees = 0.958), and social bees and social wasps (honeybees–wasps = 0.975, bumblebees–wasps = 0.929). High values of overlap were also observed between solitary bees and both flies (0.869) and hoverflies (0.840) as well as between flies and hoverflies themselves (0.758). The lowest levels of dietary overlap were seen between beetles and other groups of pollinators, particularly butterflies (0.183) and bumblebees (0.187).

By far the most frequently observed insects were honeybees ($n = 659$, 36% visits recorded) and bumblebees ($n = 538$, 29% all visits). Alongside solitary bee species ($n = 97$, 5% total insect visits), honeybees and bumblebees visited the broadest range of crop types (Figure 3), and the level of specialisation in the visitation network was similar across honeybees, solitary bees and the bumblebee species *Bombus terrestris/lucorum agg*. and *Bombus pascuorum* (Table S5). Honeybees visited all crops except strawberries and were the most frequent visitors to runner beans (56% of all insect visits) and apple and pear trees (34% visits). Honeybees had the highest species strength in the visitation network (Table S5) with strong associations with raspberries and blackberries (44% visits), cherries and plums (26% visits) and courgettes, pumpkins and squash (30% visits).

Collectively, bumblebees were the most frequent visitors to the largest range of crops, including tomatoes (80% of all visits), broad beans (66% of all visits), raspberries and blackberries (43% visits) and currants (38% visits). The long-tongued species *B. pascuorum* was the most frequently observed bumblebee ($n = 257$), had the highest species strength among the bumblebees (Table S4) and was the only insect observed visiting all types of flowering crops. *B. pascuorum* accounted for the majority of visits to broad beans (43% of all insect visits to this crop) and a substantial proportion of visits to tomatoes (40% visits), alongside the short-tongued *B. terr/luc agg*. ($n = 174$), which also accounted for 40% of visits to tomatoes and was recorded visiting the flowers of all crops except cucumbers and strawberries.

*Bombus pratorum* was observed less frequently ($n = 61$) and visited only three crop types, resulting in the second highest specialisation in the visitation network ($d' = 0.417$) after beetles, with this species accounting for 16% of all visits to currant flowers. *Bombus lapidarius* ($n = 24$), *Bombus hypnorum* ($n = 18$) and the long-tongued *Bombus hortorum* were the least frequently observed ($n = 4$) bumblebees, and none of these species had particularly strong associations with any crops surveyed (Table S4).

Solitary bees were observed visiting all crops except tomatoes, with the strongest associations with strawberry (24% all insect visits) and apple and pear flowers (19% of all visits), though they were not the most abundant visitor to any one crop type.

Beetles were the next most frequently observed insect group ($n = 339$, 18% of all crop visits), after honeybees and bumblebees.

The high frequency of observations was predominantly driven by large numbers of pollen beetles observed visiting cucumber (84% of all insect visits) and courgette, pumpkin and squash flowers (56% visits), and beetles had the highest specialisation (d′) in the visitation network (Table S4). Nonetheless, at least one visit to all crops except currants, runner beans and tomatoes was observed for beetles.

Hoverflies ($n = 89$, 5% total insect visits) were observed visiting the flowers of all crops except cucumbers and tomatoes, exhibiting low specialisation (Table S4). They were the most frequently observed insect group visiting cherry and plum flowers (29% of all insect visits) and had fairly strong associations with strawberry (20% of all visits) and broad bean flowers (14% of visits). Other fly species ($n = 84$, 5% total visits) had the strongest association with strawberry flowers, accounting for over one third of all insect visits (35%) and were also the second mostly frequently observed insect group visiting currant flowers (27%), after bumblebees. Wasps ($n = 34$, 2% total visits) were observed visiting the flowers of six different crop types (broad beans, currants, raspberries, runner beans, squash and strawberry) but did not have particularly strong associations with any crop. Butterflies were recorded most infrequently, with only five visits to crop flowers recorded in total (<1% total visits).

## 5 | POLLINATION DEFICIT EXPERIMENT

### 5.1 | Strawberry yield and fruit quality

On average, strawberries harvested from plants receiving SP had significantly more (∼+10%) fertilised achenes (Figure 5, mean ± *SD* = 77.50 ± 0.17%) compared with OP plants (mean ± *SD* = 67.80 ± 0.24%, $\chi^2 = 7.317$, $df = 1$, $p = .007$). There was no significant difference in the average number of fruits or total weight of fruit produced by OP strawberry plants versus those receiving supplemental hand pollination (Table S7). The fresh weight of individual strawberries was slightly heavier for plants that received SP compared with those produced by OP plants, but again this difference was not significant (Table S7).

Strawberries produced by plants receiving SP were also slightly wider and longer on average than those produced by OP plants though again these differences were not significant (Table S7). There was also no difference in average sugar content between berries receiving open versus supplemental hand pollination (Table S7).

The categories of market class fruit differed significantly between OP plants and those receiving SP (Figure 6, $\chi^2 = 10.375$, $p = .016$), with plants receiving open pollination producing more unmarketable fruit, compared with plants receiving SP.

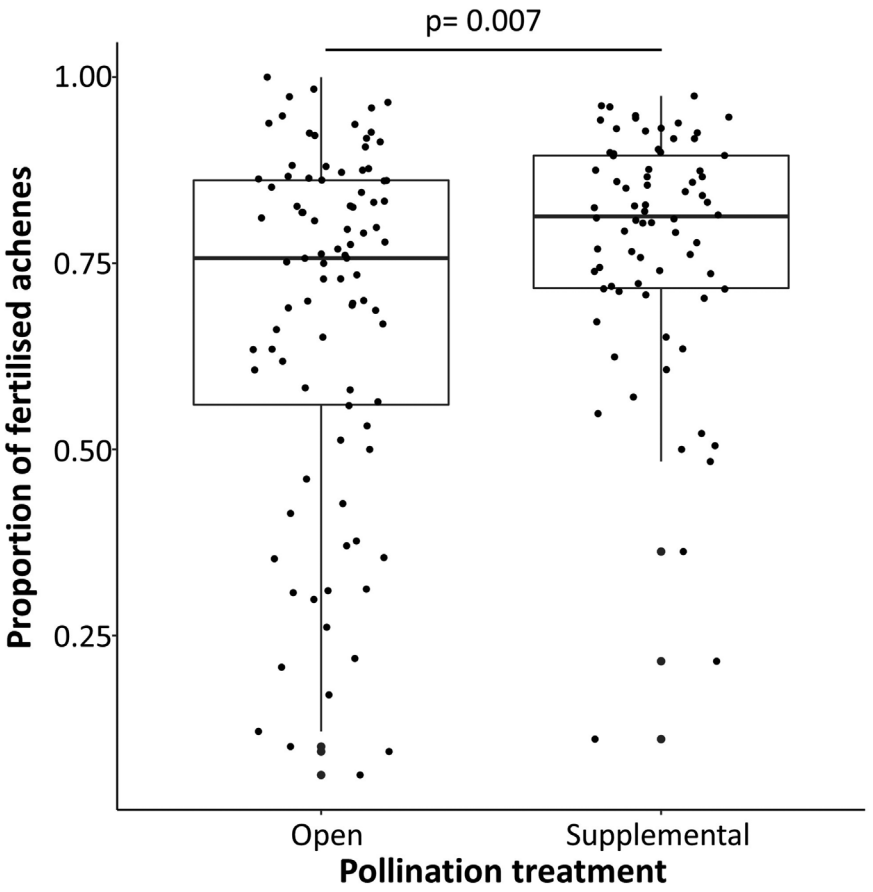



**FIGURE 5** Proportion of fertilised achenes in strawberries harvested from plants that were either open-pollinated ($n = 95$ fruits) or received supplemental hand pollination ($n = 76$ fruits), to test whether there are sufficient insects to provide adequate pollination to strawberry crops grown in an urban area in the United Kingdom. Strawberries harvested from open-pollinated plants had significantly fewer fertilised achenes indicating that the quality of pollination received was below that of plants receiving supplemental hand pollination ($\chi^2 = 7.317$, $df = 1$, $p = .007$). The box limits denote the lower and upper quartile, the bold line the median and the whiskers denote the smallest and largest values within 1.5 times the interquartile range. Individual strawberry measurements are represented by black data points.

### 5.2 | Runner bean yield and quality

There was no significant difference in the total number of pods harvested per plant, though OP plants did produce slightly more pods on average (Table 1). The total weight of pods harvested per plant was also slightly higher for OP plants and though this difference was not significant (Table 1), the total weight of beans produced was significantly higher for OP plants (Mean = 18.6 g ± 10.4) compared with those receiving SP (mean = 13.0 g ± 7.23; W = 602, $p = .024$). The average length and weight of individual pods was not significantly different between pollination treatments (Table 1), though again the weight of beans within those pods was significantly higher for OP plants (OP mean ± SD = 1.28 ± 1.43 g; SP 1.01 ± 1.09 g, W = 93,724, $p = .004$). The average number of beans per pod did not differ between pollination treatments however (Table 1).

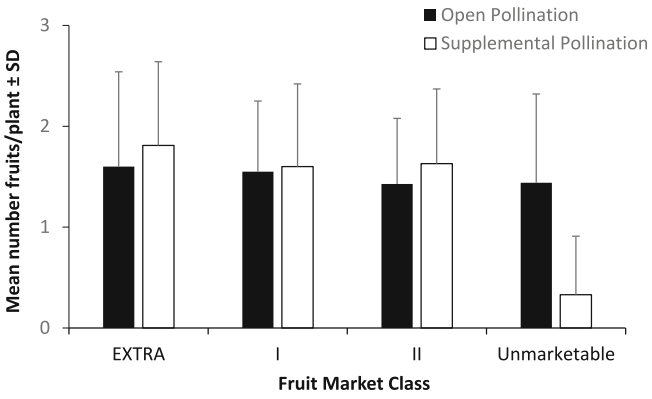



**FIGURE 6** Mean (±*SD*) number of strawberries produced per plant in open versus supplemental pollination treatment that were classified as EXTRA class, Class I, Class II and unmarketable. The categories of fruit differed significantly between open-pollinated plants and those receiving supplemental pollination (Figure 6, $\chi^2 = 10.375$, $p = .016$), with plants receiving open pollination producing more unmarketable fruit, compared with plants receiving supplemental pollination.

## 6 | DISCUSSION

Growing food in urban areas is increasingly recognised as a potential solution to more sustainably meeting the needs of a rapidly growing and urbanising global population. However, little is known about the pollination requirements of crops commonly grown in urban areas and whether insect populations in cities are sufficiently large and diverse enough to provide adequate pollination to meet current needs or a potential expansion of urban farming. We quantified crop–pollinator visitation networks in urban allotments in the city of Brighton and Hove in the south of England, UK, and found that a broad range of insect-pollinated crops were grown, and that they were visited by a diversity of insects spanning many taxonomic groups. Honeybees and bumblebees were the insects most frequently observed visiting crop flowers, and fruiting trees (apples, pears, cherries and plums), shrubs (raspberries, loganberries and blackberries) and squash flowers received the highest number of visits by insects per observation. Tomato flowers and broad beans were the least attractive crops. We also conducted pollination deficit experiments for two commonly grown crops in urban areas, strawberries and runner beans, and found little evidence that bean yields were limited by a lack of pollinator visits. However, the ratio of fertilised to unfertilised achenes was significantly lower in strawberries harvested from plants that did not receive supplemental hand pollination, and these plants produced more 'unmarketable' fruit, though overall yields did not differ. This suggests that there is room for improvement in the delivery of pollination to strawberries grown in urban areas, which were predominantly visited by flies.

### 6.1 | Urban crop–pollinator interaction network properties

Overall, the urban crop–pollinator interaction network was moderately generalised, indicating that most pollinator groups interacted with multiple crop types, and significantly more than predicted by the null model. The specialisation index ($H_2' = 0.40$) was lower than that reported for other studies of plant–pollinator interactions in urban

| | | | | Open pollination | | Supplemental pollination | |
|---|---|---|---|---|---|---|---|
| **Measurement** | $\chi^2$ | ***df*** | ***p*** | ***Mean*** | ***SD*** | ***Mean*** | ***SD*** |
| Number pods/plant | 2.692 | 1 | .101 | 14.46 | 6.17 | 12.9 | 6.68 |
| Pod length (mm) | 1.30 | 1 | .190 | 157 | 27.8 | 160 | 30.2 |
| Pod weight (g) | 0.112 | 1 | .738 | 12.5 | 3.76 | 12.6 | 4.09 |
| Number beans/pod | 3.074 | 1 | .080 | 3.67 | 1.35 | 3.94 | 1.48 |
| **Measurement** | ***W*** | ***df*** | ***p*** | ***Mean*** | ***SD*** | ***Mean*** | ***SD*** |
| Weight pods/plant | 528 | 1 | .254 | 181 | 85.6 | 162 | 86.3 |
| Weight beans/plant | 602 | 1 | **.024** | 18.6 | 10.4 | 13.0 | 7.23 |
| Weight beans/pod | 93,724 | 1 | **.004** | 1.28 | 1.43 | 1.01 | 1.09 |

**TABLE 1** Measurements of pods and beans produced by plants receiving open versus supplemental hand pollination, to test whether there are sufficient insects to provide adequate pollination to runner bean crops grown in an urban area in the United Kingdom.

*Note*: Significant differences between treatment groups are highlighted in bold. The weight of beans produced per plant (W = 602, $p = .024$) and the weight of beans produced per pod (W = 93,724, $p = .004$) were significantly higher for plants receiving open pollination.

spaces in the United Kingdom however. For example, a study of urban green spaces across four UK cities reported an average $H_2'$ of 0.47 (Baldock et al., 2015), and a study of urban gardens in Northampton reported a very specialised $H_2'$ value of 0.71 (Sirohi et al., 2022). However, both these studies recorded visits to all flowering plants, and Sirohi et al. (2022) focused only on bees, which were all identified to species. Our survey was limited to flowering insect pollinated crops only and while focusing on a broad range of taxonomic groups, only bumblebees were identified to species, making comparisons between these networks challenging. Visitor generality, that is, the average number of crops visited by each pollinator type, was 5.65. Comparisons between urban and rural areas in the context of visitor generality have typically found this to be higher for urban networks and particular garden habitats, compared with agricultural or natural areas. This trend is consistent between studies conducted in the United Kingdom (Baldock et al., 2015; Sirohi et al., 2022), France (Geslin et al., 2013) and Germany (Theodorou et al., 2017), and has been attributed to the higher floral resource availability in urban areas compared to farmland.

Interactions in the network were very evenly distributed (0.78), meaning that the interaction network was not dominated by just a few pollinator groups, highlighting the importance of maintaining insect diversity for crop pollination in urban contexts. This finding concurs with a study by Geslin et al. (2013) that compared plant–pollinator networks along a urban–rural gradient in Paris, France, and found higher network evenness in urban areas. A similar study by Udy et al. (2020) conducted in Germany reports the opposite trend however. Both studies employed standardised plots of experimental plants, though the species composition differed, highlighting the importance of characterising plant–pollinator networks and the impact of surrounding landscape for the specific plants or crops of interest.

The crop–pollinator network also had a moderate degree of nestedness, which suggests that some of the more specialist pollinator groups (e.g., wasps) visit a subset of those crops visited by more generalist pollinators (e.g., honeybees). The results of the NMDS visualisation and analysis also showed that there was a higher degree of overlap in crop visitation between pollinator types than expected by chance. Higher degrees of nestedness can lead to more stable networks (Allesina & Tang, 2012), though caution should be taken when interpreting nestedness values for small networks such as this one (Feng & Takemoto, 2014). Nonetheless, previous studies comparing urban and rural sites have typically found that urban plant–pollinator networks have higher nestedness (Sirohi et al. 2022).

## 6.2 | Which insects visited flowering fruit and vegetable crops grown in an urban area in the south of the United Kingdom?

Bees were by far the most frequently observed visitor to crop flowers, accounting for over two thirds of all plant–insect interactions. All bees exhibited low levels of crop specialisation and there was considerable overlap in the crop preferences of the social Hymenoptera; honeybees, bumblebees and social wasps. The one exception was *Bombus pratorum*, which was observed visiting flowering shrubs only (raspberries, currants and gooseberries). The colony cycle of this early spring species is usually concluded by late June, and therefore, such specialisation is likely explained by the limited crop choices early in the growing season (Goulson et al., 2018). Indeed, most crop interactions for this species were observed in May and June.

Honeybees alone accounted for over one third of all crop interactions observed. This high abundance of interactions may reflect the growing prevalence of beekeeping in urban areas. Although our study cannot determine the effectiveness of honeybees at pollinating the crops they were observed visiting (all crop types except strawberries), we know from studies conducted in conventional farming systems that visitation by honeybees alone rarely leads to maximal crop yields (Garibaldi et al., 2013; Winfree et al., 2018). Insect diversity is key to maximising fruit set in many of the crops surveyed here, including cherry and squash, and for some crops that honeybees were observed visiting, such as tomatoes and cucumbers, data suggest they do not contribute to fruit set at all (Garibaldi et al., 2013). Therefore, managing urban agricultural systems in a way that does not rely solely on honeybees and promotes pollinator diversity would likely be beneficial.

At face value, the high abundance of beetles, accounting for nearly one fifth of all plant–insect interactions may be surprising; however, this is mostly driven by large numbers of small pollen beetles visiting squash and cucumber flowers. Beetles also had the lowest levels of crop visitation overlap with other pollinator groups. In conventional flowering crops, such as oilseed rape, pollen beetles are regarded as a pest. However the potential for these beetles to contribute to pollination in cucurbits appears to have been little explored (but see Das et al., 2009; Durham, 1928; Fronk & Slater, 1956; Hurd, 1966); it may be that they move too infrequently between flowers to contribute much pollination. Honeybees and bumblebees also visited squash flowers and are both known to be pollinators of these crops (Artz & Nault, 2011; Pfister et al., 2017; Stoner, 2020), but the relative contribution of beetles is unclear.

In conventional fruit orchards, bees are typically considered the most frequent visitors and most important pollinators, and fruit growers often pay for honeybee hives to be placed in orchards, or purchase commercial bumblebee colonies to ensure adequate crop pollination (Breeze et al., 2011; Thomson & Goodell, 2001). More recently, there has been interest in cultivating solitary bee populations in orchards, for example through providing bee 'hotels' for cavity nesting bees or creating habitat to encourage ground-nesting bees, both of which have been shown to be effective fruit tree pollinators (Ladurner et al., 2004; Matsumoto et al., 2009; Vicens & Bosch, 2000). However, our results show that, at least in the urban context, the most frequent visitor of cherry and plum flowers were in fact hoverflies, which we also found exhibit a high degree of overlap in crop preferences with solitary bees, as well as other flies. A recent investigation of the relative importance of crop pollinators found that flies were the second most important order of pollinating insects, after

bees, visiting 72% of global crop plants (Rader et al., 2020), with 52% of those visits attributed to hoverflies. Though in general the pollination effectiveness of hoverflies has been relatively little explored (Doyle et al., 2020), a pollinator exclusion study in conventional apple orchards in the United Kingdom did find that hoverflies were less effective pollinators than solitary bees or bumblebees (Garratt et al., 2016). Hoverflies are typically less hairy than bees and therefore less likely to transfer pollen between flowers (Kendall & Solomon, 1973). Nonetheless, hoverflies are increasingly recognised as effective pollinators of other crops such as strawberries (Hodgkiss et al., 2018), sweet peppers (Jarlan et al., 1997) and oilseed rape (Jauker et al., 2012; Jauker & Wolters, 2008).

As highlighted in discussions above, a major limitation of the plant–insect visitor data is that we only recorded flower visitation, which does not accurately indicate whether a particular insect visitor was actually contributing to the *pollination* of the flower, or if so, how effective it is as a pollinator compared with other visitors. However, previous pollination research has shown that the more frequent insect visitors are also typically the predominant pollinators (Ballantyne et al., 2017; Vazquez et al., 2012) and though our results should be interpreted with caution, particularly given the dominance of honeybees in our interactions (Page et al., 2021), such visitation data still serve as a useful first step in identifying the most common insect visitors to food crops grown in urban areas in the United Kingdom. The current study was part of a larger project that aimed to develop a simple citizen-science methodology to facilitate the participation of urban growers across different regions of the world in data collection on insect visitation to crops grown in urban areas. Such data collection is particularly needed in low- and middle-income countries where urban growing is prevalent and provides an important source of income, but where data on urban insect-crop visitation is even more sparse. Therefore, the plant–insect visitor data in this study were collected using the same, simplified method to enable a subsequent comparison of the accuracy of citizen scientist collected data. Nonetheless, future work should aim to record insect behaviour more precisely when observing flower visits in urban areas, and ideally incorporate data on single visit pollen deposition (King et al., 2013; Lander, 2020) and/or the pollen export capacity of visitors, which could for example be estimated via facial hairiness (Stavert et al., 2016).

### 6.3 | Which flowering fruit and vegetable crops were most attractive to flower-visiting insects?

The crops that were most attractive to flower-visiting insects were flowering trees (apple, pear, cherries and plums) and shrubs (raspberries, loganberries and blackberries). These crops had the lowest specialisation, meaning they were visited by a broad range of insect visitors and therefore are likely the most important in providing resources for a diverse range of insects in urban growing spaces in temperate regions. All these crops belong to the Rosaceae and have open flowers, meaning the pollen and nectar rewards they provide are easily accessible to insects with a broad range of body sizes and tongue lengths (Wignall et al., 2020). Collectively they provide food resources to pollinators over a long flowering period, with some fruit trees flowering as early as April, and raspberries flowering into early to mid-September. From the grower's perspective, these perennial crops offer another advantage, given they do not need to be purchased and planted again each year, meaning they require less financial and labour inputs compared with annual crops such as beans, squash and tomatoes. Because they do not need to be dug up annually, they also limit soil erosion and may contribute to carbon storage in urban areas (Ledo et al., 2020).

### 6.4 | Are there sufficient insects in Brighton and Hove to provide adequate crop pollination?

As previously discussed, both our network and those of others studying plant–pollinator interactions observe high visitor generality in urban areas. This has been hypothesised to have negative implications for crop pollination, given the deposition of heterospecific pollen can affect conspecific pollen performance and seed set (Ashman & Arceo-Gómez, 2013). Comparisons of plant reproductive success along a rural–urban gradient have yielded mixed results however, with some studies reporting a positive effect of urban land cover on seed set (Theodorou et al., 2017), whereas others have found the opposite effect (Geslin et al., 2013). Specific studies of the reproductive success of food crops in urban areas however are lacking (Bennett & Lovell, 2019; Cohen et al., 2021).

We conducted a pollination deficit experiment in strawberries and runner beans and found that the yields of the OP strawberry plants and those receiving additional hand pollination did not differ in terms of fruit number, size, weight or sugar content. However, the OP plants did produce fruit with a lower proportion of fertilised achenes and produced significantly more unmarketable fruit, suggesting that the quality of pollination received was below that of plants receiving additional hand pollination pollen. This indicates that there is the potential to improve the delivery of pollination to this crop in urban areas. In the context of allotment growers producing food for their own consumption, this difference in the visual appearance of the fruit is unlikely to be important. However, existing or potential commercial growers of strawberries in urban areas, for whom market class would be more important, might consider providing habitat, such as hoverfly lagoons, to increase the population of flies (Rotheray & Rotheray, 2021), which were observed to have the strongest association with strawberry flowers in our interaction network (Ellis et al., 2017). A recent study by Udy et al. (2020) comparing pollinator species richness between rural and urban areas found that flies were typically most abundant in farmland and observed less frequently in urban areas. Doyle et al. (2020) have recently reviewed the evidence for interventions that encourage hoverflies in agroecosystems, and suggest that woody features, such as hedgerows and trees, are associated with an increase in hoverfly abundance (Dainese et al., 2017), as is delayed mowing (Meyer et al., 2017). A previous study conducted in an urban context in the United Kingdom also found that companion

planting of strawberry plants with pollinator attractive, nectar-rich flowers such as borage (*Borago officinalis*) can increase crop yields, while likely benefitting other insects as well (Griffiths-Lee et al., 2020).

The floral morphology of runner beans means that they are pollinated most effectively by legitimate visits from long-tongued bees, such as the bumblebee *Bombus pascuorum*. There are concerns across Europe regarding declines in long-tongued bee species (Bommarco et al., 2012; Dupont et al., 2011; Lye et al., 2012), which may have implications for the pollination of crops such as runner beans and broad beans that are at least partially dependent on such species. In our study, *B. pascuorum* was the most commonly observed bumblebee, though another long-tongued species, *B. hortorum*, was only recorded visiting flowers a handful of times. There was no difference in the number, weight or size of pods produced by plants receiving open versus supplemental hand pollination, and while the number of beans per pod did not differ, the weight of beans per pod and the total weight of beans per plant were actually higher for the OP plants compared to those receiving supplemental pollination. Higher individual bean weight owing to inadequate pollination has been previously demonstrated in broad beans (*Vicia faba*); however, the fact that there was no difference in the number of beans per pod suggests that this cannot completely be explained by increased plant investment into individual bean weight as suggested in the previous studies (Free, 1966; Hebblethwaite et al., 1984; Lundin & Raderschall, 2021; Poulsen, 2015). This apparent lack of limitation is perhaps not surprising given bumblebees were one of the most frequently observed visitors, alongside honeybees, and are known to be effective pollinators of this crop (Kendall & Smith, 1976).

## 7 | CONCLUSIONS

We observed high diversity in both the types of crops grown in urban areas in Brighton and Hove, UK, and in the taxonomic spread of insects observed visiting them. We found little evidence of pollinator limitation for runner beans, and although the quality of pollination delivery was sub-optimal for strawberries leading to a lower ratio of fertilised to unfertilised achenes for fruit harvested from OP plants, we did not observe differences in the weight or number of fruits harvested. While there is some room for improvement in the quality of pollination, our results indicate that pollinator populations in urban farms are likely sufficiently large and diverse enough to support the production of insect pollinated fruit and vegetables in the study area, or even a potential expansion. Future research should examine further the impact of the surrounding landscape and local site features on crop–pollinator interactions and pollination service delivery in urban areas, as well as determining which pollinators are the most effective for different crops. For example, Cohen et al. (2021) have recently shown that increasing herbaceous plant richness and the number of perennial trees and shrubs within a site can increase seed number in jalapeño peppers grown in urban areas in California.

Demand for growing space remains high in the United Kingdom (ASPE, 2022), but a recent analysis has shown that there is the capacity to meet this demand by restoring former allotment space that remains vacant or that has been repurposed into other green space (Dobson et al., 2020). Expanding the area of growing space could also lead to multiple other benefits for residents, aside from improving access to fresh nutritious food, including increased resilience to climate-related events such as flooding, and a reduction in air pollution, as well as benefits to growers in terms of improved health and wellbeing (Nicholls et al., 2020). Urban allotments and community gardens have also been shown to have considerable benefits for pollinators themselves (Baldock et al., 2019), as well as other wildlife (Borysiak et al., 2017; Colding et al., 2006; Matthies et al., 2015); therefore, expanding the area of urban allotments and community gardens could also play an important role in conserving pollinator populations.

### AUTHOR CONTRIBUTIONS

Elizabeth Nicholls, Dave Goulson and Parthiba Basu designed the study. Elizabeth Nicholls conducted the research and collected the data. Elizabeth Nicholls, Soumik Chatterjee and Janine Griffiths-Lee conducted the data analysis. Elizabeth Nicholls wrote the first draft of the manuscript and Dave Goulson and Janine Griffiths-Lee commented on subsequent drafts.

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### CONFLICT OF INTEREST STATEMENT

The authors have no conflicts of interest to declare.

### DATA AVAILABILITY STATEMENT

The data that support the findings of this study are available in the supporting information of this article.

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## SUPPORTING INFORMATION

Additional supporting information can be found online in the Supporting Information section at the end of this article.

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