Insect-mediated pollination improves fruit quality of strawberries in an urban environment

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Abstract

Pollination services provided by a diversity of pollinators are critical in agriculture since they enhance the yield of many crops. However, few studies have assessed pollination services in urban agricultural systems. We performed flower-visitor observations and pollination experiments on strawberries, *Fragaria × ananassa*, in an urban area of Paris, France, in order to assess the effects of (*i*) insect-mediated pollination service and (*ii*) potential pollination deficit on fruit set and fruit quality (size, weight, malformation and seed set). Flower-visitor observations revealed that the pollinator community was solely comprised of unmanaged pollinators, despite the presence of apiaries in the surrounding landscape. Based on the pollination experiments, we found that the pollination service mediated by wild insects improved fruit size as a qualitative value of production, but not fruit set. We also found no evidence for pollination deficit in our urban environment. These results suggest that the local community of wild urban pollinators is able to support strawberry crop production, and thus plays an important role in providing high quality, local and sustainable crops in urban areas.

Introduction

Animal pollination is essential for the reproduction of 87.5% of all flowering plants (Ollerton et al. 2011) and contributes to over half of the leading crop yield worldwide (Klein et al. 2007). Crop pollination is thought to increase agricultural outputs by 235–577 billion $US annually (Potts et al. 2016). Insects play a critical role in crop pollination (e.g. Pérez-Mendez et al. 2019; Pisanty et al. 2016; Sapir et al. 2017) in particular the Western honey bee *Apis mellifera*, which is known as an economically important pollinator in agriculture. Indeed, this species is managed by beekeepers, who place beehives in close proximity to crops to ensure the pollination service is provided (Garibaldi et al. 2017; McGregor 1976). However, wild insect pollinators provide significant contributions to crop pollination in synergy with managed pollinators (Garibaldi et al. 2013; Rader et al. 2016). Since the 19th century, wild insect pollinators have suffered an important decline and beekeepers have registered increased mortality rate in managed honey bee colonies (Goulson et al. 2015; Potts et al. 2010; Sánchez-Bayo and Wyckhuys, 2019). Pressures on pollinator populations are due mainly to intensive agricultural practices such as the use of chemical fertilizers, pesticides and herbicides, and, in the case of wild pollinators, the loss of (semi-)natural areas for nesting habitats and wild flowers for foraging (Goulson et al. 2015; Potts et al. 2010).

Beyond agricultural landscapes, pollinator populations also suffer from pressures in urban areas. On one hand, the high proportion of impervious surfaces make cities highly disturbed habitats, which favour generalist species and impact specialist species, leading to a biotic homogenization of pollinator communities (Ayers and Rehan 2021; Banaszak-Cibicka and Żmihorski 2020; Wenzel et al. 2020; Zaninotto et al. 2021). Nevertheless, urban landscapes could be considered as a refuge for certain insect pollinators (Baldock 2020; Hall et al. 2016), given that they offer a high abundance of managed ornamental plants flowering over a longer period than unmanaged plant communities (Harrison and Winfree 2015; Marquardt et al. 2021; Theodorou et al. 2021), and nesting habitats for cavity nesting bees are numerous (Fitch et al. 2019). These aspects of urban landscapes can allow cities to harbour diverse pollinator communities (Baldock et al. 2015; Fortel et al. 2014; Geslin et al. 2015). Despite a growing interest in urban pollinator diversity (Banaszak-Cibicka et al. 2018; Birdshire et al. 2020) and pollination services (Harrison and Winfree 2015; Wenzel et al. 2020), very few studies assess whether these unique urban pollinator communities can provide sufficient pollination services to support urban crop production.

Urban food production, from allotments or private gardens, provides local and sustainable fruit and vegetables for the increasing human urban population, which represents over half of the world population (United Nations 2016). A few recent studies have demonstrated the importance of taxonomically diverse pollinator communities, supported by florally diverse and dense gardens, for urban production of cucumber, eggplant (Lowenstein et al. 2015) and jalapeño peppers (Cohen et al. 2021). Indeed, pollinator species complement each other by occupying different ecological niche spaces, whereby different species have differing spatio-temporal pollinating activities thus maintaining a stable and consistent pollination service (Pisanty et al. 2016). Some studies go even beyond pollinator complementarity, illustrating synergetic effects of multi-species visits on crop production, meaning that the service provided by the multi-species community is greater than the addition of the individual contributions of each species (Pérez-Mendez et al. 2019; Sapir et al. 2017). However, in urban landscapes, the diversity of pollinator communities may be affected by rapid development of urban beekeeping (Ropars et al. 2019), since the numerically dominant managed honey bees outcompete wild pollinators (Geslin et al. 2017).

Here, we aim to evaluate the ability of an urban pollinator community to support strawberry production. This crop is commonly grown in allotments and urban gardens and strawberry fruit quality has been shown to benefit from animal pollination in studies set in agricultural landscapes (Abrol et al. 2019; Bänsch et al. 2020; Klein et al. 2007). The cultivated strawberry (*Fragaria x ananassa*), has been bred since the 18th century (Gaston et al. 2020) and comprises numerous cultivars which are produced by crossing genotypes with traits of interest (Gil-Ariza et al. 2009), which give fruits meeting commercialisation criteria (OECD 2021) and pleasing consumers (Lado et al. 2010). The contrast in pollinator community composition between urban and agricultural landscapes may affect the quality of the pollination service provided. However, little is known about the ability of urban pollinator communities to support strawberry fruit production as farmland pollinator communities do.

In the peri-urban environment of Paris (France), we surveyed the pollinator community visiting strawberry flowers and carried out pollination experiments. We used pollinator exclusion and hand pollination techniques to evaluate the effect of different pollination treatments on qualitative and quantitative measure of fruit production. These were fruit set, fruit size, weight, malformations and seed set. Fruit size and malformation are commercially important traits (OECD 2021), whereas seed set is closely linked to pollination. Indeed, the seeds, or achenes, are the true fruit of the strawberry (Davis et al. 2008). Their formation is a direct result of ovule fertilisation, which requires pollination (Andersson et al. 2012; Davis et al. 2008). Although the fleshy part of the strawberry does not develop around unfertilised achenes, causing malformations to appear (Davis et al. 2008), its formation is less closely linked to pollination. We took a particular interest in evaluating the service provided by insect pollinators, and the level of pollination deficit. This refers to a situation where the pollination service provided by insects present in the environment is not sufficient to maximise crop production (Garibaldi et al. 2017). We hypothesize that insect pollination increases fruit set and fruit quality, by increasing fruit size, weight and seed set, and decreasing fruit malformation. We further hypothesize that we will find a deficit in pollination, where pollen saturation (mediated by hand pollination) increases fruit set, fruit size and seed set, and decreases the occurrences of malformation, compared to pollination by the local pollinator community.

Materials And Methods

Study site

The study was carried out on the campus of the French National Research Institute for Sustainable Development (IRD) and the neighbouring public park, located in the peri-urban environment of Paris, France (48.91°N 2.49°E). The study area has a temperate climate (elevation: 57 m), the average yearly temperature is 11.6°C and the average annual rainfall is 723 mm (Climate data, 2021). One colony of *Apis mellifera* was present in the study site, and three others were present in close proximity to the study site (**Supplementary Information, Fig. S1**).

Biological material

Forty strawberry (*Fragaria × ananassa*) plants of the variety “Deluxe” were bought from “Veni Verdi”, a local association, in February 2021. To our knowledge, this variety has never been used in a pollination study. The “Deluxe” strawberry variety is the product of a cross between two genotypes: the “Darselect” variety and genotype 16.01.18, selected in 2004 in France (Gasic et al. 2016; Pierron-Darbonne 2015). “Deluxe” is a short-day variety, meaning that it flowers in the spring, when day length is less than 12 hours (Gasic et al. 2016). All plants were individually potted in 7.5L pots in March 2021 with the same substrate, which consisted of compost and sand for drainage purposes. We added wood chippings above the soil of each pot to ensure moisture retention. Once potted, plants were kept in the same location and thus the same climactic conditions until flowering began. When necessary, all plants were watered equal amounts, within the same hour.

Experimental design

The forty strawberry plants were placed in the study area once flowering began, on the 19th of April 2021. The plants were randomly distributed among 20 locations (two plants per location, i.e. twenty spatial replicas) within the study site (**Fig. S1**). Locations were assigned on QGIS (2020), using a 60 × 60 m grid, in which each section of the grid contained one or no plant locations (**Fig. S1**). This grid helped us ensure that plants were evenly spaced out across the study area and along a gradient from the apiaries. We avoided placing plants in areas of the study site which were accessible and commonly used by the public. The assigned locations were between 8.2 m and 314.7 m from an apiary, with a mean distance of 159 m. Thus, all plants were well within honey bee foraging range, which is on average 1.5 km (Steffan-Dewenter and Kuhn 2003). Locations were on average 55.2 m from their nearest neighbouring location, with the minimum distance being 26.2 m and the maximum 158.6 m. This design allowed us to encompass different microhabitats within the landscape, in order to encapsulate the whole pollinator community present on the site, in particular since wild pollinators have shorter foraging ranges than honey bees (Ropars et al. 2019). We consider flower visitors as a same community of pollinators due to the proximity of locations, instead of considering that locations have have independent pollinator communities. We made sure that all location points were on grassy patches close to other floral resources where pollinators were more likely to be present. We placed two plants at each location to ensure we had enough flowers to perform flower observations and pollination treatments in all locations.

Pollinator observations and pollination treatments

Flower visitor observations were performed during the whole flowering period, from the 20th of April to the 27th of May 2021 (24 observation days). Flower visitor observations consisted of a 10 minutes observation sessions carried out between 9am and 6pm. We favoured days with temperatures above 12°C, with little cloud cover and no wind although some observation sessions were carried out on cloudy days since several occurred during the flowering period. Each flower was observed several times (i.e. several 10 minute observation sessions per flower) but never on the same day. Subsequent observations of a same flower were carried out at a later date at different times of day, in order to maximise our chances of seeing a diversity of pollinators, since different pollinators are active at different times of day (Fuchs and Muller 2004; Pisanty et al. 2016). Over the flowering period (from April 19th to May 27th, 2021), we carried out 30 h and 10 min of flower observations (181 time replicates of 10-minute observations) on a total of 88 flowers (each observed on average 2.9 ± 1.1 times). We observed an average of 10.7 ± 7.4 flowers per day. An average of 4.4 ± 2.3 flowers were observed per location. Each flower visitor was counted and identified within the following 8 categories: honey bee (*Apis mellifera*), bumble bee (*Bombus* sp.), solitary bee, hoverfly (Syrphidae), other fly (Diptera), ant (Formicidae), thrips (Thysanoptera) or other insect. Time, temperature and humidity were registered for each observation session.

Independently of pollinator observations, pollination treatments were applied at each location during the same time period as pollinator observations, to assess pollination services provided by the urban pollinator community. The four treatments are as follows: (*i*) flowers open to pollinator visits, (*ii*) flowers open to pollinator visits and cross pollinated by hand, (*iii*) flowers excluded from pollinator visits (self or wind pollination only), and (*iv*) flowers cross-pollinated by hand and excluded from pollinator visits. Comparing self/wind and open pollination measures pollinator dependence. Comparing open and hand pollination indicates whether pollinators are able to saturate the flower in pollen, thus allowing it to produce fruit at its highest potential. Comparing open pollination with and without hand pollination indicates whether insect pollination alone is sufficient to maximise fruit yield. Comparing self/wind and hand pollination measures plants' level of reliance on cross-pollination. The comparison of hand pollination and open pollination with hand pollination indicates whether hand pollination only is enough to maximise fruit production. Plants from the self/wind pollination treatment and the hand pollination treatment were bagged with mesh netting (Alt'Droso Maraichage, 0.8 × 0.8 mm mesh) to prevent pollinators from visiting these flowers (**Fig. S2**). For treatments that required hand pollination, we visited each flower twice within the same day with a paintbrush to ensure cross-pollination between flowers of the same treatment. In total, 172 flowers were considered for the pollination experiment, 46 flowers were affected to the open pollination treatment (2.3 ± 1.2 per location), 28 to the hand and open pollination treatment (1.4 ± 0.9 per location), 63 to the self/wind pollination treatment (3.2 ± 1.5 per location), and 35 to the hand pollination treatment (1.8 ± 1.3 per location).

Fruit set and fruit quality

Once flowering was over, we measured fruit set by recording whether each flower from each pollination treatment successfully produced fruit or not. Fruits were then harvested once they were fully formed (i.e. as soon as fruits had fully reddened), between the 31st of May and the 10th of June 2021. We recorded fruit malformation, by considering a fruit with a clear aggregation of unfertilised achenes as showing a malformation (**Fig. S3**). We measured fruit weight (Ohaus, Adventurer, precision 0.01 g, capacity 3100 g) and fruit size as the maximum width at the widest point (France métrologie, accuracy 1 mm, capacity 1600 mm) within one day of harvesting. We chose width as the measure for fruit size since it is used to determine the commercial class of fruits (OECD 2021). Seed set was then counted once all fruits had been cropped. For maximum precision, strawberry flesh was separated from the seeds before counting, using a small meshed sieve which collected only the seeds.

Data analysis

The statistical analysis was performed in R 4.0.3 (R Core team 2020). Fruit set was measured on a binary scale, where a flower which successfully produced a fruit was given a score of 1, whereas one which failed to produce a fruit was attributed a score of 0. This measure of fruit production is used in pollination studies for various crops including strawberry (Abrol et al. 2019; Bartomeus et al. 2014). We used Generalized Linear Model (GLM) with binomial error structure to test whether fruit set differs between pollination treatments. Fruit malformation was also recorded on a binary scale, where a fruit showing a malformation received a score of 1, whereas a fruit showing no malformations received a score of 0. We used a binomial GLM to test whether fruit size and pollination treatment affected the occurrence of malformations. We used a Linear Model (LM) to test the effects of fruit weight and pollination treatment on fruit size. We tested whether the size-weight relationship was non-linear using an assumption of quadratic pattern, since quadratic relationships between fruit quality measures have been reported for other crops (Pescie and Strik 2004; Ramesey et al. 1990). Similarly, we used a LM to test whether seed set and pollination treatment affect fruit size. We tested whether the relationship between fruit size and seed set is quadratic. For all the models (GLM and LM), we use Tukey post hoc tests to compare treatments, using the “multcomp” R package (Hothorn et al. 2021).

Results

Flower visitors

We recorded a total of 84 flower visitors. Among them, non-bee insects were dominant flower visitors including ants (57%), followed by thrips (Thysanoptera) (17%) (Fig. 1). Other flower visitors include solitary bees (7%), beetles (Coleoptera) (5%), hoverflies (Syrphidae) (4%), one spider (Aranea) (1%) and one other fly (Diptera) (1%) (Fig. 1). Other insects made up 8% of observations (Fig. 1). No honey bees were observed visiting strawberry flowers despite that four beehives were present in the surrounding landscape.

Fruit set

As part of the pollination experiment, a large majority of the 172 monitored flowers successfully reached fruit set (94.2%). Each plant successfully produced on average 5.2 ± 2.1 fruits, with 8.6 ± 3.3 fruits per location. We found no difference in fruit set between pollination treatments (**Table S1**). Overall, 125 fruits were harvested from 32 different strawberry plants, across all 20 location points. Issues with consumption by pests, or fruit picking by visitors led to several fruits, for which fruit set success was recorded, not being included in the fruit quality measurements (22.8% of fruits).

Fruit malformation

The majority of fruits showed no malformations (87.2%). We found that the probability of malformations decreases with fruit size (GLM, n = 125, $z = -2.831$, $p = 0.005$; **Fig. 2**), meaning that large fruits have lower probability of malformation, but independently of the pollination treatment (**Table S2**). In other words, the insect-mediated pollination did not affect fruit malformation.

Fi g. 2 *Relationship between the probability of occurrence of a malformation and fruit size (maximum width measured in cm). Data points are represented by coloured dots. Each treatment is colour coded. All values are equal to 0 or 1, but dots where shifted to prevent overlap. A probability of 1 meaning that the fruit presented a malformation, and a probability of 0 meaning it showed no malformations. Values fitted by the GLM showing the trend for all treatments are presented along the solid black line, with the 95% confidence interval presented in grey*

Fruit size

Pollination treatments significantly affected this fruit size-weight relationship (Table 1). Fruit size is greater for fruits from open pollination than those from both self/wind pollination and hand pollination. For all other pollination treatments there was no difference in fruit size (Table 1).

Table 1
Tukey test values comparing fruit size for different pollination treatments from the GLM testing the effects of fruit weight and pollination treatment on fruit size. In bold are treatments which significantly differ in fruit size

	Estimate	Standard error	P value
Hand vs self/wind pollination	-0.008	0.042	0.997
Open vs self/wind pollination	**0.113**	0.042	**0.039**
Open + hand vs self/wind pollination	0.067	0.048	0.515
Open vs hand pollination	**0.121**	0.045	**0.039**
Open + hand vs hand pollination	0.075	0.051	0.467
Open + hand vs open pollination	-0.046	0.051	0.799

We found an interesting clear-cut non-linear, quadratic, relationship between fruit size and weight, reaching saturation for high values of weight (LM, quadratic term: n = 125, t = -7.831, p < 0.001; Fig. 3).

We then explored the effect of pollination on the relationship between fruit size and seed number, showing fruit size increasing linearly with seed number (LM, n = 125, t = 11.370, p < 0.001; Fig. 4), but independently of the pollination treatment (**Table S3**). The quadratic term was non-significant (LM, n = 125, t = -0.444, p = 0.658).

Discussion

Understanding how pollination affects crop production in urban landscapes is essential for the development of urban agriculture. Fruit quality improvement through animal-mediated pollination is well accepted (Bänsch et al. 2020; Castle et al. 2019; Hermann et al. 2019; MacInnes and Forest 2019; Wietzke et al. 2018), but little is known about the suitability of urban pollinator communities for urban crop production. We found that strawberry weight was higher for flowers exposed to insect pollination than for those excluded from it. This demonstrates the service mediated by insect pollinators on the production of strawberries in the local urban agricultural context of the study. This result, along with the other results we report, should be interpreted with care, since the sample size in this study was limited and the study was carried out during a single flowering season. However, other studies support our finding such as Scherr and Jamieson (2021) that find insect pollination improves strawberry fruit weight in an urban context, when fruits were not damaged by pests. Moreover, we found no differences in fruit set or fruit quality between the treatment open to insect pollination and the pollen-saturation treatment, indicating the absence of any pollination deficit. Studies which report more abundant and diverse pollinator communities than ours find varying results regarding pollination deficit. For instance, Wietzke et al. (2018) found that without pollen supplementation, malformations were more frequent, whereas Connelly et al. (2015) found no evidence of pollination deficit on strawberry weight. Thus, despite the few pollinator observations, the local urban pollinator community, in particular non-bee pollinators, which made up the vast majority of the flower visitors observed, appears to offer a positive contribution to urban strawberry production. Recent research has highlighted the importance of non-bee pollinators for crop production (Rader et al. 2016, 2019). These results are promising for urban agriculture and emphasize the need for conservation of wild pollinators in urban landscapes.

Recent results suggest that urban areas could host more diverse pollinator communities than agricultural land since floral resources in cities are diverse (Olsson et al. 2021; Wenzel et al. 2020). Accordingly, we recorded only wild pollinators visiting strawberry flowers, even though four honey bee colonies were present in the landscape surrounding the study site. This result is rather unexpected given that former studies found honey bees visiting strawberry flowers (Bänsch et al. 2020; Bartomeus et al. 2014; MacInness and Forest 2019), and suggests that managed pollinators did not interfere in urban strawberry pollination services. The ability of honey bees to forage at large distances from their hive (Knight et al. 2005; Ropars et al. 2019; Steffan-Dewenter and Kuhn 2003) and to focus on massive floral resources through a strategy of “flower constancy” (Grüter et al. 2011) could explain part of this result. Our strawberry plants were spread over 20 locations in our study area offering sparse floral resource that could be less attractive to honey bees than flower resources from mass flowering cherry trees, that were present in the surrounding of the study area and overlapped in blooming time with our strawberries.

Instead of managed honey bees, we observed wild pollinators visiting strawberry flowers, such as ants, which are known to thrive in urban environments (Philpott et al. 2014). Solitary bees and hoverflies were also observed on strawberry flowers. These pollinators have much shorter foraging ranges than honey bees (Ropars et al. 2019), suggesting that local, urban, populations of wild pollinators provided the observed insect-mediated pollination services. This result supports claims of the importance of wild pollinators for urban crop production. For example, former studies found similar results with jalapeño peppers (Cohen et al. 2021), cucumber and eggplant (Lowensetien et al. 2015).

During our pollinator observations we noticed that the exclusion technique used did not prevent crawling insects such as ants from visiting strawberry flowers, despite this method being commonly used (e.g. Bänsch et al. 2020; Castle et al. 2019; Hermann et al. 2019). Sricom (2017) also reported issues with excluding small crawling insects such as thrips using this exclusion method. This generalised technical bias could lead to an overestimation of insect pollination and an underestimation of pollination deficit. Nevertheless, we can suspect no effect of such crawling insects on pollination experiments given that ants are known as non-efficient pollinators in general (Beattie 1984).

Former studies found that strawberry fruit set increases when comparing flowers exposed to and excluded from insect visits (Abrol et al. 2019; Bartomeus et al. 2014; Çolak et al. 2017). Our results showed a general high fruit set success rate (94.2%) without any influence of pollination treatment, indicating that wind pollination was sufficient to maximise this trait. Yield being an essential trait for crop producers, varieties have been bred to maximise this trait (Chandler et al. 2012), which would explain why pollination has no effect on fruit set. Moreover, although strawberry is referred as dependent on animal pollination for production (Klein et al. 2007), the intensity of this dependence is related with the crop variety (Abrol et al. 2019; Bänsch et al. 2020), which may also explain why the beneficial effects of insect pollination do not always translate onto fruit set or malformation (another important outcome for economic value). Indeed, we confirmed former results showing that very few fruits present any malformation (Trillo et al. 2018) and that the pollination treatments were unrelated to fruit malformation (Muola et al. 2017, but see Ariza et al. 2012; Hermann et al. 2019; Klatt et al. 2014 for positive effects). Interestingly, this very low proportion of misshapen fruits could be linked with the study from Andersson et al. (2012) that found organic farming practices reducing the occurrences of malformations in strawberry crops. Indeed, we grew our strawberries organically since this agricultural practice is often used in urban agricultural systems. Reducing the occurrence of malformations is key for producers since the presence of malformations renders fruits unmarketable (OECD 2021). Thus, urban agricultural systems, which are key for sustainable development and local food security (Kennard and Bamford 2020), associated with wild pollinator conservation could support producers' economic outcomes.

Fruit size is a particularly important criteria for fruit commercialisation since large fruits (with width greater than 25 mm) belong to a higher quality class, and can be sold at higher prices (OECD 2021). Unsurprisingly, we find that fruit size is highly correlated with fruit weight. However, the saturation relationship observed suggests that fruit size is limited. This may be due to the fact that fruit shape is variable (Jamieson 2017), where for the same value of weight, some fruits may be wide and short whereas others may be long with smaller width. Interestingly, there are no differences in fruit size between pollination treatments when considering the relationship between fruit size and seed set. Tuhomietsa et al. (2014) report that benefits of cross-pollination to strawberry weight (highly correlated with size) do not appear for all cultivars, indicating that cultivars may vary in their dependence on pollinators. Thus, the "Deluxe" cultivar used in our experiment could be one for which benefits of insect pollination are not detectable on all measures of fruit quality. The increase in fruit size with seed number is linked to the decrease in size for fruits showing malformations since the fleshy part of the fruit develops around each seed, i.e. each fertilized achene (Davis et al. 2008). Thus, flesh does not develop around unfertilized achenes, giving small fruits with malformations.

Conclusion And Perspectives

Our results suggest that strawberry fruit production was supported by the urban community of wild, mostly non-bee pollinators present on our study site. Our study is a first step towards understanding the role of urban wild pollinators on crop pollination services. We call for future research to expand upon these results, by studying urban pollination services on various crops in urban agricultural areas, in particular those known to highly depend on insect mediated pollination. Findings may differ depending on urban policies regarding biodiversity conservation or the degree of urbanization, since this parameter is known to affect pollinator community diversity (Fortel et al. 2014), and could therefore have a knock-on effect on pollination services.

Diverse pollinator communities promoting pollination services, their conservation in urban areas is essential since urban pollinator community diversity is affected by the recent development of urban beekeeping. Indeed, managed pollinators being numerically dominant, they outcompete their wild counterparts for floral resources in cities (Geslin et al. 2017; Ropars et al. 2019). Increasing floral resource diversity can increase crop production, as shown by a study which finds that planting companion “bee-friendly” plants next to strawberry plants increased yield and fruit quality (Griffiths-Lee et al. 2020). Thus, conservation strategies to boost pollinator diversity including sewing wildflower strips and installing insect hotels (Baldock 2020) could promote pollinator diversity and the production of high quality urban crops.

Declarations

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Statements and declarations

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Competing interests

The authors reported no potential conflict of interest.

Authors' contributions

F.R. conceived the ideas and designed methodology; E.B. collected the data with logistical and technical assistance from F.R, P.S. and K.D.; E.B. and F.R. analysed the data; E.B. and F.R. led the writing of the manuscript and all authors contributed significantly to the drafts and gave their final approval for publication.

Availability of data and material

Data are publically available through the figshare repository https://doi.org/xxxx/m9.figshare.xxxxx (Blareau *et al.*, 2022).

Code availability

R script are available in supporting information.

Ethics approval

Not applicable.

Consent to participate

All authors agree with the contents of the article.

Consent for publication

All authors agree with the publication of the article.

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Figures

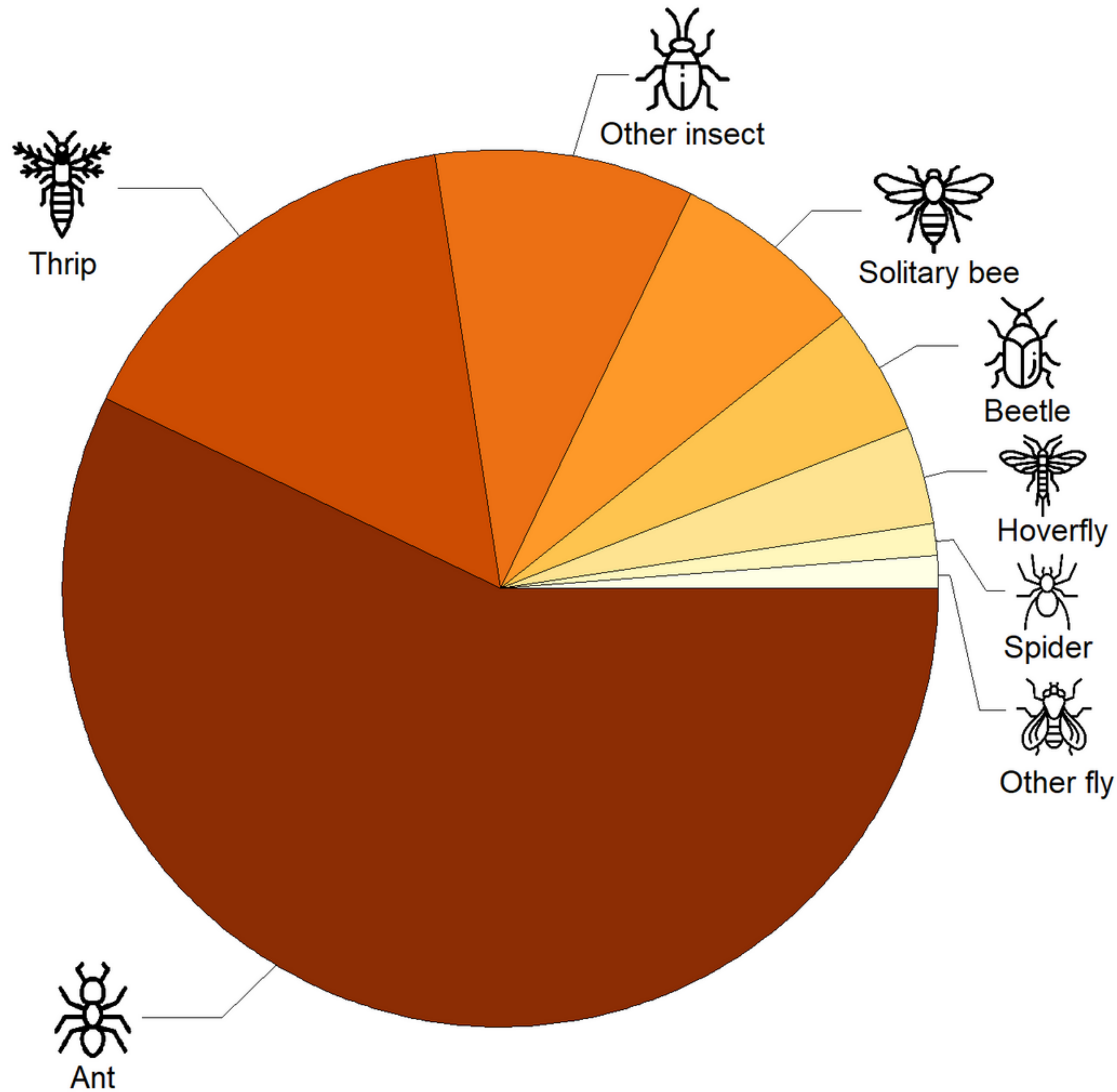

Figure 1

Diversity of flower visitors of strawberry in an urban area. Icons from flaticon.com

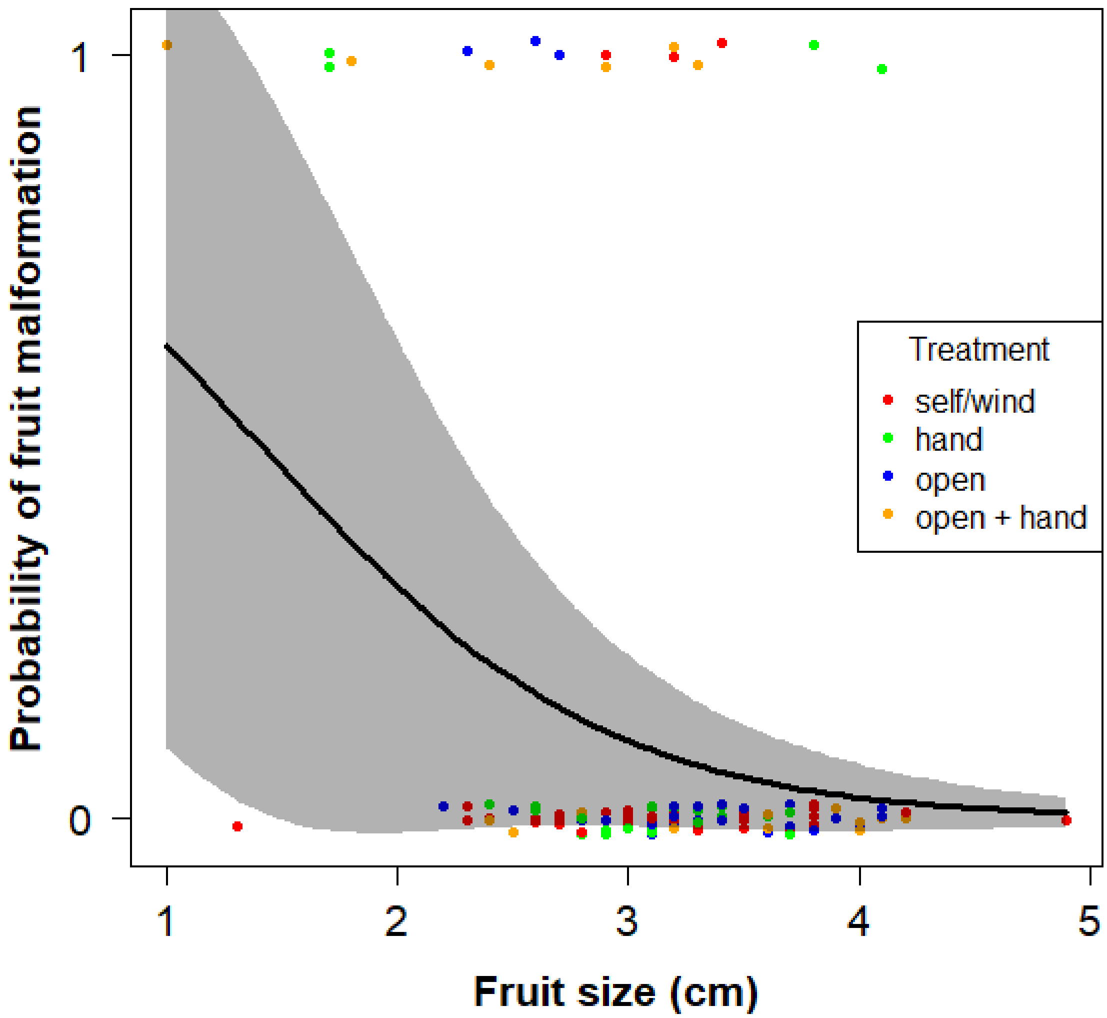

Figure 2

Relationship between the probability of occurrence of a malformation and fruit size (maximum width measured in cm). Data points are represented by coloured dots. Each treatment is colour coded. All values are equal to 0 or 1, but dots where shifted to prevent overlap. A probability of 1 meaning that the fruit presented a malformation, and a probability of 0 meaning it showed no malformations. Values fitted by the GLM showing the trend for all treatments are presented along the solid black line, with the 95% confidence interval presented in grey

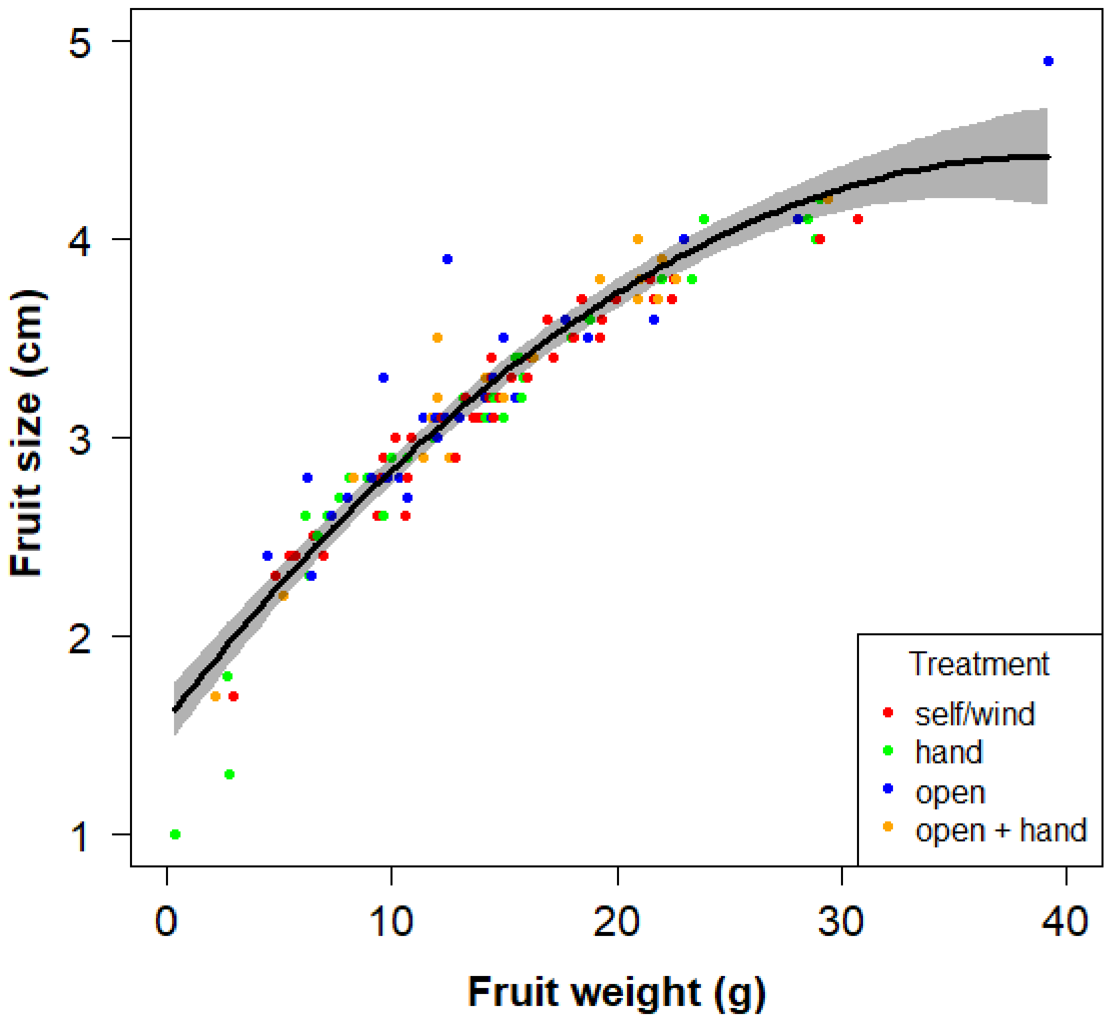

Figure 3

Relationship between fruit size (maximum width in cm) and weight (in g). Data points are represented by coloured dots. Each treatment is colour coded. Values fitted by the linear model showing the non-linear size-weight relationship are presented along the solid black line, with the 95% confidence interval presented in grey

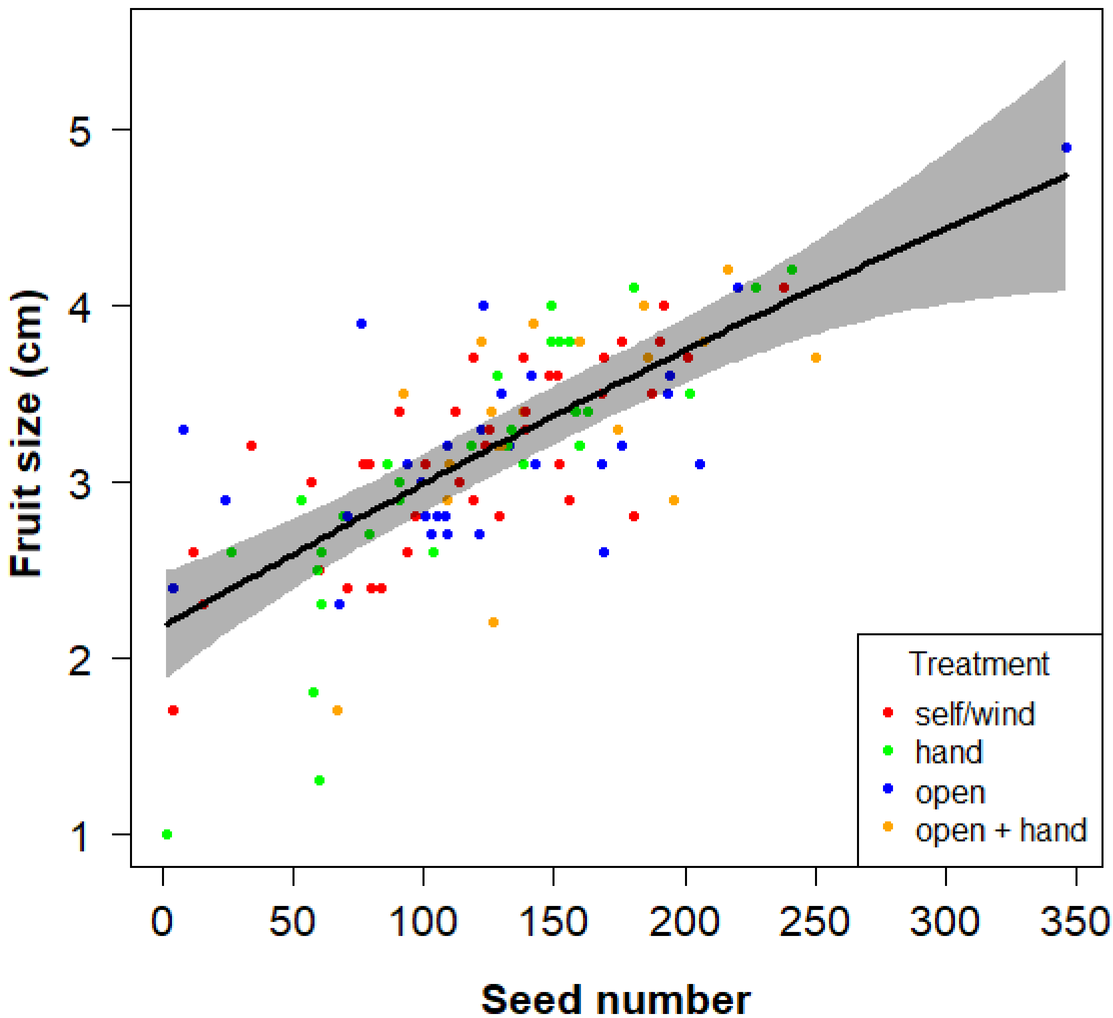

Figure 4

Relationship between fruit size (maximum width in cm) and seed number. Data points are represented by coloured dots. Each treatment is colour coded. Values fitted by the linear model showing the general trend for all treatments are presented along the solid black line, with the 95% confidence interval presented in grey

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