RESEARCH ARTICLE

The potential of wildflower strips to enhance pollination services in sweet cherry orchards grown under polytunnels

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Abstract

1. Sweet cherry production benefits from insect pollination, but the extent to which wildflower strips can boost pollinator visitation under polytunnels is unknown.

2. Wildflowers were established in alleyways between tree rows under polytunnels in 10 commercial cherry orchards. Their management involved either a single cut in September (Standard Wildflower Strips (SWS)) or being actively maintained to 20 cm with regular cutting (Actively Managed Wildflower Strips (AMWS)), compared with unsown Control Strips (CS). Flower visitors of cherry and wildflowers were recorded by visual observations for 3 years (2017–2019), while cherry production (quantity and quality) was assessed in 2019.

3. In total, 67 visitor species were identified; managed commercial species (*Apis mellifera* and *Bombus terrestris*) made up ~74% of all records. During the cherry blossom period (anthesis), AMWS had the highest visitor density to cherry blossoms compared with CS and SWS but no significant difference in harvestable fruit was recorded. After anthesis, greater visitor density, diversity and richness were observed in both wildflower treatments compared with CS, being greatest in SWS, which was consistent with differences in floral communities between treatments.

4. Although visitor density was not correlated with fruit set, pollinating insects were key for fruit yields and quality. Fruit set was ~17% from blossoms exposed to visitors compared with <1% when excluded. Furthermore, hand pollination resulted in ~32% fruit set, indicating greatest pollination deficits in CS (~50%) compared with AMWS (~28%) and SWS (~35%).

5. *Synthesis and applications.* Sweet cherry is highly dependent on pollinators to underpin commercial yields, and pollination deficits exist under polytunnels. Growers should, therefore, reconsider their pollination strategies and look to combine effective pollinator management with polytunnel use to mitigate deficits; establishing and actively managing wildflowers in alleyways could enhance wild visitors and pollination.

1 | INTRODUCTION

Sweet cherry (*Prunus avium* L.) is a commercially important fruit crop with annual global production of 2.7 million tonnes in 2021 (FAOSTAT, 2023). Yields have increased in recent decades following the adoption of approaches to improve cultivation, particularly polytunnels (plastic protective covers) (Bujdoso & Hrotko, 2017), which are used in some regions including the United Kingdom. Polytunnels can minimise fruit cracking caused by rainfall and protect against other rain-related diseases, ensuring constancy in marketable production, while enhancing fruit quality and yield (Lang, 2014). However, economically viable production can only be achieved with adequate insect pollination. Most sweet cherry cultivars of economic importance in Europe are self-incompatible (Quero-García et al., 2017) and the activity of pollinating insects enhances cross-pollination (Koumanov & Long, 2017). As intensive sweet cherry systems may be under polytunnels, effective approaches to pollinator management are needed to avoid yield deficits, particularly, since polytunnel crops can have reduced pollination (Kendall et al., 2021). Environmental factors under polytunnels are also affected: temperature is increased, while wind speed is reduced (Hall et al., 2020; Lang, 2014) and pollinator activity is impacted (Hall et al., 2020; Kendall et al., 2021). These conditions can differ from open sweet cherry orchards, affecting pollinator performance and pollination deficits. Pollination deficits have never been evaluated under polytunnels nor to what extent they can be mitigated through the establishment of wildflower strips in the alleyways.

A common approach for pollinator-dependent crops is to use managed western honeybees *Apis mellifera*, buff-tailed bumblebees *Bombus terrestris* and/or mason bees (e.g. *Osmia lignaria*) (Koumanov & Long, 2017), since growers consider bees the most important pollinators (Osterman et al., 2021). However, relying on one or two species is a high-risk strategy for growers (Williams et al., 2019) and managed pollinators can negatively impact wild pollinators (Aizen et al., 2020). Diverse wild pollinator communities can enhance pollination services in open sweet cherry orchards (Eeraerts et al., 2017, 2019; Holzschuh et al., 2012). Importantly, semi-natural habitats can play a key role in enhancing the abundance and diversity of pollinator communities in nearby sweet cherry orchards, improving pollination (Eeraerts et al., 2017, 2019; Holzschuh et al., 2012).

Sustainable approaches to manage pollinator communities should be considered, including the protection of existing semi-natural habitats in the farmed landscape and/or the creation of wildflower habitat in and around the crop (Albrecht et al., 2020; Eeraerts et al., 2019), taking into account to what extent pollination deficits could be addressed through such approaches (Eeraerts et al., 2017, 2019; Holzschuh et al., 2012; Reilly et al., 2020; Schuepp et al., 2014). Wildflower interventions between rows of fruit trees provide pollen and nectar, which can enhance pollinator abundance and diversity and improve fruit quality and yields (McKerchar et al., 2020), through ecological intensification (Bommarco et al., 2013). The influence of wildflower interventions on pollinator visits to cherry blossoms was investigated in US open sour cherry orchards, but no positive benefit was found (Wood et al., 2018). However, in Belgian (Eeraerts et al., 2019) and Australian (Gilpin et al., 2022) open sweet cherry orchards, the effect of unsown wildflowers was positively correlated with wild pollinator abundance and richness. Importantly, the benefit of sown wildflower interventions in alleyways of intensively managed sweet cherry orchards under polytunnels has never been tested. Critically, habitat interventions need to be compatible with wider management approaches and the tall vegetation between tree rows created by wildflower strips might be agronomically unacceptable to growers. Management strategies to limit possible negative impacts are required (Mateos-Fierro et al., 2021). While mowing wildflower strips will directly impact the availability of floral resources and associated pollinators (Buri et al., 2014), the benefits of increasing the cutting height to leave some resources without impacting cherry growers have never been explored.

To support the sustainable management of pollination services in intensive sweet cherry orchards under polytunnels and provide mowing recommendations to growers, the aims of this study were to (i) characterise pollinator communities in sweet cherry and (ii) compare the effects of wildflower strips under two cutting regimes (short and tall) and grower conventional practice on pollinator visitation, pollination services and pollination deficits. We hypothesised that pollinator communities would be less diverse, pollinator density and pollination services lower and pollination deficits greater in conventional alleyways, followed by short then tall wildflower alleyways.

2 | MATERIALS AND METHODS

2.1 | Study sites

This 3-year study (2017–2019) was conducted at five sites in the West Midlands, UK (range between sites: 2.8–92.9 km; mean $\pm$ SD: 57.2 $\pm$ 35.4) (Tables S1 and S2). The growers granted permission to conduct fieldwork in their orchards, and no ethical approval was required for the study. Orchards were conventionally managed and grown under polytunnels (Figure S1a,b). Managed honeybees and buff-tailed bumblebees were used by growers across the sites, although in one orchard, only honeybees were deployed (Table S2).

At each site, two orchards (N = 10) were investigated (Figure S1a). In each orchard, three alleyways adjacent to rows of the cherry

cultivar Kordia (a self-incompatible cultivar of economic importance; Quero-García et al., 2017) were selected (Table S2). Two of the alleyways randomly received one of two wildflower treatments; the third had the original alleyway vegetation (dominated by grass species but with sparse unsown wildflowers, e.g. *Taraxacum officinale* agg.) (Figure S1c–e). The three alleyway treatments were:

(i) **Control Strips (CS)**. Conventionally managed alleyways cut regularly (once/twice per month) to a height of 10 cm from May to September and 8 cm in late September.

(ii) **Standard Wildflower Strips (SWS)**. Cut annually in late September to a height of 8 cm.

(iii) **Actively Managed Wildflower Strips (AMWS)**. Cut regularly (twice/three times per month) to a height of 20 cm from May to September and 8 cm in late September.

Wildflower alleyway treatments were sown in autumn 2016 with eight forb species at 1.9 gm^{-2} and one grass species at 0.1 gm^{-2} (Mateos-Fierro et al. (2018) for details). All sown species were perennial UK natives. Due to poor initial establishment, alleyway treatments were re-sown in April and September 2017 at three and two sites, respectively. All alleyway treatments were cut regularly to 10 cm throughout 2017 (first year); all cuttings were left in situ. Wildflower strip development at one site was poor, consequently, data collection was discontinued in this orchard after the cherry blossom period (henceforth anthesis) in 2019 (only in 2019 after anthesis, $N = 8$). Floral resources (floral units/heads) were recorded in ten 0.5 m^2 quadrats randomly deployed for each alleyway treatment after anthesis. More floral units were recorded in SWS and AMWS compared with CS (mean ± SE: 2.5 ± 0.9, 1.7 ± 0.6 and 0.4 ± 0.2, respectively; Table S3). For detailed methodology and results on alleyway treatment floral resources, see Mateos-Fierro et al. (2021). Floral resources were not measured during anthesis due to the low number of flowers being present. The length of alleyway treatments was 95 m, from the orchard edge (first cherry tree) towards the centre of the orchard, but the last 76–95 m acted as a buffer and were not assessed.

Cropping patterns in the orchards and the mixing of different varieties between rows meant the distance between alleyway treatments varied from 26 to 48 m (Table S2). Distances between orchards also varied (Table S2). Due to the close proximity of treatments and the high mobility of pollinators, we assessed how pollination services delivered by existing pollinating insects were influenced by wildflower interventions through the redistribution of individuals within the orchards, rather than impacts on populations in the surrounding landscape.

2.2 | Flower visitor density and richness

Insect flower visitor (henceforth visitor) density and richness were recorded on cherry blossoms (2017–2019) during 16-min walking transect surveys along each alleyway treatment (Holzschuh

et al., 2012). Orchards were surveyed at least six times per year from balloon stage until blossom end (stages 59–69 BBCH scale; Fadón et al., 2015); typically early/mid-April to early/mid-May. Two transect surveys per visit were done in 2017 and one in 2018 and 2019, on dry days and temperatures above 8°C (mean ± SE: 16.4°C ± 0.1) from 10.30 to 17:00 h. All three alleyway treatments within the same orchard were sampled within 90 min. Visitors visiting cherry blossoms and wildflowers were recorded.

Subsequently, visitor density and richness of visitors to wildflowers in alleyway treatments were recorded in 16-min transect surveys (Blaauw & Isaacs, 2014) each month (one survey/month) from May to September 2017, June to September 2018 and May to August 2019 (mean ± SE: 24.2°C ± 0.1).

For cherry blossom and wildflower transect surveys, the plant species visited were identified. An insect net was used to catch individuals when needed for species identification. These were immediately released, while individuals not readily identified were transferred into vials for identification in the laboratory. Individuals out of reach and, therefore, not identified at least to genus were not recorded. As not all visitors were retained, multiple counts were possible; we thus consider visits rather than visitors although we use the latter term throughout for simplicity (e.g. visitor density). Visitors were categorised into five groups: (1) honeybees, (2) buff-tailed bumblebees, (3) wild bumblebees, (4) solitary bees and (5) hoverflies. All wild bumblebees (henceforth bumblebees) recorded during anthesis were queens, except two *Bombus pratorum* and one *Bombus hypnorum* workers. All buff-tailed bumblebee workers were included in the category 'buff-tailed bumblebees'. After anthesis, buff-tailed bumblebees were no longer recorded as a separate group since most managed bumblebee boxes were removed by growers. The scarce managed workers potentially recorded after anthesis were included into the 'bumblebee' category due to wild workers being present from mid-May. Workers of buff-tailed bumblebees and white-tailed bumblebees *Bombus lucorum* were grouped under the genus *Bombus*, but queens and males were identified to species.

2.3 | Measuring pollination services and deficits

In 2019, to quantify pollination deficits in the three alleyway treatments, a 'hand pollination' treatment was compared with blossoms pollinated in the presence (open pollination) and absence (insect-excluded pollination) of insects. We considered hand pollination alone (rather than supplemented open pollination with hand pollination; e.g. Holzschuh et al., 2012) as a sufficient tool to test for the presence of pollination deficits (Schuepp et al., 2014). While it does not allow us to quantify the full extent of pollination deficits in the orchards, it does allow us to compare the relative extent of deficits between alleyway treatments. The three pollination treatments were investigated in four trees per alleyway treatment (Figure S2).

On each tree, three spurs (~30 cm long from the tip), with at least 20 buds each (mean ± SD: 61.1 ± 32.7), at 1.5–2.0 m above the ground, were randomly selected prior to anthesis. One spur received

an insect exclusion treatment, using a PVC mesh bag (1.2×1.2 mm gauge) to exclude insect visits but allow pollen to move through the mesh. The second spur had blossoms open to visitors and the third spur was bagged but hand pollinated.

Mesh bags were set up and removed before and after anthesis. Blossoms at balloon stage 59 (Fadón et al., 2015) were hand-pollinated twice (Fountain et al., 2019), with an interval of 24 h. Unopened blossoms were removed to ensure all blossoms within the mesh bag had been hand-pollinated. Cv. Regina was used to cross-pollinate Kordia using a paintbrush to transfer pollen onto the stigmas of all opened flowers. Pollen was harvested by gently tapping Regina blossoms while holding a petri dish underneath. All blossoms were counted and fruit set determined in July, prior to harvest (Table S4) (Holzschuh et al., 2012).

A maximum of three fruits per spur were harvested and placed in sealable polythene bags and stored at 6°C prior to evaluation, which occurred within 48 h. Fruit quality was determined by measuring fresh mass and width (diameter) (Overbeck et al., 2017).

2.4 | Statistical analysis

All data were analysed using generalised linear mixed-effects models (GLMER) ('lme4' package; Bates et al., 2015) in the software R (version R-4.1.2) (R Core Team, 2021). Data were tested for normality prior to analysis with the Shapiro–Wilk test and analysed accordingly. For all models (Table S5) except for correlation models (see below), alleyway treatment or pollination treatment were specified as fixed effects, while random effects were orchards nested within sites. Alleyway was also included as a nested random effect for fruit set and pollination deficit models, while spur, tree and alleyway were also included for the fruit quality models. The effect of alleyway treatment on fruit set and quality was investigated using data from the open pollination treatment.

For each model, the relative importance of the fixed effects was compared by using the Akaike's information criterion (AICc) (Burnham & Anderson, 2002) using the 'MuMIn' package (Bartoń, 2022). The fixed effect of interest was compared (drop1 function) with the null model and if ΔAICc >2, then the fixed effect was considered to have a substantial level of empirical support (Burnham & Anderson, 2002). In models where ΔAICc >2, significant effects were investigated with pairwise comparisons using Tukey *post-hoc* tests ('multcomp' package; Hothorn et al., 2008) with Holm–Bonferroni corrections.

The influence of alleyway treatment on visitor density to cherry blossoms or wildflowers during and after anthesis was investigated using GLMERs with negative binomial error distributions (GLMER.NB function). Shannon diversity and species richness of visitors (only individuals identified to species were considered) were calculated per alleyway treatment, year and survey round. Effects of alleyway treatment on Shannon diversity were explored using LMERs (LMER function) while effects on species richness using GLMER.NBs. GLMER with binomial error distribution (GLMER function; family = binomial)

was used to analyse fruit set, considering the proportion of fruits that were retained to maturity. Fruit quality (fresh mass and width) was analysed using LMER. The coefficient of variation (CV) of fresh mass was also calculated to investigate consistency in mass.

We first investigated the interaction between alleyway treatment and year on visitor density to cherry and wildflowers during and after anthesis, which was significant in all cases except for visitor density to cherry. Consequently, analyses were performed for each year separately to explore how wildflowers affected visitor density and pollination each year.

We calculated pollination deficits for each alleyway treatment as the percentage of open pollination divided by hand pollination using tree-level mean values ($1 - (\text{Open/Hand}) \times 100$ (Holland et al., 2020). Differences in pollination deficits were analysed using LMER.

For each alleyway treatment, GLMER.NB or LMER were used (Table S5) to investigate the effects (correlations) of visitor density, diversity and species richness on fruit set, quality and pollination deficits. LMER was used to explore the correlations between floral density, diversity and richness and visitor density, diversity and richness, respectively, in 2018 and 2019. Random effects were orchards nested within sites.

To investigate differences in visitor and floral communities (species) between alleyway treatments, we compared Bray–Curtis dissimilarity using non-metric multi-dimensional scaling (NMDS) plots and ANOSIM tests ('vegan' package; Oksanen et al., 2013). Pairwise *post-hoc* tests (pairwise.adonis function; package 'pairwiseAdonis'; Martinez Arbizu, 2021) with Holm–Bonferroni corrections were used to identify differences in visitor and floral communities between alleyway treatments after first testing for differences in dispersion (betadisper function; 'vegan' package; Oksanen et al., 2013), and further tested with Tukey pairwise *post-hoc* tests with Holm–Bonferroni corrections, when appropriate.

3 | RESULTS

3.1 | Visitor density and richness

Throughout the 3-year study, 10535 visitors were recorded (Table S6), belonging to 67 species: the western honeybee, 10 bumblebees, 23 solitary bees and 33 hoverflies (Table S7).

3.1.1 | Anthesis

A total of 9408 visitors were recorded during all transect surveys conducted during anthesis (April–May) across the 3-year study (Table S6). Of those, 9179 (97.6%) were recorded visiting cherry blossoms and 229 (2.4%) visiting wildflowers. Of the 9408 visitors, 7742 (82.3%) were managed pollinators (4809 honeybees and 2933 buff-tailed bumblebees). Wild pollinators included 689 bumblebees, 551 hoverflies and 426 solitary bees. A total of 39 species were recorded visiting cherry blossoms (Figure S3a–c; Table S7).

During anthesis, very few wildflowers bloomed, and only four species (one sown, three unsown) were visited (Table S8) with *T. officinale* (unsown), accounting for 94.8% of total visits to wildflowers.

3.1.2 | After anthesis

A total of 1127 wildflower visitors were recorded during all transect surveys conducted after anthesis (mid-May to late September) between 2017 and 2019 (Table S6). The most abundant visitor group was hoverflies (775 individuals), followed by bumblebees (218), honeybees (90) and solitary bees (44). These included 54 visitor species (Figure S3d–f; Table S7).

A total of 25 plant species were visited (Table S8), the most frequent being the unsown species *Trifolium repens* (198 visits), followed by the sown species *Leucanthemum vulgare* (181 visits); hoverflies visited the most wildflowers (Tables S8 and S9). Floral density is presented in Table S3.

3.2 | The influence of alleyway treatment on visitor density

3.2.1 | Anthesis

Cherry visitor density increased from 2017 to 2019, but no effect of alleyway treatment was observed (ΔAICc: interaction: −3.9) in any year (ΔAICc: 2017: −0.9; 2018: −3.5; 2019: −1.9; Table S10)

(Figure 1a). Similarly, there was no significant effect of alleyway treatment on any visitor group (honeybees, buff-tailed bumblebees, bumblebees, solitary bees and hoverflies) or on Shannon diversity or species richness (Figure 1b,c; Table S10). The betadisper test revealed homogenous dispersions between visitor communities according to geographical location ($p = 0.17$), while the ANOSIM tests (ANOSIM: 2017: $R = −0.09$, $p = 0.99$; 2018: $R = −0.10$, $p = 0.99$; 2019: $R = −0.09$, $p = 0.96$) indicated that visitor communities between treatments were similar each year (Figure S4a–c).

The response of total wildflower visitor density to alleyway treatment differed between years (ΔAICc: interaction: 30.4) (Figure 1d); alleyway treatment was an important factor in 2017 (ΔAICc: 29.8; Table S10). Visitor density was greater in CS compared with AMWS and SWS (Table S11). This was consistent for honeybees (ΔAICc: 10.6), hoverflies (ΔAICc: 11.2) and species richness (ΔAICc: 22.9) (Figure 1f; Tables S10 and S11). The betadisper test showed homogenous dispersions between locations ($p = 0.95$). The ANOSIM tests revealed differences in visitor communities in 2017 (ANOSIM: $R = 0.28$, $p < 0.05$) as no visitors were recorded in SWS but not in 2018 and 2019 (ANOSIM: 2018: $R = 0.01$, $p = 0.37$; 2019: $R = −0.001$, $p = 0.47$) (Figure S4d–f).

3.2.2 | After anthesis

Wildflower visitor density responded differently to alleyway treatments throughout the study (ΔAICc: interaction: 18.8), and differences were recorded each year (ΔAICc: 2017: 3.1; 2018: 2.9; 2019: 15.7; Table S10) (Figure 1g). In 2017, a greater density of all visitors
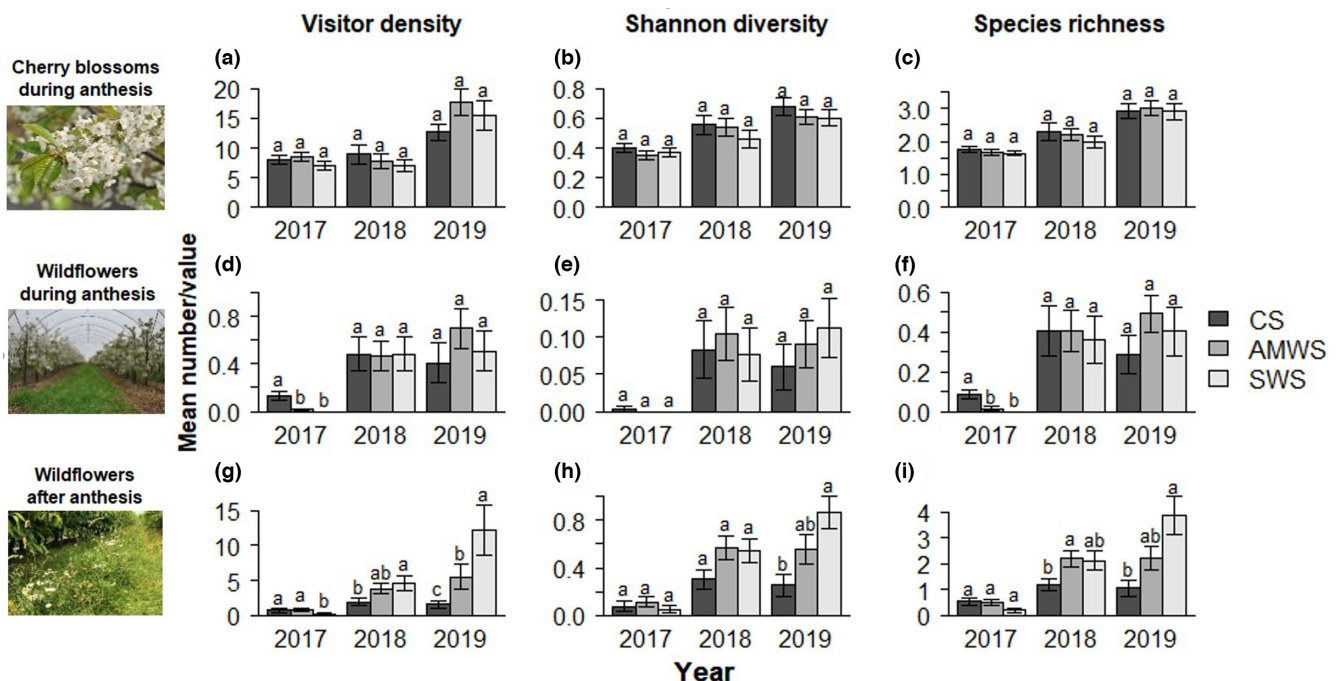

FIGURE 1 Mean numbers and values (± SE) of visitor density recorded and Shannon diversity and species richness calculated per alleyway treatment visiting (a–c) cherry blossoms and (d–f) wildflowers during anthesis and (g–i) wildflowers after anthesis, respectively, according to year and alleyway treatment. Values with same superscript letters do not differ significantly (Tukey test: $p > 0.05$) within years (Table S11). CS (Control Strips), AMWS (Actively Managed Wildflower Strips) and SWS (Standard Wildflower Strips). Note differences in *y*-axes scales.

was recorded in CS and AMWS compared with SWS (Table S11). However, bumblebees (ΔAICc: 3.3) were more often recorded in CS compared with SWS (Table S11). Although species richness was also affected (ΔAICc: 2.7), being lowest in SWS (Figure 1i), Tukey tests did not support significant differences (Table S11).

In contrast, in 2018, visitor density was significantly greater in SWS compared with CS (Table S11). In particular, bumblebees were more abundant in SWS compared with CS and AMWS, while hoverflies visited SWS and AMWS more than CS (Table S11). Species richness was greater in AMWS than in CS (Figure 1i; Table S11).

In 2019, the greatest visitor density was recorded in SWS compared with CS and AMWS, with significantly greater wildflower visitor density in AMWS than in CS (Table S11). This was consistent for bumblebees and hoverflies, but differences were only significant between SWS and CS (Table S11). Similarly, Shannon diversity and species richness were only significantly greater in SWS than in CS (Figure 1h,i; Table S11).

The betadisper test showed heterogeneous dispersions between locations ($p < 0.05$); *post-hoc* tests confirmed differences between Orchards 4 and 10 and 4 and 7 ($p < 0.05$). Visitor communities differed between alleyway treatments in 2018 (ANOSIM: $R = 0.02$, $p < 0.05$) and 2019 (ANOSIM: $R = 0.06$, $p < 0.001$) but not in 2017 (ANOSIM: $R = 0.01$, $p = 0.20$) (Figure S4g–i). However, *post-hoc* tests only supported significant differences between visitor communities in CS compared with SWS in 2019 ($p < 0.01$).

Differences in floral communities also differed between alleyway treatments in 2018 (ANOSIM: $R = 0.29$, $p < 0.001$) and 2019 (ANOSIM: $R = 0.34$, $p < 0.001$). In both years, *post-hoc* tests supported significant differences between floral communities in AMWS and SWS compared with CS ($p < 0.01$) and in SWS compared with AMWS ($p < 0.05$) (Figure 2). Additionally, floral density increased from 2018 to 2019, being greatest in June and July, respectively (Figure S5). In 2019, visitor density was positively correlated with floral density (ΔAICc: 74.7), visitor diversity with floral diversity (ΔAICc: 9.6) and visitor richness with floral richness (ΔAICc: 10.6), but not in 2018 (Figure S6; Table S12). This was consistent with visits of honeybees and bumblebees to *T. repens* (Figure S7a; Table S12), which was their most visited wildflower

(Table S8). For the three wildflower species most visited by hoverflies (*Achillea millefolium*, *L. vulgare* and *Matricaria* spp.; Table S8), the correlations were also positive (Figure S7b; Table S12).

3.3 | Pollination

3.3.1 | The influence of wildflower interventions on insect pollination

Fruit set
Alleyway treatment did not significantly affect the fruit set in 2019 (ΔAICc: −0.1; Table S13), even though 17.7% more fruit was recorded on trees adjacent to AMWS compared with trees next to CS and SWS (Figure 3). In AMWS, the positive correlations between fruit set with visitor diversity and species richness were significant but not with visitor density (Figure S8a–c; Table S14).

Fruit quality
Fruit mass (mean ± SE: CS: 12.4 ± 0.2 g, AMWS: 11.9 ± 0.2 g and SWS: 12.1 ± 0.2 g) was not affected by alleyway treatment (ΔAICc mass = −3.8; Table S13) despite fruit mass CV being lowest with CS (CS: 13.6%, AMWS: 14.8% and SWS: 17.9%). Although alleyway treatment affected width (CS: 29.2 ± 0.1 mm, AMWS: 28.8 ± 0.2 mm and SWS: 28.7 ± 0.2 mm) (ΔAICc width = 10.2; Table S13), the Tukey test did not support significant differences (Table S15). Correlations between either fruit parameter and visitor density, Shannon diversity and species richness were not significant for any of the alleyway treatments (Figures S8d–i; Table S14).

3.3.2 | Pollination services and deficits

Fruit set
Fruit set was strongly affected by pollination treatment (ΔAICc: 2954.5; Table S13). A higher fruit set was obtained from blossoms that were hand pollinated (mean ± SE: 32.5% ± 1.3) compared with


FIGURE 2 Non-metric multidimensional scaling (NMDS) plots of the Bray–Curtis dissimilarity for floral communities according to alleyway treatment after cherry anthesis in (a) 2018 and (b) 2019. NMDS plot stress: (a) = 0.19, (b) = 0.19. Individual points represent species recorded. Ellipsoids represent a 95% confidence interval surrounding each treatment. Control Strips (CS), Actively Managed Wildflower Strips (AMWS) and Standard Wildflower Strips (SWS).
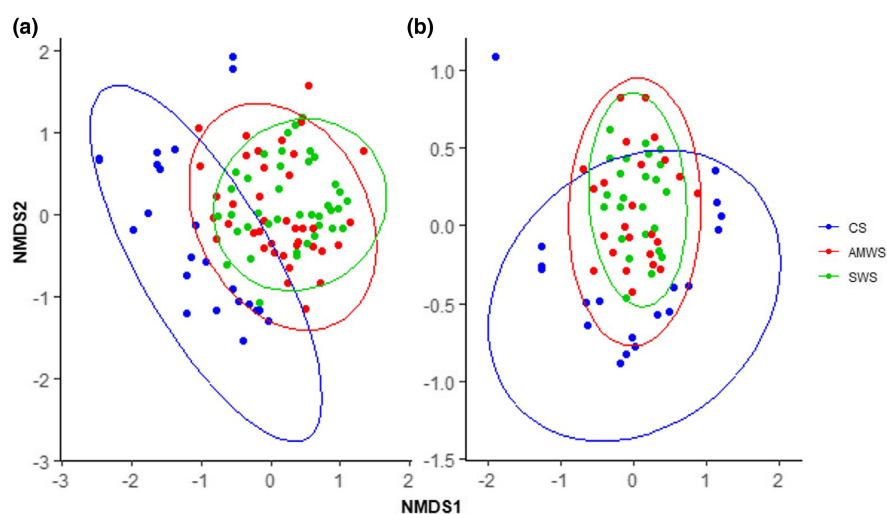
open-pollinated (16.8%±1.0) and insect-excluded (0.6%±0.1) blossoms (Figure 4a; Table S15). This was observed in all alleyway treatments. The greater fruit set with hand-pollinated compared with open-pollinated blossoms represented an overall pollination deficit of 48.4%; which differed between alleyway treatments (ΔAICc: 18.1; Table S13), being significantly greater in CS than in AMWS (Figure 4b; Table S15). Pollination deficits were correlated with visitor density (positive in CS and AMWS), diversity (negative in all alleyway treatments) and richness (positive in AMWS and negative in CS and SWS) (Figure S8j–l; Table S14).

Fruit quality
Pollination treatment influenced cherry width but not mass (ΔAICc: mass: 1.2; width: 2.7; Table S13), despite fruit mass being greater with blossoms hand and open-pollinated compared with when insects were excluded (hand: 12.1±0.1 g, open: 12.1±0.1 g and insect excluded: 11.2±0.4 g). This was consistent with the CV (hand: 15.6%, open: 15.6% and insect excluded: 23.1%). Cherry width was significantly greater in hand and open pollinated blossoms compared with insect excluded (hand: 29.0±0.1 mm, open:
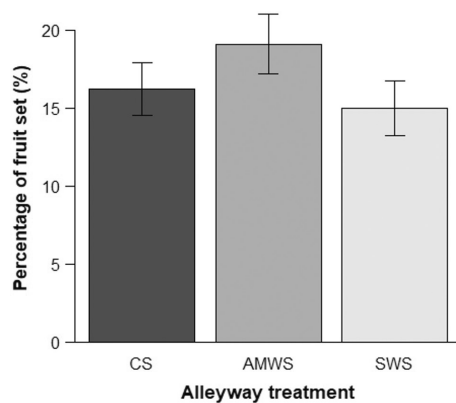
28.9±0.1 mm and insect excluded: 27.9±0.4 mm) (Table S15). No significant difference was found between hand and open pollination.

4 | DISCUSSION

4.1 | The influence of wildflowers on visitor density

Wildflower strips under both cutting regimes were associated with increased visitor density, diversity and richness after cherry anthesis by the third year of study (Figure 1g–i) highlighting positive outcomes of such interventions over time. This might be a consequence of the increase in floral density (Mateos-Fierro et al., 2021) and differences in floral diversity (Figure 2; Table S6) in wildflower treatments compared with CS. Due to the close proximity of treatments, it is likely this is a result of visitor re-distribution within the orchards with the wildflower strips attracting visitors rather than local populations being increased by improved nectar and pollen availability. Wildflower strips could have boosted local populations after anthesis to some extent as demonstrated by greater visitor density in spring 2019 compared with previous springs. However, visitor re-distribution could have happened again during anthesis, perhaps because all three alleyways had few wildflowers blooming. Importantly, wildflower strips in alleyways could reduce visitor reticence to enter into the polytunnels (Hall et al., 2020).

This study has demonstrated the potential benefits of actively managing wildflower alleyways in increasing visitor activity in polytunnels while simultaneously minimising the inconvenience of tall vegetation for growers, thereby reducing barriers to uptake. However, the greater visitor density associated with SWS after anthesis in 2019 indicates the potential role of this management approach in better supporting populations in subsequent years (Blaauw & Isaacs, 2014), confirming our hypothesis that more floral resources will be associated with greater visitor density, diversity and richness. An effective strategy for pollinators could incorporate

FIGURE 3 Mean percentage (± SE) of fruit set recorded on open-pollinated blossoms in 2019 according to alleyway treatment. CS (Control Strips), AMWS (Actively Managed Wildflower Strips) and SWS (Standard Wildflower Strips).
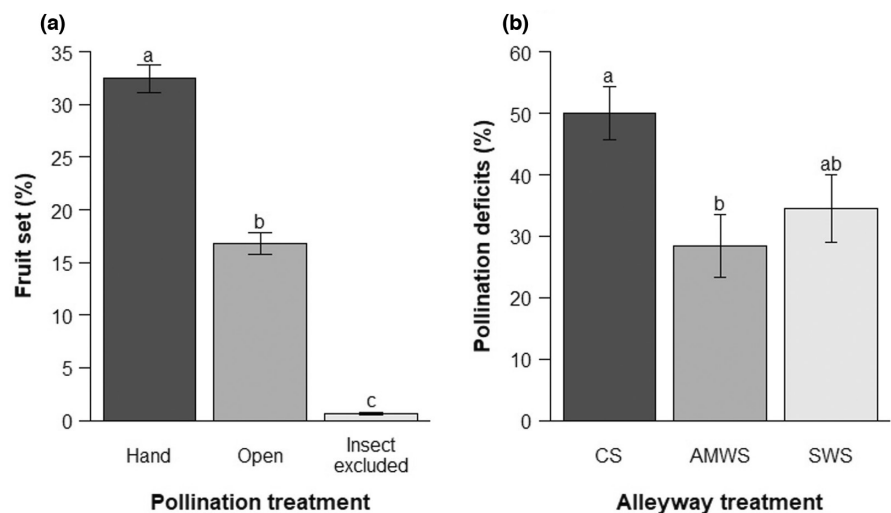

FIGURE 4 Mean percentages (± SE) of (a) fruit set according to pollination treatment and (b) pollination deficits according to alleyway treatment in 2019. Values with same superscript letters do not differ significantly (Tukey test: *p* > 0.05) (Table S15). Control Strips (CS), Actively Managed Wildflower Strips (AMWS) and Standard Wildflower Strips (SWS).

AMWS within orchards and taller SWS at the boundaries (Albrecht et al., 2020). The costs of wildflower interventions should be considered, including the cost of establishment and the longevity of any benefits they provide (Blaauw & Isaacs, 2014). Greater benefits of implementing wildflower strips might have been realised if further data had been collected in subsequent years (e.g. 2020), and long-term studies are required to fully quantify economic costs and benefits for such interventions.

Competition for visitors between flowering crops and additional non-crop resources is a concern for growers (Foulis & Goulson, 2014). However, this study conducted under polytunnels demonstrated that insect visits to cherry blossoms were not negatively impacted by co-flowering plants, which is consistent with Gilpin et al. (2022) in open orchards. However, this could have been due to only one sown (*Silene dioica*) and a few unsown (*T. officinale*, *Ranunculus repens* and *Brassica* spp.) species flowered concurrently with cherry. Of those, *T. officinale* was the most visited species, concurring with Eeraerts et al. (2019, 2021). Moreover, in other studies, the presence of wildflowers during crop flowering enhanced fruit set in almond (Lundin et al., 2017) and strawberry (Feltham et al., 2015) crops.

More wildflowers co-blooming with cherry could have the potential to enhance pollination services (Gilpin et al., 2022) although the wildflower strips at the margins studied by Wood et al. (2018) bloomed in synchrony with cherry and this was not associated with increased cherry blossom visits, even after 5 years. However, the greater visitor density in wildflower strips compared with CS after anthesis in this study suggests that visitor densities could also be boosted during anthesis into orchards if wildflowers, flowering at the same time as cherry, were incorporated in the alleyways, potentially resulting in more visits to crop blossoms (Gilpin et al., 2022).

The plant mix used in this study was designed to enhance wild visitor groups. Plant species such as *L. vulgare* and *A. millefolium* were mostly visited by hoverflies and solitary bees, while *Prunella vulgaris* and *Trifolium pratense* mostly by bumblebees. Yet the low number of solitary bees recorded, particularly *Andrena* species, concurs with Wood et al. (2018). Species of this genus are the main solitary bee visitors of cherry blossom in Europe (Eeraerts et al., 2017, 2019; Holzschuh et al., 2012; Mateos-Fierro et al., 2022; Schuepp et al., 2014), emerging early in the season, indicating the need to sow more early flowering wildflower species. This contrasts with bumblebees, which were frequently recorded visiting legumes, demonstrating this group can benefit from resources during anthesis (queens) and post-anthesis (workers) (Wood et al., 2018). In fact, bumblebees exhibit a foraging behaviour likely to facilitate cherry pollination (Mateos-Fierro et al., 2022). Consequently, they may be the most promising group to target with summer wildflowers. Our wildflower mix also included species blooming late in the season (e.g. *Leontodon hispidus*). Unfortunately, wildflower density decreased during/after harvest (August) due to harvest impacts on the wildflower strips (i.e. trampling), which reduced the benefits of late-season wildflowers.

Hoverflies were recorded most frequently and not only contributed to pollination but also delivered pest regulation services (Mateos-Fierro et al., 2021). Hence, the establishment of wildflower strips can provide additional benefits as part of Integrated Pest Management programmes.

4.2 | Pollination services and deficits

The non-significant positive correlation between visitor density and fruit set in AMWS compared with CS and SWS indicates that other factors, apart from visitors, may be in play, not fulfilling our hypothesis of greater pollination services in wildflower treatments. For instance, different rates of physiological development of cherry blossoms due to climatic factors in different alleyway treatments could have occurred (Blanusa et al., 2006; Gratacós et al., 2017). Similarly, these factors might have affected the 17% increase in fruit set recorded in AMWS compared with SWS, which is still important for production. Temperature and humidity could have varied between alleyway treatments under polytunnels leading to differences in fruit set, but also differences in rates of fruit abscission (Fadón et al., 2015). However, the fact that pollination deficits were greatest in CS indicates that these differences in production are likely to be linked to insect pollination.

The lower fruit set when insects were excluded from blossoms (0.6%) compared with open-pollinated blossoms (16.8%) demonstrates the importance of insect pollination services, essential for achieving commercial yields in sweet cherry orchards. This is consistent with Holzschuh et al. (2012) and Schuepp et al. (2014), where a fruit set of <3% and 5% was achieved in open sweet cherry orchards when insects were excluded and ~18% and 34% in open pollination, respectively. Yet, the greater percentage of fruit set in hand-pollinated blossoms (32.5%) compared with open-pollinated blossoms is indicative of a pollination deficit of 48.4% in our study orchards. However, we cannot quantify the full extent of this deficit in terms of production because unopened blossoms were removed in the hand pollination treatment only and these blossoms were not supplemented with open pollination. While not supplementing hand pollination with open pollination might underestimate pollination. Similarly, Holzschuh et al. (2012) recorded deficits with a fruit set of ~17% when blossoms were hand pollinated (open + hand pollination), and for Schuepp et al. (2014), ~52% was achieved with hand pollination. This suggests that factors other than polytunnels might influence open and hand pollination. Yet, due to our methodology, we were unable to determine the extent to which pollination services and deficits were affected by the polytunnels. However, detecting shortfalls in pollination helps target management (i.e. wildflower interventions) and investment to increase production (Garratt et al., 2019). The greater pollination deficit recorded in CS compared with AMWS, as we hypothesised, indicates that actively managed wildflowers in alleyways may reduce deficits.

Fruit quality is influenced by pollination and in cherries, fruit size is directly linked to commercial value (Whiting et al., 2006). The greater cherry mass and width underpinned by open pollination (and also hand pollination), compared with blossoms that had insects excluded, indicates the importance of visitors not only

for yields but also for maximising fruit quality. This is important for an industry with high-quality standards, where a minimum mass of 11–12 g and a width of 29–30 mm are specified (Kappel et al., 1996).

5 | CONCLUSIONS

UK sweet cherry production under polytunnels is highly dependent on pollinators. Wild visitors are important for sweet cherry and their presence could increase sustainability and resilience of pollination services, especially as they are more efficient at pollinating cherry blossoms than managed pollinators. Our study suggests that wildflower alleyways are effective at enhancing visitor density and richness in commercial sweet cherry orchards. Importantly, actively managing wildflower alleyways could increase productivity while decreasing pollination deficits.

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SUPPORTING INFORMATION

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

Figure S1: Example of the experimental design deployed at one out of the five sites, with the two separate orchards (defined as a separate parcel of land; orchards are delimited by the black polygons) and the three 95 m alleyway treatments in each, parallel to the cherry tree rows. Control Strips (blue), Actively Managed Wildflower Strips (green), Standard Wildflower Strips (red).

Figure S2: Spurs randomly selected to investigate pollination services and deficits (a) before, (b) during, and (c) after cherry anthesis in 2019.

Figure S3: Proportion of insect flower visitor density by species to cherry blossoms during cherry anthesis in (a) 2017, (b) 2018, and (c) 2019, and to wildflowers after cherry anthesis in (d) 2017, (f) 2018, and (e) 2019 according to alleyway treatment.

Figure S4: Non-metric multidimensional scaling (NMDS) plots of the Bray–Curtis dissimilarity (9999 permutations) according to treatment for insect flower visitor communities: visiting cherry blossoms during cherry anthesis in (a) 2017, (b) 2018, and (c) 2019; visiting wildflowers during cherry anthesis in (d) 2017, (e) 2018, and (f) 2019; and visiting wildflowers after cherry anthesis in (g) 2017, (h) 2018, and (i) 2019.

Figure S5: Total number of wildflower floral density (flower units/heads per 0.5 m^2 quadrat) recorded per alleyway treatment by plant species after cherry anthesis according to month (Jun = June, Jul = July, Aug = August, Sep = September) in Control Strips (CS), Actively Managed Wildflower Strips (AMWS), and Standard Wildflower Strips (SWS) in (a), (b), (c) 2018 and in (d), (e), (f) 2019, respectively.

Figure S6: Correlations between (a) insect flower visitor density and floral density, (b) insect flower visitor Shannon diversity and floral Shannon diversity, and (c) insect flower visitor richness and floral richness in 2018 and 2019.

Figure S7: Correlations between the total number of visits by (a) *Apis mellifera* (honeybees) and *Bombus* spp. (wild bumblebees) with density of *Trifolium repens* (unsown) and (b) the total number of visits by Syrphidae (hoverflies) with densities of *Achillea millefolium* (sown), *Leucanthemum vulgare* (sown), and *Matricaria* spp. (unsown) after cherry anthesis in 2018 and 2019 combined.

Figure S8: Correlations between fruit set with (a) insect flower visitor density (b) insect flower visitor Shannon diversity and (c) insect flower visitor richness; between fresh mass (g) with (d) insect flower visitor density (e) insect flower visitor Shannon diversity and (f) insect flower visitor richness; between width (mm) with (g) insect flower visitor density (h) insect flower visitor Shannon diversity and (f) insect flower visitor richness; and between pollination deficits with (j) insect flower visitor density (k) insect flower visitor Shannon diversity and (k) insect flower visitor richness according the alleyway treatment in 2019.

Table S1: Landscape context of the study sites, the percentage cover of different land use types within a 1 km radius of each orchard (including mean ± SE) was determined using ArcGIS and R (R Core Team, 2021).

Table S2: Details of the 10 study orchards, including (i) the coordinates, (ii) the size (ha), (iii) the date when Kordia cherry trees were planted, (iv) the rootstock used, (v) the area of the two alleyway treatments (each 95 m^2) which were sown with wildflowers "wildflower area sown" is the sum area (%) of these both sown alleyways relative to their orchard.

Table S3: Mean number (± SE) of floral units/heads in Control Strips, Actively Managed Wildflower Strips, and Standard Wildflower Strips of the sown and unsown plant species per quadrat (0.5 × 0.5 m) across all surveys and years (2018 and 2019).

Table S4: Number of cherry blossoms and cherry fruits that set (fruit set) recorded in 2019.

Table S5: Statistical models used to analyse all datasets according to the results from the Shapiro-Wilk tests and confirmed with comparisons using the Akaike information criterion (AICc) from testing different models.

Table S6: Total number (inds. = individuals), mean number (±SE), and percentage (%) per alleyway of insect flower visitors recorded on the transect surveys during and after cherry anthesis (cherry phenology) throughout the three-year study according to insect flower visitor group and cherry blossom or wildflower visit.

Table S7: Total number of species and individuals of insect flower visitors recorded during all the transect surveys during and after cherry anthesis throughout the three-year study.

Table S8: Total number and percentage (%) of visits to wildflower plant species according to insect flower visitor group recorded during the transect surveys during and after cherry anthesis throughout the three-year study.

Table S9: Total number of visits to floral units/heads of wildflowers (sown and unsown) and total number of wildflower plant species visited (total per insect flower visitor group throughout the three-year study) according to insect flower visitor group, year, and alleyway treatment recorded during the transect surveys after cherry anthesis.

Table S10: Comparisons in the generalized linear mixed-effects models with negative binomial distributions (GLMER.NB) and Linear Mixed-Effects Models (LMER) (Table S5) for the insect flower visitor density (total and groups), insect flower Shannon diversity, and insect flower species richness visiting cherry blossoms or wildflowers during and after cherry anthesis (cherry phenology) for each year using the Akaike information criterion (AICc).

Table S11: Pairwise comparisons (*Z* and *p* values) according to the *post-hoc* Tukey tests between alleyway treatments for the significantly different response variables visiting wildflowers (Table S10) during and after cherry anthesis (cherry phenology) for each year.

Table S12: Comparisons in the linear mixed-effects models (LMER) for dataset *i*, the effect of floral density on insect flower visitor density (total and groups), floral Shannon diversity on insect flower Shannon diversity, and floral richness on insect flower species richness after cherry anthesis in 2018 and 2019, and for dataset ii, the effect of *Trifolium repens* density on honeybees (*Apis mellifera*) and

buff-tailed bumblebees (*Bombus terrestris*) and *Achillea millefolium*, *Leucanthemum vulgare*, and *Matricaria* spp. on hoverflies (Syrphidae) in 2018 and 2019 combined using the Akaike information criterion (AICc).

Table S13: Comparisons in the generalized linear mixed-effects models with binomial error distributions (GLMER.NB) (fruit set) and linear mixed-effects models (LMER) (fruit quality: fresh mass and width, and pollination deficits) using the Akaike information criterion (AICc).

Table S14: Comparisons in the generalized linear mixed-effects models with negative binomial distributions (GLMER.NB) or linear mixed-effects models (LMER) (according to the Shapiro-Wilk tests; see Table S5) for the effect of insect flower visitor density (total and groups), insect flower Shannon diversity, and insect flower species richness visiting cherry blossoms during cherry anthesis on fruit set (%) and quality (fresh mass and width), and pollination deficits for each alleyway treatment in 2019 using the Akaike information criterion (AICc).

Table S15: Pairwise comparisons (*Z* and *p* values) according to the *post-hoc* Tukey tests between alleyway treatments and pollination treatments for the significantly different response variables (Table S13).