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Establishment and management of wildflower areas for insect pollinators in commercial orchards

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Abstract

Sown wildflower areas are increasingly recommended as an agri-environmental intervention measure, but evidence for their success is limited to particular insect groups or hampered by the challenges of establishing seed mixes and maintaining flower abundance over time. We conducted a replicated experiment to establish wildflower areas to support insect pollinators in apple orchards. Over three years, and across 23 commercial UK orchards with and without sown wildflowers, we conducted 828 transect surveys across various non-crop habitats. We found that the abundance of flower-visiting solitary bees, bumblebees, honeybees, and beetles was increased in sown wildflower areas, compared with existing non-crop habitats in control orchards, from the second year following floral establishment. Abundance of hoverflies and other non-syrphid flies was increased in wildflower areas from the first year. Beyond the effect of wildflower areas, solitary bee abundance was also positively related to levels of floral cover in other local habitats within orchards, but neither local nor wider landscape-scale context affected abundance of other studied insect taxa within study orchards. There was a change in plant community composition on the sown wildflower areas between years, and in patterns of flowering within and between years, showing a succession from unsown weedy species towards a dominance of sown species over time. We discuss how the successful establishment of sown wildflower areas and delivery of benefits for different insect taxa relies on appropriate and reactive management practices as a key component of any such agri-environment scheme.

Keywords: Insects; bees; Apidae; Syrphidae; agri-environment; flower mix; orchard management; sustainable agriculture

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Introduction

Sown wildflower areas are increasingly recommended as an agri-environmental intervention measure in agricultural landscapes to mitigate the loss of key habitats and resources caused by intensive farming and the resulting negative impacts on biodiversity (Albrecht, Kleijn, Williams, Tschumi, Blaauw et al., 2020; Pywell, Heard, Woodcock, Hinsley, Ridding et al., 2015). These wildflower areas are known to attract flower-visiting insects, benefitting both local abundance and species richness (Carvell, Meek, Pywell, Goulson & Nowakowski 2007; Williams, Ward, Pope, Isaacs, Wilson et al., 2015). When suitably targeted, in terms of flower species composition, area sown and spatial location, they can increase survival and reproduction in bumblebees (Carvell, Bourke, Dreier, Freeman, Hulmes et al., 2017) and solitary wild bees (Ganser, Albrecht & Knop 2021). However, while the benefits for groups such as bumblebees have been well documented, sown wildflower areas may be of limited value (or have little evidence to support their benefits) to the many other insects that may be key pollinators of crops or wild plants or provide other ecosystem services such as natural pest control (Orford, Vaughan & Memmott 2015; Wood, Holland & Goulson 2016). Furthermore, whilst many studies in Northern Europe have featured experimental wildflower areas on non-productive ex-arable land, their success is often hampered by a lack of farmer experience in the challenges of establishing and managing seed mixes (McCracken, Woodcock, Lobley, Pywell, Saratsi et al., 2015). In addition, fewer studies have tested the impacts of wildflower areas alongside perennial fruit crops (but see Blaauw & Isaacs 2014; Albrecht et al., 2020; Wood et al., 2018). This may be because of the challenge of establishing perennial wildflower mixes in areas of permanent grassland typical of orchard farming systems and their associated intensive management practices (McKerchar, Potts, Fountain, Garratt & Westbury 2020). Here we use data on known key apple pollinators (Garratt, Breeze, Boreux, Fountain, McKerchar et al., 2016; Kleijn, Winfree, Bartomeus, Carvalheiro, Henry et al., 2015) to design and establish wildflower areas to support these key pollinators and other insects in commercial UK apple orchards from the end of apple bloom and throughout the flight period.

Insect pollinators provide an essential ecosystem service for production, significantly impacting the yield, fruit quality and market value of many crops (Klein, Vaissière, Cane, Steffan-Dewenter, Cunningham et al., 2007). The contribution of pollinators to economic output in UK apples was estimated at £92M in 2012 (Garratt, Breeze, Jenner, Polce, Biesmeijer et al., 2014), with the majority of this contribution provided by wild bees (Garratt et al., 2016; Garratt, Truslove, Coston, Evans, Moss et al., 2013). Recent research has suggested that crop pollination by both managed and wild pollinators is not meeting the increased demands for food production in the UK (Breeze, Vaissière, Bommarco, Petanidou, Seraphides et al., 2014). Indeed, pollination deficits in excess of £6k/ha in UK dessert apple orchards have been identified (Garratt et al., 2014). Simultaneously, many wild bee and hoverfly species have significantly declined in occupancy across Britain (Powney, Carvell, Edwards, Morris, Roy et al., 2019), and there is uncertainty surrounding trends in their abundance (Breeze, Bailey, Balcombe, Brereton, Comont et al., 2021). Therefore an opportunity exists, through management of wild pollinators, to increase economic returns by improving both the quality and resilience of fruit production under environmental change.

Landscape context is a driver of pollinator communities sampled within intensive apple orchards (Marini, Quaranta, Fontana, Biesmeijer & Bommarco 2012) and other pollinator-dependent crop systems (Tscharntke, Klein, Kruess, Steffan-Dewenter & Thies 2005), with crop-dominated landscapes typically having a negative impact on the abundance and species richness of wild bees. Local availability of floral resources and other habitat components within the orchard system are also critical to support the lifecycle requirements of beneficial insects both during and following crop bloom (Rosa García & Miñarro 2014). Thus landscape context has the potential to greatly influence the effectiveness of sown wildflower areas as a management strategy for pollinators. However, there are few studies that have tested impacts of local orchard habitats and landscape context on insect responses to sown wildflower areas within commercial orchards.

We conducted a replicated experiment to design, establish and monitor wildflower areas to support insect pollinators in commercial orchard systems. We use the term “insect pollinators” to refer to the insect groups included in our study and known to include many examples of species that provide pollination to either apple crops, wildflowers or both, whilst recognising that our study does not identify individuals to species level. Over three years, and across 23 commercial UK apple orchards with and without (as a control) sown wildflowers, we assessed whether the abundance of flower-visiting insects of a number of taxonomic groups differed between enhanced wildflower areas and existing orchard habitats and how this changed over time. We investigated effects of sown wildflower areas, and of local and landscape-scale resources on insect flower visitor abundance throughout the season, during and after apple bloom. We also recorded change in the plant communities occurring on the sown wildflower areas between years, and in patterns of flowering within and between years.

We hypothesised that: 1) plant communities on sown wildflower areas would change over time as sown species establish, with flower abundance being consistently higher in wildflower areas than other orchard habitats; 2) insect flower visitor counts would be higher and increase year-on-year on sown wildflower areas compared with existing orchard headlands; 3) there would be a spillover of insect pollinators from wildflower areas into orchard grass alleyways in comparison to control orchards, and 4) pollinator responses to sown wildflower areas would be modified by levels of floral cover in local habitats within the orchard and/or wider landscape context surrounding the orchard. Based on previous findings

(Carvell, Osborne, Bourke, Freeman, Pywell et al., 2011; Scheper, Holzschuh, Kuussaari, Potts, Rundlöf et al., 2013), we predicted a larger increase in pollinator counts in more intensively managed orchards with fewer extant floral resources and in more 'simplified' landscapes.

Materials and Methods

Overall study design

We selected 24 established commercial cv. Gala apple (*Malus domestica*) orchards, in Kent, UK. Each orchard was assigned to one of two treatments in 2016; 1) to support an adjacent sown wildflower area or 2) to receive no wildflower intervention as a control. All other aspects of orchard management (including cutting and spraying regimes) remained as the growers' standard practice for conventional management. Orchards assigned to each treatment were distributed evenly across the study region, with a minimum separation distance of one kilometre to minimise dispersal of insects between sites (Appendix A, Fig. A1). Due to unforeseen issues during establishment of the wildflower area, one site was excluded from the study leaving a total of 23 sites: 11 'wildflower area' orchards and 12 control orchards. Orchards ranged in size from 0.47 ha to 6.43 ha (mean = 2.05ha).

Design of wildflower seed mix

The seed mix (Table 1) was designed to meet the following criteria: 1) to provide a range of flower structures

Table 1. Plant community composition of sown wildflower areas. Composition of perennial and annual seed mixes (% of mix planted), the number of orchard sites (n=11) on which species and components were recorded within quadrats as established in years one (2017) and three (2019) after sowing, and mean (±SE) % vegetative cover per quadrat (n=10). English names are given in brackets.

			Number of orchards		Mean vegetative cover (%)			
Vegetation component	Species	% of mix	2017	2019	2017 Mean	± SE	2019 Mean	± SE
Perennial mix	*Achillea millefolium* (Yarrow)	0.83	11	11	1.82	0.5	3.54	1.7
	Anthyllis vulneraria (Kidney Vetch)	0.83	6	1	0.14	0.1	0.05	0.1
	Barbarea vulgaris (Winter-cress)	3.33	2	1	0.06	0.0	0.03	0.0
	Centaurea nigra (Common Knapweed)	5.00	10	11	2.78	0.8	24.35	4.3
	Daucus carota (Wild Carrot)	1.67	11	11	2.23	0.4	2.55	0.6
	Leontodon hispidus (Rough Hawkbit)	3.33	4	5	0.13	0.1	0.25	0.1
	Leucanthemum vulgare (Oxeye Daisy)	1.67	11	11	3.02	0.9	24.95	4.9
	Lotus corniculatus (Birdsfoot Trefoil)	3.33	11	11	1.63	0.9	13.18	3.3
	Plantago media (Hoary Plantain)	0.83	3	3	0.07	0.1	0.11	0.1
	Primula veris (Cowslip)	1.67	0	1	0.00	0.0	0.05	0.0
	Ranunculus acris (Meadow Buttercup)	5.00	3	9	0.21	0.1	0.37	0.1
	Reseda lutea (Wild Mignonette)	0.83	5	1	0.15	0.1	0.17	0.2
	Silene dioica (Red Campion)	0.83	5	3	0.14	0.1	0.08	0.1
	Taraxacum officinale (Dandelion)	3.33	11	10	3.03	1.0	2.21	0.7
	Trifolium pratense (Red Clover)	0.83	9	10	0.9	0.4	1.56	0.4
	Sown perennial flowers TOTAL (4 kg/ha)	33.33	11	11	16.30	4.3	73.45	6.0
	Basic fine grass mix (8 kg/ha) [a]	67.00	9	11	5.76	2.9	11.06	3.5
Annual mix [b]	*Alliaria petiolata* (Garlic Mustard)	10.00	0	0	0.00	0.0	0.00	0.0
	Anthemis austriaca (Corn Chamomile)	5.00	11	1	6.17	1.0	0.0	0.0
	Brassica spp. (Winter oilseed rape)	10.00	1	0	0.01	0.0	0.0	0.0
	Camelina sativa (Gold of Pleasure)	15.00	8	0	1.04	0.3	0.0	0.0
	Centaurea cyanus (Cornflower)	10.00	10	0	1.37	0.4	0.0	0.0
	Echium vulgare (Viper's Bugloss)	10.00	0	0	0.00	0.0	0.0	0.0
	Glebionis segetum (Corn Marigold)	5.00	9	0	1.06	0.4	0.0	0.0
	Papaver rhoeas (Common Poppy)	10.00	10	1	0.74	0.3	0.0	0.0
	Raphanus sativus (Fodder raddish)	10.00	5	0	0.43	0.2	0.0	0.0
	Trifolium incarnatum (Crimson Clover)	15.00	8	0	0.68	0.3	0.0	0.0
	Sown annual flowers TOTAL (10 kg/ha)	100	11	2	11.5	1.8	0.0	0.0
Unsown forbs			11	11	52.0	10.3	17.6	4.3
Unsown grasses			11	11	12.2	6.5	13.9	4.9
Bare ground			11	11	15.4	2.2	1.6	0.7

[a]The basic grass mixture consisted of four low-growing fine grasses: *Cynosurus cristatus* (Crested Dogstail), *Festuca rubra* (Slender-creeping Red-fescue), *Festuca rubra* ssp. commutata (Chewing's Fescue) and *Poa pratensis* (Smooth-stalked Meadow-grass).
[b]The annual/biennial mix was over-sown by hand across one end of the wildflower area.

attractive to the key bee species and other insects delivering pollination services to UK apples; 2) to maximize provision of pollen and nectar resources from the end of apple bloom and throughout the summer, catering for both first and second generations of double-brooded species (e.g. *A. dorsata*) and the full foraging period of other insect taxa (e.g. *Bombus* spp.); 3) to include commercially available perennial wildflowers and grasses along with a few annual species to provide flowers during the first year of the experiment. Key bee species were identified from the literature on UK apple pollinators as *Andrena haemorrhoa, Andrena dorsata, Andrena nitida, Bombus terrestris/lucorum* and *B. lapidarius* (Garratt et al., 2016; Kleijn et al., 2015). Their foraging preferences were taken from expert knowledge among the authors together with a database of plant-pollinator interactions based on biological records from across Britain (Redhead, Coombes, Dean, Dyer, Oliver et al., 2018). From these plant species lists, fifteen perennial wildflowers and four low-growing fine grass species that were commercially available and known to perform on a variety of soil types, flowering across the season, were selected (Nowakowski, Pywell pers. comm). We supplemented the perennial mix with a selection of ten annual flower species to provide pollen and nectar during the first year of the experiment (Table 1).

Establishment and management of sown wildflower areas

Wildflower areas were located along an area of uncropped grassy headland typically at one side of the orchard (Appendix A, Fig. A1, inset B), where there was less disturbance from orchard management operations. The sown area was adjusted to cover between 1 − 3% of the total area of apple orchards within 500 m of the study orchard (Fig. A.2). This resulted in sown wildflower areas ranging from 0.07 ha to 0.62 ha (mean sown area = 0.3 ha), covering an area equivalent to ~12% of each study orchard.

Prior to sowing, weed pressure at each site was assessed to determine suitability for autumn vs. spring sowing. Seven sites with lower weed pressure were autumn sown. These were sprayed with glyphosate (4 l a.i. ha^{-1}) in August 2016, and cultivated to create a firm, fine seedbed (see Box 1). In late August, the perennial wildflower seed mix was broadcast onto the soil surface and ring-rolled, at a rate of 4 kg ha^{-1} for the flower component and 8 kg ha^{-1} for the grass component (Table 1). The annual mix was over-sown by hand across one end of the wildflower area covering between 100 − 200 m^2. Four sites with higher weed pressure were mown in late August and re-growth sprayed with glyphosate. These sites were cultivated over the winter and lightly harrowed prior to sowing in April 2017. Due to a significant drought period following autumn sowing and failure of sown species to establish, three of the autumn-sown sites were re-sown following further light cultivation in April 2017. During the first year, wildflower areas were cut in June or July (avoiding the section over-sown with annuals), and again in October (over the full area) to reduce competition from weeds. Thereafter cutting was undertaken annually in September with all cuttings collected and removed (see Box 1 for details).

Box 1. Practical steps for establishing and managing perennial wildflower areas in UK conventional farming systems.

- Weed-free seedbed creation is vital: start by spraying off existing vegetation with broad-spectrum herbicide (following label recommendations).
- Where sowing in place of permanent grass, vigorously cultivate to break up the turf and create a firm, fine, weed-free seedbed.
- Sow ideally in early autumn (August in UK), or spring (April).
- Select a seed mix including perennial herbs (at least ten species) and fine grasses (three species) at a recommended weight ratio of around 20 (min):80 and a rate of 20 kg/ha. The proportion of grasses may be reduced to give a rate of 4 kg/ha flowers: 8 kg/ha grasses.
- Directly broadcast seed onto the surface of the prepared seedbed, then ring roll to ensure the seeds are in contact with the soil, ideally just before rain is due.
- Annual species can be added to part of the area if flowering is required in first year.
- In the first year, cut regularly to a height of 8-10 cm to reduce competition, and if possible remove the cuttings, to reduce the risk of smothering the wildflowers with herbage.
- Use spot treatment with selective herbicides where pernicious weedy species persist (following label recommendations).
- From the second year onwards, cut annually to 8-10 cm either before or after fruit harvest in autumn, and potentially also in March depending on winter growth.
- With successful establishment by the third year, vegetative cover of sown herb species should reach 50-80% and cover of sown grasses 10-20%.

To record change in the plant communities occurring on the sown wildflower areas between years, we recorded vegetative cover of all species within ten quadrats of 1 × 1 m in early July of each study year. Quadrats were randomly placed across each sown area, but ensuring that two were located within the area over-sown with the annual mix.

Insect transect surveys

Insect surveys were conducted on four occasions (just before and during early apple bloom to the summer period following bloom) from April to August 2017, 2018 and 2019, with a minimum of three weeks between surveys on a given site. Surveys were carried out between 10:00 and 16:30 hours during dry weather, when ambient temperature was above 13 °C with at least 60% clear sky, or 17 °C under any sky conditions (Carvell et al., 2011).

Three transects of 2 m width and 100 m length were mapped out within each orchard and remained for the duration of the study (Appendix A, Fig. A1). In orchards with wildflower areas, two “headland” transects (T1 and T2) were located within the sown area, avoiding the outer 2 m edge where possible. These covered both the main area sown with perennials (90 m) and the area over-sown with annuals (10 m), with a minimum of 2 m separation between any parallel transects. In control orchards, T1 and T2 were located along the uncropped orchard headland or grassy margin, avoiding heavily disturbed areas. These control “headland” transects were either parallel, where space allowed with a minimum of

2 m separation, or end-to-end around the orchard headland. In both wildflower and control orchards, a third "alleyway" transect (T3) was located along the existing grass alleyways between apple tree rows, covering two sections of 50 m each running from the middle of one edge towards the centre of the orchard (Fig. A1, inset B, C).

At each survey, transects were walked at a steady pace, counting all flower-visiting insects and the plant species on which they were observed. Insects were identified on the wing (without being captured) and classified into one of the following taxonomic groups: solitary bees, bumblebees, honeybees (*Apis mellifera*), hoverflies (syrphid flies), other (non-syrphid) flies, beetles, wasps, butterflies, moths and other insects. Following each pollinator survey, we estimated the number of floral units of all species in flower within each of ten (10 × 2 m) sections along the 100 m transect using the scale of Carvell et al., (2011): 1−5; 6−25; 26−200; 201−1000; 1001−4999; and

5000+ floral units. Floral units were defined as a single flower or an umbel, head, spike, or capitulum on multi-flowered stems. Floral units were summed across all sections of the transect, giving a monthly estimate of flower abundance.

Measuring floral cover in other orchard habitats and wider landscape context

Levels of floral cover within all non-crop habitats of each study orchard were measured on habitat surveys conducted in May and July of each year. Each habitat parcel within and immediately surrounding the orchard (with a 5 m buffer to include boundary features such as hedgerows) was mapped to identify its spatial extent and a central GPS grid reference. On each survey, the percentage cover of each plant species or family within each parcel and the percentage of that plant cover with flowers was estimated, in order to measure the area (in m^2) of flowers present within the orchard. Subsequently, the percentage area of flowers in each orchard was estimated (Redhead et al., 2018), using the summed area of key non-crop forage plants for pollinators in flower (*Trifolium repens, Cirsium* spp., yellow and white composites e.g. *Taraxacum* spp., Apiaceae or Umbelliferae and woody hedgerow species (e.g. *Crataegus, Salix, Prunus* and *Rubus* spp.)) across all parcels, together with the known area of each orchard.

The coverage of all top fruit orchards (those growing fruit on trees such as apple and pear) within a 1000 m radius (and nested radii of 250 m and 500 m) of each study orchard was estimated using aerial imagery. Coverage of agricultural land (arable and horticultural + improved grassland) and semi-natural land (broadleaved woodland + neutral grassland) within the radii were derived from the UK-CEH Land Cover Map (Rowland, Morton, Carrasco, McShane, O'Neil et al., 2017) and OS Vector Map Local (https://www.ordnancesurvey.co.uk/business-government/products/vectormap-local) (Appendix A, Fig. A.2). While landscape composition varied between orchards, preliminary analyses suggested that patterns of land cover between the three different radii were very similar across orchard sites. Further, whilst we know that honeybees and some bumblebee species will forage well beyond 500 m, there is evidence to suggest that the majority of foraging flights for many species are near this distance (Redhead, Dreier, Bourke, Heard, Jordan et al., 2016). We therefore selected the radius of 500 m to represent the range of foraging distances of the pollinating insects being recorded (Marini et al., 2012).

Data analysis

Generalized mixed-effect models were constructed to test the effects of orchard treatment, year and month on counts of the different insect groups. For each group we considered a model of the form [Insect count ~ Treatment + Year + Month + Treatment: Year + Treatment: Month + Flower abundance + Random-Effect] where treatment (wildflower area or control), year and month were included as categorical fixed effects along with two-way interactions for Treatment with Year and Month. The total number of all flower units recorded on each transect was included as a continuous variable. We used the Random-Effect term (1 | Orchard/Transect Number) for headland transects, and (1 | Orchard) for alleyway transects, where Orchard represents the orchard sites and Transect Number was added as a nested random effect within orchards for the "headland" transect models that included transects T1 and T2, but not for the "alleyway" transect models that contained a single transect per treatment on each survey. The Treatment: Month interaction term was excluded for two insect groups ("headland" transect models for Bumblebees and "alleyway" transect models for beetles) because the insect counts were constant (zeros) in at least one month/ treatment combination (where confidence intervals' estimates would be infinity). Also the Treatment: Year term was excluded for Bumblebees with the "alleyway" transect model because the counts were constant (zeros) for Alleyway transects in wildflower area orchards in 2018.

A negative binomial distribution was assumed for the insect counts. Modelling was performed using the glmmTMB function in R (glmmTMB stands for "generalized linear mixed models with the Template Model Builder"). The Template Model Builder approach was selected as it works faster than other algorithms, and as it employs automatic differentiation along with Laplace approximation.

For model selection, we considered all possible combinations of the explanatory fixed variables, but constraining the models to include Treatment, Year and Month as the variables of interest. Thus, flower abundance and interaction terms were optional and all combinations included variants without these variables, with one of them, two or all of them, providing 8 models per insect group. The results are given in relation to the reference level (eg. year 2017). We ranked all candidate models according to sample-size adjusted Akaike's Information Criteria (AICc). The models with <=6 ΔAICc of the best model (i.e. the model with the lowest AICc) were subjected to model averaging with function 'model.avg' (Burnham & Anderson 2002; Lukacs, Burnham & Anderson 2009) in R (MuMIn package), in order to include weighted parameter estimates for all potentially important variables for each insect group.

A second set of models was employed as described but with the addition of the three landscape variables: % key forage flowers in the orchard, area of top fruit orchards and semi-natural land respectively within a 500 m radius of the study orchard. % key forage flowers measured in May were matched with transects conducted in April and June, and those measured in July paired with transects in July and August. Only orchard and semi-natural areas were included to describe wider landscape due to multicollinearity with the area of agricultural land within 500 m (Appendix A, Fig. A.2).

Results

Establishment of sown wildflower areas

After three years, all 15 perennial species and eight of the ten sown annual species were recorded in the wildflower areas (Table 1). However, establishment varied between orchard sites and species. Only seven perennials (*Achillea millefolium, Centaurea nigra, Daucus carota, Leucanthemum vulgare, Lotus corniculatus, Taraxacum officinale* and *Trifolium pratense*) and three annuals (*Anthemis austriaca, Centaurea cyanus* and *Papaver rhoeas*) were established on ten or more sites. Overall, cover of sown perennials increased from 16.3 (mean ± 4.3 SE) to 73.45 (± 6.0 SE) % cover per quadrat between the first and third year after sowing, with cover of annuals decreasing from 11.5 (± 1.8) to 0% cover per quadrat. The cover and prevalence of unsown forb species also decreased over time to 17.6 (± 4.3) % cover in the third year, as the sown flowers and grasses established (Table 1), although a few unsown weedy species such as *Chenopodium album* and *Holcus lanatus* persisted at low levels at specific sites.

Flower abundance on sown areas vs. other orchard habitats

Patterns of change in total flower abundance recorded from the 100 m insect transects on sown wildflower areas reflected the data on vegetative percentage cover (Fig. 1). Flowers of sown perennial species increased in the second and third year, while flowers of sown annual species and unsown species decreased. Within years, relatively few floral resources were available on sown areas in April/ early

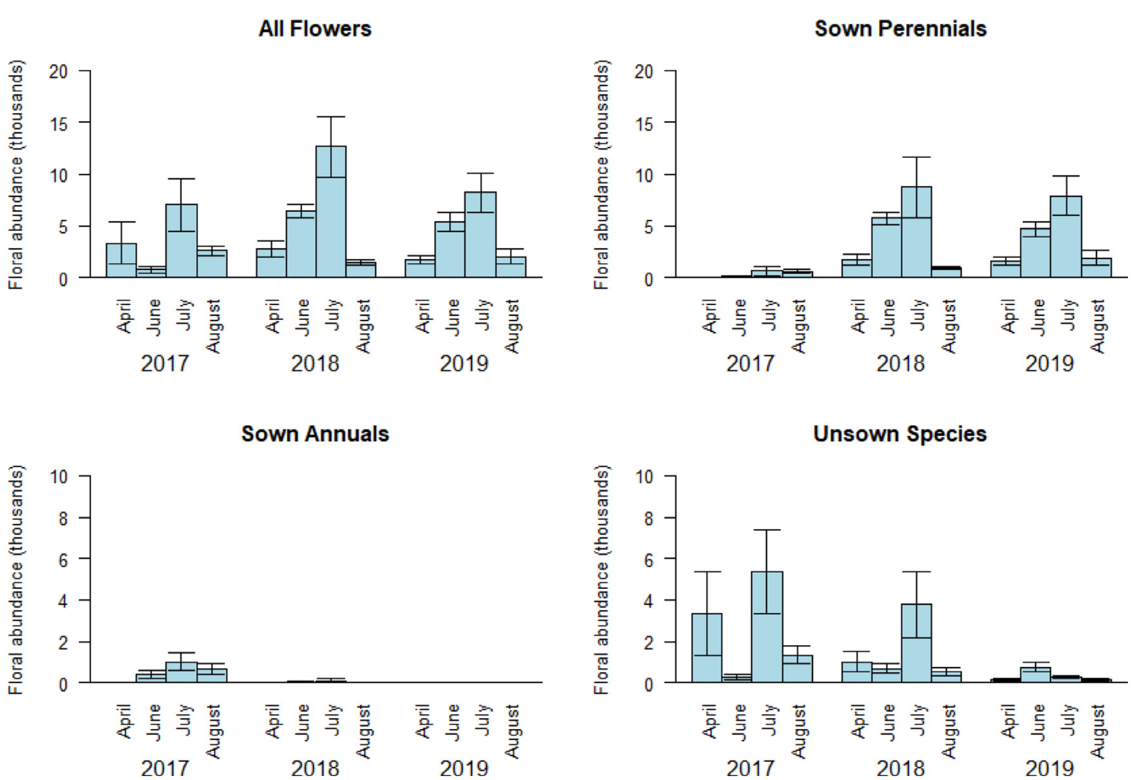

Fig. 1. Change in floral abundance of all plant species (all flowers), sown species and unsown species in sown wildflower areas (n = 11) by month and year (means +/- 1SE).

Table 2. Summary table of GLMM results after multimodel averaging of best candidate models (within <=6 Δ AICc of the best model) showing effects of each explanatory variable on insect group counts on orchard headlands and alleyways. Relative importance of predictor variables (%), parameter estimates with standard error (±SE) and p-values (Pr(>|z|). Bold values indicate a significant effect at P < 0.05.

		Headland transects (T1, T2)					Alleyway transects (T3)				
Insect group model [a]	Variable name [b]	Rel imp (%)	Model estimate [c]	± SE	Pr(>|z|) [d]		Rel imp (%)	Model estimate [c]	± SE	Pr(>|z|) [d]	
Solitary bees	Treatment (control)		-0.369	0.472	0.434			-0.252	0.762	0.741	
	Year 2018		1.699	0.274	**0.000**	***		-0.072	0.483	0.883	
	Year 2019		1.108	0.279	**0.000**	***		0.550	0.413	0.185	
	Month June		-0.144	0.307	0.638			-1.856	0.644	**0.004**	**
	Month July		0.648	0.318	**0.042**	*		-1.225	0.586	**0.037**	*
	Month August		-0.089	0.319	0.779			-1.230	0.878	0.162	
	Treatment (control): Y 2018		-1.484	0.457	**0.001**	***	23	-0.202	0.520	0.697	
	Treatment (control): Y 2019		0.110	0.438	0.802		23	-0.051	0.358	0.886	
	Treatment (control): M June		-2.367	0.601	**0.000**	***	71	0.202	0.821	0.807	
	Treatment (control): M July		-1.910	0.485	**0.000**	***	71	0.846	0.832	0.311	
	Treatment (control): M Aug		0.135	0.450	0.764		71	1.558	1.215	0.200	
	Flower abundance		0.380	0.100	**0.000**	***	100	3.505	0.858	**0.000**	***
Bumblebees	Treatment (control)		-0.575	0.361	0.111			0.357	1.076	0.741	
	Year 2018		0.979	0.257	**0.000**	***		-1.831	0.555	**0.001**	**
	Year 2019		1.117	0.249	**0.000**	***		-0.732	0.354	**0.039**	*
	Month June		3.010	0.353	**0.000**	***		2.260	0.942	**0.017**	*
	Month July		2.777	0.357	**0.000**	***		0.631	1.129	0.578	
	Month August		2.864	0.359	**0.000**	***		0.794	1.316	0.548	
	Treatment (control): Y 2018		-2.582	0.499	**0.000**	***		NA	NA	NA	
	Treatment (control): Y 2019		-2.018	0.433	**0.000**	***		NA	NA	NA	
	Treatment (control): M June		NA	NA	NA		64	-0.383	1.106	0.730	
	Treatment (control): M July		NA	NA	NA		64	0.839	1.291	0.517	
	Treatment (control): M Aug		NA	NA	NA		64	0.835	1.452	0.567	
	Flower abundance		0.481	0.081	**0.000**	***	100	2.899	0.635	**0.000**	***
Honeybees	Treatment (control)		-1.904	1.222	0.120			-0.468	1.149	0.685	
	Year 2018		0.171	0.413	0.679			-1.565	0.742	**0.036**	*
	Year 2019		1.010	0.417	**0.016**	*		-0.298	0.559	0.596	
	Month June		0.294	0.405	0.468			-1.692	0.942	0.074	
	Month July		2.226	0.389	**0.000**	***		0.705	0.647	0.277	
	Month August		1.355	0.530	**0.011**	*		-0.655	1.213	0.590	
	Treatment (control): Y 2018	96	-1.593	0.665	**0.017**	*	38	-0.518	0.894	0.563	
	Treatment (control): Y 2019	96	-1.436	0.617	**0.020**	*	38	-0.410	0.685	0.550	
	Treatment (control): M June	80	1.166	1.041	0.263		68	0.625	1.218	0.609	
	Treatment (control): M July	80	1.157	0.997	0.246		68	0.909	0.951	0.340	
	Treatment (control): M Aug	80	1.936	1.276	0.130		68	1.918	1.618	0.237	
	Flower abundance	100	0.457	0.110	**0.000**	***	100	3.018	0.809	**0.000**	***
Hoverflies	Treatment (control)		-1.161	0.382	**0.002**	**		-0.198	0.711	0.781	
	Year 2018		1.330	0.237	**0.000**	***		0.678	0.337	**0.045**	*
	Year 2019		0.903	0.224	**0.000**	***		0.685	0.333	**0.040**	*
	Month June		0.946	0.206	**0.000**	***		0.440	0.484	0.365	
	Month July		0.909	0.212	**0.000**	***		1.004	0.505	**0.048**	*
	Month August		1.555	0.203	**0.000**	***		1.231	0.605	**0.042**	*
	Treatment (control): Y 2018	84	-0.774	0.463	0.095		15	-0.060	0.274	0.826	
	Treatment (control): Y 2019	84	-0.577	0.410	0.160		15	-0.048	0.258	0.854	
	Treatment (control): M June	5	-0.014	0.114	0.904		45	0.366	0.651	0.575	
	Treatment (control): M July	5	-0.016	0.120	0.894		45	0.523	0.751	0.487	
	Treatment (control): M Aug	5	-0.015	0.114	0.895		45	0.739	0.940	0.432	
	Flower abundance	100	0.429	0.070	**0.000**	***	100	2.635	0.740	**0.000**	***

(*continued*)

Table 2 (*Continued*)

Insect group model [a]	Variable name [b]	Headland transects (T1, T2) Rel imp (%)	Model estimate [c]	± SE	Pr(>|z|) [d]		Alleyway transects (T3) Rel imp (%)	Model estimate [c]	± SE	Pr(>|z|) [d]	
Other flies	Treatment (control)		-0.419	0.385	0.277			0.725	0.575	0.208	
	Year 2018		1.020	0.204	**0.000**	***		0.168	0.353	0.635	
	Year 2019		0.258	0.195	0.186			0.569	0.298	0.058	
	Month June		1.854	0.237	**0.000**	***		1.332	0.448	**0.003**	**
	Month July		1.221	0.259	**0.000**	***		0.730	0.481	0.130	
	Month August		2.891	0.245	**0.000**	***		1.445	0.414	**0.001**	***
	Treatment (control): Y 2018		-1.201	0.313	**0.000**	***	25	-0.179	0.405	0.660	
	Treatment (control): Y 2019		0.307	0.298	0.303		25	-0.083	0.289	0.774	
	Treatment (control): M June		-0.393	0.362	0.277		29	0.314	0.593	0.597	
	Treatment (control): M July		-0.562	0.386	0.146		29	0.351	0.649	0.589	
	Treatment (control): M Aug		-1.809	0.367	0.000	***	29	0.214	0.470	0.650	
	Flower abundance		0.337	0.073	**0.000**	***	100	2.602	0.641	**0.000**	***
Beetles	Treatment (control)		-1.205	0.760	0.114			6.078	2.006	**0.003**	**
	Year 2018		1.196	0.415	**0.004**	**		3.597	1.741	**0.040**	*
	Year 2019		1.495	0.428	**0.000**	***		5.994	1.853	**0.001**	**
	Month June		2.887	0.437	**0.000**	***		2.522	1.140	**0.028**	*
	Month July		2.058	0.432	**0.000**	***		-0.636	1.158	0.585	
	Month August		-0.340	0.436	0.436			-14.351	213.429	0.947	
	Treatment (control): Y 2018	95	-0.345	0.604	0.569		100	-4.455	2.368	0.061	
	Treatment (control): Y 2019	95	-1.836	0.773	**0.018**	**	100	-8.222	2.180	**0.000**	***
	Treatment (control): M June	16	-0.148	0.460	0.748			NA	NA	NA	
	Treatment (control): M July	16	-0.194	0.531	0.715			NA	NA	NA	
	Treatment (control): M Aug	16	-0.180	0.540	0.739			NA	NA	NA	
	Flower abundance	100	0.467	0.135	**0.001**	***	67	2.332	2.328	0.318	

[a]For Solitary Bees, Bumblebees and Other flies on the headland transects, the full models were selected as the best models with AICc differences greater by at least 10 units than the next best model, therefore full model results are presented and no relative importance is given.

[b]Wildflower area (Treatment), 2017 (Year) and April (Month) are used as baseline levels for the models.

[c]Positive estimates indicate higher numbers e.g. higher insect counts in control than wildflower area orchards (Treatment); higher counts in 2018 than 2017, and vice versa for negative estimates.

[d]p-values (to test the null hypothesis that the coefficient estimate is equal to zero, ie. no effect) were calculated from z-values, the ratio between the estimated coefficient and the standard error of the estimate (estimate/SE). Large z-values show that the estimate is large (in relation to its SE) and can be accounted as significantly different from zero. Significance levels: * <0.05, ** <0.01, ***<0.001.

May (during crop bloom), increasing in June and July and decreasing again in August (Fig. 1).

The summed total flower abundance of all species was significantly higher in sown wildflower areas than in equivalent existing headlands in control orchards or in the orchard alleyway habitats within both wildflower and control orchards (Tukey pairwise post-hoc tests $p<0.001$) and in all three study years (Appendix B, Fig. B.1). Analysis of variance (ANOVA) on mean total flowers per transect showed a significant effect of treatment ($F = 84.59$, df = 3, $p<0.001$) but not of year (Fig. B.1).

Effects of treatment, year and month on insect counts

We recorded a total of 16,667 insects across all transect surveys (n = 828) undertaken during the three-year study. These included solitary bees (10% of the total), bumblebees (6%), honeybees (*Apis mellifera*, 7%), hoverflies (syrphid flies, 12%), other (non-syrphid) flies (21%), beetles (28%), with wasps, butterflies, moths and other insects recorded in lower numbers (15%) and excluded from further analyses.

Flower abundance on the survey transect had a highly significant positive effect on insect counts for all groups, on both headland and alleyway transects, apart from beetles on alleyway transects (Table 2). Survey year and month were significant variables for all taxa. Counts were typically higher in 2018 and/or 2019 than in 2017, and in June and/or July transects compared with April and August transects for bees and beetles, and also higher in August for the hoverflies and other flies (Table 2).

On the headland transects, effects of treatment were dependent on year and month but counts were generally higher on sown wildflower areas than the equivalent existing headlands in control orchards (Table 2). Orchard treatment: year (Fig. 2) and treatment: month (Appendix C, Fig. C.1)

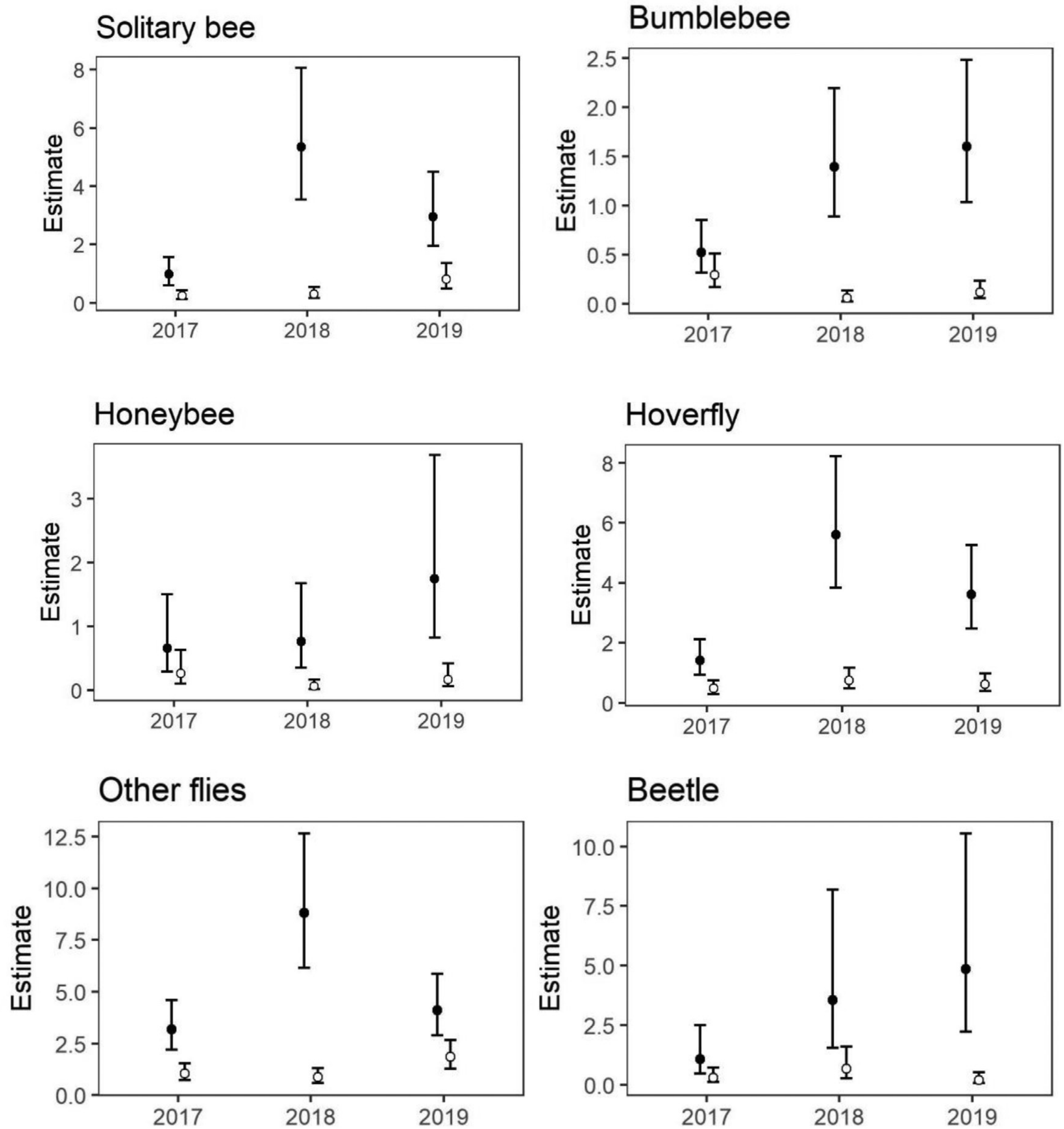

Fig. 2. Model-fitted estimates of insect counts on orchard headland transects, showing interactions between orchard treatment (black filled circle = wildflower area orchards; open circle = control orchards) and year. Error bars represent 95% confidence intervals, showing variation within each treatment across all explanatory variables (fixed effects) that were included in the best models (Table 2).

interactions were significant for all insect groups apart from hoverflies, for which counts were consistently higher on wildflower areas regardless of month or year (Fig. 2, Table 2). The increase in counts on wildflower areas compared with control headlands was greater in 2018 than in 2017 for solitary bees, bumblebees, honeybees and other flies, and this difference was maintained in 2019 for bumblebees, honeybees and beetles. Higher counts on wildflower areas than control headlands were found for solitary bees and bumblebees in June and July but not in April, and for non-syrphid flies in August. On the orchard alleyway transects, we found no effects of treatment on any insect group apart from beetles, for which the treatment: year interaction was significant suggesting higher counts on alleyways in orchards with wildflower areas in 2019. However, beetle counts were highly variable and often dominated by large numbers of pollen beetles (*Meligethes* spp.).

Effects of floral cover in orchard habitats and wider landscape context on insect counts

Adding local floral cover within the orchard and the two landscape variables, area of orchards or semi-natural habitats within a 500 m radius, to the models did not affect the significance of effects of the core variables as presented in Table 2 for any group (Appendix C, Table C.1). Solitary bee counts (but not counts of other groups) were significantly positively related to the percentage area of the orchard covered with flowers of key non-crop forage plants (GLMM model estimate 0.322, (± 0.11 SE), $p<0.01$, relative importance 100%). We did not detect effects of wider landscape context on insect counts for any group (Table C.1).

Discussion

Our study demonstrates a robust approach to managing sown wildflower areas in commercial orchards, overcoming issues of seed mix establishment and weed control to provide enhanced floral resources from the end of crop bloom and throughout the season (Box 1). The findings confirm our first hypothesis, that plant communities on sown wildflower areas change as sown species establish, and our results provide a benchmark against which cover of sown and unsown species can be monitored over time in other similar crop systems (Table 1). There were temporal and taxon-specific effects of sown wildflower areas on insect counts, when compared with existing (control) orchard headlands. Insect numbers were higher on sown wildflower areas for solitary bees and bumblebees as well as honeybees, flies and beetles, but effects were dependent on year following establishment for most taxa, and varied over the season, thus partly confirming hypothesis 2. We did not detect spillover of insects from wildflower areas onto grass alleyways between orchard rows, counter to hypothesis 3. Finally we found significant positive effects of levels of floral cover in local habitats within the orchard on solitary bee numbers, but not on other insect groups, and no effects of wider landscape context on insect counts or on their responses to sown wildflower areas, thus offering little support to hypothesis 4.

The interaction between treatment and year for solitary bees, bumblebees, honeybees and beetles (Fig. 1) indicates that wildflower areas may not attract significantly more insects than equivalent existing orchard headlands until the second year following establishment (2018). Our data suggests that the increase in floral abundance due to the sown wildflower areas may have enhanced bee populations through increased nectar and pollen provision during 2017 (particularly from the sown annual flowers), leading to higher numbers of flower visitors in subsequent years. Sown wildflower areas are demonstrated to reduce foraging trip duration and parasitism rates and increase reproductive success of solitary bees nesting nearby, when compared to bees nesting in isolated sites in a single year study (Ganser et al., 2021). Our three-year study suggests that this effect may persist, provided floral abundance is maintained. Hoverflies and other flies showed a similar response to the other taxa and although evidence for significantly higher numbers of hoverflies in the first year was weak, they were more abundant on wildflower areas than control headlands in all years. This may have been due to their mobility and lack of central-place foraging, combined with a preference for open flower structures such as provided by umbellifers (e.g. *Daucus carota*) and the annuals (e.g. *Anthemis austriaca*) which flowered consistently during the first year of the study.

Our aim to design a wildflower seed mix that provided foraging resources for insect pollinators from the end of crop bloom and throughout their active flight seasons was largely met (Fig. 1). The interactions between treatment and month suggest that sown wildflower areas were attracting only low numbers of pollinators during April/ early May, including the period of apple bloom, then coming into flower in early summer when floral resources in existing orchard headlands and grass alleyways were severely limited (Fig. B.1). Low numbers of solitary bees and bumblebees during April would be expected with this being their period of nest establishment and colony founding, but previous research has suggested that a lack of phenological overlap between insect pollinator activity periods, particularly those of solitary bees (*Andrena* spp.), and flowering time in selected wildflower mixes may limit the benefits received by bees (Campbell, Wilby, Sutton & Wäckers 2017). Our study suggests that this can be overcome, but also emphasises the challenges of selecting a single wildflower mix to attract and retain a range of pollinating insects (M'Gonigle, Williams, Lonsdorf & Kremen 2016). Our finding of significant effects of transect-level flower abundance on counts of all studied insect groups also supports the benefits of existing nectar and pollen resources provided by dandelion (*Taraxacum* spp.) and other naturally occurring plant species in headlands and alleyways. Indeed, dandelion (*Taraxacum* spp.) abundance in UK cider apple orchards increased visitation rates of wild insects to apple flowers (Campbell et al., 2017), and could be promoted through reduced mowing regimes as a low-cost means of providing valuable forage.

Where we directly compared insect counts on alleyway transects between orchards with and without sown wildflower areas, there was no evidence for spillover into these predominantly grass areas between tree rows. Although this may be due to these areas being generally low in flowers, and thus supporting relatively few pollinators whatever their local abundance, it should be borne in mind that the benefits of sown wildflower areas for biodiversity may not always spill over to adjacent crops (which were not measured in this study) or may require more than three years to build populations and show significant benefits to fruit production (Campbell et al., 2017; Pywell et al., 2015). It is also critical to consider species-level patterns and insect interactions with flowering plants through the season (both on and off the apple crop). These are areas under which research is ongoing within the same orchard experiment, but are beyond the scope of the current paper.

Our study was not designed to directly test impacts of landscape context on pollinator responses to wildflower areas, such as by using a gradient of land use intensity (Carvell et al., 2011). However, there was substantial variation in the proportional cover of semi-natural land classes (range 0-33%) and top fruit orchards (range 8-82%) around the study orchards. We found no evidence to suggest effects of wider landscape context on the insect counts on non-crop habitats, or on the effectiveness of wildflower areas in attracting pollinators. Pollinator diversity and visitation rates to crop flowers may be influenced by landscape context (Albrecht et al., 2020; Scheper et al., 2013) and should be key measures in future studies. However, our findings did confirm the importance of local floral cover in habitats within the orchard (in addition to sown wildflower areas) for solitary bees in particular. Such habitats included hedgerow bases, woodland edges and patches of unmanaged herbaceous vegetation. These habitats, typical of less intensive management, may also provide critical non-flowering habitat components such as nest sites and overwintering refuges for a range of beneficial insects (Lye, Park, Osborne, Holland & Goulson 2009; Pywell, James, Herbert, Meek, Carvell et al., 2005).

We conclude that sown wildflower areas can be an effective tool for promoting the abundance of insect pollinators in commercial orchard systems, and that this effectiveness is likely to be consistent despite variation in landscape context. Whether these benefits extend to provision of enhanced fruit pollination and crop yield requires further research, including consideration of the scale and spatial distribution of interventions within or around the orchard (Dicks, Baude, Roberts, Phillips, Green et al., 2015; McKerchar et al., 2020). The successful establishment of sown wildflower areas and delivery of benefits for pollinators relies on appropriate and reactive management practices (Box 1) as a key component of any such agri-environment scheme.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Supplementary materials

Supplementary material associated with this article can be found in the online version at doi:10.1016/j.baae.2021.11.001.

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