**Original citation:** Mckerchar, Megan, Potts, S.G., Fountain, M.T., Garratt, M.P.D. and Westbury, Duncan (2020) *The potential for wildflower interventions to enhance natural enemies and pollinators in commercial apple orchards is limited by other management practices.* Agriculture, Ecosystems and Environment, 301. Article no. 107034. ISSN 0167-8809

**Permanent WRaP URL**: https://eprints.worc.ac.uk/id/eprint/9460

**Copyright and reuse:**

The Worcester Research and Publications (WRaP) makes this work available open access under the following conditions. Copyright © and all moral rights to the version of the paper presented here belong to the individual author(s) and/or other copyright owners. To the extent reasonable and practicable the material made available in WRaP has been checked for eligibility before being made available.

Copies of full items can be used for personal research or study, educational, or not-for-profit purposes without prior permission or charge, provided that the authors, title and full bibliographic details are credited, a hyperlink and/or URL is given for the original metadata page and the content is not changed in any way.

**Publisher's statement:**

This is an Accepted Manuscript of an article published by Elsevier in Agriculture, Ecosystems and Environment available online: https://www.sciencedirect.com/science/article/pii/S016788092030219X. © 2020 Elsevier. Licensed under the Creative Commons Attribution-NonCommercial-NoDerivatives 4.0 International. http://creativecommons.org/licenses/by-nc-nd/4.0/

**A note on versions:**

The version presented here may differ from the published version or, version of record, if you wish to cite this item you are advised to consult the publisher's version. Please see the 'permanent WRaP URL' above for details on accessing the published version and note that access may require a subscription.

**For more information, please contact wrapteam@worc.ac.uk**

# The potential for wildflower interventions to enhance natural enemies and pollinators in commercial apple orchards is limited by other management practices

McKerchar, M[1], Potts, SG[2], Fountain, MT[3], Garratt, MPD[2], & Westbury, DB[1]*

[1]*School of Science & the Environment, University of Worcester, Henwick Grove, Worcester, WR2 6AJ, UK.*

[2]*Centre for Agri-Environmental Research, School of Agriculture, Policy & Development, University of Reading, Reading, RG6 6AR, UK.*

[3]*NIAB EMR, New Road, East Malling, Kent, ME19 6BJ, UK.*

**Corresponding author: Tel: + 44 (0)1905 542461; E-mail: d.westbury@worc.ac.uk*

**Keywords:** Integrated Pest Management, IPM, Conservation biological control, Natural enemies, Pollinators, Insecticides, Acaricides

## Abstract

Modern fruit production has successfully increased yields and fruit quality to meet market demands mainly through intensification and the use of Plant Protection Products (PPPs). Due to the associated environmental impacts and consumers increasingly demanding food produced more sustainably, the tree fruit sector is seeking to reduce its reliance on PPPs. Despite intensification, apple production is still highly dependent on ecosystem services, including pest regulation and pollination. The aim of this study was to investigate the response of natural enemies and pollinators in commercial apple orchards to the provision of a wildflower habitat. It was hypothesised that the abundance and diversity of beneficial invertebrate species would be enhanced leading to an increased control of apple pests and enhanced pollination of apple blossom. We also investigated the effect of orchard pesticide toxicity on natural enemies and pest regulation services and how responses varied between apple cultivars (Jazz and Braeburn). The study was carried out in five orchards of each apple variety across Kent (UK), using a split-plot experimental design. At each site, a one-hectare orchard plot was established with wildflower strips in alleyways between rows of trees and compared with a one-hectare control plot where alleyways were managed conventionally with regular cutting. Responses of natural enemies and pollinators were recorded over a period of three and four years, respectively. The presence of wildflower strips did not contribute significantly towards the delivery of natural pest regulation or pollination services. However, hoverfly diversity and species richness were greater in orchards with wildflower strips, and whilst this was not associated with increased rates of pest regulation, such a response could potentially provide more resilient pest regulation and pollination services. Braeburn orchards had higher bee abundance, and pest predation rates, which were associated with a greater abundance of earwigs, compared to Jazz orchards. Of key significance for growers is that high values of cumulative pesticide toxicity negatively affected natural enemy populations, especially earwigs. If growers want to support natural enemies and wild pollinators in modern apple orchards following the principles of ecological intensification, they need to consider both the types and frequency of pesticide sprays used, in conjunction with interventions aimed at promoting beneficial invertebrates.

## 1. Introduction

Intensive modern fruit production has successfully increased yields and fruit quality to meet market demands. This has mainly been achieved through denser planting systems, the use of grafted M9 rootstocks, precision farming technologies, and changes in the use of chemical inputs (van de Zande *et al.*, 2008; Bloch *et al.*, 2018). Apple production, however, still receives significant benefits from ecosystem service inputs, including pollination and natural pest regulation (Cross *et al.*, 2015; Demestihas *et al.*, 2017; Samnegard *et al.*, 2019). Unfortunately, the use of Plant Protection Products (PPPs) has resulted in a number of negative impacts. Regular inputs have increased insecticide resistance reducing their efficacy (Dunley and Welter, 2000), and effects on non-target organisms are reported for bees (Stanley *et al.*, 2015) and natural enemies (Marko *et al.*, 2009; Fountain and Harris, 2015). Consequently, many products now have restricted use or are being withdrawn, leading to the increased application of other less effective PPPs (Hillocks, 2012). The drive to reduce the reliance of growers on PPPs coupled with consumers increasingly demanding high quality food that is produced with lower environmental impacts (Vermeir and Verbeke, 2006), has required the sector to seek sustainable approaches to production. This has included reduced inputs of agro-chemicals and more effective management of ecosystem services including pollination and natural pest control.

For commercial apple production, Integrated Pest Management (IPM) can be a robust and sustainable method for the control of pests (Suckling *et al.*, 1999). As part of IPM, many different approaches are used, including cultural techniques (Morrison *et al.*, 2019), conservation biological control (Heimpel, 2019), the direct release of natural enemies (Sigsgaard *et al.*, 2017) and the deployment of semio-chemicals for pest mating disruption (Sigsgaard *et al.*, 2006). IPM aims to integrate these control methods in conjunction with the timely use of selective PPPs, enabling growers to keep pest populations below economically damaging thresholds, whilst reducing environmental impacts. During the 1990s, in western Europe, only 35% of pome fruit (apple, pears and quince) was grown using IPM techniques (Kogan and Bajwa, 1999), but since 2014, the European Sustainable Use Directive (2009/128/EC) has made it compulsory for all member states to adopt IPM methods (Birch *et al.*, 2011). However, IPM may not be fully implemented by growers due to a lack of awareness, a greater risk to the crop, increased costs of adoption (including more intensive monitoring), combined with a lack of knowledge and training on how to effectively implement measures (Fitter *et al.*, 2010; Damos *et al.*, 2015).

For the effective control of orchard pests by natural enemies as part of IPM, it appears a wide range of predators are required (Nicholas *et al.*, 2005; Dib *et al.*, 2010). In addition to target pests, many natural enemies also require pollen, nectar, alternative prey, and shelter (van Emden, 2002). Ground vegetation in modern orchard systems usually consists of species-poor grassland communities, which is cut regularly, primarily to reduce competition with the crop (Granatstein and Sánchez, 2009). This regime prevents the development of suitable habitat (shelter) for natural enemies and associated floral resources (nectar and pollen). However, these resources can be provided by introducing appropriately managed wildflower strips directly into orchards (Bugg and Waddington, 1994). The presence of wildflower habitat has the potential to contribute to natural pest regulation services as part of an IPM strategy (Landis *et al.*, 2000; Duru *et al.*, 2015).

The intensification of food production systems has also been associated with declines in pollinators (Potts *et al.*, 2016), such as wild bees and hoverflies (Biesmeijer *et al.*, 2006; Goulson *et al.*, 2008; Potts *et al.*, 2010a; Carvalheiro *et al.*, 2013), but also managed honeybees in some regions (Potts *et al.*, 2010b). Key drivers linked to declines are habitat loss and fragmentation, increased use of agrochemicals, greater disease prevalence, and the effects of non-native species, all set within the context of climate change (Potts *et al.*, 2016). Wild pollinators and honeybees are both vital for effective crop pollination (Garibaldi *et al.*, 2013), but pollination services provided to crops are being disrupted (Deguines *et al.*, 2014), resulting in sub-optimal pollination (Garratt *et al.*, 2014b). To support crop pollination the presence of wildflower strips has been shown to enhance pollinator visitation and pollination to mango (Carvalheiro *et al.*, 2012), blueberries (Blaauw and Isaacs, 2014), strawberries (Feltham *et al.*, 2015), oilseed rape, and field beans (Pywell *et al.*, 2015). Due to the increased provision of nectar, pollen and other forage resources, wildflower strips in modern apple orchards might therefore be expected to enhance local pollinator communities and the delivery of pollination services, helping address pollination deficits (Garratt *et al.*, 2014a; Garratt *et al.*, 2014b). Wildflower strips can be deployed at field boundaries (Blaauw and Isaacs, 2014), or within cropped areas (Marko *et al.*, 2013). In modern orchards however, field boundaries are usually maintained for vehicle access (including turning at the end of rows) and the storage of apple bins prior to harvest. Establishing wildflower strips between rows of trees is therefore more acceptable to growers and this approach is more likely to increase spill-over of beneficial insects into the crop (Gomez-Marco *et al.*, 2016).

The aim of this study was to investigate natural enemies and pollinators in commercial apple orchards in response to the provision of an introduced wildflower habitat. We hypothesised that the increased availability of habitat resources would elevate abundance and diversity of beneficial species and concomitantly increase the regulation of apple pests and pollination services to apple blossom. Furthermore, due to the potential impact of PPPs, we tested the hypothesis that the abundance and diversity of natural enemies and the services they provide would be relatively lower in orchards with high levels of PPPs or their cumulative toxicity (Thomson and Hoffmann, 2006). Given the potential for differences in responses based on apple cultivar (Minarro and Dapena, 2007), we also hypothesised that responses might be different in two commercially important apple varieties, Jazz and Braeburn.

## 2. Method

### *2.1. Experimental Design*

A split-plot experimental design was used to investigate responses of natural pest regulation and pollination services in ten apple orchard sites across Kent (UK). Five of the orchard sites contained the apple cultivar Jazz, and five Braeburn. At each of the sites, two, one-hectare orchard plots were identified, and one received the wildflower treatment in alleyways between rows of trees. This was compared with a one-hectare control plot managed conventionally with the regular cutting of alleyway vegetation throughout the season. The two plots at each site were separated by at least 150 m. Orchards were located within a typical agricultural matrix surrounded by other orchards, soft fruit production, and cereal crops. The Jazz orchards were on loam textured soils, whereas the Braeburn orchards were either on loam or clayey-loam soils.

In March 2013, a native perennial seed mix (supplied by Emorsgate Seeds, Norfolk, UK) was used to establish the wildflower habitat in alleyways between rows of trees. Prior to sowing, alleyways were sprayed with glyphosate to remove competition from existing vegetation and cultivated after five days to provide a rough seed bed. Dead vegetation was left *in situ*. Perennial species only were sown to reduce variation in floral resource availability between years, which can result from using mixes containing annuals and biennials (Campbell *et al.*, 2017a). The mix consisted of nine herbaceous species and one grass species (Table 1). The herbaceous species were selected for their different vegetative structure, flowering morphology and phenology, whilst *Dactylis glomerata*, a tussock forming grass species, was sown to provide vegetation structure for natural enemies. Seed was sown in spring 2013 at a rate of 5 kg ha$^{-1}$. After hand-sowing the seed mixed with sand (to attain a more even distribution), the wildflower strips were rolled to firm contact of the seed with the soil. Due to poor initial establishment at some sites, in August 2013 all the wildflower strips were lightly cultivated, and further seed was sown at the same rate as in spring 2013 (5 kg ha$^{-1}$). The wildflower plots consisted of 16 sown inter-row strips (70 cm wide and 100 m long) established in alternate alleyways between rows of trees. Hence, in each 1 ha plot, 11.2% (1,120 $m^2$) of the area was established with a sown wildflower resource. The abundance of flowering resource was determined by counting the number of floral units present in twenty 50 x 50 cm quadrats randomly placed in the alleyways. A floral unit was defined according to Carvalheiro *et al*. (2008). In year one, surveys took place in April and August, and monthly from April to August in years two and three (Table 2).

**Table 1.** Plant species sown in the wildflower strips in alleyways between rows of apple trees**.**

| Scientific name | Common name | Sowing rate (seeds $m^{-2}$) | Sowing rate (kgha$^{-1}$) |
|---|---|---|---|
| *Achillea millefolium* | Yarrow | 25 | 0.04 |
| *Centaurea nigra* | Black Knapweed | 50 | 1.25 |
| *Dactylis glomerata* (wild type) | Orchard grass | 10 | 0.10 |
| *Galium verum* | Lady's bedstraw | 50 | 0.26 |
| *Leontodon hispidus* | Rough hawkbit | 50 | 0.56 |
| *Leucanthemum vulgare* | Oxeye daisy | 25 | 0.13 |
| *Lotus corniculatus* (wild type) | Bird’s-foot-trefoil | 50 | 1.00 |
| *Prunella vulgaris* | Selfheal | 50 | 0.50 |
| *Silene dioica* | Red campion | 50 | 0.50 |
| *Trifolium pratense* (wild type) | Red Clover | 50 | 0.67 |

During the establishment year (year one, 2013), the strips were kept to a height of 8 cm with regular cutting. This helped promote plant establishment and enabled baseline data to be collected. During years two and three (2014 & 2015) the strips were managed with a single September cut to a height of 8 cm. All cuttings were left *in situ*.

For all sampling methods, the one-hectare plots at each site were sampled on the same day to reduce temporal and climatic variability. To reduce edge effects, no sampling was done within the first 20 m of plot edges.

**Table 2**. Average counts of floral units from sown wildflower species (number of flower units per 0.25 m$^2$) (±SE) in alleyways between rows of apple trees according to apple cultivar, treatment and year, recorded from April to August. Values for the control treatment indicate natural occurrence of sown species.

| Apple Cultivar | Site Number | Year 1 |  | Year 2 |  | Year 3 |  |
|---|---|---|---|---|---|---|---|
|  |  | Control | Wildflower Treatment | Control | Wildflower Treatment | Control | Wildflower Treatment |
| Jazz | 1 | 0.03 | 0.00 | 0.00 | 0.45 | 0.00 | 12.10 |
|  | 2 | 0.00 | 0.00 | 0.00 | 2.65 | 0.80 | 15.46 |
|  | 3 | 0.00 | 0.17 | 0.20 | 25.33 | 0.00 | 3.35 |
|  | 4 | 0.00 | 0.00 | 0.00 | 0.00 | - | - |
|  | 5 | 0.00 | 0.20 | 0.00 | 10.62 | 0.60 | 9.15 |
| **Averages (±SE)** |  | **0.01 (±0.01)** | **0.07 (±0.05)** | **0.04 (±0.04)** | **7.81 (±4.78)** | **0.35 (±0.21)** | **10.02 (±2.57)** |
| Braeburn | 6 | 0.00 | 0.81 | 0.00 | 6.25 | 0.00 | 6.80 |
|  | 7 | 0.17 | 0.17 | 0.30 | 4.65 | 0.00 | 26.61 |
|  | 8 | 0.50 | 0.33 | 0.60 | 0.20 | - | - |
|  | 9 | 0.13 | 0.17 | 0.00 | 7.60 | 0.00 | 5.42 |
|  | 10 | 0.00 | 0.33 | 0.15 | 6.25 | 0.00 | 22.42 |
| **Averages (±SE)** |  | **0.16 (±0.09)** | **0.36 (±0.12)** | **0.21 (±0.11)** | **4.99 (±1.29)** | **0.00 (±0.00)** | **15.31 (±5.39)** |

### *2.2. Cumulative toxicity*

To make a broad assessment of the level of exposure of natural enemies to pesticides at each site, average cumulative toxicity was used (Thomson and Hoffmann, 2006; Marliac *et al.*, 2015). This was calculated for each site and for each year using spray records provided by the growers. There was no difference in the use of sprays between treatments at each site. Only insecticides and acaricides were included in the analysis as they tend to be the most toxic to invertebrates (Pekar, 1999). To provide indicative values of toxicity for each product, potential effects on a range of natural enemy groups were estimated, including Anthocoridae, Chrysopidae, Miridae, parasitoids and predatory mites. The potential impact of PPPs on pollinators was not considered in this study. This is because growers are restricted from applying products harmful to bees during the apple blossom period.

Potential effects on the natural enemies were determined by assigning a score according to a four-point scale: 1 = low toxicity (harmless, <25% mortality), 2 = slightly harmful (25-50% mortality), 3 = moderately harmful (50-75%), and 4 = very harmful (> 75% mortality) for each of these groups. These categories were based on information from Koppert (2019) and Biobest (2019), which follow guidelines from the International Organisation for Biological Control (IOBC), combined with the published research (Giolo *et al.*, 2009; Godoy *et al.*, 2010; Amarasekare and Shearer, 2013a, b). IOBC guidelines are also used for registering products in the European Union (Council Directive 91/414/EEC). An average score across the five taxonomic groups for each active ingredient was calculated to provide an overall product toxicity value (Supplementary Table S1).

A total of 12 active ingredients were used by growers, eight of which were insecticides, and four acaricides. The main insecticide products used were flonicamid, which accounted for 22% of all spray applications (both insecticides and acaricides), chlorantraniliprole (19%), chlorpyrifos (11%), thiacloprid (11%), and methoxyfenozide (9%). Cumulative toxicities in orchards ranged from 2.5 to 22.8 and averaged 9.72 (± 0.95) (Table 3). The total number of insecticide and acaricide sprays applied to an orchard varied between three and 16 sprays per year, with an average of 6.5 (± 0.6) sprays per year.

Values of cumulative toxicity were determined by summing toxicity scores according to the products used and their frequency of use across the year for each site (Marliac *et al.*, 2015). Based on these values, sites were assigned to two different categories of toxicity. Sites were deemed to have relatively low values of cumulative toxicity if values ranged from 2.5-7.8, and relatively high values of cumulative toxicity if values were 8.0-22.8. Low scoring sites tended to be associated with the use of less toxic products and fewer spray applications.

**Table 3**. Values of cumulative orchard toxicity and number of PPP spray applications according to apple cultivar, site and year.

| **Apple Cultivar** | **Site Number** | **Year 1** | | **Year 2** | | **Year 3** | |
|---|---|---|---|---|---|---|---|
| | | Cumulative Toxicity | Number of Sprays | Cumulative Toxicity | Number of Sprays | Cumulative Toxicity | Number of Sprays |
| Jazz | 1 | 22.8 | 16 | 16.5 | 9 | 13.5 | 10 |
| | 2 | 5.0 | 3 | 3.0 | 4 | 2.5 | 3 |
| | 3 | 8.0 | 5 | 14.2 | 8 | 5.5 | 5 |
| | 4 | 17.3 | 13 | 16.5 | 9 | - | - |
| | 5 | 8.0 | 5 | 14.2 | 8 | 5.0 | 4 |
| **Averages (±SE)** | | **12.2 (±3.4)** | **8.4 (±2.6)** | **12.9 (±2.5)** | **7.6 (±0.9)** | **6.6 (±2.4)** | **5.5 (±1.6)** |
| Braeburn | 6 | 7.8 | 6 | 5.0 | 5 | 7.7 | 4 |
| | 7 | 9.5 | 8 | 5.7 | 5 | 6.7 | 5 |
| | 8 | 8.3 | 7 | 9.5 | 7 | - | - |
| | 9 | 9.5 | 4 | 16.0 | 7 | 13.0 | 6 |
| | 10 | 9.2 | 7 | 5.7 | 5 | 6.7 | 5 |
| **Averages (±SE)** | | **8.9 (±0.3)** | **6.4 (±0.7)** | **8.4 (±2.1)** | **5.8 (±0.5)** | **8.5 (±1.5)** | **5.0 (±0.4)** |

### *2.3. Natural enemy abundance*

To investigate the abundance and diversity of natural enemies in the tree canopy, tap sampling was used over three consecutive years (Knutson *et al.*, 2008; Wearing *et al.*, 2011). Orchard plots were sampled once a month from April/May to September, with at least a 20-day interval between individual samples. In years one and two, five rounds of tap sampling were completed, and six in year three. In year three the number of orchards sampled for natural enemies was reduced to eight (four Jazz and four Braeburn) following the very low occurrence of sown floral units in association with the wildflower treatment (Table 2).

In each orchard plot, fifteen trees were randomly selected. Three branches on each tree were tapped three times above a white 36 cm x 46 cm plastic tray to collect the target arthropods (Schuber *et al.*, 2012). Sampling was done only when tree foliage was dry, and between 09:00 hrs and 18:00 hrs

(McCaffrey *et al.*, 1983). The target arthropods were unable to fly (spiders, and hoverfly larvae, ladybird larvae and lacewing larvae), or reluctant to fly (earwigs, minute pirate bugs, capsid bugs, adult ladybirds). Adult lacewings were identified to family before flight. All target arthropods were recorded to family either in the field, or in the lab following storage in 70% ethanol. Spiders were identified to family (Roberts 1985a, b; 1987) from year two.

### *2.4. Pest abundance and pest regulation*

In years one to three, the presence of Rosy Apple Aphids (RAA) (*Dysaphis plantaginea*) and Woolly Apple Aphids (WAA) (*Eriosoma lanigerum*) was investigated using direct searches for 30 seconds on fifteen apple trees randomly selected in each orchard plot. If a colony was identified, the whole tree was inspected with no time limit (but typically for ten minutes). During inspections RAA and WAA colonies were brushed individually onto a white tray using a paintbrush, enabling accurate counts of aphids and aphid mummies (parasitized aphids). This provided a total number of aphids and aphid mummies per tree. For statistical analysis, average numbers per tree per orchard plot were calculated, whilst percentage occurrence was based on the number of trees in each plot found to support RAA/WAA.

In year three, natural pest regulation in orchards was investigated by recording the depletion of aphids from baited cards. Pea aphids (*Acyrthosiphon pisum*) were used as bait (Geiger *et al.*, 2010) by gluing their back legs or side to white plastic labels with PVA glue. Ten aphids were attached to each card and cards were placed individually on six different trees in the centre of orchard plots, approximately 10 m apart at a height of approximately 1.4 m above the ground. To prevent rain washing off the aphids, cards were bent at a 90° angle and attached perpendicular to the tree using a cable tie (Geiger *et al.*, 2010). Cards were only deployed on dry days between 09:00 hrs and 12:00 hrs. After 24 to 28 hours, the number of aphids depleted on each card was recorded. Aphids remaining on the cards were examined to ensure they were not covered in glue and therefore unpalatable to natural enemies (Geiger *et al.*, 2010). Values of natural pest regulation were based on the number of aphids removed compared to the number of aphids remaining on the card. Monthly rounds were completed in June, July and August.

### *2.5. Pollinator and pollination surveys*

Pollinator surveys took place for a period of four consecutive years (2013-2016) in April/May when the percentage of apple buds in flower was between 10-90%. The proportion of blossoms in flower was determined by randomly selecting five trees within each orchard plot and calculating an average. The blossom period lasted between two and four weeks, which was reflected in the number of sampling rounds each year. At each site a minimum of two rounds were completed and at most, four rounds. Two different approaches were used to investigate the pollinators: transect surveys and crop flower visitation surveys; with the latter method being used as an indirect proxy of pollination services (Garratt *et al.*, 2016).

Timed transect surveys were used to simultaneously assess the number of pollinator species and their abundance along tree rows and alleyways. All bees and adult hoverflies observed along transects were collected by hand-netting and subsequently identified to species (Potts *et al.*, 2005). Each transect consisted of ten minutes, moving at approximately ten metres per minute. Sampling effort was standardised by halting the clock during the handling and processing of specimens, and when moving between alleyways. For each sampling round, one transect was recorded for each orchard plot at each site. For statistical analysis, total numbers of bees and hoverflies per orchard plot were calculated for each year of study. These values were also used to determine values of Shannon diversity and the total number of species recorded.

Crop flower visitation surveys were used to record the number of legitimate flower visits by bees and hoverflies to the apple blossom, which was based on stigma contact indicating a possible pollination event. Three trees were observed in each orchard plot for ten minutes for each round of sampling. Three rounds (30 mins of observations) were completed in each plot during all four years of study. In orchard plots with wildflower strips, trees adjacent to the strips were observed. In the orchard plots with wildflower strips, trees adjacent to the strips were observed. Trees were randomly selected, excluding those which were dead, newly planted replacements, or those neighbouring newly planted or dead trees. An unshaded, 1 m$^2$ area (including the lower tree branches) of each tree was surveyed.

Pollinator surveys were only performed on dry days and when the apple blossom was also dry. All surveys were conducted between 09:30hrs and 16:30hrs (Westphal *et al.*, 2008; Adamson *et al.*, 2012), and sampling rounds at each site were alternated between morning (09:30hrs - 13:00hrs) and afternoon (13:00hrs - 16:30hrs), to account for diurnal behaviour patterns. Surveys were only completed when winds were no more than three on the Beaufort scale (Adamson *et al.*, 2012), combined with a threshold temperature of 12°C on clear days, and 15°C on overcast days (Carvell *et al.*, 2007).

### *2.6. Statistical Analysis*

All responses were analysed using mixed linear models in SAS Studio (Version 3.8, 2018).
Orchard treatment (wildflower presence / absence), apple cultivar (Jazz / Braeburn), site cumulative toxicity (low / high), and year (where applicable), including their interactions were specified as fixed effects. Site, and month (where applicable) nested within site were specified as random effects. Year and month (where applicable) were specified as a repeated measure with an autoregressive covariance structure. Degrees of freedom were calculated using the iterative Satterthwaite's method (Schabenberger and Pierce, 2002). Simplification of the global model was performed by sequentially deleting interactions and then factors that were not significant, unless part of significant interaction term ($P < 0.05$) (Westbury *et al*. 2017). When a factor was significant and not part of a significant interaction, Tukey ($P = 0.05$) post-hoc pairwise comparisons were made. Prior to analyses, all count data (values were pooled for each sampling round in each orchard), including values of species/family richness (number of different species / families recorded) were natural log transformed (n+1), whilst values of percentage occurrence were arcsine square root transformed.

## 3. Results

### *3.1 Natural enemy abundance*

Spiders (Araneae) were the most frequently recorded order of natural enemy across all sites irrespective of treatment and constituted 70.3% of the potential natural enemies of apple pests observed during the three-year study. A total of 4,470 spiders were recorded. Of the 3,251 spiders identified to family in years two and three, samples were dominated by Theridiidae (comb-footed spiders) (Table 4).

There was no effect of orchard treatment on the total number of spiders (Araneae) or any of the spider families recorded (Table 5). However, total spider numbers and Araneidae were significantly greater in year three compared to year two. Total numbers were also more frequent in Jazz orchards compared to Braeburn, which was reflected by the Theridiidae (Figure 1). High values of orchard pesticide toxicity negatively influenced the number of Araneidae and Philodromidae. However, a significant interaction between orchard pesticide toxicity and cultivar was found for Philodromidae, for which there was a tendency for numbers to be lower in Braeburn orchards, especially in those with higher values of cumulative toxicity. No significant effects on Anyphaenidae, Clubionidae, Linyphiidae, or Tetragnatha were found.

Spider family richness and diversity were not affected by orchard treatment (Table 6).
However, cultivar type and values of cumulative orchard pesticide toxicity strongly influenced values. Significant interactions were also found between orchard pesticide toxicity and cultivar, and toxicity and year. Spider family richness and diversity were higher in Jazz orchards, whilst spider diversity increased between years and was consistently higher in Jazz orchards. The significant interaction between year and orchard pesticide toxicity indicated that family richness and diversity were greater in year three in orchards associated with lower toxicity values.

**Table 4.** Spider (Araneae) occurrence in orchards during years two and three.

| Spider Family | Number Recorded | Percentage of Records | Most abundant species |
|---|---|---|---|
| Anyphaenidae | 90 | 2.8% | *Anyphaena accentuata* |
| Araneidae | 769 | 23.7% | *Araniella opistographa* |
| Clubionidae | 59 | 1.8% | *Clubionia* spp. |
| Linyphiidae | 512 | 15.7% | *Entelecara flavipes*, *Lepthyphentes tenuis*, *Tenuiphantes tenuis* |
| Philodromidae | 386 | 11.9% | *Philodromus cespitum* |
| Tetragnathidae | 76 | 2.3% | *Tetragnatha extensa* |
| Theridiidae | 1,359 | 41.8% | *Anelosimus vittatus*, *Theridion mystaceum*, *Theridion varians* |
| **All Araneae** | **3,251** | **100.0%** | |

**Table 5**. Response of spider (Araneae) abundance to orchard treatment (wildflower presence/absence), values of orchard pesticide toxicity (high/low), apple cultivar (Jazz/Braeburn), year and significant interactions between these factors when found.

| Response Variable | Orchard Treatment | Orchard Toxicity | Cultivar | Year | Cultivar x Year | Cultivar x Orchard Toxicity |
|---|---|---|---|---|---|---|
| **All Araneae** | ns | ns | $F_{1,6.93} = 18.87$, $P <0.01$ | $F_{1,56.3} = 10.33$, $P <0.01$ | ns | ns |
| **Anyphaenidae** | ns | ns | ns | ns | ns | ns |
| **Araneidae** | ns | ns | ns | $F_{1,52.1} = 13.41$, $P <0.001$ | $F_{1,52.1} = 7.78$, $P <0.01$ | $F_{1,10.8} = 7.36$, $P <0.05$ |
| **Clubionidae** | ns | ns | ns | ns | ns | ns |
| **Linyphiidae** | ns | ns | ns | ns | ns | ns |
| **Philodromidae** | ns | $F_{1,64.5} = 7.24$, $P <0.01$ | ns | ns | ns | ns |
| **Tetragnathidae** | ns | ns | ns | ns | ns | ns |
| **Theridiidae** | ns | ns | $F_{1,109} = 12.63$, $P <0.001$ | ns | ns | ns |

**Table 6**. Spider (Araneae) family richness and diversity responses to orchard treatment (wildflower presence/absence), values of orchard pesticide toxicity (high/low), apple cultivar (Jazz/Braeburn), year and significant interactions between these factors when found.

| **Response Variable** | **Orchard Treatment** | **Orchard Toxicity** | **Cultivar** | **Year** | **Cultivar x Year** | **Cultivar x Orchard Toxicity** | **Orchard Toxicity x Year** |
|---|---|---|---|---|---|---|---|
| **Richness** | ns | $F_{1,107} = 12.27$, $P < 0.001$ | $F_{1,109} = 30.69$, $P < 0.001$ | ns | ns | $F_{1,108} = 11.58$, $P < 0.001$ | $F_{1,57.9} = 6.44$, $P < 0.05$ |
| **Diversity** | ns | $F_{1,78.4} = 9.46$, $P < 0.01$ | $F_{1,80.7} = 9.24$, $P < 0.01$ | ns | $F_{1,56.3} = 5.54$, $P < 0.05$ | $F_{1,78.5} = 14.13$, $P < 0.001$ | $F_{1,56.4} = 18.84$, $P < 0.001$ |

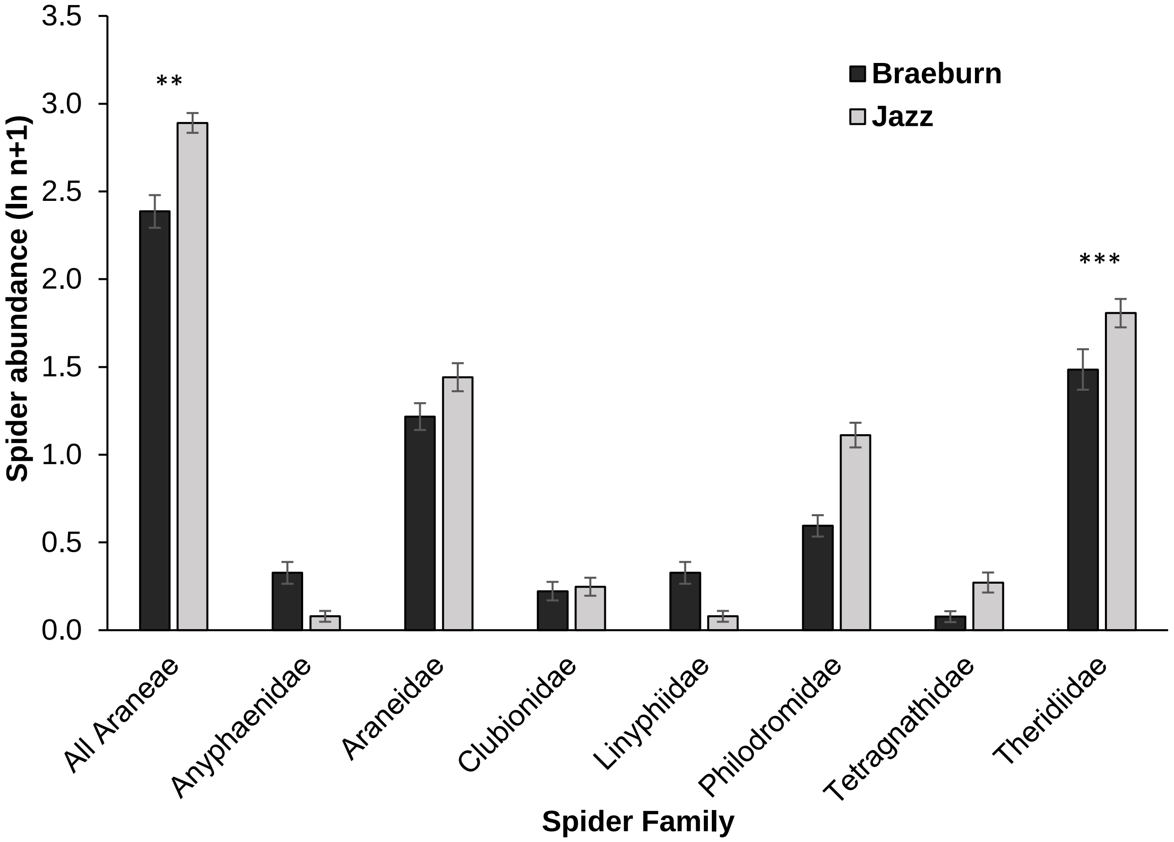

**Figure 1**. Spider abundance according to family group and their responses according to apple variety (±SE). Values with an asterisk indicate a significant difference between cultivars ** = $P < 0.01$ *** = $P < 0.001$.

Specialist aphidophagous predators contributed 29.7% of the total 6,361 natural enemies recorded during the three-year study. Of the aphidophagous predators, Dermaptera were represented only by the European earwig (*Forficula auricularia*), whilst Coccinellidae were represented by larvae and no adults were recorded (Table 7). The total number of aphidophagous predators recorded was not influenced by orchard treatment. However, a significant effect of year and orchard pesticide toxicity was found (Table 8) (Figure 2). Both these factors also interacted significantly in a three-way interaction with apple cultivar. This was associated with higher numbers of aphidophagous predators in Braeburn orchards and lower numbers in year one. Responses to combinations of orchard pesticide toxicity, cultivar and year were highly variable.

**Table 7.** Aphidophagous predator occurrence in orchards during the three-year study

| **Predator Group** | **Number Recorded** | **Percentage of Records** |
|---|---|---|
| Anthocoridae | 175 | 9.3% |
| Coccinellidae larvae | 229 | 12.1% |
| Dermaptera | 1,012 | 53.5% |
| Miridae (predatory) | 357 | 18.9% |
| Neuroptera larvae | 97 | 5.1 |
| Syrphidae larvae | 21 | 1.1% |
| **All Predators** | **1,891** | **100.0%** |

The number of Dermaptera (earwigs) recorded was influenced by orchard pesticide toxicity, with significantly fewer in orchards with higher toxicities (Table 8). Orchard pesticide toxicity also interacted significantly with cultivar, with more earwigs being associated with Braeburn orchards and fewer in orchards with higher toxicities. A significant interaction between orchard pesticide toxicity and year was also found. Numbers were greater in years two and three compared to year one, and in orchards with lower values or toxicity. There was no effect of orchard treatment on earwig numbers.

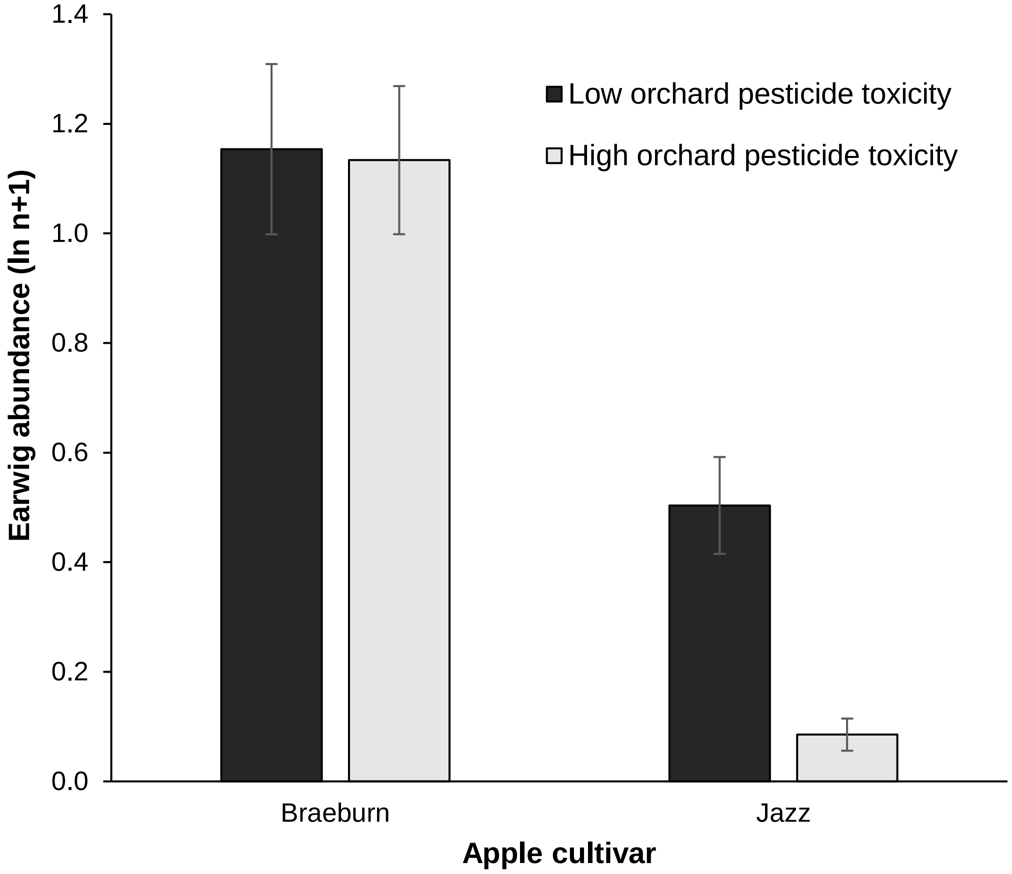

**Figure 2**. Dermaptera (earwig) abundance according to apple cultivar (Braeburn and Jazz) and values of orchard pesticide toxicity (low / high) (±SE).

Responses of Anthocoridae were only significant for the interaction between cultivar and year (Table 8). Numbers increased between years in Jazz orchards but decreased substantially in Braeburn orchards by the third year. Numbers of predatory Miridae and Coccinellidae larvae were influenced only by year. Miridae increased significantly between years (Tukey test, $P < 0.05$), whilst for Coccinellidae larvae, numbers were significantly greater in year three, and no difference was found between years one and two (Tukey test, $P < 0.05$). Significant interactions between cultivar and year, and orchard pesticide toxicity and year, were found for the number of Syrphidae larvae. Numbers increased between years and there was a tendency for greater values in orchards of higher toxicity and in Jazz orchards. A significant interaction between orchard pesticide toxicity, apple cultivar, and year was found for numbers of Neuroptera larvae. Responses were highly variable between the different combinations, but values were greater in year three in Jazz orchards that were also associated with high values of orchard pesticide toxicity. The interaction between cultivar and year was also significant. Numbers of Neuroptera larvae increased between years in both cultivars, and whilst numbers were similar according to cultivar in year three, values increased to a greater extent in Jazz orchards from year two.

**Table 8.** Responses of aphidophagous predators (number) to orchard treatment (wildflower presence/absence), values of orchard pesticide toxicity (high/low), apple cultivar (Jazz/Braeburn), year and significant interactions between these factors when found.

| Response Variable | Orchard Treatment | Orchard Toxicity | Cultivar | Year | Cultivar x Year | Orchard Toxicity x Year | Orchard Toxicity x Cultivar | Cultivar x Orchard Toxicity x Year |
|---|---|---|---|---|---|---|---|---|
| **All Predators** | ns | $F_{1,95.6} = 5.34$, $P < 0.05$ | ns | $F_{2,93.3} = 8.93$, $P < 0.001$ | ns | ns | ns | $F_{7,93.5} = 2.73$, $P < 0.05$ |
| **Anthocoridae** | ns | ns | ns | ns | $F_{2,108} = 4.72$, $P < 0.05$ | ns | ns | ns |
| **Coccinellidae larvae** | ns | ns | ns | $F_{2,94.2} = 13.37$, $P < 0.001$ | ns | ns | ns | ns |
| **Dermaptera** | ns | $F_{1,104} = 6.36$, $P < 0.05$ | $F_{1,216} = 4.77$, $P < 0.05$ | ns | ns | $F_{2,96.7} = 4.26$, $P < 0.05$ | $F_{1,104} = 7.13$, $P < 0.01$ | $F_{4,98} = 2.70$, $P < 0.05$ |
| **Miridae (predatory)** | ns | ns | ns | $F_{2,120} = 13.06$, $P < 0.001$ | ns | ns | ns | ns |
| **Neuroptera larvae** | ns | ns | ns | $F_{2,109} = 3.71$, $P < 0.05$ | $F_{2,109} = 3.26$, $P < 0.05$ | ns | ns | $F_{5,48.9} = 2.86$, $P < 0.05$ |
| **Syrphidae larvae** | ns | ns | $F_{1,9.7} = 7.73$, $P < 0.05$ | $F_{2,114} = 3.20$ $P < 0.05$ | $F_{2,114} = 3.71$, $P < 0.05$ | ns | ns | $F_{5,58.4} = 2.77$, $P < 0.05$ |

### *3.3. Pest abundance and regulation*

*3.3.1. Rosy apple aphids*

Orchard treatment had no effect on the percentage of trees supporting Rosy Apple Aphids (RAA). The factor most influencing occurrence was orchard pesticide toxicity. Significantly more trees supported RAA colonies in orchards with higher toxicities ($F_{1,84.5} = 4.71$, $P < 0.05$). However, significant interactions were also found between orchard pesticide toxicity and cultivar ($F_{1,84.5} = 4.07$, $P < 0.05$); toxicity and year ($F_{2,97} = 5.21$, $P < 0.05$), and toxicity, cultivar, and year ($F_{4,99.2} = 3.94$, $P < 0.01$). The average number of RAA recorded on trees was strongly influenced by toxicity, cultivar, and year, for which a significant interaction was found between these factors ($F_{7,87.9} = 3.04$, $P < 0.01$). There was a tendency for numbers to be greater in Jazz orchards and for values in years two and three to be lower in orchards of high toxicity. However, in year three, no RAA were recorded in the Braeburn orchards, and numbers in Jazz orchards were greater in association with high values of cumulative toxicity.

*3.3.2. Woolly apple aphids*

Orchard treatment had no significant effect on the percentage of apple trees supporting Woolly Apple Aphids (WAA), but the occurrence of WAA did differ significantly between years ($F_{2,99.6} = 6.91$, $P < 0.01$). A higher percentage of trees with WAA was observed in year three compared to years one and two. A significant interaction between cultivar, orchard pesticide toxicity and year was also found ($F_{3,48.8} = 13.20$, $P < 0.001$). A higher percentage of trees supported WAA in in Jazz orchards that were associated with higher levels of toxicity, especially in year three. The average number of WAA recorded on trees was also influenced by a significant three interaction between cultivar, toxicity and year was also found ($F_{2,94.7} = 22.93$, $P < 0.001$). Numbers were generally higher in orchards associated with low toxicities, and were greater in Braeburn orchards in year two, and in Jazz orchards in year three.

*3.3.3. Aphid parasitism*

No effects of orchard treatment, orchard pesticide toxicity, or cultivar were found to influence the occurrence of RAA and WAA mummies. Despite RAA and WAA being present across all three years of study, no RAA mummies (indicating parasitism) were recorded in years one and three, and no WAA mummies were recorded in years one and two. In total, 149 RAA mummies and 816 WAA mummies were recorded. This is equivalent to 0.7% and 11.9% of aphids being parasitized, respectively.

### *3.3.4. Aphid baited cards*

The depletion of aphids from the baited cards was not influenced by orchard treatment or orchard pesticide toxicity. However, month was shown to significantly influence depletion rates ($F_{2,23.7}$ = 6.76, $P < 0.01$), with more aphids being depleted in July, compared to June and August. However, month also interacted significantly with cultivar ($F_{2, 23.7}$ = 6.34, $P < 0.01$). There was a tendency for levels of predation to be greater in Braeburn orchards, particularly in August and July (Figure 3).

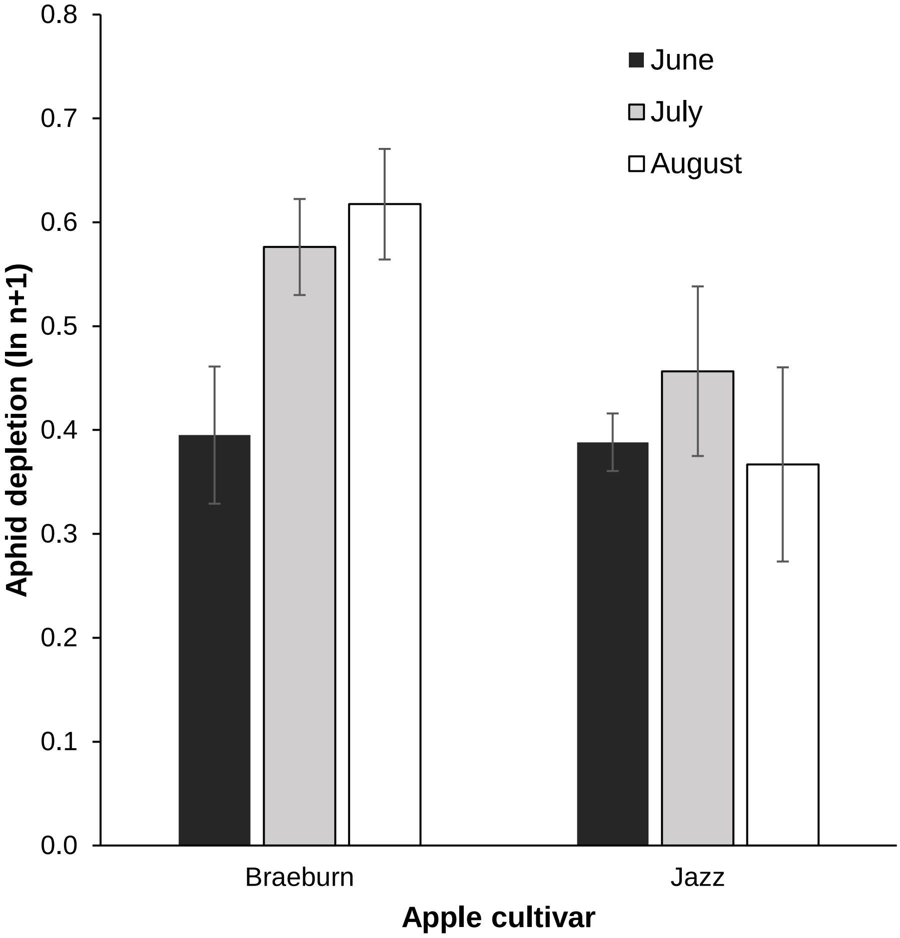

**Figure 3**. Aphid depletion from baited cards based on the proportion removed according to apple cultivar (Braeburn and Jazz) and month (±SE).

### ***3.4. Pollinators and Pollination Services***

#### *3.4.1. Transect surveys*

Over the four-year study, 1,002 bees, comprised of 42 species, and 246 hoverflies comprised of 25 species were recorded. Thirty-two of the bee species were polylectic, consisting of eight bumblebee species (primarily *Bombus lapidarius* and *B. terrestris*) (contributing 20.4% of all polylectic bees recorded), solitary bees (e.g. *Andrena nitida*) (56.6% of records), eusocial mining bees (e.g. *Lasioglossom albipes*) (2.8% of records), and honeybee (*Apis mellifera*) (20.2% of records). In addition, six parasitic species were recorded (e.g. *Nomada goodeniana*), and two were specialists of flower types other than apple blossom (e.g. the endangered *Andrena ferox*, which specialises on *Quercus* spp). The most frequently recorded hoverflies were in the *Platycheirus* genus, which contributed 49.6% of all records.

Ten bee species were recorded only in plots with wildflower strips, including *B. ruderatus* and *B. rupestris*. Whilst, three species were recorded only in the control plots without wildflower strips, including *A. ferox* (although only one individual was observed). However, there was no overall effect of orchard treatment on the number of bee species, their abundance, or diversity. A greater abundance of bees was recorded in Braeburn orchards compared to Jazz, whilst the number of bee species, values of Shannon diversity, and bee abundance, all varied significantly with year (Table 9). Values were consistently greater in year two compared to all other years (Tukey *P* <0.05), and no significant differences were found between other years.

Values of adult hoverfly species richness and diversity were significantly greater in orchards containing wildflower strips (Table 9). Species richness was also greater in Jazz orchards compared to Braeburn, but species richness and diversity also varied significantly with year. Species richness and diversity were greater in year three compared to years two and four (Tukey, *P* <0.05). The number of hoverfly individuals recorded also varied according to year and cultivar type (Table 9). A greater number were recorded in Jazz orchards.

**Table 9.** Transect surveys of pollinators and responses to orchard treatment (wildflower presence/absence), apple cultivar (Jazz/Braeburn), and year.

| Response Variable | Orchard Treatment | Cultivar | Year |
|---|---|---|---|
| **All Bees (abundance)** | ns | $F_{1,73} = 5.57$, $P < 0.05$ | $F_{3,73} = 29.93$, $P < 0.001$ |
| **Bee species richness** | ns | ns | $F_{3.65.2} = 7.25$, $P < 0.001$ |
| **Bee diversity** | ns | ns | $F_{3,65.1} = 5.96$, $P < 0.01$ |
| **Hoverfly abundance** | ns | $F_{1,7.8} = 6.63$, $P < 0.05$ | $F_{3,65.4} = 3.37$, $P < 0.05$ |
| **Hoverfly species richness** | $F_{1,63.9} = 5.53$, $P < 0.05$ | $F_{1,7.9} = 6.86$, $P < 0.05$ | $F_{3,64.4} = 3.67$, $P < 0.05$ |
| **Hoverfly diversity** | $F_{1,64.1} = 6.04$, $P < 0.05$ | ns | $F_{3,64.4} = 8.21$, $P < 0.001$ |

### *3.4.2. Crop visitation surveys*

Out of 2,485 observations of apple blossom visitation by bees and hoverflies across all four-years of study, honeybees (*Apis mellifera*) made the greatest number of legitimate flower visits (48.4%), followed by solitary bees (mainly *Andrena* spp.) (28.5%), and *Bombus* spp. (21.1%).

The total number of visits made to apple blossom was strongly influenced by year (Table 10). A significantly greater number of visits was observed in year two compared to all other years (Tukey $P < 0.05$). This response was also reflected by the number of honeybee visits and bumblebee visits. Significantly more honeybee and bumblebee visits were recorded in year two compared to all other years (Tukey $P < 0.05$). A significant year effect was also found for all wild visits (bumblebees, solitary bees, and hoverflies) (Table 10), with significantly more visits in year two compared to years three and four (Tukey test, $P <0.05$). However, the number of solitary bee and hoverfly visits were not influenced by year. Visits by all pollinator groups were not influenced by orchard treatment or apple cultivar.

**Table 10.** Crop visitation surveys of pollinators and responses to orchard treatment (wildflower presence/absence), apple cultivar (Jazz/Braeburn), and year.

| Response Variable | Orchard Treatment | Cultivar | Year |
|---|---|---|---|
| **Total number of visits** | ns | ns | $F_{3,65.1} = 7.60$, $P < 0.001$ |
| **Honeybee visits** | ns | ns | $F_{3,64.8} = 5.44$, $P < 0.01$ |
| **Total wild visits** | ns | ns | $F_{3,65.6} = 10.78$, $P < 0.001$ |
| **Bumblebee visits** | ns | ns | $F_{3,74} = 17.48$, $P < 0.001$ |
| **Hoverfly visits** | ns | ns | ns |
| **Solitary bee visits** | ns | ns | ns |

## 4. Discussion

The deployment of wildflower strips in alleyways between rows of apple trees was used as a strategy to increase crop interactions with pollinators and natural enemies to enhance the delivery of pollination and pest regulation ecosystem services (Campbell *et al*., 2017b). Positive trends for some beneficial species in response to wildflower provision were observed, but it is evident that although the study was not specifically designed to also investigate the impacts of Plant Protection Products (PPPs), their continued use contributing to values of orchard cumulative toxicity was a key factor influencing responses. Responses were further confounded by the variability between apple cultivars and between years, demonstrating the complexity of delivering ecosystem services in modern apple orchards.

### *4.1. Natural enemies and pest regulation*

The continued use of PPPs in the orchards is likely to have masked the overall benefits of wildflower provision for natural enemies (Albert *et al.*, 2017; Lefebvre *et al.*,2017; Gagic *et al.*, 2019), which culminated in similar levels of pest incidence (RAA and WAA) between orchard treatments. Greater differences in responses might have been observed in organic or other low input systems (Lefebvre *et al.*,2017). For example, in cider apple orchards fruit aesthetics are not an essential aspect of product quality and this allows growers to use fewer sprays compared to dessert apple orchards (Albert *et al.*, 2017). This regime can then lead to a greater abundance of aphidophagous predators in trees adjacent to wildflower strips and an increased control of RAA (Albert *et al.*, 2017). Increased depletion rates from baited cards in trees adjacent to wildflower strips have also been observed in cider orchards (Campbell *et al.*, 2017b). A more lenient approach to the use of PPPs in cider orchards provides an indication of what might be achieved in dessert apple orchards if growers are willing to reduce not only the types of sprays used, but also the number of spray applications.

The indiscriminate action of some PPPs can prevent populations of natural enemies obtaining the numbers required to control pests below threshold levels (Nicholas *et al.*, 2005). Deploying wildflower habitat at orchard boundaries might therefore be a more suitable approach to reduce PPP impacts directly on the wildflower habitat. For example, the provision of wildflower habitat in the margins surrounding Mediterranean apple orchards can increase the abundance of parasitoids and consequently the rates of RAA parasitism (Rodriguez-Gasol *et al.*, 2019). However, the spill-over of beneficial insects into the cropped area would be lower than from strips within orchards (Woodcock *et al.*, 2016), and the continued use of PPPs would still reduce the benefits gained.

Collectively, the spider and aphidophagous predators were negatively affected by high values of cumulative toxicity, with strong responses from the Araneidae (e.g. *Araniella opistographa*), Philodromidae (e.g. *Philodromus cespitum*) and Dermaptera (European earwig, *Forficula auricularia*). Earwigs were the most affected group of aphidophagous predators, which have excellent potential to control key pest species. In orchards they have been shown to significantly reduce the abundance of RAA (Dib *et al.*, 2010) and WAA (Mueller *et al.*, 1988). However, they are also highly susceptible to PPPs (Fountain and Harris, 2015). The most frequently used active PPP ingredient across all orchards was flonicamid, which is used for the control of sucking insects, including aphids. Although its toxicity is deemed relatively low (Table S1), its use has been associated with a reduced number of earwigs foraging in apple trees (Fountain and Harris, 2015). However, this response could also be due to the loss of prey (pests) following insecticide use. The pest regulation service provided by earwigs is readily disrupted by insecticide use (Mueller *et al.*, 1988; Nicholas *et al.*, 2005), even in orchards managed under IPM (Suchail *et al.*, 2018).

Spiders were the most abundant group of natural enemies in the orchards, and they can also be effective natural enemies of RAA but only in insecticide-free orchards (Lefebvre *et al*., 2017). Ghost spiders (Anyphaenidae) and money spiders (Linyphiidae) have been shown to be important predators of aphids (Sunderland *et al.*, 1986; Renouard *et al.*, 2004; Marko *et al.*, 2009), with a greater number of spiders in orchards receiving PPPs of lower toxicity (Marko *et al.*, 2009). Overall, we observed a greater number of spiders in orchards with lower values of cumulative toxicity, particularly in association with Jazz orchards, but lower values of orchard pesticide toxicity were not associated with higher levels of predation. Apple cultivar was more influential, with higher levels of predation being recorded in Braeburn orchards which were also associated with a greater abundance of earwigs. Rates were also higher in July when earwigs are at their peak activity (Gobin *et al.*, 2006). In contrast, other aphidophagous predators including Anthocoridae, Syrphidae larvae and Neuroptera larvae were recorded in greater numbers in Jazz orchards, and for Syrphidae and Neuroptera, to a greater extent in orchards with higher values of toxicity. This positive response to high values of orchard pesticide toxicity coincided with an increased likelihood of finding RAA and WAA in these orchards, particularly in Jazz orchards, where fewer aphidophagous predators were recorded overall. High values of cumulative toxicity are most likely a result of orchards being more prone to pest incidence, which through the increased use of PPPs negatively impacts natural enemies leading to higher pest populations. The relationship between the highly mobile natural enemies and their prey species (RAA and WAA) could be a direct response to pest availability leading to oviposition by Syrphid and Neuroptera adults (Minarro *et al*., 2005; Rodriguez-Gasol *et al*., 2019). These mobile natural enemies have greater potential to avoid the impacts of insecticide sprays enabling them to recolonise rapidly after use (Rodriguez-Gasol *et al*., 2019).

Although the number of Syrphidae larvae recorded in apple trees was not influenced by the presence of the wildflower strips, species richness and diversity of adult hoverflies was greater in association with the wildflower strips during the apple blossom period. Adults are more likely to lay eggs in close proximity to floral resources (Haenke *et al.*, 2009), which can lead to the delivery of pest regulation services in apple orchards (Rodriguez-Gasol *et al*., 2019). Although actual numbers of hoverflies did not differ significantly between treatments, the greater species richness and diversity is likely to improve pest regulation and pollination service (Dainese *et al.*, 2019; Woodcock *et al.,* 2019). The continued presence of wildflowers in alleyways throughout the summer period might also be expected to support adult hoverflies in the orchards (Campbell *et al.*, 2017b), further increasing the potential for pest regulation.

Wildflower strips can also support parasitoids in modern orchards and therefore pest regulation services (Hatt *et al.*, 2018). Parasitoids are also highly mobile and can be important natural enemies of RAA in apple orchards (Rodriguez-Gasol *et al*., 2019). However, no treatment effect was found for rates of aphid parasitism, and the value of 0.7% of RAA parasitism is consistent with Albert *et al.* (2017) who recorded less than 0.2% in all years and orchards. In comparison 11.9% of WAA were parasitised, but values in excess of 40% have been recorded (Peñalver-Cruz *et al*., 2020). It appears that there is greater potential for parasitoids to control WAA than RAA.

### ***4.2. Pollinators and Pollination Services***

Our study investigated whether pollination services to apple blossom could be enhanced by introducing wildflower strips between rows of apple trees. During the apple blossom period, only one of the sown species was in flower (*Silene dioica*), albeit sparsely, coupled with a few unsown species (e.g. *Taraxacum officinale* agg.). The low abundance of floral resources in the wildflower plots during the blossom period was therefore unlikely to attract more pollinators into these plots, which was demonstrated by the lack of difference in bee abundance, richness, and diversity between treatments. Concerns that wildflowers might attract pollinators away from the crop were therefore not realised (Free, 1967; Nicholson *et al.*, 2019). However, ten bee species were recorded only in plots containing wildflower strips, compared to three species unique to the control plots. This indicates to the potential for wildflower strips to support improved pollination service (Woodcock *et al.*, 2019), especially when coupled with the greater richness and diversity of hoverflies.

As managed pollinators, honeybees were expected to provide an important contribution to apple pollination, contributing nearly half of all legitimate flower visits (stigma contacts), although pollination might not have been as effective as some wild pollinators (Garibaldi *et al.*, 2013). It was not possible to separate the proportion of *Bombus terrestris* visits that were from managed *B. terrestris* colonies, but as *Bombus* spp. accounted for 21% of all visits recorded, they were clearly also an important group of pollinators (Garratt *et al.*, 2016). The importance of solitary bees, especially *Andrena* spp. has also been demonstrated. Thirty-two of the bee species recorded were polylectic, and the larvae of such species have been shown to benefit from the availability of diverse floral resources (Eckhardt *et al.*, 2014). To support these groups of wild pollinators in orchards throughout the growing season, the composition of wildflower strips should therefore be tailored accordingly (Campbell *et al.*, 2017a). However, it is also important to consider the extent of the resource area (Dicks *et al*., 2015). To have observed a significant response of wild bees to the wildflower strips, local populations would need to benefit from the additional resource provision, boosting abundance. During June to August, Campbell *et al.* (2017b) found a greater use of wildflower strips by insect pollinators in cider apple orchards compared to the control alleyways managed with regular cutting, indicating the value of strips outside of the blossom period. However, to increase the abundance of six common wild pollinator species it has been suggested that for every 100 ha of farmland, 2% should contain high quality wildflower areas, coupled with species-rich hedgerows (Dicks *et al.*, 2015). Although 11.2% of the orchard area was established with wildflower strips, this was only in 1 ha blocks, equating to 0.11 ha. If the wildflower strips deployed in the orchards were the only high value floral resource available, it is unlikely that population responses would have been observed (Dicks *et al.*, 2015). The extent of resource area is also an important consideration for natural enemies, coupled with the need for habitat heterogeneity (Bellone *et al*., 2020).

In addition to the potential of wildflower strips to support pollinators and natural enemies, the presence of wildflower strips could also help improve soil quality through greater accumulation of soil organic matter and nitrogen (De Deyn *et al.*, 2011). It is well documented that an increase in soil organic matter can increase soil microbial activity (Canali *et al.*, 2009) and therefore nutrient cycling (De Deyn *et al.*, 2011), which ultimately can improve the quality of orchard soils (Canali *et al.*, 2009). Some wildflower species can also contribute towards the maintenance of mycelial networks of Arbuscular Mycorrhizal Fungi (AMF) (Turrini *et al.*, 2017), improving the availability of nutrients to fruit trees and increasing the tolerance to biotic and abiotic stresses (Turrini *et al.*, 2017). The wider benefits of introducing floral resources into agri-environments should also be considered.

## 5. Conclusion

Wildflower strips in modern apple orchards have the potential to contribute towards the delivery of natural pest regulation and pollination services as part of a more sustainable approach to apple production. However, of key relevance for growers is that benefits may be reduced under certain spray regimes (Gagic *et al.*, 2019). If growers want to support natural enemies in modern apple orchards as part of a robust IPM strategy, not only do they need to consider the types of sprays being used, but also their frequency of use; several of the insecticides used in the study are now banned or have restricted use. Growers also had a high dependence on managed pollination services. To increase resilience, growers need to support wild pollinators by dedicating areas for wildflower habitats. Ultimately, further research is needed to identify ways to integrate wildflower habitat and a reduced use of PPPs to improve the contribution of beneficial invertebrates to crop production as part of an ecological intensification strategy.

## Acknowledgments

We would like to thank the growers for allowing us to conduct this study in their orchards and for facilitating the establishment of the wildflower strips. Funding was gratefully received from Waitrose & Partners, Fruition PO, and the University of Worcester.

## References

Adamson, N.L., Roulston, T.H., Fell, R.D., Mullins, D.E., 2012. From April to August - wild bees pollinating crops through the growing season in Virginia, USA. Environ. Entomol. 41, 813-821.

Albert, L., Franck, P., Gilles, Y., Plantegenest, M., 2017. Impact of agroecological infrastructures on the dynamics of *Dysaphis plantaginea* (Hemiptera: Aphididae) and its natural enemies in apple orchards in northwestern France. Environ. Entomol. 46, 528-537.

Amarasekare, K.G., Shearer, P.W., 2013a. Comparing effects of insecticides on two green lacewings species, *Chrysoperla johnsoni* and *Chrysoperla carnea* (Neuroptera: Chrysopidae). J. Econ. Entomol. 106, 1126-1133.

Amarasekare, K.G., Shearer, P.W., 2013b. Laboratory bioassays to estimate the lethal and sublethal effects of various insecticides and fungicides on *Deraeocoris brevis* (Hemiptera: Miridae). J. Econ. Entomol. 106, 776-785.

Bellone, D., Bjorkman, C., Klapwijk, M.J., 2020. Top-down pressure by generalist and specialist natural enemies in relation to habitat heterogeneity and resource availability. Basic Appl. Ecol. 43, 16-26.

Biesmeijer, J.C., Roberts, S.P.M., Reemer, M., Ohlemuller, R., Edwards, M., Peeters, T., Schaffers, A.P., Potts, S.G., Kleukers, R., Thomas, C.D., Settele, J., Kunin, W.E., 2006. Parallel declines in pollinators and insect-pollinated plants in Britain and the Netherlands. Science 313, 351-354.

Biobest, 2019. Side effect manual. http://www.biobestgroup.com/en/side-effect-manual (accessed 4 June 2019).

Birch, A.N.E., Begg, G.S., Squire, G.R., 2011. How agro-ecological research helps to address food security issues under new IPM and pesticide reduction policies for global crop production systems. J. Exp. Bot. 62, 3251-3261.

Blaauw, B.R., Isaacs, R., 2014. Flower plantings increase wild bee abundance and the pollination services provided to a pollination-dependent crop. J. Appl. Ecol. 51, 890-898.

Bloch, V., Degani, A., Bechar, A., 2018. A methodology of orchard architecture design for an optimal harvesting robot. Biosyst. Eng. 166, 126-137.

Bugg, R.L., Waddington, C., 1994. Using cover crops to manage arthropod pests of orchards - a review. Agriculture Ecosystems & Environment 50, 11-28.

Campbell, A.J., Wilby, A., Sutton, P., Wackers, F.L., 2017a. Do sown flower strips boost wild pollinator abundance and pollination services in a spring-flowering crop? A case study from UK cider apple orchards. Agriculture Ecosystems & Environment 239, 20-29.

Campbell, A.J., Wilby, A., Sutton, P., Wackers, F.L., 2017b. Getting more power from your flowers: multi-functional flower strips enhance pollinators and pest control agents in apple orchards. Insects 8.

Canali, S., Di Bartolomeo, E., Trinchera, A., Nisini, L., Tittarelli, F., Intrigliolo, F., Roccuzzo, G., Calabretta, M.L., 2009. Effect of different management strategies on soil quality of citrus orchards in Southern Italy. Soil Use and Management 25, 34-42.

Carvalheiro, L.G., Barbosa, E.R.M., Memmott, J., 2008. Pollinator networks, alien species and the conservation of rare plants: Trinia glauca as a case study. J. Appl. Ecol. 45, 1419-1427.

Carvalheiro, L.G., Kunin, W.E., Keil, P., Aguirre-Gutierrez, J., Ellis, W.N., Fox, R., Groom, Q., Hennekens, S., Van Landuyt, W., Maes, D., Van de Meutter, F., Michez, D., Rasmont, P., Ode, B., Potts, S.G., Reemer, M., Roberts, S.P.M., Schaminee, J., WallisDeVries, M.F.,

Biesmeijer, J.C., 2013. Species richness declines and biotic homogenisation have slowed down for NW-European pollinators and plants. Ecol. Lett. 16, 870-878.

Carvalheiro, L.G., Seymour, C.L., Nicolson, S.W., Veldtman, R., 2012. Creating patches of native flowers facilitates crop pollination in large agricultural fields: mango as a case study. J. Appl. Ecol. 49, 1373-1383.

Carvell, C., Meek, W.R., Pywell, R.F., Goulson, D., Nowakowski, M., 2007. Comparing the efficacy of agri-environment schemes to enhance bumble bee abundance and diversity on arable field margins. J. Appl. Ecol. 44, 29-40.

Cross, J., Fountain, M., Marko, V., Nagy, C., 2015. Arthropod ecosystem services in apple orchards and their economic benefits. Ecol. Entomol. 40, 82-96.

Dainese, M., Martin, E.A., Aizen, M.A., Albrecht, M., Bartomeus, I., Bommarco, R., Carvalheiro, L.G., Chaplin-Kramer, R., Gagic, V., Garibaldi, L.A., Ghazoul, J., Grab, H., Jonsson, M., Karp, D.S., Kennedy, C.M., Kleijn, D., Kremen, C., Landis, D.A., Letourneau, D.K., Marini, L., Poveda, K., Rader, R., Smith, H.G., Tscharntke, T., Andersson, G.K.S., Badenhausser, I., Baensch, S., Bezerra, A.D.M., Bianchi, F., Boreux, V., Bretagnolle, V., Caballero-Lopez, B., Cavigliasso, P., Cetkovic, A., Chacoff, N.P., Classen, A., Cusser, S., Silva, F., de Groot, G.A., Dudenhoffer, J.H., Ekroos, J., Fijen, T., Franck, P., Freitas, B.M., Garratt, M.P.D., Gratton, C., Hipolito, J., Holzschuh, A., Hunt, L., Iverson, A.L., Jha, S., Keasar, T., Kim, T.N., Kishinevsky, M., Klatt, B.K., Klein, A.M., Krewenka, K.M., Krishnan, S., Larsen, A.E., Lavigne, C., Liere, H., Maas, B., Mallinger, R.E., Pachon, E.M., Martinez-Salinas, A., Meehan, T.D., Mitchell, M.G.E., Molina, G.A.R., Nesper, M., Nilsson, L., O'Rourke, M.E., Peters, M.K., Plecas, M., Potts, S.G., Ramos, D.D., Rosenheim, J.A., Rundlof, M., Rusch, A., Saez, A., Scheper, J., Schleuning, M., Schmack, J.M., Sciligo, A.R., Seymour, C., Stanley, D.A., Stewart, R., Stout, J.C., Sutter, L., Takada, M.B., Taki, H., Tamburini, G., Tschumi, M., Viana, B.F., Westphal, C., Willcox, B.K., Wratten, S.D., Yoshioka, A., Zaragoza-Trello, C., Zhang, W., Zou, Y., Steffan-Dewenter, I., 2019. A global synthesis reveals biodiversity-mediated benefits for crop production. Sci. Adv. 5.

Damos, P., Colomar, L.A.E., Ioriatti, C., 2015. Integrated fruit production and pest management in Europe: The apple case study and how far we are from the original concept? Insects 6, 626-657.

De Deyn, G.B., Shiel, R.S., Ostle, N.J., McNamara, N.P., Oakley, S., Young, I., Freeman, C., Fenner, N., Quirk, H., Bardgett, R.D., 2011. Additional carbon sequestration benefits of grassland diversity restoration. J. Appl. Ecol. 48, 600-608.

Deguines, N., Jono, C., Baude, M., Henry, M., Julliard, R., Fontaine, C., 2014. Large- scale trade- off between agricultural intensification and crop pollination services. Frontiers in Ecology and the Environment 12, 212-217.

Demestihas, C., Plenet, D., Genard, M., Raynal, C., Lescourret, F., 2017. Ecosystem services in orchards. A review. Agron. Sustain. Dev. 37.

Dib, H., Simon, S., Sauphanor, B., Capowiez, Y., 2010. The role of natural enemies on the population dynamics of the rosy apple aphid, *Dysaphis plantaginea* Passerini (Hemiptera: Aphididae) in organic apple orchards in south-eastern France. Biol. Control 55, 97-109.

Dicks, L.V., Baude, M., Roberts, S.P.M., Phillips, J., Green, M., Carvell, C., 2015. How much flower-rich habitat is enough for wild pollinators? Answering a key policy question with incomplete knowledge. Ecol. Entomol. 40, 22-35.

Dunley, J.E., Welter, S.C., 2000. Correlated insecticide cross-resistance in azinphosmethyl resistant codling moth (Lepidoptera : Tortricidae). J. Econ. Entomol. 93, 955-962.

Duru, M., Therond, O., Martin, G., Martin-Clouaire, R., Magne, M.A., Justes, E., Journet, E.P., Aubertot, J.N., Savary, S., Bergez, J.E., Sarthou, J., 2015. How to implement biodiversity-based agriculture to enhance ecosystem services: a review. Agron. Sustain. Dev. 35, 1259-1281.

Eckhardt, M., Haider, M., Dorn, S., Muller, A., 2014. Pollen mixing in pollen generalist solitary bees: a possible strategy to complement or mitigate unfavourable pollen properties? J. Anim. Ecol. 83, 588-597.

Feltham, H., Park, K., Minderman, J., Goulson, D., 2015. Experimental evidence that wildflower strips increase pollinator visits to crops. Ecol. Evol. 5, 3523-3530.

Fitter, A., Elmqvist, T., Haines-young, R.O.Y., Potschin, M., Rinaldo, A., Seta, H., Stoll-kleemann, S., Zobel, M., 2010. An assessment of ecosystem services and biodiversity in Europe. Issues in Environmental Science and Technology 30, 1-28.

Fountain, M.T., Harris, A.L., 2015. Non-target consequences of insecticides used in apple and pear orchards on *Forficula auricularia* L. (Dermaptera: Forficulidae). Biol. Control 91, 27-33.

Free, J.B., 1967. Dandelions as a competitor to fruit trees. J. Appl. Ecol. 5, 169-178.

Gagic, V., Hulthen, A.D., Marcora, A., Wang, X., Jones, L., Schellhorn, N.A., 2019. Biocontrol in insecticide sprayed crops does not benefit from semi-natural habitats and recovers slowly after spraying. J. Appl. Ecol. 56, 2176-2185.

Garibaldi, L.A., Steffan-Dewenter, I., Winfree, R., Aizen, M.A., Bommarco, R., Cunningham, S.A., Kremen, C., Carvalheiro, L.G., Harder, L.D., Afik, O., Bartomeus, I., Benjamin, F., Boreux, V., Cariveau, D., Chacoff, N.P., Dudenhoffer, J.H., Freitas, B.M., Ghazoul, J., Greenleaf, S., Hipolito, J., Holzschuh, A., Howlett, B., Isaacs, R., Javorek, S.K., Kennedy, C.M., Krewenka, K.M., Krishnan, S., Mandelik, Y., Mayfield, M.M., Motzke, I., Munyuli, T., Nault, B.A., Otieno, M., Petersen, J., Pisanty, G., Potts, S.G., Rader, R., Ricketts, T.H., Rundlof, M., Seymour, C.L., Schuepp, C., Szentgyorgyi, H., Taki, H., Tscharntke, T., Vergara, C.H., Viana, B.F., Wanger, T.C., Westphal, C., Williams, N., Klein, A.M., 2013. Wild pollinators enhance fruit set of crops regardless of honey bee abundance. Science 339, 1608-+.

Garratt, M., Truslove, C., Coston, D., Evans, R., Moss, E., Dodson, C., Jenner, N., Biesmeijer, J.C., Potts, S.G., 2014a. Pollination deficits in UK apple orchards. Journal of Pollination Ecology 12, 9-14.

Garratt, M.P.D., Breeze, T.D., Boreux, V., Fountain, M.T., McKerchar, M., Webber, S.M., Coston, D.J., Jenner, N., Dean, R., Westbury, D.B., Biesmeijer, J.C., Potts, S.G., 2016. Apple pollination: demand depends on variety and supply depends on pollinator identity. PloS one 11.

Garratt, M.P.D., Breeze, T.D., Jenner, N., Polce, C., Biesmeijer, J.C., Potts, S.G., 2014b. Avoiding a bad apple: Insect pollination enhances fruit quality and economic value. Agriculture Ecosystems & Environment 184, 34-40.

Geiger, F., Bengtsson, J., Berendse, F., Weisser, W.W., Emmerson, M., Morales, M.B., Ceryngier, P., Liira, J., Tscharntke, T., Winqvist, C., Eggers, S., Bommarco, R., Part, T., Bretagnolle, V., Plantegenest, M., Clement, L.W., Dennis, C., Palmer, C., Onate, J.J., Guerrero, I., Hawro, V., Aavik, T., Thies, C., Flohre, A., Hanke, S., Fischer, C., Goedhart, P.W., Inchausti, P., 2010. Persistent negative effects of pesticides on biodiversity and biological control potential on European farmland. Basic Appl. Ecol. 11, 97-105.

Giolo, F.P., Medina, P., Grutzmacher, A.D., Vinuela, E., 2009. Effects of pesticides commonly used in peach orchards in Brazil on predatory lacewing *Chrysoperla carnea* under laboratory conditions. Biocontrol 54, 625-635.

Gobin, B., Marien, A., Davis, S., Leirs, H., 2006. Enhancing earwig populations in Belgian orchards. Communications in agricultural and applied biological sciences 71, 269-273.

Godoy, M.S., Carvalho, G.A., Carvalho, B.F., Lasmar, O., 2010. Physiological selectivity of insecticides to two lacewing species. Pesqui. Agropecu. Bras. 45, 1253-1258.

Gomez-Marco, F., Urbaneja, A., Tena, A., 2016. A sown grass cover enriched with wild forb plants improves the biological control of aphids in citrus. Basic Appl. Ecol. 17, 210-219.

Goulson, D., Lye, G.C., Darvill, B., 2008. Decline and conservation of bumble bees. Annu. Rev. Entomol., pp. 191-208.

Granatstein, D., Sánchez, E., 2009. Research knowledge and needs for orchard floor management in organic tree fruit systems. International Journal of Fruit Science 9, 257-281.

Haenke, S., Scheid, B., Schaefer, M., Tscharntke, T., Thies, C., 2009. Increasing syrphid fly diversity and density in sown flower strips within simple vs. complex landscapes. J. Appl. Ecol. 46, 1106-1114.

Heimpel, G.E., 2019. Linking parasitoid nectar feeding and dispersal in conservation biological control. Biol. Control 132, 36-41.

Hillocks, R.J., 2012. Farming with fewer pesticides: EU pesticide review and resulting challenges for UK agriculture. Crop Prot. 31, 85-93.

Knutson, A.E., Muegge, M.A., Wilson, L.T., Naranjo, S.E., 2008. Evaluation of sampling methods and development of sample plans for estimating predator densities in cotton. J. Econ. Entomol. 101, 1501-1509.

Kogan, M., Bajwa, W.I., 1999. Integrated pest management: a global reality? Anais da Sociedade Entomológica do Brasil 28, 01-25.

Koppert, B.V., 2019. Side effects database. https://www.koppert.co.uk/side-effects-database/ (accessed 4 June 2019).

Landis, D.A., Wratten, S.D., Gurr, G.M., 2000. Habitat management to conserve natural enemies of arthropod pests in agriculture. Annu. Rev. Entomol. 45, 175-201.

Lefebvre, M., Franck, P., Olivares, J., Ricard, J.-M., Mandrin, J.-F., Lavigne, C., 2017. Spider predation on rosy apple aphid in conventional, organic and insecticide-free orchards and its impact on aphid populations. Biol. Control 104, 57-65.

Marko, V., Jenser, G., Kondorosy, E., Abraham, L., Balazs, K., 2013. Flowers for better pest control? The effects of apple orchard ground cover management on green apple aphids (Aphis spp.) (Hemiptera: Aphididae), their predators and the canopy insect community. Biocontrol Sci. Technol. 23, 126-145.

Marko, V., Keresztes, B., Fountain, M.T., Cross, J.V., 2009. Prey availability, pesticides and the abundance of orchard spider communities. Biol. Control 48, 115-124.

Marliac, G., Penvern, S., Barbier, J.M., Lescourret, F., Capowiez, Y., 2015. Impact of crop protection strategies on natural enemies in organic apple production. Agron. Sustain. Dev. 35, 803-813.

McCaffrey, J.P., Parrella, M.P., Horsburgh, R.L., 1983. Evaluation of the limb-beating sampling method for estimating spider (Araneae) populations on apple trees. J. Arachnol. 11, 363-368.

Minarro, M., Hemptinne, J.L., Dapena, E., 2005. Colonization of apple orchards by predators of *Dysaphis plantaginea*: sequential arrival, response to prey abundance and consequences for biological control. Biocontrol 50, 403-414.

Minarro, M., Dapena, E., 2007. Resistance of apple cultivars to *Dysaphis plantaginea* (Hemiptera : Aphididae): Role of tree phenology in infestation avoidance. Environ. Entomol. 36, 1206-1211.

Morrison, W.R., Bruce, A., Wilkins, R.V., Albin, C.E., Arthur, F.H., 2019. Sanitation improves stored product insect pest management. Insects 10.

Mueller, T.F., Blommers, L.H.M., Mols, P.J.M., 1988. Earwig (*Forticula auricularia*) predation of the woolly apple aphid, *Eriosoma lanigerum*. Entomol. Exp. Appl. 47, 145-152.

Nicholas, A.H., Spooner-Hart, R.N., Vickers, R.A., 2005. Abundance and natural control of the woolly aphid *Eriosoma lanigerum* in an Australian apple orchard IPM program. Biocontrol 50, 271-291.

Nicholson, C.C., Ricketts, T.H., Koh, I., Smith, H.G., Lonsdorf, E.V., Olsson, O., 2019. Flowering resources distract pollinators from crops: Model predictions from landscape simulations. J. Appl. Ecol. 56, 618-628.

Pekar, S., 1999. Foraging mode: a factor affecting the susceptibility of spiders (Araneae) to insecticide applications. Pestic. Sci. 55, 1077-1082.

Peñalver-Cruz, A., Alvarez, D., Lavandero, B., 2020. Do hedgerows influence the natural biological control of woolly apple aphids in orchards? J. Pest Sci. 93, 219-234.

Potts, S.G., Biesmeijer, J.C., Kremen, C., Neumann, P., Schweiger, O., Kunin, W.E., 2010a. Global pollinator declines: trends, impacts and drivers. Trends Ecol. Evol. 25, 345-353.

Potts, S.G., Imperatriz-Fonseca, V., Ngo, H.T., Aizen, M.A., Biesmeijer, J.C., Breeze, T.D., Dicks, L.V., Garibaldi, L.A., Hill, R., Settele, J., Vanbergen, A.J., 2016. Safeguarding pollinators and their values to human well-being. Nature 540, 220-229.

Potts, S.G., Kevan, P.G., Boone, J.W., 2005. Conservation in pollination: collecting, surveying and monitoring. In: Dafni, A., Kevan, P.G., Husband, B.C. (Eds.), Practical pollination biology. Enviroquest Ltd, pp. 401–434.

Potts, S.G., Roberts, S.P.M., Dean, R., Marris, G., Brown, M.A., Jones, R., Neumann, P., Settele, J., 2010b. Declines of managed honey bees and beekeepers in Europe. J. Apic. Res. 49, 15-22.

Pywell, R.F., Heard, M.S., Woodcock, B.A., Hinsley, S., Ridding, L., Nowakowski, M., Bullock, J.M., 2015. Wildlife-friendly farming increases crop yield: evidence for ecological intensification. Proceedings of the Royal Society B-Biological Sciences 282.

Renouard, J.J., Creamer, R., Richman, D.B., 2004. Gut content analysis of the spider *Hibana incursa* (Aranae : Anyphaenidae) using serological methods. Southw. Entomol. 29, 91-97.

Roberts, M.J., 1985a. The Spiders of Great Britain and Ireland. Vol. 1 Atypidae to Theridiosomatidae. Harley Books, Essex, England, UK.

Roberts, M.J., 1985b. The Spiders of Great Britain and Ireland. Vol. 3. Colour Plates. Harley Books, Essex, England, UK.

Roberts, M.J. 1987. The Spiders of Great Britain and Ireland. Vol. 2 Linyphiidae and check list. Harley Books, Essex, England, UK.

Rodriguez-Gasol, N., Avilla, J., Aparicio, Y., Arno, J., Gabarra, R., Riudavets, J., Alegre, S., Lordan, J., Alins, G., 2019. The contribution of surrounding margins in the promotion of natural enemies in Mediterranean apple orchards. Insects 10.

Samnegard, U., Alins, G., Boreux, V., Bosch, J., Garcia, D., Happe, A.K., Klein, A.M., Minarro, M., Mody, K., Porcel, M., Rodrigo, A., Roquer-Beni, L., Tasin, M., Hamback, P.A., 2019. Management trade-offs on ecosystem services in apple orchards across Europe: Direct and indirect effects of organic production. J. Appl. Ecol. 56, 802-811.

Schabenberger, O., Pierce, F.J., 2002. Contemporary statistical models for the plant and soil sciences. CRC Press, London, UK.

Schuber, J.M., Monteiro, L.B., Almeida, L.M., Zawadneak, M.A.C., 2012. Natural enemies associated to aphids in peach orchards in Araucaria, Parana, Brazil. Braz. J. Biol. 72, 847-852.

Sigsgaard, L., Esbjerg, P.H.M., Philipsen, H., 2006. Controlling pear psyllids by mass-releasing *Anthocoris nemoralis* and *A. nemorum* (Heteroptera: Anthocoridae). Journal of Fruit and Ornamental Plant Research 14, 89-98.

Sigsgaard, L., Herz, A., Korsgaard, M., Wuhrer, B., 2017. Mass release of *Trichogramma evanescens* and *T. cacoeciae* can reduce damage by the apple codling moth *Cydia pomonella* in organic orchards under pheromone disruption. Insects 8.

Stanley, D.A., Garratt, M.P.D., Wickens, J.B., Wickens, V.J., Potts, S.G., Raine, N.E., 2015. Neonicotinoid pesticide exposure impairs crop pollination services provided by bumblebees. Nature 528, 548-+.

Suchail, S., Le Navenant, A., Capowiez, Y., Thiery, A., Rault, M., 2018. An exploratory study of energy reserves and biometry as potential tools for assessing the effects of pest management strategies on the earwig, *Forficula auricularia* L. Environ. Sci. Pollut. Res. 25, 22766-22774.

Suckling, D.M., Walker, J.T.S., Wearing, C.H., 1999. Ecological impact of three pest management systems in New Zealand apple orchards. Agriculture Ecosystems & Environment 73, 129-140.

Sunderland, K.D., Fraser, A.M., Dixon, A.F.G., 1986. Field and Laboratory Studies on Money Spiders (Linyphiidae) as Predators of Cereal Aphids. J. Appl. Ecol. 23, 433-447.

Thomson, L.J., Hoffmann, A.A., 2006. Field validation of laboratory-derived IOBC toxicity ratings for natural enemies in commercial vineyards. Biol. Control 39, 507-515.

Turrini, A., Agnolucci, M., Palla, M., Tome, E., Tagliavini, M., Scandellari, F., Giovannetti, M., 2017. Species diversity and community composition of native arbuscular mycorrhizal fungi in apple roots are affected by site and orchard management. Appl. Soil Ecol. 116, 42-54.

van de Zande, J.C., Huijsmans, J.F.M., Porskamp, H.A.J., Michielsen, J.M.G.P., Stallinga, H., Holterman, H.J., de Jong, A., 2008. Spray techniques: how to optimise spray deposition and minimise spray drift. The Environmentalist 28, 9-17.

van Emden, H., 2002. Conservation biological control: from theory to practice., 1st International Symposium on Biological Control of Arthropods. , Honolulu, Hawaii, USA, pp. 199–208.

Vermeir, I., Verbeke, W., 2006. Sustainable food consumption: Exploring the consumer "attitude - behavioral intention" gap. J. Agric. Environ. Ethics 19, 169-194.

Wearing, C.H., Colhoun, K., Attfield, B., Marshall, R.R., 2011. Diversity of natural enemies in Central Otago, New Zealand apple orchards: a practical measure of sustainability in pest management? Biocontrol Sci. Technol. 21, 1273-1296.

Westbury, D.B., Woodcock, B.A., Harris, S.J., Brown, V.K., Potts, S.G., 2017. Buffer strip management to deliver plant and invertebrate resources for farmland birds in agricultural landscapes. Agriculture Ecosystems & Environment 240, 215-223.

Westphal, C., Bommarco, R., Carre, G., Lamborn, E., Morison, N., Petanidou, T., Potts, S.G., Roberts, S.P.M., Szentgyorgyi, H., Tscheulin, T., Vaissiere, B.E., Woyciechowski, M., Biesmeijer, J.C., Kunin, W.E., Settele, J., Steffan-Dewenter, I., 2008. Mearuing bee diversity in different European habitats and biogeographical regions. Ecol. Monogr. 78, 653-671.

Woodcock, B.A., Bullock, J.M., McCracken, M., Chapman, R.E., Ball, S.L., Edwards, M.E., Nowakowski, M., Pywell, R.F., 2016. Spill-over of pest control and pollination services into arable crops. Agriculture Ecosystems & Environment 231, 15-23.

Woodcock, B.A., Garratt, M.P.D., Powney, G.D., Shaw, R.F., Osborne, J.L., Soroka, J., Lindstrom, S.A.M., Stanley, D., Ouvrard, P., Edwards, M.E., Jauker, F., McCracken, M.E., Zou, Y., Potts, S.G., Rundlof, M., Noriega, J.A., Greenop, A., Smith, H.G., Bommarco, R., van der Werf, W., Stout, J.C., Steffan-Dewenter, I., Morandin, L., Bullock, J.M., Pywell, R.F., 2019. Meta-analysis reveals that pollinator functional diversity and abundance enhance crop pollination and yield. Nat. Commun. 10.

**Supplementary Material**

**Table S1**. Toxicity scores for each of the active ingredients (acaricides and insecticides) used in the study orchards calculated according to Koppert (2019) and Biobest (2019), following guidelines from the International Organisation for Biological Control (IOBC). Product scores for each natural enemy group were averaged to provide an overall average toxicity score for each active ingredient. Due to some differences in toxicity ratings for predatory mites according to Koppert (2019) and Biobest (2019), average values were calculated. 1 = low toxicity (harmless, <25% mortality), 2 = slightly harmful (25-50% mortality), 3 = moderately harmful (50-75%), and 4 = very harmful (> 75% mortality).

| **Active ingredient** | **Type** | **Natural Enemy Group** | | | | | **Average toxicity score** |
|---|---|---|---|---|---|---|---|
| | | Anthocoridae | Chrysopidae | Miridae | Parasitoids | Predatory mites | |
| Clofentezine | Acaricide | 1 | 1 | 1 | 1 | 1 | 1.00 |
| Fenpyroximate | Acaricide | 2 | 2 | 1 | 3 | 3.22 | 2.24 |
| Spirodiclofen | Acaricide | 4 | 1 | 3 | 1 | 1.75 | 2.15 |
| Tebufenpyrad | Acaricide | 4 | 3 | 3 | 4 | 2.27 | 3.25 |
| | | | | | | | |
| Chlorantraniliprole | Insecticide | 1 | 2 | 1 | 1 | 1 | 1.20 |
| Chlorpyrifos | Insecticide | 4 | 4 | 4 | 4 | 3 | 3.80 |
| Cypermethrin | Insecticide | 4 | 4 | 4 | 4 | 4 | 4.00 |
| Flonicamid | Insecticide | 1 | 1 | 1 | 2 | 1 | 1.20 |
| Indoxacarb | Insecticide | 3 | 1 | 3 | 3 | 1 | 2.20 |
| Methoxyfenozide | Insecticide | 4 | 1 | 4 | 1 | 1.17 | 2.23 |
| Pirimicarb | Insecticide | 2 | 2 | 3 | 4 | 2 | 2.60 |
| Thiacloprid | Insecticide | 4 | 4 | 4 | 3 | 3 | 3.60 |