# Impacts of wildflower interventions on beneficial insects in fruit crops: a review

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## Summary

Integrated pest management (IPM) has been practised by the fruit industry for at least 30 years. Naturally occurring beneficial insects have been encouraged to thrive alongside introduced predatory insects. However, Conservation Biological Control and augmented biocontrol through the release of large numbers of natural enemies is normally only widely adopted when a pest has become resistant to available conventional pesticides and control has begun to break down. In addition, the incorporation of wild pollinator management, essential to fruit production has, in the past, not been a priority but is now increasingly recognised through Integrated Pest and Pollinator Management (IPPM). This review focuses on the benefits provided to pest regulation and pollination services in fruit crops through the delivery of natural enemies and pollinating insects by provisioning areas of fruiting crops with floral resources. Most of the studies in this review highlighted beneficial or benign impacts of floral resource prevision to fruit crops. However, placement in the landscape and spill-over of beneficial arthropods into the crop can be influential and limiting. The review also highlights the need for longer-term ecological studies to understand the impacts of changing arthropod communities, over time and the opportunity to tailor wildflower mixes to specific crops for increased pest control and pollination benefits, ultimately impacting fruit growers bottom-line with less reliance on plant protection products.

**Keywords:** Agroecology, agri-environment schemes, habitat, landscape, production, sowing

# Grower Recommendations

## Landscape and habitat management

- Landscapes with short flowering seasons, e.g. tree fruit dominated farms do not provide season long insect forage. Landscapes with tree and soft fruit crops are complementary and capable of providing season-long bee forage for crop pollinators (e.g. ground nesting solitary bees and bumblebees).

- In general, high quality and increased areas of sown flower rich habitat improves abundance and diversity of natural enemies and wild pollinators (including hoverflies, solitary bees and bumblebees).

- Significant improvement is realised through high-quality semi-natural or sown flora in combination with heterogeneous landscapes which provide a mixture of habitat types including woodlands, hedgerows, improved grasslands and bare earth, catering for the different life stages of beneficial arthropods.

- Diverse landscapes promote floral resources throughout the entire foraging period of pollinators and niches for natural enemies.

- Although organic orchards tend to have a greater diversity of natural enemies and pollinators, consideration should be given to management practices that disrupt nesting of beneficial insects including soil tillage.

## Economic and production impacts of flower-rich interventions

- Removing unproductive areas of fields and creating habitat (primarily floral resources) can lead to increased yield in the cropped areas of the fields despite the loss of crop land for habitat creation.

- Increasing distance from natural or seminatural habitats results in decreasing pollinator crop visits and pollinator richness even though there is often less evidence of a decline in fruit yield.

- However, results vary between crops and landscapes and many studies show that improving farm habitat increases fruit set and yields.

- It is generally agreed that wildflower habitat needs to be adjacent or within the fruit production area and part of a heterogeneous landscape with habitat connectivity.

- The age of habitat also has a significant impact on beneficial fauna (abundance and diversity) and ecosystem services, improving over time typically for wildflower plantings 3 years onwards.

- Positive impacts in some studies have been detected the first year after perennial mixes have flowered. Spill-over from wildflowers planted in orchard alleyways can result in >10% increase in natural enemies in the trees, with resulting reductions in codling moth damage and early aphid.

- However, it is clear from some studies that the benefits of wildflower plantings can be mitigated by the use and/or timing of harmful Plant Protection Products (PPP), hence fruit growers should plan carefully whether an application is necessary, the toxicity of the product, and timing of application.

- Fruit growers can support pollinators and natural enemies by incorporating flower-rich habitat into farmland, and by reducing PPP use through adopting more sustainable farming methods.

- Managing commercially reared pollinators according to best practice will also ensure that transmission of parasites and diseases to wild bees is minimised, e.g. health checks and treatment of honeybees and appropriate disposal of commercial bumblebee hives.

## Benefits to natural enemies in fruit crops

- Studies have demonstrated that where floral alleyways have been established in orchards, populations of natural enemies have increased, but have not consistently delivered a corresponding increase in pest control.

- Wildflower alleyways reduce codling moth larvae and damaged fruits, but this may not equate to reduced economic damage.

- Using more diverse floral alleyways, spider numbers and their webs are increased, reducing numbers of aphids returning from their summer host plants.

- Dense and diverse vegetation also provides more abundant and diverse alternative prey including leafhoppers, herbivorous beetles, dipterans, mirids and thrips. This results in a spill-over of natural enemies into the crop, as natural enemy populations build in the floral strips, resulting in increased predation rates in the crop.

- Rosy apple aphid and green apple aphid were less abundant in orchards with sown floral strips where numbers of natural enemies were increased.

- Faster suppression of woolly apple aphid occurred on apple trees closer to sweet alyssum flowers, the result of higher densities of natural enemies moving between the alyssum and the trees.

- One study found less damage by European tarnished plant bug and summer tortricid moths in florally managed apple plots compared to conventionally managed controls.

- Alleyway floral sowings in organic pear orchards decreased sucker, aphid, and mealybug populations and in some cases delayed their establishment.

- Floral margins can be relied upon to boost local levels of natural enemies and maintain pests at low levels. They can maintain acceptable control of pests which cause superficial damage to foliage, but those that cause serious damage to fruits like codling moth, may remain at commercially damaging levels.


## Benefits to pollinators in fruit crops

- Pollinator diversity and abundance is increased in fruit crop landscapes containing hedgerows, and wildflower meadows.

- Promoting floral resources around the farm helps to sustain diverse wild bee populations for fruit crop pollination.

- Orchards with alleyway wildflowers can increase pollinator visit to apple flowers by up to 40%. This effect is more pronounced when the orchards are in a landscape with semi-natural habitat.

- Mass flowering of a single crop can adversely affect populations of pollinating insects including bumblebees, solitary bees, honeybees, and hoverflies if provision is not made throughout the rest of the growing season to meet feeding and nesting needs.

- Fruit crops typically bloom for a short period of time and cannot sustain insect pollinators alone. Additional floral resources in orchards can provide a greater diversity and abundance of flowering plants before, during

and after blossom to support and attract pollinating insects in and around fruit crops for long- term, interannual stability.

- Dispersing patches of natural habitat throughout the landscape to create habitat heterogeneity also supports higher bee abundance even in landscapes with a low proportion of natural habitat overall.

## Potential detrimental effects of wildflower strips

- Some species of wildflowers can act as hosts to fruit crop pests so thought needs to be given to the choice of wildflowers and to weigh up the positive benefits with the potential drawbacks.

- An increase in apple scab in plots with wildflower alleyways was shown in one study compared to crops where weeds were controlled by mechanical means. However, tillage may also disrupt nesting bees and earwigs if applied during the main nesting period.

- Some cover crops increase capsid bugs but resulting damage to fruit crops is uncertain.

- Many perceived negative effects are often transient and occur in the crop establishment year, until beneficial fauna has built in abundance.

- Careful selection of plants is important to avoid risk of enhancing pest populations or offering an alternate host for plant pathogens and other noxious organisms. Ideally, the species chosen should be botanically unrelated to the crop.

## Quality, area, edge of wildflower provision

- Simply allowing resident vegetation including flora in fruit crops to grow unhindered yields few benefits and can result in pest problems; hence commercial growers need to utilise purpose sown wildflower mixes which can outcompete undesirable host plants of pest species.

- Pollinators and natural enemies need food (pollen, nectar, prey etc) and habitats to allow them to nest, and to shelter (over-winter, from weather and from predators); sown species should be selected with this in mind.

- Plant diversity and species richness has been repeatedly demonstrated as key to beneficial fauna abundance and diversity in agro-ecosystems. Pollinator visits to flowering crops are also increased.

- There is some evidence that several small fragments of flower-rich habitat support more butterfly and parasitoid species than the same area composed of only one or two fragments. Small habitat areas should be scattered to maximize diversity and minimise the risk of species loss.

- The more isolated a floral area is from crops, the lower the crop pollinator visitor richness, visitation rate and fruit set in the crop, and only areas of flower rich habitats within 500-1,000 m improve the richness of hoverflies and bees in the crop.

- Some solitary bee species need to be within 150 m of the crop.

- Less mobile beneficial fauna, for example parasitoids, only spill over into crops at around 10 m, hence interplanting wildflowers is likely to be more effective for some pest control services.

- Many natural enemies decrease in abundance further into the crop especially from ~40 m into the crop.

- Sowing wildflowers into crops can extend the distance of benefits to at least 100 m.

- Wildflower areas need to be considered in relation to other beneficial fauna needs and should not be planted without consideration of connectivity to hedgerows, woodlands, water sources, and semi-natural grasslands.

## Choice of wildflower species to sow

- Farm managers should follow four strategies when managing wildflowers on their land;

    - **Identify** and **Protect** areas of good quality flora,
    - **Enhance** and **Improve** areas that are adequate, but are not currently giving the best service,
    - **Connect** areas of floral resource (e.g. hedgerows or meadows) by creating corridors to enable beneficials to move around the landscape and,
    - **Create** new areas of floral resource on farm areas lacking heterogeneity.

- Species chosen should be suited to the beneficial fauna required for the crop. For instance, cornflower (*Centaurea cyanus*), mint (*Mentha spicata*), yarrow (*Achillea millefolium*) and Phacelia (*Phacelia tanacetifolia*) are attractive to pollinators.

- Parasitoids tend to have short mouthparts, so flora with easily accessible nectar should be selected, e.g. creeping cinquefoil (*Potentilla reptans*), yarrow (*Achillea millefolium*), white clover (*Trifolium repens*), and common hedge parsley (*Torilis arvensis*).

- Plants like yarrow (*A. millefolium*) and oxeye daisy (*Leucanthemum vulgare*) attract multiple beneficial arthropods.

- Perennial stinging nettle (*Urtica dioica*) is a reservoir of natural enemies including pirate bugs (Anthocoridae), Miridae and ladybirds.

- Anthocorids are also abundant on cornflower (*Centaurea cyanus*) and corn chamomile (*Anthemis arvensis*).

- Kidney vetch (*Anthyllis vulneraria*) and meadow cranesbill (*Geranium pratense*) are highly attractive to bumblebees.

- Smooth hawk's-beard (*Crepis capillaris*), wild mustard (*Sinapsis arvensis*), field bindweed (*Convolvulus arvensis*) and rough chervil (*Chaerophyllum temulum*) are attractive to solitary bees.

- Dandelions (*Taraxicum* spp.) are utilised by ground nesting andrenid bees, key pollinators of apple, so should be encouraged in orchards as an early flowering resource.

- Flower density is a good predictor of insect diversity, so growers may consider minimising the ratio of grasses to flora where economically possible.

## Establishing and managing wildflower areas

- For greatest effect, a diverse mix and functional groups of flowering plants should be chosen.

- Wildflower margins need to be at least 3-10 metres in width and can be sown on a range of soils.

- The aim should be to achieve an ecologically intensive area that can regulate, support, and even increase production.

- Alleyway sowings allow beneficial insects to penetrate further into cropping areas than margins alone.

- A quick guide to success is at https://www.silenceofthebees.eu/wp-content/uploads/2021/06/BEESPOKE-Establishing-Perennial-Wildflowers-Leaflet-WEB.pdf

- To establish a perennial wildflower area, ensure that the seedbed is firm, fine, and weed free and broadcast seeds on the soil surface before rolling.

- Once established, cutting only half the margin mid-season will prolong the floral resources available.

- In addition, high mowing preserves vegetative and flower buds and permits regrowth.

- Another strategy is to have a selection of floral areas at different stages of succession and different plants to provide habitats for various insect groups and seasonal continuity.

- In summary, wildflower areas provide 1) alternative prey or hosts when pests become temporarily scarce, 2) alternative food sources such as nectar and pollen for adult predators, parasitoids, and pollinators and 3) shelter or undisturbed habitats as refuges and overwintering sites.

## Management of other grassed areas

- Reducing both mowing frequency and the use of chemical herbicides.

- Reduced management intensity will encourage web-building spiders and other insects. Reducing mowing regimes from 2-3, to only once per month, increases the numbers of predators and parasitoids in orchards.

# Introduction

The estimated total area of fruit (including apples, pears, plums and soft fruit) grown in the UK in 2010 was 34,324 ha compared to 33,639 in 2020 (provisional data Defra 2021) with 559.3 and 657.0 thousand tonnes produced on that land respectively. This represents an increase in production of 97.7 thousand tonnes of fruit on slightly less land with almost double the value £580M to £1,045M to the UK economy in just 10 years.

Post war there was a worldwide push for the intensification of agriculture (Fig. 1) with a transition from traditionally diverse agro-ecosystems to industrial modes of agriculture with simplified, and chemically dependent agricultural management resulting in subsequent detrimental effects on plant diversity and habitats for beneficial insects, including pollinators (Nicholls and Altieri 2013, Senapathi, Carvalheiro et al. 2015). Natural England (England 2011) estimated by 1984 in lowland England and Wales, semi-natural grassland had declined by 97% over the previous 50 years and only 7,500 ha remained by 2010. Losses continued during the1980 and 1990s at a rate of 2–10% per annum in some parts of England.



**Figure 1.** Intensively grown pear orchard with low floral diversity. Credit NIAB EMR.

Integrated Pest Management (IPM) has long been a proposed approach to managing pests in crops, comprising minimal and integrated use of pesticides as part of the programme. This is now part of legislation with National Actions Plans commissioned (e.g. (DEFRA 2013)). However, IPM requires more effort in monitoring, use of prediction tools, biological controls, and expert knowledge. In addition, pest and disease levels need to be identified and knowledge of the natural enemies (predators and parasitoids) are required and until recently wild pollinators as part of an agro-ecosystem has largely been ignored. In more recent years, the withdrawal of

pesticide approvals and development of pesticide resistance, combined with increases in exotic pests and diseases has offered an incentive to farmers and growers to engage and implement IPM practices.

When considering tools for an IPM approach, farm landscape and ecosystem need to be considered in decision making. For example, when choosing a method for pest control there might also be additional benefits for pollinating insects – key contributors to fruit growing – for both yield and quality (Larson, Kevan et al. 2001, Klein, Vaissiere et al. 2007, Pardo and Borges 2020). Indeed, the implementation of IPM practices increase crop yields through the preservation of pollinating insects (Pecenka, Ingwell et al. 2021). Recently, (Egan, Dicks et al. 2020) proposed the introduction of a systematic framework for Integrated Pest and Pollinator Management (IPPM). They highlighted that pest and pollinator management currently remain largely uncoordinated. There is an opportunity when implementing IPM for pest control to boost critical pollinating insects in flowering crops and the wider landscape.

Conservation Biological Control (CBC, (McCravy 2008)), and augmented biocontrol through the release of large numbers of natural enemies, has been part of the toolbox for various crops (Michaud 2018). However, Biological Control Agents (BCA) are not normally widely adopted until a pest has become resistant to conventional pesticides and control begins to break down (e.g. pear sucker, western flower thrips). (Michaud 2018) also argues that although helpful, this approach does not constitute an ecologically sustainable solution because it requires continued inputs compared to more sustainable objectives, especially in open crops.

Before embarking on designing new habitats or modifying existing habitats to support the natural enemies and pollinators required for specific crops, there is a need to understand the biology, ecology, and interactions at a habitat scale (Kremen, Williams et al. 2002, Pardo and Borges 2020, Pardo, Lopes et al. 2020). Further, to make these approaches economical it is possible to apply more targeted tactics (Holland, Jeanneret et al. 2020), but evidence of success needs long-term (years) implementation, and close monitoring in fully replicated experiments – which of course requires investment (Pardo and Borges 2020). CBC, for example, is not a quick fix and it can take years to build diversity and populations of beneficials – especially those with low mobility or low interannual generations. Scientific studies are often limited by the length of funding available - typically 3-4 years at most.

Currently, farmers and growers are encouraged to plant and sow areas of wildflowers to provide environmental benefits, but also services to crops. Ecosystem service is a term used to describe the benefits (goods and services) that humans gain from the natural world (Losey and Vaughan 2006, Lautenbach, Kugel et al. 2011). Hence, the conservation of habitat which promotes beneficial insects (natural enemies and pollinators) provides a service to fruit growers in natural pest regulation and pollination (Andow 1991, Klein, Vaissiere et al. 2007, Jonsson, Wratten et al. 2010, Wratten, Gillespie et al. 2012, Klatt, Holzschuh et al. 2014). It is increasingly important to observe the additional benefits that such measures bring to the farm and surrounding landscape, for example, increases in biodiversity (Andow 1991), soil protection (Burel, 1996), and improved water quality (Granatstein and Sánchez 2009), by mitigating runoff and protecting against soil erosion (Altieri and Schmidt 1986, Wratten, Gillespie et al. 2012), and weed suppression (Altieri and Schmidt 1986, Meagher Jr and Meyer 1990, Denys and Tscharntke 2002, Harrington, Hartley et al. 2005, Granatstein and Sánchez 2009). Habitat improvements also enhance rural aesthetics giving additional secondary benefits (Wratten, Gillespie et al. 2012), which are not always considered in economic assessments.

This review encompasses over 130 peer reviewed papers which examine the benefits and costs to crops of cover crops and/or wildflower plantings. Although there is a focus on fruit crops, arable, vegetable, and other

horticultural crops are included to provide weight of evidence. This review focuses on the benefits provided to pest regulation and pollination services through the provision of natural enemies (predators and parasitoids) and pollinating insects.

Modern perennial fruit crops are planted at high densities in rows, often with alleyway that are sown at planting with a grass sward, typically *Lolium perenne* L., *Festuca* spp. and *Poa pratensis* L. (Morlat and Jacquet 2003) or unsown ('tumble-down') to allow for natural development of the resident grass and forb community (Fig. 1).

There are a range of terminologies used to describe purpose sown vegetation that is not directly a harvested crop. Cover crops are traditionally grown for the protection and enrichment of the soil but might also be selected or managed to avoid pests, divert pests, alter host-plant nutrition, reduce dust and drought stress, change the microclimate, and increase natural enemy efficiency (Bugg and Waddington 1994, Green 2015). In addition, they may also provide food resource for pollinators and birds. They tend to be annual or biannual and often comprise agricultural seeds. In contrast, perennial sowings are often more complex mixes of plants, described as wildflower strips, which can be sown on the margin or within the crop (alleyways) (Green 2015). They often consist of a range of native floral types and non-competitive grasses. Generally, floral margins and alleyways in orchards aim to increase the abundance and diversity of beneficial arthropods, which should outcompete or predate/parasitize pests (Cross, Fountain et al. 2015). Semi-natural habitats are also referenced in this review; in general, these are areas where minimal intervention has been applied (Ricketts, Regetz et al. 2008) (Fig. 2).
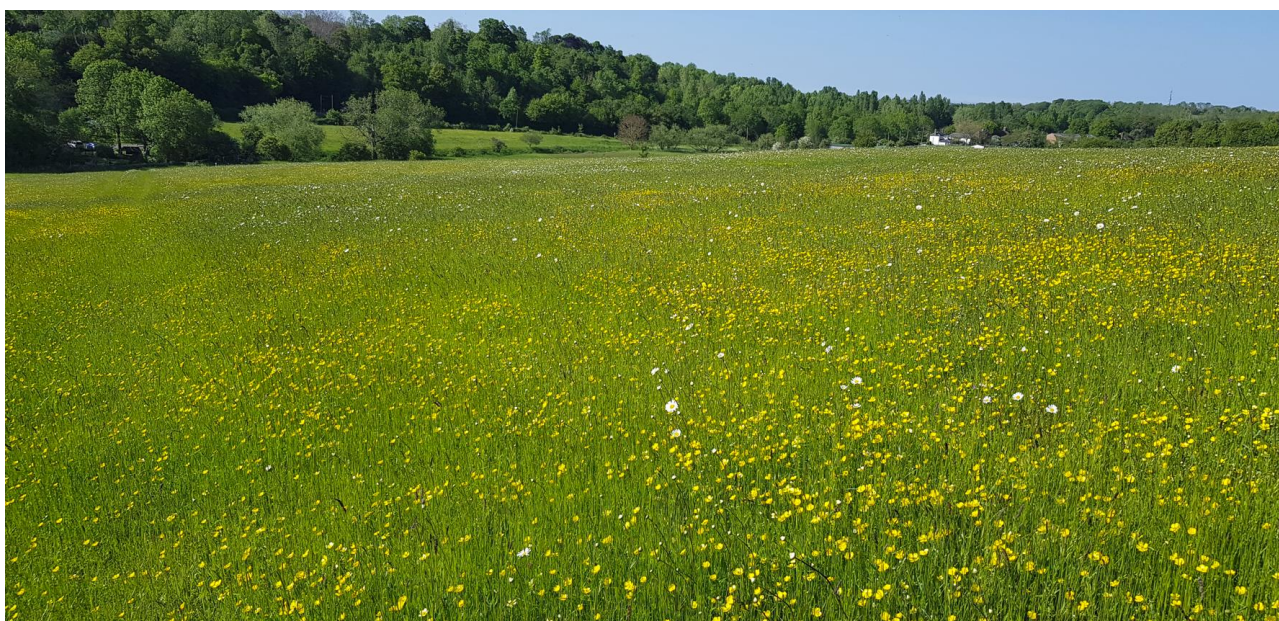


**Figure 2.** Semi-natural wildflower meadow in June, Kent, UK. Credit Konstantinos Tsiolis.

Currently, agri-environment schemes which encourage and subsidise habitat manipulations do not measure successful implementation, or the benefits provided (Kleijn and Sutherland 2003, Wood, Holland et al. 2016), but this is likely to change with the Environmental Land Management Schemes in the UK (ELMs) (DEFRA 2020). Often flower rich habitat (cover crops or wildflower plantings) to enhance pollen and nectar resource and shelter

for arthropods, are installed without measurements of the benefits, or indeed, detrimental effects they might create. Incentives for farmers, to benefit the environment, also need robust evaluation and considered responses in simple (high impact) and complex (low impact) agricultural landscapes so that implementation can be tailored to specific conditions (Kleijn and Sutherland 2003, Tscharntke, Klein et al. 2005). (Kleijn and Sutherland 2003) found that 54% of species in agri-environment schemes increased and 6% decreased in species richness or abundance compared with controls. The analysis of 20 studies revealed that 11 studies increased, no study decreased, and three both increased and decreased species richness or abundance of arthropods (Kleijn and Sutherland 2003).



**Figure 3.** Wildflower planting on margin of polytunnel grown raspberry. Credit Celine Silva

Most floral interventions need specialist knowledge and equipment to install (Fig. 3), but once established they also require ongoing monitoring and management to maximise benefits (Mateos-Fierro, Fountain et al. 2021) including timing of mowing, scarifying or tillage to influence the floristic composition and longevity (Altieri and Whitcomb 1980). Floristic species composition should be selected with soil conditions (Hill and Ramsay 1977)

and establishment in mind (e.g. herbicide applications) (Meagher Jr and Meyer 1990, Bugg and Waddington 1994).

Although intensive land use generally reduces functional species richness, actual species richness of generalist insect groups may be unaffected (Schweiger, Musche et al. 2007). The quality of local habitat may only affect specialist groups for example, rather than providing the functional groups that growers may require in the crop (Schweiger, Musche et al. 2007). Conversely, service management does not equate to biodiversity, but maintaining species diversity improves pest regulation and provides ecosystem resilience in preparation for future environmental changes (Snyder, Snyder et al. 2006, Senapathi, Biesmeijer et al. 2015). In addition, simply increasing biodiversity (or species richness) does not always result in improved ecosystem function (Schwartz, Brigham et al. 2000), hence a considered and tailored approach to flower rich habitat is recommended to realize the benefits for the landscape, biodiversity, crop and farmer/grower.

Only rarely are natural enemies and pollinators considered together in the literature, even though the provision of resource for one group may have additional benefits for the other and the resulting crop (Wratten, Gillespie et al. 2012, Sutter and Albrecht 2016).

This review focuses on the benefits that additional floral resources in the vicinity of fruit crops provide to pest regulation and pollination services through the provision of natural enemies (predators and parasitoids) and pollinating insects. This review summarises the 1. Impact of farm and landscape scale floral components, and 2. Economic and production impacts of floral resources on fruit crops. It then poses the questions 3. Does the length of time a floral resource is in place impact benefits, 4. What is the impact of vegetation resource quality?, 5. What is the impact floral resource size?, and 6. Do distance from the crop and edge impact effectiveness of wildflowers? The review goes on to summarise the 7. Benefits of floral resources to natural enemies and pollinators, and detrimental impacts on crop production, before reviewing the 8. Choice of floral resources, and 9. Establishment and management of floral resource, finally drawing conclusions and recommendations for future research.


# Recent reviews of the impacts of floral interventions

This section summarises 8 review articles.

Ricketts, *et al.* completed a meta-data analysis of 23 studies, incorporating 16 crops on five continents, on the relationship between pollination services and distance from natural or semi-natural habitats. They estimated that visitation rates of wild pollinators to flower crops dropped to half of its maximum at 0.6 km from natural habitat, compared to 1.5 km for pollinator species richness. Honeybee numbers also declined with distance from the semi-natural habitat, but less steeply (50% decline at over 2 km).

(Nicholls and Altieri 2013) reviewed the impact of habitat in agriculture on pollinators and recommended that some weeds species were important pollen and nectar sources for pollinators and levels of weeds should be tolerated below economic impact to help support pollinators. Areas of intensive farming, field margins, field edges and paths, headlands, fence-lines, rights of way and nearby uncultivated patches of land were important pollinator refuges, and these could be optimised for pollinators with appropriate management.

A more recent review (Pardo and Borges 2020) highlighted that a large proportion of studies showed that wild pollinators are abundant and frequently more effective apple pollinators than honeybees, adding support to the

necessity of preserving wild pollinators in agroecosystems. Indeed, honeybees should be thought as supplementary pollinators rather than relied upon for pollination of pollinator dependant crops (Garibaldi, Steffan-Dewenter et al. 2013). (Pardo and Borges 2020) also emphasized the need for heterogenous landscapes to support populations and the gap in management practices to support pollinators. The need for more long-term studies on the direct and indirect impacts on biodiversity including native habitat change, invasive species, pollinators diseases, and impacts on apple yield and quality, was also emphasised.

(Bugg and Waddington 1994) focused on natural enemies of codling moth in fruit crops including tree nuts, pome fruits, stone fruits and citrus, and concluded that parasitism of codling moth and tortrix larvae was significantly greater under trees with a rich flowering understory.

(Prieto-Benítez and Méndez 2011) did a meta-data analysis on natural enemies focusing on spiders for pest control. They found negative impacts on spider species richness and abundance for all 10 kinds of land management identified in the study, except forests.

(Simon, Bouvier et al. 2010) reviewed impacts on natural enemies and subsequent pest control in fruit crops. Plant management was mostly positive (16 cases), or had no-effect (9), but there were five cases that had a negative impact. The magnitude of pest control was not sufficient to reduce the use of pesticides except where high levels could be tolerated due to no direct effects on fruit damage or yield, e.g. mites and psyllids.

A meta-analysis of 109 studies found most insect pollinator groups responded positively to increasing plant species richness, but plant selection was key to this interaction and needed careful consideration to support agroecosystems and improve biodiversity (Kral-O'Brien, O'Brien et al. 2021).

(He, Kiær et al. 2021) reviewed 70 articles on the dietary value of floral resources in supporting predatory arthropods, including their effect on longevity and fecundity. Floral resources significantly increased predator longevity but the effect varied greatly among plant species. Flowers with more open or exposed nectaries were more likely to prolong predator longevity.

## Impact of farm and landscape scale floral components

There has been a focus in the last couple of decades on the impacts and interactions between landscape scale management alone, or in combination with floral rich habitat provision.

### Flower strips

In a study on nine farms with flower strips along a gradient of landscape heterogeneity and farming intensity, solitary bees declined with increasing distance from flower strips, but only in complex landscapes (Jönsson, Ekroos et al. 2015). Bumblebees, but not solitary bees, increased in abundance in field borders outside the flower strips in floristically enhanced landscapes compared with landscapes that did not have additional flower strips (Jönsson, Ekroos et al. 2015); mostly likely because bumblebees can forage for greater distances than solitary bees (Redhead, Dreier et al. 2016). Species richness and abundance of solitary bees were related to the amount of seminatural habitat at small scales, up to 750 m (Steffan-Dewenter, Münzenberg et al. 2002). Honeybees, however, were correlated with landscape context at large scales (3000 m) (Steffan-Dewenter, Münzenberg et al. 2002). In addition, there is some evidence that providing wildflower strips to enhance wild bees can be countered by installing manged honeybees into floral resource landscapes. Wild bee abundance

decreased by 48%, species richness by 20%, and strawberry fruit counts by 18% across farms provisioned with honeybee hives, regardless of wildflower strip presence (Angelella, McCullough et al. 2021).

Bumblebees forage at shorter distances where the local landscape has a high cover and low fragmentation of seminatural vegetation, including managed agri-environmental field margins, but the effect is bumblebee species dependent (Redhead, Dreier et al. 2016). In general, the higher the quality and/or area of forage (sown flower rich habitat) within a farm the higher the abundance of bumblebees and solitary bees (Földesi, Kovács-Hostyánszki et al. 2016). Landscapes with seminatural grassland on 24 farms did not improve solitary bee and bumblebee visitation rates, but more species of solitary bees were observed in landscapes with a high cover of seminatural grassland within 2 km radius of surrounding crops (Woodcock, Edwards et al. 2013). (Larkin and Stanley 2021) found that bumblebees did respond positively to field-scale management in semi-natural grasslands with higher floral diversity, whereas hoverflies responded positively to low-intensity landscape management.

Wild bee visitation to cherry increased with the proportion of high-diversity bee habitats in the surrounding landscape (1 km radius) (Holzschuh, Dudenhöffer et al. 2012). Crop visitation rates were also higher for managed honeybees in high quality landscapes with relatively large areas of alternative foraging habitat (Woodcock, Edwards et al. 2013) and flower resources as part of the groundcover of orchards (Földesi, Kovács-Hostyánszki et al. 2016). In sweet cherry orchards, at a 100 m landscape scale, inter-orchard flora supported pollinator species richness and wild pollinator abundance visiting cherry blossoms. At the 1 km scale, pollinator species richness also improved with increasing cover of floral resources (Eeraerts, Smagghe et al. 2019). For solitary bees, floral resources should be combined with provision of nesting habitat (Potts, Vulliamy et al. 2003, Woodcock, Edwards et al. 2013).

## Woodland

Woodland is also an important habitat as part of a diverse landscape setting (Martínez-Sastre, Miñarro et al. 2020). In a large study (35 orchards, 18 counties), (Mallinger, Gibbs et al. 2016) observed increased bee species richness and abundance in orchards in more diverse landscapes. They suggested that diverse landscapes, with both open (grassland) and closed (woodland) semi-natural habitats, supported spring wild bees by providing flowers and diverse niches throughout the entire foraging period for different species (Patrício-Roberto and Campos 2014, Mallinger, Gibbs et al. 2016). Woodlands are also important overwintering habitats for some hoverfly (Syrphidae) species (Sarthou, Ouin et al. 2005). In a study of 26 cider apple orchards, pollinators responded positively to cover of seminatural woodland and orchard habitats in a landscape (Martínez-Sastre, Miñarro et al. 2020). Woodlands compliment fruit orchards by providing complementary resources (food and nesting) to wild pollinators during the flight season (Eeraerts, Van Den Berge et al. 2021). Hence, both local and landscape cover improve bee species richness and composition with changes in edge habitats between major land classes also having a key influence (Holzschuh, Dudenhöffer et al. 2012, Shackelford, Steward et al. 2013, Senapathi, Biesmeijer et al. 2015).

## Field size, scale, and connectivity

Numbers of wild bee species and individuals are positively related to landscape factors up to 3 km, especially the presence of bare soil and the presence of ecological focus areas (Hellwig, Schubert et al. 2022). Increasing distance between crops and wild bee nesting habitat because of large field sizes impacts bee foraging distance into crops (optimum foraging theory) and decreases crop flower visits by pollinators (Lautenbach, Kugel et al.

2011). Conversely, wild bee species richness is positively affected by complex landscape configuration (Hopfenmuller, Steffan-Dewenter et al. 2014). Population density of bees also increases with habitat connectivity (Steffan‑Dewenter 2003) and a combination of large, high-quality, patches and heterogeneous landscapes can maintain high bee species richness and communities with diverse trait composition. This will help to stabilize pollination services provided to crops (Kremen, Williams et al. 2004, Shackelford, Steward et al. 2013, Hopfenmuller, Steffan-Dewenter et al. 2014). Connectivity of woodlands to hedgerows also increased yields of marketable strawberry fruits in adjacent crops by around 15% compared to isolated hedgerows (Castle, Grass et al. 2019). Wildflower plantings embedded within complex landscapes support a high abundance of bumblebees, whereas isolated plantings are predominantly visited by predatory hoverflies, pollen beetles, and other agricultural generalists (Grass, Albrecht et al. 2016), but hoverflies respond positively to landscape heterogeneity (Toivonen, Herzon et al. 2021).

Also at the local habitat scale, perennial grasslands support a greater abundance of uncommon, native coccinellids and host distinct species assemblages compared to crops (biofuel corn) (Werling, Meehan et al. 2011). However, at the landscape scale, abundances of exotic and uncommon native ladybirds (Coccinellidae) decreased with the area of herbaceous perennials and annual crops, respectively (Werling, Meehan et al. 2011). Anthocorid and syrphid abundance increased over fivefold with the area of herbaceous, perennial habitat in the landscape surrounding corn, suggesting that perennial grasslands could conserve natural enemies that are less abundant in crops (Werling, Meehan et al. 2011). In addition, increasing either plant species richness in adjacent grassland or hedge length in landscapes can increase aphid predation rates (sentinel bait cards) in sunflower fields (Badenhausser, Gross et al. 2020). However, although spider activity/density had a positive effect on predation, ground beetle species richness and activity-density were not related to aphid predation (Badenhausser, Gross et al. 2020). Species richness of web-building spiders in maize (gradient of 12 landscapes) increased with plant diversity and vegetation cover and which promoted the diversity of alternative prey. Conversely, intense management reduced prey diversity and aphid capture rates; aphids per web decreased from 8.5 on unmown sites to 4.7 aphids at sites that were managed by cutting (Diehl, Mader et al. 2013). For a 4-ha highbush blueberry field, (Blaauw, Isaacs et al. 2014) calculated an economic benefit within 4 years next to a 0.8 ha wildflower planting. In addition, small patches of native flora, planted in non-productive margins of large mango orchards, enhanced abundance, and diversity of mango pollinators (Carvalheiro, Seymour et al. 2012) and the maintenance of semi-natural habitats within 500 m of apple orchards enhanced wild pollinator communities and apple production (Földesi, Kovács-Hostyánszki et al. 2016).

## Complexity, diversity, and mass flowering crops

Local and landscape complexity has positive effects on both pollinators and natural enemies, but there is variation in responses of different taxa. For example, bees and spiders commonly respond positively, whereas the impacts on parasitoids and predatory beetles (mostly Carabidae and Staphylinidae) are often inconclusive (Shackelford, Steward et al. 2013). Spider species richness was more positively influenced by habitat complexity than spider abundance, possibly because of differences between generalists and specialists, or between arthropods that depend on non-crop habitats (Shackelford, Steward et al. 2013). The influence of mass flowering crops cannot be ignored in a landscape setting. Bumblebee densities increase in landscapes with mass flowering oilseed rape (Westphal, Steffan-Dewenter et al. 2003). Indeed, landscapes with orchards and soft fruit crops can complement each other by providing season-long bee forage for key pollinators (ground nesting solitary bees and bumblebees) (Martins, Albert et al. 2018). Conversely, (Pisman, Eeraerts et al. 2021) found

no positive impact on wild pollinator abundance of mass-flowering apple and cherry (Fig. 4). Although planted flower-rich strips did not improve hoverfly abundance at local scales (1 km), they did improve hoverfly abundance in simple (low complexity) landscapes (Jönsson, Straub et al. 2015, Földesi, Kovács-Hostyánszki et al. 2016). However, it is important not to only focus on flower strips in complex landscapes but the other requirements of pollinator's lifecycles, for example nesting. A more recent study of wild bee species diversity and abundance at landscape scales from 200 m to 10 km highlighted the positive impacts of wildflower strips on solitary and social wild bees (Hellwig, Schubert et al. 2022). These authors demonstrated the importance of bare soil (between 0.5-3 km), wood structures (especially up to 200 m) and grassland (0.5-5 km) in the landscape and showed that landscape complexity was more important for solitary than social wild bees observed on flower strips.



**Figure 4.** Mass-flowering of apple orchard with bumblebee visit to a blossom. Credit Michelle Fountain

Species richness of natural enemies also increases with landscape diversity (Steffan‑Dewenter 2003). Because a high level of non-cropped areas can enhance natural enemy populations (e.g. parasitoids in oil seed rape (OSR)), differences in abundance between the edge and the centre of crops were only observed in structurally simple but not in structurally complex landscapes (Thies and Tscharntke 1999). For example, natural pest control of aphids in brassica crops increased up to six-fold from simple to complex landscapes (Martin, Reineking et al. 2015) and landscape complexity was not only important for long distance flying bees (Redhead, Dreier et al. 2016) but also for dispersing flying natural enemies (Martin, Reineking et al. 2015). In complex landscapes, total aphid control was supplied by the combined contribution of flying insects and ground-dwellers. In this study, aphid control by flying insects and ground-dwellers was complementary but flying insects (e.g. hoverflies) were considered key to pest control particularly in the complex landscapes (Martin, Reineking et al.

2015). Continuity of flowering is also important and fruit growers should aim to supply pollen and nectar throughout the year whilst bees are active (Langlois, Jacquemart et al. 2020).

## Organic and IPM farming

In a 1 km scale study, across 42 wheat fields, in organic and conventional managed farms, a higher diversity of bees was observed under organic management (Holzschuh, Steffan‑Dewenter et al. 2007) probably because weed management impacted cover and diversity of flowering plants which are favoured in organic management. Organic farming favours hoverflies, with landscape heterogeneity increasing the abundance of aphid feeding (aphidophagous) species (Rand and Tscharntke 2007, Andersson, Birkhofer et al. 2013). Organic management also increased the abundance and diversity of spiders in the canopy of olive trees than the IPM and conventional systems (Cardenas, Pascual et al. 2015). Weed management practices also impact non-target species diversity within orchards (Gurr, Wratten et al. 2003). When the influence of flowers is removed, bee diversity is significantly positively improved by increasing landscape heterogeneity (Holzschuh, Steffan‑Dewenter et al. 2007, Andersson, Birkhofer et al. 2013, Todd, Malone et al. 2016, Pardo and Borges 2020). Organic orchards also tend to have a greater diversity of other natural enemy, and detritivore taxa. This was correlated with the application of fewer conventional agrochemical sprays and increased vegetative ground cover (Todd, Malone et al. 2016). However, (Ostandie, Giffard et al. 2021) demonstrated a lower abundance of pollinators in organic compared to conventionally manged vineyards, attributed to the higher tillage practice in organic farming. In summary, the breadth of species is reduced on conventional farms because homogeneity on these farms results in a loss of species with no close relatives (Andersson, Birkhofer et al. 2013).

However, a study on 85 apple orchards demonstrated that fruit damage at harvest was higher in organic orchards, creating an indirect negative effect (Samnegård, Alins et al. 2018). Organic orchards had 38% more species, for the same production of apples, but there was no impact of Agri-Environment Schemes (AES) on the species richness of beneficial arthropods, natural enemy abundance, nor fruit. Overall, organic management resulted in 48% lower yield than in IPM orchards, even though some organic orchards had higher yields than some IPM orchards (Samnegård, Alins et al. 2018), suggesting that it is possible within a landscape to achieve high yields with fewer pesticide inputs.

In a landscape study on 12 organic and 13 IPM orchards, wild bee abundance increased with grassland cover within 3 km and forest cover at 500 m (Bartholomée, Aullo et al. 2020). Landscape variables alone explained 30 % of the variance in pollinator communities, while plot-scale variables explained 6 % (Bartholomée, Aullo et al. 2020). (Winfree, Williams et al. 2008) found that crop visitation by wild bees was not associated with organic farming, nor with natural habitat cover at either local or landscape scale on 29 farms. However, in this study, field size, crop diversity and weed flower diversity did not differ between farms. Solitary bees were associated with the abundance of weedy flowers in the fields (Winfree, Williams et al. 2008). The study concluded that farm-site characteristics were more important than organic farming by itself.

Landscape variables and management practices also influence control of codling moth, *Cydia pomonella* L.. Predation of moth sentinel eggs and larvae by earwigs depended mostly on the toxicity of the crop protection programmes and was lower in orchards surrounded by large areas of conventional orchards (Monteiro, Lavigne et al. 2013). Codling moth parasitism rates were significantly higher in organic orchards and orchards surrounded by a low proportion of conventional orchards (250 m vicinity) compared to conventional orchards

(Maalouly, Franck et al. 2013). This indicates that landscape management practices need to be followed with consideration to the pesticide programmes being employed (McKerchar, Potts et al. 2020).

## Economic and production impacts of floral resources on fruit crops

Fewer than 15 studies in this review, followed implementation of flower-rich interventions through to economic or production impacts on neighbouring crops and very few of these related outcomes to the floral intervention directly. The area improved for wildlife has an impact on yield. Removing unproductive areas of fields and creating habitat, primarily floral resources, led to increased yield in the cropped areas of the fields despite the loss of cropland for habitat creation (Pywell, Heard et al. 2015).

### Pollinators

A meta-data analyses (synthesis of 23 studies – representing 16 crops on five continents), of the relationship between pollination services and distance from natural or seminatural habitats provided evidence of decreasing crop visits and pollinator richness with distance from natural habitat but less evidence of a decline in fruit and seed set (variables that directly affect yields) (Ricketts, Regetz et al. 2008). However, in mango there was significantly higher fruit production near to native wildflowers. Yield increased by 15 kg of commercially saleable mango per tree. This was attributed to a higher diversity and abundance of mango insect visitors near to the native wildflowers (Carvalheiro, Seymour et al. 2012).

Cherry blossoms exposed to insect visits produced 30.2% more marketable fruit compared to only 1.4% fruit if insects were excluded (using excluding mesh bags). However, hand pollinated blossoms achieved 51.7%, indicating significant pollination deficit in some cherry orchards (Mateos-Fierro, Fountain et al. 2021). The same was true for cacao where hand pollination significantly increased numbers of mature fruits (Forbes and Northfield 2017). In another study, where pollinator species richness and wild pollinator abundance had a strong and positive influence on fruit set of sweet cherry, the link to floral interventions was not clear (Eeraerts, Smagghe et al. 2019). (Holzschuh, Dudenhöffer et al. 2012) concluded that an increase of high-diversity bee habitats in the landscape from 20% to 50% enhanced fruit set in cherry orchards by 150% because of higher wild bee visitation to cherry blossoms with increased proportion of high-diversity bee habitats in the surrounding landscape (1 km radius). The value of pollinating insects to sweet cherry in the UK is estimated at £11.3 million (£14,731.8 ha$^{-1}$), whilst this could be increased to ~£25,607.9 ha$^{-1}$ if pollination management was improved (Mateos-Fierro, Fountain et al. 2021).

Wild bees are particularly important to apple production and can negate crop losses when honeybees are distracted by other co-flowering crops like OSR (Osterman, Theodorou et al. 2021). Fruit set of cider apples was positively related to wild insect flower visitor richness and andrenid bees (ground nesting solitary bees), but not flower strips, even though visit rate to apple blossoms of wild bees and Diptera increased to 40% in orchards with wildflower alleyways (Campbell, Wilby et al. 2017). Likewise, dessert apple had a higher fruit set where the species richness of wild bees (Fig. 5) was higher, regardless of the presence of honeybees (Földesi, Kovács-Hostyánszki et al. 2016). Fruit set responded positively to a higher abundance and richness of wild bees, whereas seed set depended on the abundance of wild pollinators in cider apple orchards (Martínez-Sastre, Miñarro et al. 2020). Strawberry fruit yields were lower when honeybees were installed onto farm, where wild

bee abundance and diversity also decreased (Angelella, McCullough et al. 2021). Strawberries grown in landscapes with well-connected semi-natural habitats increased in commercial value from 9.27 € per 1000 strawberries compared to plants grown on grassy margins to 14.95 € through increased yield and quality, most likely facilitated through easier movement of pollinators through the landscape to the crop (Castle, Grass et al. 2019). OSR yield gains (c. 0.4 t ha 1) are also correlated with pollinator (bees and flies) visitation rates (Woodcock, Bullock et al. 2016). Fruit set, weight (Bone, Thomson et al. 2009), and mature seeds can be positively impacted. However, a more recent study found fewer seeds in apples with enhanced floral landscapes and no consistent improvement in fruit quality or yield (Gervais, Belisle et al. 2021).

Fruit quality was significantly greater in blueberry fields adjacent to wildflower plantings, 3 and 4 years after establishment, leading to higher crop yields and the increased associated revenue exceeded the cost of wildflower establishment and maintenance (Blaauw and Isaacs 2014). Crop yields increased by 40-60% in avocado fields next to native flower habitats due to increases in the numbers of flies responsible for pollination (Muñoz, Plantegenest et al. 2021).



**Figure 5.** Andrenid bee on apple flower, an important pollinator of apple. Credit Konstantinos Tsiolis.

## Natural enemies

The Pest regulation services can also be improved in cherry orchards with wildflower alleyways. Natural enemies increased by 73.9% and 12.9% in alleyways and trees, respectively compared to cherry trees rows with no adjacent floral intervention (Mateos-Fierro, Fountain et al. 2021).

In apple, where no insecticides were applied for 5 years, plots with wildflower alleyways had 9.2% damaged fruits compared to 32.5% damaged fruits in (no manipulation) controls, primarily due to reduced damage by tarnished plant bugs and summer Lepidoptera, as the wildflowers attracted and retained arthropod beneficials that effectively managed several of the arthropod pests (Bostanian, Goulet et al. 2004). However, in UK commercial apple orchards, (McKerchar, Potts et al. 2020) showed that the presence of wildflower strips in alleyways did not contribute to delivery of natural pest regulation even though hoverfly diversity and species richness were greater in orchards with wildflower strips.   This was attributed to the cumulative pesticide toxicity negatively affecting natural enemy populations, especially earwigs (McKerchar, Potts et al. 2020).

Although (Markó, Jenser et al. 2012) showed no impact on fruit injury by insect pests including CM and tortrix in apple orchards with wildflower alleyways, Fountain et al. (unpublished) showed significantly reduced CM and tortrix damaged fruit in orchards with wildflower alleyways in combination with earwig refuges in trees and semiochemical hoverfly attractants. (Altieri and Schmidt 1986) also found fewer codling moth (Fig. 6) in orchards with floral alleyway sowings (36.1% infested apple compared to 45.0% in the control plots). In other organic apple orchards, fruit damage was reduced in orchards with floral alleyways due to slower *D. plantaginea* population increase and promotion of a whole complex of aphidophagous and generalist predators (Cahenzli, Sigsgaard et al. 2019). Species richness of beneficial arthropods in orchards was not correlated with fruit production in organic apple, suggesting that diversity could be increased without large yield losses (Samnegård, Alins et al. 2018). In addition, the most productive organic orchards exceeded the mean of IPM orchards, but fruit damage at harvest was higher in organic orchards, creating an indirect negative effect. However, flower visitation rates were higher in organic orchards, creating indirect positive effects from organic management on apple production (Samnegård, Alins et al. 2018).

**Figure 6.** Codling moth larvae in apple. Credit NIAB EMR.

In kale crops, the provision of floral resources enhanced parasitism rates of diamondback moth (*Plutella xylostella*) and aphids (*Brevicoryne brassicae* and *Myzus persicae*), in moderately simple landscapes but not in highly complex landscapes. This resulted in reduced pest numbers and increased crop yield related to *P. xylostella* control (Jönsson, Straub et al. 2015). Likewise, neither aphid population growth nor cumulated densities led to a decrease in final brassica crop biomass, but a high proportion of hoverflies had a positive impact on biomass, indicating a link via pest suppression between the predators and the provision of yields (Martin, Reineking et al. 2015). In the same study, neither parasitism rate nor parasitoid density significantly affected crop biomass (Martin, Reineking et al. 2015). (Jacometti, Jørgensen et al. 2010) observed no influence of buckwheat sowing adjacent to alfalfa crops, on yield, even though pest numbers were reduced because of an increased abundance of natural enemies.

Wildflower margins can be a part of increasing landscape complexity. (Thies and Tscharntke 1999) demonstrated that structurally simplistic landscapes are correlated with higher plant damage by pollen beetle and low larval mortality caused by lower parasitism (study in OSR). Mateos-Fierro, *et al.* concluded that wildflower plantings in orchard alleyways are an effective approach in orchards to enhance ecosystem services delivered by natural enemies and pollinators that could reduce pesticide inputs and increase yields, subsequently increasing profits to growers. If fruit growers want to support natural enemies and wild pollinators in crops through ecological intensification, not only do they need to consider the types of sprays being used, but also the frequency of their use. It is evident that further research is needed to identify approaches to successfully integrate wildflower habitats into modern fruit systems (McKerchar, Potts et al. 2020).

## Does the length of time a floral resource is in place impact benefits?

Of over 130 papers reviewed, 18 had studies that were 3 years in duration. Three studies each were 4 and 5 years in duration and five studies were 6 years long. Given the time for perennial floral margins to establish and arthropods to colonise and diversify, studying over a longer period is key to interpreting the impact that floral interventions have on cropping systems. Studies that are shorter than 4 years may miss long-term benefits.

For example, the economic benefits of floral margins in highbush blueberry were only seen in years 3-4 after establishment where wild bee and hoverfly abundance increased annually in the fields adjacent to wildflower plantings (Blaauw and Isaacs 2014). In Quebec apple orchards, significantly higher percentages (98%) of undamaged fruits were only recorded 5 years after sowing and several seasons were required to build up populations of beneficials to achieve effective biocontrol of pests (Bostanian, Goulet et al. 2004). Populations of predators (mainly spiders) and predator-prey ratios were also higher in 6- compared to 1-year-old floral strips (Denys and Tscharntke 2002).

In arable landscapes, habitat creation, including wildflower resources, increased yields, but it took around 4 years for the beneficial effects on crop yield to be realised, with effects becoming more pronounced over 6 years (Pywell, Heard et al. 2015). Parasitism of OSR pollen beetle (*Meligethes aeneus*) in the centre of the fields was enhanced by 6-year-old field margins (50% parasitism), compared to 1-year-old field margins (20% parasitism), resulting in increased mortality of pollen beetles (Thies and Tscharntke 1999). The reason proposed was that parasitoids utilised the undisturbed soil to overwinter (Thies and Tscharntke 1999). In unsprayed apple orchards, after 5 years, there was 9.2% fruit damaged by tarnished plant bug and summer Lepidoptera in floral treatments

(sown flower mix) compared to 32.5% damage in control (no manipulation) orchards (Bostanian, Goulet et al. 2004). Several seasons were needed to build up beneficials, but companion plants attracted and retained beneficials that effectively managed several arthropod pests (Bostanian, Goulet et al. 2004). In another 5-year study, no significant effects from the presence of flowering weeds (primarily wild carrot, parsnip, hogweed) were observed on the prey-predator or host-parasite relationship studied in apple (cider) orchards (Gruys 1982). This may have been because the alleyways were not purpose sown with a tailored mix to improve the diversity of floral resources. Indeed, simply allowing the resident flora of alleyways to grow unhindered in apple orchards can result in pest problems (e.g. encouraging pernicious weeds like dock can promote damage by dock sawfly to apples (pers. obs.) and, in the latter study, encouraged the proliferation of *Lygocoris pabulinus*. Hence purpose sown wildflower mixes can outcompete undesirable host plants of pest species.

In general, three years seems minimum for effects on pest control to begin to establish. As with beetle banks (Thomas, Wratten et al. 1992) it is likely that successional changes will occur over time from pioneering species (r-selected) towards more permanent specialist K-selected species. Species also vary between years as demonstrated in a study in apple orchards on parasitoid community compositions (Maalouly, Franck et al. 2013).

In some studies, effects have been observed more instantly. Cover crops in pear orchards of summer savoury (*Satureja hortensis*), ageratum (*Ageratum houstonianum*) and basil (*Ocimum basilicum*), decreased *Psylla chinensis*, *Aphis citricola* and *Pseudococcus comstocki* because numbers of their dominant natural enemies (*Coccinella septempunctata*, *Phytoseiulus persimilis* and *Chrysoperla sinica*) increased (Beizhou, Jie et al. 2011). Early effects, within the first year of establishment were detected in newly sown apple orchards (Fountain, *et al.* unpublished). Spring occurrence of aphids, and a reduction in codling moth damage to apples in combination with increases in hoverflies and lacewings were observed in orchards with alleyway wildflower sowings. However, in this study, hoverfly attractants and overwintering refuges were also employed and could have played a role. Natural enemies increased from 73.9% and 12.9% in alleyways and trees respectively in alleyways managed for wildflowers compared to regularly mown alleyways within 3 years of establishment in protected cherry orchards (Mateos-Fierro, Fountain et al. 2021). McKerchar*, et al.* demonstrated an increase in hoverfly diversity and species richness in apple orchards with wildflower alleyways, although there was no impact in the 3-year study on aphid removal from bait cards and no decrease in pests (rosy apple aphid (Fig. 7), woolly apple aphid). This was attributed to high values of cumulative pesticide toxicity negatively affecting natural enemy populations, especially earwigs, but the poor dispersal and single generation of earwigs mean that longer establishment times may also be needed to allow these beneficials to benefit from floral resources. In contrast, more mobile arthropods, such as 'ballooning' spiders, are more likely to be encouraged into orchards earlier with floral alleyways and margins significantly reducing the numbers of aphids returning to the trees in the autumn (Wyss 1995, Wyss, Niggli et al. 1995).

**Figure 7.** Rosy apple aphid colony on apple. Credit NIAB EMR.

In a 6-year study of pests and natural enemies in apple orchards, Markó, *et al.* found no additional control of pests in alleyway sowings of perennial flowering herbs although the abundance and diversity of predatory phytoseiid mites increased with flowering ground cover in spring and autumn and *Typhlodromus pyri* Scheuten gradually displaced *Amblyseius andersoni* (Chant) in the presence of flowers. Although lacewing, parasitoid wasps and spider numbers were higher in flower sown orchard compared to control orchards (6-year study), no significant increase in pest control was observed (Markó, Jenser et al. 2013, Markó and Keresztes 2014). Markó, *et al.* also pointed to the impact of several highly active insecticides disguising any potential effects of natural biocontrol.

Populations of spider mites on hop foliage were significantly lower within 2 years in cover-crops of California poppy (*Eschscholzia californica*), dwarf cornflower (*Centaurea cyanus*) and buckwheat (*Fagopyrum esculentum*) sowings compared to mown plots (Grasswitz and James 2008). For some beneficial and pest groups, short studies do not allow a clear response/correlation over time to be measured. Adult coccinellids were higher in cover-cropped plots, but only in one of the 3 years, demonstrating the inconsistencies between years (Grasswitz and James 2008) and the need for longer-term monitoring. European grapevine moth (*Lobesia botrana* (Denis & Schiffermüller)) was more abundant in tilled plots compared to plots with native flowering plants but the damage to grape bunches varied from year-to-year (12%, 42% and 14% in 2002, 2003 and 2004) (Serra, Lentini et al. 2006).

Likewise, many pollinators can take time to respond to floral provision because many species have only one generation a year. However, more pollinators were recorded in actively managed floral alleyways (maintained at 20 cm height) compared to regularly mown alleyways, leading to a 6.1% increase in fruit set in protected cherry orchards in a 3-year project (Mateos-Fierro, Fountain et al. 2021). The greater floral resource also led to an increase in pollinating insects in summer (after the cherry blossom period) compared to unsown alleyways, supporting pollinators after mass flowering. Wildflower strips also enhanced local bee abundance and richness in a 3-year study comparing wildflower margins and mown areas (Scheper, Bommarco et al. 2015) in arable

landscapes. Effects on solitary bees decreased with increasing amounts of late-season alternative floral resources in the landscape, whereas effects on bumblebees increased with increasing early-season landscape-wide floral resource availability, but actual population-level effects were uncertain in this short time (Scheper, Bommarco et al. 2015). In an orchard study species richness and the abundance of three bumblebee queen species increased with 3-year-old enriched habitats including wildflower margins (Gervais, Belisle et al. 2021). In arable landscapes, pollination services (bumblebees), species richness of bumblebees, butterflies and diurnal moths also increased over 3 years where adjacent wildflower strips were sown (Korpela, Hyvönen et al. 2013). In contrast, we saw an uplift in the number of solitary bees on apple blossoms at sites with flower plots within the first year (Garratt et al. submitted), although the extent of this uplift was not significantly different between year 1, 2 and 3 after flower establishment. In the same study, we observed solitary bees utilising the sown flower margins (Carvell, Mitschunas et al. 2022).

## What is the impact of vegetation resource quality?

Pollinators and natural enemies need food (pollen, nectar, prey etc.) to provide nutrition which may include different resources depending on life stage, physiological state, time of year etc., from a diverse range of sources. But this habitat needs to be connected to nesting habitat (for reproduction), nesting material, structure (e.g. web-building spiders), and shelter sites (for overwintering, protection from weather, predation etc.). For, example, the diversity of solitary wild bees is limited not only by floral resources but by nesting habitat (Hellwig, Schubert et al. 2022).

Sward architecture was the primary factor increasing species richness of predatory and phytophagous arthropods (Woodcock, Potts et al. 2009).

Plant diversity and species richness is key to providing resources required by insects (Woodcock, Potts et al. 2009, Nicholls and Altieri 2013, Scheper, Bommarco et al. 2015, Kral-O'Brien, O'Brien et al. 2021). In observations of a gradient of grassland plant species richness (73 plots), the frequency of pollinator visits increased linearly with both blossom cover and the number of flowering plant species (Ebeling, Klein et al. 2008). Pollinator visits were also closely related to the number of plant species, and blossom cover. In addition, the presence of attractive plant species enhanced the temporal stability of flower visits (Ebeling, Klein et al. 2008, Senapathi, Frund et al. 2021) and the impact of floral resource can be increased by contrasting what is sown with what is already in the local environment (Scheper, Bommarco et al. 2015).

Nutritional quality is also key when selecting plants to include in wildflower strips. In a UK study of flower meadows by (Hicks, Ouvrard et al. 2016), the nutritional status (pollen and nectar) of flowers in annual and perennial seed mixes was compared to weed species. Flowers which provided the highest rewards included *Leontodon hispidus*, *Centaurea cyanus,* and *C. nigra*, dandelion (*Taraxacum* spp. (Fig. 8)) for nectar, and *Papaver rhoeas*, *Eschscholzia californica* and *Malva moschata* for pollen (Hicks, Ouvrard et al. 2016). The wildflower meadows provided resource later in the season with pollinators relying on weed species for early forage. Early pollen and resources are especially important for solitary bees whereas bumblebees require forage for a longer period through the season (Scheper, Bommarco et al. 2015). Floral species richness is key to increasing bee nesting near orchards (Bihaly, Kovács-Hostyánszki et al. 2020).

**Figure 8.** *Andrena haemorrhoa*, a ground nesting solitary bee, on dandelion. Credit Konstantinos Tsiolis

## What is the impact floral resource size?

Natural enemy density, group richness and diversity increased with wildflower plot size (from 1 to 100 m$^2$) and a reduction in the focal soybean crop pest (*Aphis glycines*) (Blaauw and Isaacs 2012). (Dicks, Baude et al. 2015), tentatively suggested that 2% flower-rich habitat and 1 km flowering hedgerow were sufficient provision for six common pollinator species with pollen, although this would depend on wildflower mix quality (see above). In contrast (Heard, Carvell et al. 2007) found no impact on bumblebee densities of wildflower patch size (including 0.25, 0.5 and 1.0 ha), of sown legume and grass mix. Westphal, *et al.* demonstrated that bumblebee numbers were not determined by the proportion of semi-natural habitats in agricultural landscapes, but by the availability of highly rewarding mass flowering crops (i.e., oilseed rape) in the landscape and highlighted the need for management schemes in a landscape. In contrast, semi-natural habitats were found to be key to wild bee diversity in agricultural landscapes, with floral strips offering only a partial substitute (Hevia, Carmona et al. 2021). However, purpose sown flora can offer more flowerhead abundance that some semi-natural grasslands and, as a result, are often more pollinator rich (McHugh, Bown et al. 2022).

In a study on 344 fields, from 33 pollinator-dependent crops, in Africa, Asia, and Latin America it was concluded that increasing the floral provision for pollinators in smaller compared to larger cropping areas had a greater impact and improved yields (Garibaldi, Carvalheiro et al. 2016). Indeed, wild bees were the dominant pollinators in small blueberry fields (58% of flower-visiting bees) compared to large blueberry fields (97% honeybees) (Isaacs and Kirk 2010).

Several small fragments of flower-rich habitat have been found to support more butterfly and parasitoid species than the same area composed of only one or two fragments (Tscharntke, Steffan-Dewenter et al. 2002). Parasitism also increased with increased fragment area (either several small or one large area). These authors

suggested that small habitat areas should be scattered to maximize diversity and minimise the risk of species loss (Tscharntke, Steffan-Dewenter et al. 2002). Kremen, *et al.* suggested a target of 10% upland habitat could provide 20–40% of pollination needs for watermelon, and potentially benefit other fruit crops (Delaplane and Mayer 2000).

## Do distance from the crop and edge impact effectiveness of wildflowers?

The more isolated a floral area is from crops, the lower the flower insect visitor richness, visitation rate (except honeybees), and fruit set in the crop (Garibaldi, Steffan-Dewenter et al. 2011, Lentini, Martin et al. 2012). The stability of pollinators in crops is also affected by distance from floral habitat (Garibaldi, Steffan-Dewenter et al. 2011). Hence crops that are largely wild pollinator dependent (contrasted with honeybee dependent) require floristic habitat closer to the crop. Only areas of flower rich habitats within 500-1000 m (study from 250-2000 m) improved the richness of hoverflies and bees (Kleijn and van Langevelde 2006). At smaller scales, the spill-over of insects from floral margins to crop edges halves from 0 m to 12 m (Denys and Tscharntke 2002). In Californian vineyards, spider abundance was significantly higher at the vineyard edge than at the furthest distance from woodland and abundance was higher at 0 and 50 m into the woodland compared to 50 and 250 m into the vineyard (Hogg and Daane 2010).

No evidence of decreasing abundances of bumblebees or hoverflies with increasing distance from flower strips (1-800 m) into crops was observed (Jönsson, Ekroos et al. 2015) and solitary bees, but not bumblebees, declined at 400 m range from flower strips (in complex landscapes). This is likely because bees are more centrally-placed foragers and need to return to a nest, whereas hoverflies which do not have a nest may benefit from even small single flower strips (Jönsson, Ekroos et al. 2015). The provision of 6 m floral margins improved bee diversity in the centre of adjacent crops compared to crops with no marginal pollen and nectar provision (Marshall and West 2006).

The proximity of floral strips to the crop and the mobility of the target arthropod has a direct effect on the impact that floral interventions can achieve. Nevertheless, although edge responses are deemed predictable and consistent (Ries, Fletcher et al. 2004), the ability to bring together the data for consistent and reliable positive edge responses to drive pest control and pollination services has not been synthesised. Hedgerow and floral margins create spill-over of organisms into managed cropping areas (Blitzer, Dormann et al. 2012), but by providing floral resource within the crop, e.g. alleyways, we anticipate that the spill-over will occur from the alleyway into the orchard trees directly.

### Natural enemies

Hedgerows (ranging from 5 m to 57 m in length) adjacent to orchards, increased the abundance of rosy apple aphid (*D. plantaginea*) populations, whereas the abundance and duration of rosy apple aphid decreased with proximity of flower strips, most likely because natural enemies increased in proximity to flower strips (Albert, Franck et al. 2017). Hoverfly and ladybird eggs and larvae, increased in orchards near to floral strips, whereas aphid attending ants significantly decrease with the distance to flower strips. It is hypothesised that by providing alternative sugar resources, flower strips could distract ants from protecting rosy apple aphid attendance and reduce aphid abundance through increased predation by natural enemies (Albert, Franck et al. 2017, Shaw, Nagy et al. 2021). Predation rates of the aphid, *Rhopalosiphum padi* in wheat fields were always greatest where sentinel aphid colonies were established next to flower rich areas as opposed to grass only areas, even at a 50 m distance into the crop (Woodcock, Bullock et al. 2016). However, although predator numbers increased in

flower margins next to potato fields there was no significant spill-over into the crop (Middleton, MacRae et al. 2021).

Beneficial insect abundance in blueberry fields was more pronounced in fields adjacent to flowering margins, especially in the latter half of the growing season, and natural enemy abundance decreased with increasing distance (0, 20 and 40 m transects) from the field border (Walton and Isaacs 2011). Plant bugs (Miridae), hoppers (suborder Auchenorrhyncha) and thrips (Thysanoptera) were also more abundant in fields next to wildflower strips (Walton and Isaacs 2011). However, in the latter study, species were not identified hence it is not known if these were crop pests.

Sampling in apple and pear orchards for natural enemies at 0–60 m, 60–120 m and 120+ m showed that spiders and parasitoids declined significantly as distance from semi-natural habitat increased (Miliczky and Horton 2005). The steepest declines were between 0 and 120 m into the orchard, but there were no further declines between 60 and 120 m (Miliczky and Horton 2005).

Aphidophagous hoverflies which fed on phacelia and buckwheat floral strips adjacent to broccoli crops dispersed up to 17.5 m from the floral strips and very few were observed 50 m from phacelia floral strips (Laubertie 2007). (Wratten, White et al. 1995) also captured the highest numbers of hoverflies close to phacelia strips and concluded that they do not disperse very far from a pollen resource. However, as aphidophagous hoverflies are highly mobile and the latter experiment was rather small-scale, with traps placed up to 12.5 m from the flower strip, it is likely that hoverflies would travel further in search of larval resources for oviposition. (Lövei, Hodgson et al. 1993) trapped hoverflies with phacelia or coriander pollen up to 75 m from the flower source. Hoverflies are highly mobile (Salveter 1998) and phacelia pollen was found in the guts of Melanostoma fasciatum up to 180 m from the source; a similar trend was observed with Episyrphus balteatus and Metasyrphus corollae where pollen was recorded up to 200 m (Wratten, Bowie et al. 2003) and E. balteatus up to 250 m from the flower source (Harwood, Hickman et al. 1994). Higher numbers of aphidophagous hoverflies are observed in crops adjacent to weed strips, probably females searching for aphid colonies in which to lay eggs (Frank 1999). No significant effect of edge on arable fields next to grassland remnants was observed on ladybird abundance (Fig. 9) (Rand and Louda 2006).

**Figure 9.** Ladybird larva. Credit NIAB EMR.

Sown wildflower areas enhanced the densities, but not species richness of crab spiders (Thomisidae), ground spiders (Gnaphosidae), wolf spiders (Lycosidae) and young orb weavers (Araneidae) in adjacent wheat fields (3 m vs 30 m) (Schmidt-Entling and Döbeli 2009). Numbers of wolf spiders and ground spiders were higher towards field edges and densities of all spiders increased with the percentage of perennial habitats within a 1.5 km radius. Cursorial (fast moving/hunting) spiders (Gnaphosidae, Lycosidae, Thomisidae) and young orb weavers (Fig. 10) were at higher densities in fields with adjoining wildflower areas, than in fields with grassy margins (Schmidt-Entling and Döbeli 2009). In a meta-analysis, edge effects on spiders depended on the ecosystem studied. In general, forest ecosystem edges had a significantly higher spider abundance than forest interiors, whereas in unmanaged agroecosystem edges had higher spider species richness, but not abundance, than managed sites (Prieto-Benítez and Méndez 2011). At smaller spatial scales, the colonization of foliage-dwelling spiders into small, insecticide-free apple orchards at 10 and 50 m from an adjacent deciduous forest revealed that species composition was intermediate at 10 m between the forest and 50 m from the forest, demonstrating the importance of forests as a source of annual spider colonists into orchards (Sackett, Buddle et al. 2009).

**Figure 10.** Orb-weaving spider in apple orchard. Credit NIAB EMR.

*Dolichogenidea tasmanica*, a parasitoid wasp of light brown apple moth (*Epiphyas postvittana*) marked with rubidium from feeding on RbCl sprayed buckwheat plants, were trapped up to 30 m away within seven days (Scarratt, Wratten et al. 2008). Sphecidae, Eumenidae, Pompilidae (cavity nesting solitary wasps) were highest at forest edges, which provided natural nesting sites, and lowest in grass strips possibly contributing to higher biocontrol of pest caterpillars within the foraging range around these nests (Holzschuh, Steffan-Dewenter et al. 2009). Grass-strip corridors also enhanced the colonization of nesting sites, presumably by facilitating wasp movements (Holzschuh, Steffan-Dewenter et al. 2009). Conversely, wildflower strips did not enhance egg parasitism rates in artificially exposed cabbage moth (*Mamestra brassicae*) eggs and did not change significantly with increasing distance (up to 24 m) to the field border of plots with and without wildflower strips, although predation on *M. brassicae* eggs was higher on plants near to the wildflower strip (Pfiffner, Luka et al. 2009). In wheat fields, parasitism rates of the aphid, *Metopolophium dirhodum* declined exponentially with increasing distance from buckwheat floral patches, reaching zero beyond 14 m (Tylianakis, Didham et al. 2004). Quality and/or age of margins can affect the ability of parasitoids (Fig. 11) to build up and increase parasitism in crops. In OSR three univoltine parasitoids (*Tersilochus heterocerus, Phradis interstitia¡is, and Phradis morionellus*) of rape pollen beetle (Meligethes aeneus) were studied. Parasitism was 50% at field edges, dropping to 20% in field centres with 1-year old strips or no strips, but remaining as high as the edges if field margins were 6 years old. This is most likely because it takes time for parasitoids to build in numbers and because the parasitoids were provided with a non-disturbed habitat in which to overwinter in the older margins (Thies and Tscharntke 1999). In strawberry crops, parasitism by *Copidosoma aretas* of the tortricid*, Acleris comariana*, was measured at 1, 6, and 11 m distances from buckwheat flower strips. Caterpillar mortality was highest near to the buckwheat plots (Sigsgaard, Betzer et al. 2013). However, as this was not found to be in relation to parasitism it was more likely due to the complex suite of natural enemies in the margins (Sigsgaard, Betzer et al. 2013).

**Figure 11.** Summer fruit tortrix ectoparasite. Credit NIAB EMR.

In a study that incorporated wildflower strips into the alleyways of tunnel protected cherry orchards, Mateos-Fierro*, et al.* (2021) and (Mateos-Fierro 2020) found that whilst natural enemies were not influenced by the proximity to the edge of the orchard (indicating that the floral strips had improved natural enemies along the length of the tree row), pollinating insects were affected by the proximity to the edge. A greater number and higher species richness of pollinators was recorded near to the orchard boundaries.

Previous research in arable crops suggests that additional floral resources can boost flower visitor numbers as far as 100 m (Carvell, Meek et al. 2006). In orchards not provisioned with wildflower strips (Fountain, Mateos-Fierro et al. 2019) found no effect of distance from the edge (up to 50 m) on the quality of pears, and no consistent difference in the guild of insects visiting at distances from the orchard boundary. Likewise, there was no evidence that OSR yield gain declined with distance from the crop edge (over 10, 25, 50, 100 and 200 m), even though honeybees, bumblebees, solitary bees, and flies showed evidence of declining visitation rates with distance from the crop edge (Woodcock, Edwards et al. 2013, Woodcock, Bullock et al. 2016). Honeybees, bumblebees, and solitary bees (Fig. 12) were responsible for the significant decline in apple foraging activity into the orchard from the woodland edge (15, 35, 55, 100, and 200 m from edge) in some years, but this was not consistent and varied between pollinator group and year (Joshi, Otieno et al. 2016). In addition, it is suggested that for Megachilidae solitary bees, flower strips should be within ~150 m of the nesting resource (Hofmann, Fleischmann et al. 2020). In sunflower fields, the increase in pollinator species richness (but not abundance) mitigated any effect of distance from seminatural habitat (Carvalheiro, Veldtman et al. 2011).

The abundance of wild pollinators in cider apple orchards was improved up to 100 m from orchard edges with wildflower alleyways; the same effect was not seen for honeybees (Campbell, Wilby et al. 2017). In tomato fields there was a decrease in pollinators at increasing distance into the field (edge compared to 100 m). Uncommon species of native bees were sevenfold more abundant on hedgerow flowers than on flowers at weedy, unmanaged edges with no significant differences observed in syrphid abundance with distance into fields.

Hedgerows also supported honeybees and acted as net exporters of native bees into adjacent crops (Morandin and Kremen 2013). In OSR, bee abundance and taxa richness were negatively affected by the distance from forest edge (Bailey, Requier et al. 2014), however responses varied according to bee group. For example, there was a greater abundance of *Nomada* spp (cuckoo bees of *Andrena* spp.) and *Andrena* spp. males at forest edges (Bailey, Requier et al. 2014), where the female hosts are likely to be nesting.

At larger scales, seminatural habitats had a marginal positive effect on species richness of hoverflies and wild bees around apple orchards within a radius of 300 m and 500 m respectively (Földesi, Kovács-Hostyánszki et al. 2016). In addition, flower resources in the alleyways of orchards supported honeybees (Földesi, Kovács-Hostyánszki et al. 2016). Visitation rates to OSR were higher for honeybees in high quality landscapes with relatively large areas of alternative foraging habitat, but visitation rates of honeybees were also more frequent in the vicinity of managed hives (Woodcock, Edwards et al. 2013). In the same study, no effect of habitat quality was found for visitation rates of bumblebees or solitary bees although farms with high habitat quality supported more species than those of either moderate or low quality (Woodcock, Edwards et al. 2013). At the 100 m and 1,000 m landscape scale, inter-orchard herb layer (12 flowering plant species) and cover of floral resources in the herb layer supported pollinator species richness to cherry blossoms (Eeraerts, Smagghe et al. 2019). The presence of pollinators in potato crops was not enhanced by floral margins (Middleton, MacRae et al. 2021).

In a meta-analysis of 23 studies, including 16 crops on five continents, (Ricketts, Regetz et al. 2008) examined the relationship between pollination services and distance from natural or semi-natural habitats. Crop visitation rates by most pollinators declined at increasing distances into crops, dropping to half at 600 m from the natural habitat; although 2,170 m for honeybees. Distances at which visitation rate drops to 50% of the maximum was estimated at 439 m and 591 m for social and solitary bees, respectively. Species richness of pollinators declined by half at 1,500 m from seminatural habitat (Ricketts, Regetz et al. 2008). The maximum foraging distances of small (*Hylaeus punctulatissimus*), medium (*Chelostoma rapunculi*), and large (*Hoplitis adunca*) solitary bees was 1,100 m, 1,275 m, and 1,400 m, respectively (Gathmann and Tscharntke 2002, Greenleaf, Williams et al. 2007). However, 50% of female *H. punctulatissimus* and *H. adunca* did not forage at distances greater than 100–225 m and 300 m (Zurbuchen, Landert et al. 2010) and it is likely that foraging distance decreases with increasing number of plant species for solitary bees (Gathmann and Tscharntke 2002). Mean foraging distances for bumblebees were calculated between 272 and 551 m (worker foraging distances *Bombus terrestris* 551 m, *B. lapidaries* 536 m, *B. ruderatus* 501 m, *B. hortorum* 336 m, and *B. pascuorum* 272 m (Redhead, Dreier et al. 2016).

**Figure 12.** Solitary bee visiting apple flower. Credit NIAB EMR

Sunflower seed head mass declined significantly with distance from seminatural habitat (Carvalheiro, Veldtman et al. 2011). Equally, isolation from natural habitat was associated with declines in mango pollinators and in mango production (kg of marketable fresh fruit), but the presence of native wildflower areas corrected these declines (Carvalheiro, Seymour et al. 2012). In mango, 42% less production was observed at 500 m from the natural habitat and was attributed to both pollinator abundance and diversity (Carvalheiro, Seymour et al. 2010).

In tunnelled cherry, fruit set and consequently production along the tree rows is impacted. Trees closest to the orchard edge developed more cherries, but of smaller size thought to be associated with higher numbers of pollinators at the edge of these polythene protected orchards (Mateos-Fierro, Fountain et al. 2021). Likewise, in other protected crops stingless bees and honeybees were more abundant at the ends of tunnels and there were fewer visits to flowers toward the middle of tunnels. Fruit shape was improved in raspberry with greater pollinator abundance, and per plant yield and mean berry weight were positively associated with pollinator abundance and hence lower at the centre of tunnels than at the edge in blueberry (Hall, Jones et al. 2019).

Reassuringly, most edge effect manipulations appear to elicit repeatable responses (Ries, Fletcher et al. 2004), hence benefits can be applied across multiple crops. Edges, whether floral margins or woodlands, offer alternative habitats from cropping systems and provide resources not readily available in crops which might be important for certain life stages or simply as shelter or a host of natural enemies (e.g. (Bennewicz 2011)) and need sympathetic management to retain this service. The spill-over of organisms from margins is not only dictated by distance but also the quality of the margin area (Duelli, Studer et al. 1990). The latter author concluded that 'in cultivated areas a mosaic landscape of small sized crop fields and semi-natural habitats

maximizes arthropod diversity and decreases the probability for overall extinction ….'. Hence, in diverse landscapes colonisation by beneficials is dependent on habitat suitability rather than size or distance from other non-crop habitats (Duelli, Studer et al. 1990). It might also be prudent to consider spill-over in the opposite direction, especially when floral resources in orchards wain or overwintering habitats are sought by natural enemies (Blitzer, Dormann et al. 2012).

# Benefits of floral resources to natural enemies, pollinators and crop production

Most studies (>50 studies) reviewed, tested the impact of floral margins, with >30 studies incorporating floral plantings into the crop alleyways and understory. Increasingly, guidance is available on the establishment and management of wildflower strips in and around crops (e.g. (Nowakowski and Pywell 2016); https://northsearegion.eu/beespoke/publications-downloads/). To maintain the ecosystem services provided by insect pollinators and natural enemies, a diverse mix of species and functional groups of flowering plants are needed (Isbell, Calcagno et al. 2011). Planting areas are recommended to be at least 3–10 m in width and can be selected for sowing on a range of soils (Pfiffner and Wyss 2004). They should form part of an ecological intensification approach which aims to regulate, support, and even increase crop production (Pywell, Heard et al. 2015). Sowing orchards with field margins is complicated by restricted space and continuous travel by vehicles on headlands. However inter-row (alleyway) sowings may be beneficial, particularly if orchards are too large to allow natural enemies to penetrate (Altieri and Schmidt 1986). It may even be possible to adjust wildflower mixtures with aromatic plants such as summer savory (*Satureja hortensis*), ageratum (*Ageratum houstonianum*) and basil (*Ocimum basilicum*), to repel specific pests (Beizhou, Jie et al. 2011). In addition, the area available from alleyways for floral resource far outweighs that of the orchard perimeter, ensuring food and shelter for pollinators and natural enemies throughout most of the fruit growing season.

## Evidence of benefits

Natural enemies in fruit crops (Table 1): Most studies aimed at pest control in fruit crops using floral interventions have been applied to the orchard area and usually in the crop alleyways. The majority have demonstrated increases in the numbers of natural enemies but not always a corresponding increase in pest control. Fewer studies have measured benefits to production. In addition, some of the literature reported poor establishment of wildflower sowings with differences between treated and control plots in floral establishment being low, so the resulting impact was not significant (e.g. Bone *, et al.* .

A simple sowing of wheat (*Triticum aestivum*) as a cover crop did not increase natural enemies important to pear production such as *Anthocoris* spp. and *Deraeocoris* spp. (Fye 1983). However, studies in apple (Stephens, France et al. 1998) and vines (Scarratt, Wratten et al. 2008) using buckwheat (*F. esculentum*) resulted in higher parasitism levels (34% compared with 20% in unsown plots) of leaf rolling torticids (Stephens, France et al. 1998).

Spiders (Altieri and Schmidt 1986, Miliczky and Horton 2005, Markó and Keresztes 2014, Cardenas, Pascual et al. 2015) and parasitoids (Miliczky and Horton 2005, Markó, Jenser et al. 2012) benefit from the introduction of floral strips in or adjacent to orchards (Miliczky and Horton 2005), increasing three to seven-fold in one study in apple (Bostanian, Goulet et al. 2004, Markó, Jenser et al. 2013), although not always associated with a significant increase in pest control (Dib, Libourel et al. 2012).

Markó, *et al.* also observed no effect of florally enhanced ground cover on codling moth (*Cydia pomonella*) and summer fruit tortrix moth (*Adoxophyes orana*) fruit injury. Codling moth infested 36% of apples in organic systems with a cover crop of bell beans (*Vicia faba*), compared to 45% in clean-cultivated organic orchards (Altieri and Schmidt 1986). Fewer codling moth larvae and damaged fruits were recorded in orchards with wild-flower alleyways compared to mown alleyway plots [Fountain, *et al.* unpublished, (Cahenzli, Sigsgaard et al. 2019). However, when deploying codling moth egg sentinel cards, higher predation was observed in short grass cover plots compared to tall grass plots (66 vs. 38 % respectively) later in the season (July and August) (Marliac, Simon et al. 2015). This was attributed to higher vegetation pulling natural enemies away from the trees; there was a higher abundance of the earwig, *Forficula pubescens,* in the short grass plots and no impact of the treatments on spiders or *F. auricularia* (Marliac, Simon et al. 2015). Hence, simply allowing native alleyway flora to grow ('tumbledown') does not benefit natural enemies compared to purpose selected floral alleyway sowings. Similarly, encouraging natural flora (wild carrot, parsnip, hogweed, and many other species) in cider orchards did not improve control of fruit tree red spider mite (*Panonychus ulmi*), apple pigmy (*Stigmella malella*), aphids, nor summer fruit tortrix (*A. orana*) (Gruys 1982).

An early study on the parasitism of codling moth larvae found an increase in parasitism from 7% to 34% where nectar-rich flora was implemented (Leius 1967). Floral alleyways (in a one-year study) increased codling moth parasitoids (Dib, Libourel et al. 2012), whilst alleyways provisioned with buckwheat in one of two vineyards increased parasitism of leafroller species by >50% (Berndt, Wratten et al. 2006). Adult *Anagrus*, sometimes used as a biocontrol agent, were more abundant within the edge of vines sown with buckwheat compared to vines sown with clover (*Trifolium repens*) or mown cock's-foot (*Dactylis glomerata*), especially early in the season (English-Loeb, Rhainds et al. 2003). In addition, parasitism of 'sentinel' leafhopper eggs was higher on vines with buckwheat and parasitism by *Anagrus* of leafhopper eggs on grapes was greater when adults had access to flowering buckwheat rather than buckwheat without flowers (English-Loeb, Rhainds et al. 2003). Leaf-hoppers were not influenced by the cover crops used in the same study (English-Loeb, Rhainds et al. 2003), this maybe important given the future threat *Xylella* transmitted by some species of leaf hopper. Buckwheat is also a host of *Xylella fastidiosa* and which can be transmitted to grapevines (Irvin, Bistline-East et al. 2016). Rates of parasitism of released light brown apple moth larvae (*E. postvittana*) by *Dolichogenidea tasmanica* were higher in areas sown with buckwheat and alyssum compared to phacelia and controls, consequently leafroller damage was almost 29% lower in floral understorey treatments compared with controls (Irvin, Scarratt et al. 2006). There were twice as many *D. tasmanica* cocoons in the alyssum and buckwheat treatments compared to the controls (Irvin, Scarratt et al. 2006). Encouragingly, the parasitoid (*Anacharis zealandica*) of the brown lacewing (natural enemy) was not enhanced by the under-sowings (Stephens, France et al. 1998, Irvin, Scarratt et al. 2006).

Six predator taxa consumed light brown apple moth on ground with cover (*T. repens* and *D. glomerata*), whereas only earwigs (Fig. 13) consumed leafrollers in the vine canopy (x10 activity) (Frank, Wratten et al. 2007). Also, on vines, whilst leafhopper and thrips populations were not influenced by ground cover, European grapevine moth (*Lobesia botrana*) was always higher in tilled plots compared to native natural ground cover. However, vine mealybug (*Planococcus ficus*) was twice as abundant in vines with a cover crop compared to tilled areas; probably because ants, which protect the mealybugs from their natural enemies, were more abundant in these plots (28% vs. 12% of bunches damaged, (Serra, Lentini et al. 2006).

**Figure 13.** European earwig in apple aphid colony at night. Credit Csaba Nagy.

Employing more diverse floral alleyways, spider numbers and their webs increased in apple and cherry trees, reducing numbers of aphids able to return from their summer host plants (Wyss, Niggli et al. 1995, Markó and Keresztes 2014, Mateos-Fierro, Fountain et al. 2021). This increase in webs is not always mirrored by an increase in web building spider families (web builders (Theridiidae) and orb web builders (mainly Araneidae)), but species richness of spiders is increased and numbers of jumping spiders (Salticidae) benefit from more complex vegetation cover (Markó and Keresztes 2014). Of the total 11 families identified in alleyways and trees, Linyphiidae, Theridiidae, and Araneidae are the most abundant on apple and cherry trees (Chant 1956, McKerchar, Potts et al. 2020, Mateos-Fierro, Fountain et al. 2021). Individuals of these families use webs to catch prey; whilst Lycosidae, a ground-dwelling spider, only recorded in alleyway vegetation, is an active predator (Solomon, Cross et al. 2000). It is likely that dense and diverse vegetation in alleys provide more abundant and diverse prey including leafhoppers, herbivorous beetles, dipterans, mirids and thrips (Walton and Isaacs 2011, Markó, Jenser et al. 2013). Alternative prey can enhance spider abundance and species richness in the canopy of apple trees (Markó, Jenser et al. 2013) and help to buffer natural enemies from the effects of disturbance in the crop (Walton and Isaacs 2011).

Floral strips increase the abundance of beneficial insects, particularly later in the season (Walton and Isaacs 2011), providing late season natural control. In citrus orchards, ground cover of managed flower mixes enhanced numbers of spiders, parasitoid wasps, ladybirds and lacewings in the tree canopy in comparison to plots with bare soil (Silva, Franco et al. 2010). Cover crops in organic apple also increased the abundance of spiders, parasitic wasps and ladybirds in the adjacent trees (Altieri and Schmidt 1986).

Aphids (e.g. *D. plantaginea*, *A. pomi*) were less abundant in apple trees where floral strips or cover crops were sown (Altieri and Schmidt 1986) in orchards where numbers of natural enemies (Anthocoridae, Miridae, Namidae, Crysopidae and Coccinellidae) are generally increased (Wyss 1995, Wyss 1996). However, Markó, *et al.* found no evidence that habitat diversification enhanced the biological control of green apple aphid (*Aphis* spp.). Cahenzli, *et al.* demonstrated slower *D. plantaginea* population increase as compared with standard orchard vegetation, resulting in reduced fruit damage after the second fruit drop. This was coupled with higher numbers of natural enemies in *D. plantaginea* colonies on trees associated with flower strips (Cahenzli, Sigsgaard et al. 2019). In spring assessments of apple shoots, the abundance of aphids was significantly lower in one year where floral strips were sown in the alleyways compared to unsown and mown alleyways (Fountain, *et al.* unpublished). In cherry, natural enemies increased by 73.9% and 12.9% in alleyways and trees, respectively, compared to the growers' standard grass alleyways and as a result, aphid removal from sentinel cards was 25.3% greater in cherry trees adjacent to wildflower strips compared to controls (Mateos-Fierro, Fountain et al. 2021). Higher densities of web building spiders in orchard plots with wildflowers reduced winged aphids returning from their summer host plants resulting in fewer *D. plantaginea* in the trees the following spring (Wyss, Niggli et al. 1995). Although (Vogt and Weigel 1999) did not see an impact of flora on *D. plantaginea* on the trees there was suppression effect of the green apple aphid (*A. pomi*). *D. plantaginea* and ants were also less abundant in cider apple trees near to flower margins which also favoured natural enemies (Albert, Franck et al. 2017).

Faster suppression of woolly apple aphid (*Eriosoma lanigerum*) (Fig. 14) occurred on apple trees closer to sweet alyssum flowers compared to mowed grass. Higher densities of natural enemies were also observed near sweet alyssum plantings and were found to move between alyssum and adjacent apple trees (Gontijo, Beers et al. 2013).



**Figure 14.** Woolly apple aphid colony. Credit NIAB EMR.

The abundance and diversity of predatory phytoseiid mites increased with flowering ground cover in the spring and autumn preventing a build-up of spider mite (Markó, Jenser et al. 2012). However single species sowings

of 14 different flowering plants did not affect fruit tree red spider mite (*P. ulmi*) abundance in trees (Fitzgerald and Solomon 2004).

Encouragingly European tarnished plant bug (*Lygus rugulipennis*) was less abundant in sown flower compared to control (regularly mown) plots and cockchafers (*M. melolontha*) were less abundant in the floral compared to bare ground plots (Markó, Jenser et al. 2013). (Bostanian, Goulet et al. 2004) also observed less damage by tarnished plant bugs and summer torticids in florally managed apple plots compared to conventionally managed controls. Conversely, ground cover that included wild carrot, parsnip, and hogweed did favour common green capsid (*Lygocoris pabulinus*) (Gruys 1982).

Lacewing adults (*Chrysoperla carnea*) were also more abundant where flower mixes were established (Markó, Jenser et al. 2013) and coriander planted in strawberry crops increased lacewing egg laying in aphid colonies (Hodgkiss, Brown et al. 2019).

In a pear orchard study by (Winkler, Helsen et al. 2007), numbers of anthocorids in adjacent pear trees were initially significantly higher in floral (*Centaurea cyanus*, *Fagopyrum esculentum*, *Lobularia maritima*, *Thymus serphyllum*, *Sinapis alba*) than in control plots. In this study it was not possible to detect an impact on the control of pear sucker (*Cacopsylla pyri*) because management (including reduced pesticide use) meant that pear sucker declined in the control equally well to the florally treated areas (Winkler, Helsen et al. 2007). In semi-field experiments with single species of flowering plants around pear trees, anthocorid numbers were boosted by corn chamomile and cornflower and seasonal totals of anthocorids were higher in the under-sown trees with floral provision than the bare earth plots (Fitzgerald and Solomon 2004). Although none of the 14 individual sown species in this experiment affected abundance of pear sucker (*Cacopsylla pyricola*), numbers of psyllid larvae did decline more quickly on the trees surrounded by flowering plants (Fitzgerald and Solomon 2004). Alleyway floral sowings in organic pear orchards decreased sucker (*Psylla chinensis*), aphid (*Aphis citricola*) and mealybug (*Pseudococcus comstocki*) and in some cases delayed their establishment (Beizhou, Jie et al. 2011). Also in pear orchards, natural ground cover and sown ground cover (*Lolium perenne*, white mustard *Sinapis alba* and white clover *T. repens*) sheltered distinct arthropod communities with the former characterised by spiders and the sown ground cover characterized by ants. Anthocoridae (Heteroptera) and Miridae (Heteroptera) were the main beneficials on pear trees in sown areas with Empididae (Diptera) and Miridae more abundant in the natural ground cover area; and earwigs and Miridae more abundant in bare ground areas (Rieux, Simon et al. 1999).

The provision of floral strips usually has a positive effect on hoverflies (Bostanian, Goulet et al. 2004, Walton and Isaacs 2011, McKerchar, Potts et al. 2020). In experiments, screening fourteen flowering plant species, ladybirds were particularly abundant on cornflower (Fitzgerald and Solomon 2004). The impact of floral margins can also vary between years with increases in hoverflies and lacewings not being evident every year (Fountain, *et al.* unpublished). In protected cherry orchards, flower sowings in alleyways had greater pest regulation services (measured using aphid baited cards) compared to regularly mown, predominantly grass, alleyways (by 25.3%). Natural enemies increased by 73.9% and 12.9% in alleyways and trees respectively compared to the conventional control (Mateos-Fierro, Fountain et al. 2021). Numbers of natural enemies (*Coccinella septempunctata*, *Phytoseiulus persimilis* and *Chrysoperla sinica*) increased in organic pear orchards with alleyway sowings of the aromatic plants summer savory (*S. hortensis*), ageratum (*A. houstonianum*) and basil (*O. basilicum*) with the ratio of natural enemies to pests being higher in orchards with inter-row plantings (Beizhou, Jie et al. 2011). More Ichneumonoidea and hoverflies were observed in floral experimental blocks (*Tanacetum*

*vulgare*, *Chrysanthemum maximum*, *Aster tongolensis* and *Achillea millefolium*) than untreated control blocks in apple orchards, with no increase in damage by key pests compared to the control plots in a 5-year study (Bostanian, Goulet et al. 2004). Sweet alyssum flowers are also attractive to hoverflies (Gontijo, Beers et al. 2013).

The provision of perennial flower areas managed to promote natural enemies can also have a beneficial side effect of outcompeting annual weeds that encourage tarnished plant bug, *Lygus* spp.. In North Carolinian peach orchards, (Meagher Jr and Meyer 1990) demonstrated that weedy plots dominated by chickweed (*Stellaria media*) and Carolina geranium (*Geranium carolinianum*) had higher percentages of Lygus damaged fruits. In 1986, damage was 8.9% in weedy plots vs. 2.6% and 2.2% in plots with no winter annuals and bare ground, respectively. The corresponding values for 1987 were 28.2%, 14.4%, and 10.2%.

In general, crops which have enhanced ground cover have lower pest levels, a greater number of species with higher abundance of predaceous arthropods, and higher removal rates of artificially placed prey compared to crops which have florally impoverished ground cover (Altieri and Schmidt 1986). However, a more recent study in apple orchards demonstrated that whilst floral alley margins have the potential to enhance numbers of predators in orchards, this is often negated by the high values of cumulative pesticide applications, which adversely affect natural enemy populations, especially earwigs (McKerchar, Potts et al. 2020).

Nevertheless, it is unlikely that key pests will be sufficiently controlled by floral interventions to a commercially acceptable level. For example, codling moth has a very low threshold because one caterpillar can render a single fruit unmarketable. However, for pests that do not directly damage fruits and cause superficial damage to foliage for example, floral margins can boost local levels of natural enemies which negate the need for some insecticide applications (Cross, Fountain et al. 2015). This strategy will rely greatly on regular and accurate pest scouting, monitoring, tracking and reporting.

To conclude, orchards with flowering ground cover contribute to pest management by boosting natural enemies with variable and context dependent outcomes. The effect will depend greatly on the floral resource provided, location, landscape, pesticide use and even management of the floral resource.

**Table 1.** Effects of wildflower of cover crop floral enhancements on the control of fruit pests updated from Simon*, et al.* [1], and updates[2]. The effect of plant manipulation on pest control is considered to be positive, null or negative when either the density of the pest arthropod of the fruit tree, fruit damage and/or the number of pesticide applications against the target pest is lower, equal or higher, respectively, compared with control. NB: different effects may be due to species grown, location or timing.

| | Fruit Crop | Pest Group | Targe pest(s) | Plant manipulation(s) or presence | Effect on pest control | Source |
|---|---|---|---|---|---|---|
| [1] | Apple | Aphid | *Dysaphis plantaginea* | Flower strips | Negative | (Vogt, Weigel et al. 1998, Vogt and Weigel 1999) |
| [1] | Peach | Hemiptera | Leafhoppers | Plant cover | Negative | (McClure, Andreadis et al. 1982) |
| [1] | Peach | Hemiptera | Hemiptera species | Plant cover | Negative | (Meagher Jr and Meyer 1990) |
| [2] | Apple | Heteroptera | *Lygus* | Flower plant mixture, alleyways | Negative | (Altieri and Schmidt 1986) |
| [2] | Apple | Heteroptera | *Lygocoris pabulinus* | Flowering weeds, alleyways | Negative | (Gruys 1982) |
| [2] | Pear | Heteroptera | *Lygus* | Cover crops, wheat | Negative | (Fye 1983) |
| [2] | Apple | Homoptera | *Eriosoma lanigerum* | Flower plant mixture, alleyways | Negative | (Markó, Jenser et al. 2013) |
| [1] | Peach | Spider mites | *Tetranychus urticae* | Plant cover | Negative | (Meagher Jr and Meyer 1990) |
| [1] | Apple | Aphid | Apple aphids | Peach nectaries | Null | (Spellman, Brown et al. 2006) |
| [1] | Apple | Aphid | *Aphis spiraecola* | Buckwheat | Null | (Spellman, Brown et al. 2006) |
| [1] | Apple | Aphid | *Aphis pomi* | Flower strips | Null | (Vogt, Weigel et al. 1998, Vogt and Weigel 1999) |
| [2] | Vines | Cicadellidae | Leafhoppers | Buckwheat, alleyways | Null | (English-Loeb, Rhainds et al. 2003) |
| [2] | Apple | General | Various | Flowering weeds, alleyways | Null | (Gruys 1982) |
| [1] | Apple | General | Apple pests | Plant cover | Null | (Jenser, Balázs et al. 1999) |

| | Crop | Pest group | Pest | Plant | Effect | Reference |
|---|---|---|---|---|---|---|
| [2] | Apple | General | Various | Flower plant mixture, alleyways | Null | (Markó and Keresztes 2014) |
| [2] | Apple | General | Various | Flower plant mixture, alleyways | Null | (McKerchar, Potts et al. 2020) |
| [2] | Apple | Homoptera | Green apple aphids (*Aphis* spp.) | Flower plant mixture, alleyways | Null | (Markó, Jenser et al. 2013) |
| [2] | Apple | Lepidoptera | Codling moth | Flower plant mixture | Null | (Dib, Libourel et al. 2012) |
| [1] | Apple | Lepidoptera | Tortricidae | Phacelia | Null | (Irvin, Scarratt et al. 2006) |
| [2] | Pear | Psyllid | *Cacopsylla pyricola* | Flower plant mixture, alleyways | Null | (Fitzgerald and Solomon 2004) |
| [2] | Pear | Psyllid | *Cacopsylla pyri* | Ash, ivy, polar hedgerow | Null | (Rieux, Simon et al. 1999) |
| [2] | Apple | Spider mites | *Panonychus ulmi* | Flower plant mixture, alleyways | Null | (Fitzgerald and Solomon 2004) |
| [1] | Apple | Spider mites | *Panonychus ulmi* | Plant cover | Null | (Nyrop, Minns et al. 1994) |
| [2] | Vines | Lepidoptera | Tortricidae | Buckwheat | Null, Positive | (Berndt, Wratten et al. 2006) |
| [1] | Apple | General | Apple pests | Plant cover and or interplanted fruit trees | Null, Variable | (Brown 2001) |
| [1] | Peach | General | Peach pests | Plant cover and or interplanted fruit trees | Null, Variable | (Brown 2001) |
| [1] | Apple | Aphid | *Dysaphis plantaginea* | Flower strips | Positive | (Pfammatter and Vuignier 1998) |
| [1] | Apple | Aphid | *Aphis pomi, Dysaphis plantaginea* | Flower strips | Positive | (Wyss 1995, Wyss, Niggli et al. 1995) |
| [2] | Vines | Cicadellidae | Leafhoppers | Flower plant mixture, alleyways | Positive | (Costello and Daane 2003) |
| [2] | Blueberry | General | Various | Flower plant mixture, margins | Positive | (Walton and Isaacs 2011) |
| [2] | Apple | Homoptera | *Lygus* | Flower plant mixture, alleyways | Positive | (Markó, Jenser et al. 2013) |

| | | | | | |
|---|---|---|---|---|---|
| [2] | Cherry | Homoptera | Aphid bait cards | Flower plant mixture, alleyways | Positive | (Mateos-Fierro, Fountain et al. 2021) |
| [2] | Apple | Homoptera, Cicadellidae, Lepidoptera | *Dysaphis plantaginea*, leaf hopper, codling moth | Flower plant mixture, alleyways | Positive | (Altieri and Schmidt 1986) |
| [2] | Apple | Homoptera, Formicidae | *Dysaphis plantaginea*, ants | Flower margins | Positive | (Albert, Franck et al. 2017) |
| [1] | Apple | Lepidoptera | Tortricidae | Peach nectaries | Positive | (Brown, Mathews et al. 2008) |
| [2] | Strawberry | Lepidoptera | Acleris comariana, Tortricidae | Margin, buckwheat | Positive | (Sigsgaard, Betzer et al. 2013) |
| [2] | Vines | Lepidoptera | Tortricidae | Margin, buckwheat | Positive | (Scarratt, Wratten et al. 2008) |
| [2] | Apple | Lepidoptera, Hompotera | Codling moth, *Dysaphis plantaginea* | Flower plant mixture, alleyways | Positive | (Cahenzli, Sigsgaard et al. 2019) |
| [2] | Apple | Lepidoptera, Hompotera | Codling moth, aphids | Flower plant mixture, alleyways | Positive | Fountain *et al.* (unpublished) |
| [1] | Pear | Psyllid | *Cacopsylla pyri* | Hedgerow | Positive | (Debras 2002, Debras 2007) |
| [1] | Pear | Psyllid | *Cacopsylla pyri* | Plant cover | Positive | (Rieux, Simon et al. 1999) |
| [2] | pear | Psyllid, Homoptera, Pseudococcidae | *Psylla chinensis, Aphis citricola* and *Pseudococcus comstocki* | Aramatic plants, alleyways | Positive | (Beizhou, Jie et al. 2011) |
| [1] | Apple | Spider mites | *Tetranychus* spp. | Understory plants | Positive | (Alston 1994) |
| [1] | Apple | Spider mites | Spider mites | Understory plants | Positive | (Croft 1982) |
| [1] | Apple | Spider mites | *Panonychus ulmi* | Adjacent bushes | Positive | (Tuovinen 1994) |

| | | | | | | |
|---|---|---|---|---|---|---|
| [1] | Apple | Spider mites | *Tetranychus* spp. | Plant cover | Positive | (Yan, Yu et al. 1997) |
| [2] | Apple | Heteroptera, Lepidoptera | *Lygus*, caterpillars | Flower plant mixture, alleyways | Positive | (Bostanian, Goulet et al. 2004) |
| [2] | Apple | Homoptera | *Eriosoma lanigerum* | Flowers | Positive | (Gontijo, Beers et al. 2013) |
| [1] | Apple | Lepidoptera | Tortricidae | Buckwheat | Positive | (Irvin, Scarratt et al. 2006) |
| [1] | Apple | Lepidoptera | Tortricidae | Alyssum | Positive | (Irvin, Scarratt et al. 2006) |
| [1] | Apple | Lepidoptera | Tent caterpillar and codling moth | Understorey plants | Positive | (Leius 1967) |
| [1] | Apple | Lepidoptera | Tortricidae | Buckwheat, alleyways | Positive | (Stephens, France et al. 1998) |
| [2] | Apple | Various | Spider mites, *Leucoptera malifoliella*, codling moth, Tortricidae | Flower plant mixture, alleyways | Positive, Null | (Markó, Jenser et al. 2012) |
| [2] | Vines | General | Various | Flowers, alleyways | Variable | (Serra, Lentini et al. 2006) |
| [2] | Vines | General | Various | Buckwheat | Negative | (Irvin, Bistline-East et al. 2016) |

**Table 2.** Effects of wildflower or cover crop floral enhancements on insect pollinators and fruit production. The effect of plant manipulation on pollinator numbers and/or diversity is positive, null or negative.   NB: different effects may be due to species grown, location or timing

| Fruit crop | Target pollinators | Plant manipulation(s) or presence | Location/ scale | Effect on crop | Effect on pollinator | Source |
|---|---|---|---|---|---|---|
| Blueberry (highbush) | Honeybees, wild bees, hoverflies | 15 perennial wildflower species | Margin | Fruit set, berry weight, mature seeds, yield greater in fields adjacent to wildflower plantings | Null (Honeybees), Positive (wild bees and hoverflies) | (Blaauw and Isaacs 2014) |
| Apple (cider) | Honeybees, wild bees, hoverflies | 25 wildflower species | Alley | Increase visits to apple blossoms, fruit set | Positive (wild bees, (Andrenid) and flies) | (Campbell, Wilby et al. 2017) |
| Mango | Pollinators | *Aloe greatheadii, Barleria obtusa* | Margin | Higher production | Positive | (Carvalheiro, Seymour et al. 2012) |
| Strawberry | Honeybees, wild bees, hoverflies | Annual and biennial fowering species | Margin | Not measured | Positive (wild bees and bumblebees) | (Feltham, Park et al. 2015) |
| Apple | Honeybees, wild bees, hoverflies | Nine herbaceous species | Alley | None | Null (bees), Positive (hoverflies) | (McKerchar, Potts et al. 2020) |
| Blueberry, sour-cherry, watermelon | Wild bees | Enhanced floral margins | Margin | Not measured | Positive (wild bees) | (Nicholson, Ward et al. 2019) |
| Apple | *Osmia lignaria* | Bigleaf lupine, *Lupinus polyphyllus* | Margin | Not measured | Positive | (Sheffield, Westby et al. 2008) |
| Cherry (protected) | Pollinating insects | Perennial wildflower mix | Alley | Not measured | Positive | (Mateos-Fierro 2020) |

| Crop | Pollinator | Intervention | Scale | Effect measured | Outcome | Reference |
|---|---|---|---|---|---|---|
| Cherry | Wild bees | Semi-natural habitat including floral resources in orchards | Alley and landscape | Wild pollinator positive influence on fruit set | Positive | (Eeraerts, Smagghe et al. 2019) |
| Apple | honeybees | Semi-natural habitat including floral resources in orchards | Within orchard | Not measured | Positive (honeybees) | (Földesi, Kovács-Hostyánszki et al. 2016) |
| Cherry | Honeybees, wild bees | Non-intensively managed areas | Landscape | Increased bee resources from 20% to 50% enhanced fruit set by 150% | Positive (wild bees) | (Holzschuh, Dudenhöffer et al. 2012) |
| Apple | wild bees | Local and landscape flora | Landscape and local | Not measured | Positive (spring wild bees) | (Mallinger, Gibbs et al. 2016) |
| Apple, cider | Wild pollinators | Landscape and small-scale orchard features | Landscape and local | Increase fruit set and seed set | Positive (wild pollinators) | (Martínez-Sastre, Miñarro et al. 2020) |
| Apple | Wild pollinators | Organic vs. integrated management | Margin, landscape | Reduced pollination deficit measured | Positive (wild pollinators) | (Samnegård, Alins et al. 2018) |
| Apple | | Hedgerows, flower strips | Landscape, margins | No consistent impact on fruit quality | Positive (bumblebees) | (Gervais, Belisle et al. 2021) |
| Apple | Wild pollinators | Dandelion | Alley | Larger apples | Positive (apples), null (pollinators) | (Son and Jung 2021) |

Benefits to other crops: Much research on floral interventions in non-fruit crops has focused on plantings around the perimeter of arable crops and vegetable with demonstration that wildflower strips enhance diversity and abundance of generalist predators (Pfiffner and Wyss 2004). In annual crops, wildflowers encourage spiders and carabids, in particular (Pfiffner and Luka 2000).

Woodcock*, et al.* demonstrated that the rate of decline of aphids (*R. padi*) was more rapid in wheat fields adjacent to flower rich field margins as opposed to grass only field margins, even at 50 m distance into the crop. The floral margins were neither significant habitat for early development of the first hoverfly generation nor for additional generations after wheat harvest. (Salveter 1998) suggested that the importance of floral strips was not to provide alternative prey for juvenile stages of aphid natural enemies, but as a source of pollen and nectar for the adults. In contrast, (Sutherland, Sullivan et al. 2001) highlight that margins are probably providing aphid resources, shelter from predation, lekking sites, and suitable flight-paths from which hoverfly adults can disperse to find aphids in crops (Salveter 1998, Sutherland, Sullivan et al. 2001). In floral margins greater than 4 years old, and involving 31 fields, hoverflies responded to field scale interventions and weed management within crops; weedier fields supported a higher species richness and a higher diversity of hoverflies (Marshall and West 2006). Floral strips also reduced aphid numbers where hoverfly numbers are improved next to wheat compared to wheat with no adjacent floral resource (Hatt, Lopes et al. 2016). In addition, the abundance of hoverfly larvae was positively correlated with the aphid density on tillers (Hatt, Lopes et al. 2016). The marmalade hoverfly (*E. balteatus*) was significantly more abundant in spring barley next to flower rich margins compared to an unsown margin (MacLeod 1999). Floral composition is essential to encourage different natural enemy groups (Hatt, Uyttenbroeck et al. 2017) and is often influenced by the natural enemy's capability to gain access to the flora resource (e.g. pollen and nectar) (van Rijn, Wäckers et al. 2016). For example, *E. balteatus* survival is related to flower depth which needs to be less than the length of the hoverfly's proboscis (1.6 mm) (van Rijn, Wäckers et al. 2016). Sown areas of knapweed (*Centaurea jacea*) and wild parsnip (*Pastinaca sativa*) also encourage high hoverfly larva densities (Salveter 1998) with phacelia adjacent to winter wheat having more hoverfly eggs of aphidophagous hoverflies and fewer aphids than control plots (Hickman and Wratten 1996). Increasing either plant species richness, as grassland or hedge length within 0.25 km of sunflower crops also resulted in increased aphid predation rates in the crop (Badenhausser, Gross et al. 2020).

Flower margins adjacent to potato fields increased the number of eggs deposited by hoverflies and lacewings by 127% and 48%, respectively, and reduced numbers of aphids by 75% in adjacent potato crops (Tschumi, Albrecht et al. 2016). Correspondingly, hoverfly species richness was greatly enhanced in tailored flower strips compared with potato control strips where natural enemies spilled over into the adjacent crops (Tschumi, Albrecht et al. 2016). Aphid infestation of crops near wildflower strips or weedy fields was also lower and the predator–prey relationship between specialist predators and aphids was enhanced compared to the control area (Hausammann 1996).

In broccoli field trials, where buckwheat patches were sown, hoverflies (*M. fasciatum* and *M. novaezelandiae*) laid more eggs, but this did not lead to improved aphid population suppression (Laubertie 2007). In the same study in greenhouse experiments, larvae of *E. balteatus* could initiate a decline in aphid numbers but this control did not persist (Laubertie 2007). Although flower margins, which incorporate buckwheat, phacelia, and cornflower are attractive to hoverflies, their presence does not always translate into pest control in the crop (van Rijn, Kooijman et al. 2006, Laubertie 2007).

Buckwheat has commonly been used to enhance natural enemy populations in arable crops. Buckwheat increased lacewing populations by 70% and decreased aphid numbers by 39%, in alfalfa in field cage trials (Jacometti, Jørgensen et al. 2010). In field studies, the relationship between landscape and floral margins is more complex. Experimental provision of buckwheat close to kale crops enhanced parasitism rates of diamond back moth (*P. xylostella*) and aphids (*B. brassicae*, *M. persicae*) in simple landscapes, reducing pest abundance. This effect was not observed in more complex landscapes (Jönsson, Straub et al. 2015). Buckwheat is beneficial to parasitic wasps, increasing their fecundity and longevity, and hence increasing the parasitism rate of aphids (Tylianakis, Didham et al. 2004). More recently a systematic review of the literature has revealed an extended longevity and increased fecundity for a range of insect predators, including ladybirds, with good quality floral resource (He, Kiær et al. 2021, Holm, He et al. 2021).

Provision of different mixes of flora next to OSR crops did not increase aphid control in a short study (one season) in one field, even though parasitoids benefitted from the floral margins (Hatt, Uyttenbroeck et al. 2018). Also in wheat, there was no effect of wildflower margins on populations of adult lacewings, ladybirds, or parasitoids (Hatt, Lopes et al. 2016). In winter wheat, parasitism was not enhanced with increasing levels of flowering plants in adjacent field margins (Vollhardt, Bianchi et al. 2010). However, at high aphid densities, in computer simulations (with a higher supply and availability of aphid honeydew), parasitoids almost entirely relied on honeydew as food (Vollhardt, Bianchi et al. 2010). Parasitism rates of larval cabbage moth (*Pieris rapae*) were significantly enhanced by wildflower strips (24 species sown) at one of two experimental sites in comparison to the control sites (Pfiffner, Luka et al. 2009).

The addition of a floral meadow-mix in hops resulted in fewer migrant aphids settling and lower aphid populations. Nevertheless, the difference was insufficient to prevent peak populations of ca. 1,000 aphid per leaf (Campbell 2018). The meadow-mix also had the highest population densities of spider mites, and associated phytoseiids. However, (Grasswitz and James 2008) recorded significantly fewer spider mites on hop foliage where a flower mix, including buckwheat, was compared to resident vegetation managed by occasional mowing. In addition, spiders, nabids, anthocorids, geocorids and parasitic Hymenoptera were more abundant in hops with ground flora (Grasswitz and James 2008). Adult ladybirds were also higher in flower plots, but only in one year (Grasswitz and James 2008) whilst *Anthocoris nemoralis* (Fabricius) was more abundant in phacelia plots compared to bare soil in hops (Campbell 2018).

The maturity of floral margins is important; diverse perennial wildflower margins allowed to develop over several years (6) have increased numbers of spiders with higher predator prey ratios compared to one-year-old margins and older fallows compared to young fallows (Denys and Tscharntke 2002). Sown wildflower areas enhance densities of crab spiders (Thomisidae), ground spiders (Gnaphosidae), wolf spiders (Lycosidae) and young orb weavers (Araneidae) in wheat fields (Schmidt-Entling and Döbeli 2009), with numbers of wolf spiders and ground spiders higher at field edges compared to fields with grassy margins. Aphid predation was also explained by predator communities in sunflower fields, particularly spider activity/density (Badenhausser, Gross et al. 2020). In addition, higher vegetation complexity promotes diversity of web-building spiders and their prey, whereas intense management (e.g. regular mowing) reduces the diversity of prey and aphid capture rates (Diehl, Mader et al. 2013).

Hence wildflower strips provide a source of natural enemy populations that contribute to field invasion early in the season (Lemke and Poehling 2002).

Pollinators in fruit crops (Table 2): Most fruit crops are highly dependent on insect pollinators (Holzschuh, Dudenhöffer et al. 2012) and pollinator diversity is higher in fruit crop landscapes containing hedgerows, meadows, and suburban areas, as these provide nesting and floral resources throughout the spring and summer for species that are reliant on resources beyond the crop area (Martins, Albert et al. 2018). Because most fruit pollinating bees are generalist species, promoting floral resources around the farm and landscape will help to sustain diverse wild bee populations for fruit crop pollination (Martins, Albert et al. 2018). Apple seed set is increased, shape is improved, and pollen limitation decreased if wild bee species richness and abundance is increased, resulting is less reliance on honeybees (Garratt, Breeze et al. 2014, Blitzer, Gibbs et al. 2016).

Ratios of pollinator groups visiting crops varies; the ratios of honeybees to wild bees in apple, pear, blueberries, and raspberries for example was 10:1, 2:1, 1:5 and 5:1 respectively (Martins, Albert et al. 2018, Fountain, Mateos-Fierro et al. 2019) with Andrena the most abundant wild bees visiting apple and pear flowers (Garratt, Breeze et al. 2016, Martins, Albert et al. 2018, Fountain, Mateos-Fierro et al. 2019).

Although honeybee abundance remained static, 3 and 4 years after sowing wildflower plantings adjacent to blueberry crops, wild bee and hoverfly numbers increased in the crop. However, orchard ground cover is crucial in supporting honeybees in apple orchards, with wild bee visitation increasing with the proportion of high-diversity bee habitats in the surrounding landscape (1 km radius) (Földesi, Kovács-Hostyánszki et al. 2016). Orchard mason bee (*Osmia lignaria*) nests installed in areas adjacent to apple orchards were more successful if they had access to sowings of bigleaf lupine (*Lupinus polyphyllus*) with significantly greater population recovery than nests located farther away (approximately 600 m) (Sheffield, Westby et al. 2008).

Cider apple orchards with alleyway wildflowers, increased wild bees and Diptera visits to apple flowers by 40% (Campbell, Wilby et al. 2017). This effect was more pronounced when the orchards were also next to semi-natural habitat (Campbell, Wilby et al. 2017). In a 2-year study on blueberry, sour cherry, and watermelon, a 117% greater wild bee abundance, 75% greater richness and 57% greater diversity in the floral margins, did not improve pollinator abundance in the crops (Nicholson, Ward et al. 2019), suggesting that in some instances benefits to the wild bee community gained from enhancements do not spill over into the crops. However, in a large-scale study involving 85 apple orchards, on a landscape gradient, higher cover of flowering plants within and adjacent to apple trees did increase flower visitation rates by pollinating insects (Samnegård, Alins et al. 2018). In commercial dessert apple orchards, although hoverfly diversity and species richness were greater in orchards with wildflower strips this did not translate to more visits to apple blossoms by any pollinator group and was attributed to the use of pesticides in the orchards (McKerchar, Potts et al. 2020). Pesticide use was also found to be a key contributor to pollinator decline in pigeon pea (*Cajanus cajan*) despite practices to improve pollinator abundance (Otieno, Woodcock et al. 2011) and resulted in the lower species richness of bumblebees in apple orchards (Gervais, Belisle et al. 2021). Orchard management should incorporate consideration of pollinators into IPM and adopt integrated pollinator-pest management (IPPM) considering the creation of habitats for pollinators, landscape management and agroecosystem diversification with a move toward better times and selection of softer protection products (Jung 2021, Lundin, Rundlöf et al. 2021).

In polytunnel strawberry crops, the frequency of pollinator visits was 25% higher in crops with adjacent flower strips compared to those without, with a combination of wild and commercial bumblebees accounting for 67% of all pollinators observed (Feltham, Park et al. 2015). In a 3-year study on polytunnel grown cherry, floral alleyway sowings resulted in an increase in pollinating insects in the summer (after the cherry blossom period) with benefits to production (Mateos-Fierro 2020). Flowering plants in alleyways of cherry orchards are also a

driver of pollinator diversity and abundance, and fruit set of sweet cherry(Eeraerts, Smagghe et al. 2019). How-ever, although two thirds of all flower visitors to sweet cherry were honeybees, fruit set was linked to wild bee visitation (Holzschuh, Dudenhöffer et al. 2012). Not all perennial crops benefit from wildflower interventions, for example Cocoa production is reliant on flower visits by ceratopogonid midges, hence augmentation of the ground cover using mulches is needed to increase yield in this crop (Forbes and Northfield 2017).

It is essential that wildflower habitats are not considered in isolation and are combined with a landscape man-agement approaches for pollinators (Korpela, Hyvönen et al. 2013, Bartholomée, Aullo et al. 2020). Although they often provide food, other landscapes such as woodlands may be needed for nesting (Mallinger, Gibbs et al. 2016, Martínez-Sastre, Miñarro et al. 2020). Lack of these other habitats are known to be a limiting factor of bee abundance and diversity (Potts, Vulliamy et al. 2003, Holzschuh, Steffan-Dewenter et al. 2009). Where mass flowering crop cover increases in a landscape, the densities of bumblebees, solitary bees, honeybees, and hoverflies (Fig. 15) decreases by 15, 10, 15 and 7% respectively, creating a diluting effect (Holzschuh, Dainese et al. 2016). In addition, field margins in landscapes with flower strips have higher bumblebee abun-dances compared to landscapes without flower strips, while farms with higher quality and area of flower strips have more bumblebees and solitary bees in field borders (Jönsson, Ekroos et al. 2015). Pollinators are subject to multiple stressors including parasites, and pesticides and a lack of resources. Fruit growers can support pollinators by incorporating flower-rich habitat into farmland, reducing pesticide use through adopting more sus-tainable farming methods, and managing commercially reared pollinators so that the transmission of parasites and diseases is minimised (Goulson, Nicholls et al. 2015). Pollinators are more affected by landscape hetero-geneity than adjacent field margins (Toivonen, Herzon et al. 2021), and dispersing patches of natural habitat throughout the landscape to create habitat heterogeneity will support higher bee abundance even in landscapes with a low proportion of natural habitat overall (Winfree, Williams et al. 2008). Fruit crops typically bloom for a short period of time and cannot sustain insect pollinators in isolation. Additional floral resources in orchards can provide a greater diversity and abundance of flowering plants before, during and after blossom to support and attract pollinating insects in and around fruit crops (Eeraerts, Smagghe et al. 2019).



**Figure 15.** Hoverfly on strawberry flower. Credit NIAB EMR.

Other crops: Many arable crops are not dependent on pollinators for crop quality and yield, but legumes (Otieno, Woodcock et al. 2011), OSR (Morandin, Winston et al. 2007), tomatoes (Morandin and Kremen 2013) and sunflowers (Carvalheiro, Veldtman et al. 2011) are examples of where pollinators are essential for improving quality and yields of produce and where wildflower strips could be of benefit to production. On arable farms, bee diversity is related to flower cover and diversity of flowering plants and are mainly resource-mediated (Holzschuh, Steffan‑Dewenter et al. 2007, Winfree, Williams et al. 2008). More species of solitary bees were found in OSR in landscapes with a high cover of semi-natural (hence florally rich) grassland, but no effect of overall habitat quality was found for visitation rates of bumblebees or solitary bees. Farms with high habitat quality supported more species than those of either moderate or low quality (Woodcock, Edwards et al. 2013). In addition, the abundance of OSR and field bean pollinators (*Apis mellifera* and *Bombus* spp.) increased over the period of a 4-year study with high quality compared to lower quality, cheaper, flower mixes including a positive impact on crop yield (Pywell, Heard et al. 2015). In wildflowers adjacent to OSR, nearly all insect pollinator visitors in the crop and wildflowers carried crop pollen, with more than half the insects carrying pollen from wild plants (Stanley and Stout 2014). This demonstrates the importance of wild plants in field margins and hedgerows as sources of alternative forage for pollinating insects even when a crop is mass flowering (Stanley and Stout 2014, Pisman, Eeraerts et al. 2021).

## Detrimental effects

When implementing floral resources near to crops, the potential negative effects of some flowering species on pest populations and orchard agronomic practices needs to be considered. It is essential that flora introduced into perennial crops do not act as alternative hosts or introduce pests, diseases or storage rots (Forge, Neilsen et al. 2016).

Pests, diseases, and natural enemies: In organic apple orchards, although most impacts were positive, there was more damage to fruit from apple scab (*Venturia inaequalis*) (Fig. 16) in plots with wildflower alleyways than in crops where 'weeds' were controlled by mechanical disking (Agnello, Cox et al. 2017).
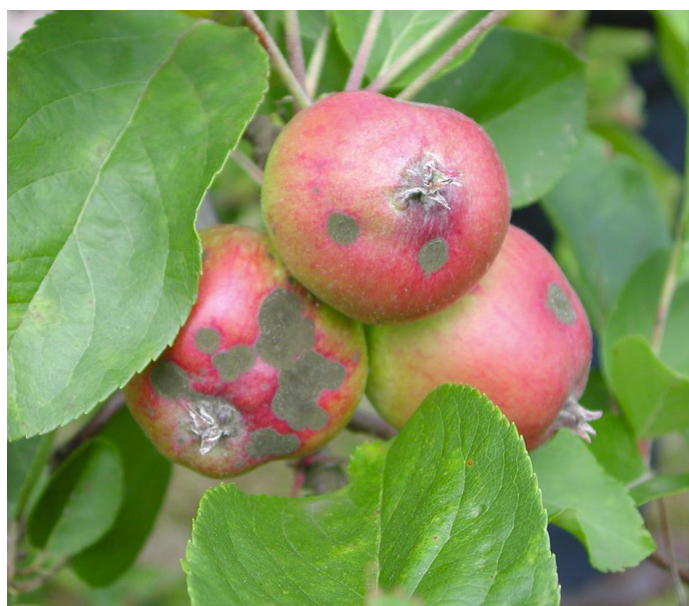


**Figure 16.** Apple scab (*Venturia inaequalis*) damaged fruits. Credit NIAB EMR.

*Lygus* spp. have been detected in some alleyway cover crops in apple and hops (Altieri and Schmidt 1986, Campbell 2018), although damage to fruit was not recorded in these studies. Floral ground cover increased numbers of common green capsid (*L. pabulinus*) in cider apple orchards in the Netherlands (Gruys 1982) but in apple floral strips in Hungary, European tarnished plant bug (*L. rugulipennis*) was less abundant than in the control treatments (Markó, Jenser et al. 2013). Likewise, damage by tarnished plant bug was lower in managed plots compared to controls after five years (no insecticides) (Bostanian, Goulet et al. 2004). In general, Heteroptera diversity is increased in orchards with floral plots including some predatory species (Kinkorová and Kocourek 2000). (Killian and Meyer 1984) recorded lower cat-facing damage to peaches in herbicide-treated blocks compared to fruit sampled from weedy areas, demonstrating the need to implement the most beneficial flora within orchards.

The mullein bug (*Campyloma verbasci*) may also be encountered in higher incidence in florally sown orchards (Thistlewood, Borden et al. 1990).

Increased woolly apple aphid infestations were observed in floral treated plots in one trial, but only in the first year after establishment (Markó, Jenser et al. 2013).

In a 2-year study, in an experimental apple orchard, two pests, apple sucker (*Psylla mali*) and the cercopid froghopper (*Philaenus spumarius*) probably benefitted from flower alleyways and increased in number, although major damage to the apple trees was not observed (Wyss 1996). The implications for *Xylella fastidiosa* (a bacterial disease of woody species) spread, should be considered with increases of *P. spumarius* which is a vector of the disease.

*C. cyanus* and *L. vulgare* attracted high proportions of thrips (some of which are pests), and *K. arvensis* and *A. millefolium* were attractive to pollen beetles (Carrié, George et al. 2012). However, this study did not relate the impact of the floral resource to crop damage and it is not known if these areas act as a sink or a source of pests, or indeed a combination of these factors.

In blueberry fields, groups of insect herbivores were more abundant in fields adjacent to flower strips, compared with control fields. Plant bugs (Miridae) were also more abundant in fields with flowering plant strips, as were plant hoppers (suborder Auchenorrhyncha) and thrips. However, the species were not identified so it is not clear if these were crop pests (Walton and Isaacs 2011). Hence, phytophagous insects are generally increased in areas treated with floral interventions, but these are primarily non-pest species and serve as alternative prey for natural enemies (Lethmayer, Nentwig et al. 1997). This is useful in periods when crop pest abundance is low e.g. earlier in the season.

For fruit crop diseases, Hawthorn (*Crataegus* spp.) might be avoided near to pear orchards to reduce the spread of fireblight (Rieux, Simon et al. 1999). White mustard sowing had a negative impact on apples resulting in increased russet and reduce fruit weight (Bone, Thomson et al. 2009). Also, significantly more disease has been observed in apple orchards with white clover (*Trifolium repens* L.) cover crops (Sholberg 1998), especially postharvest storage rots of apples (Sholberg and Gaudet 1992). In addition, white clover harbors few beneficial insects in comparison with annual clovers (*Trifolium* spp.) and vetches (*Vicia* spp.) (Bugg and Waddington 1994).

Albert*, et al.* found the only significant negative effect of hedgerows in the vicinity of cider apple orchards was a decrease in the presence of ladybird larvae in the orchard. However higher numbers of hoverfly larvae and eggs were found in the crop adjacent to hedgerows.

Some negative impacts of floral alleyways have been attributed to an increase in spider mite (e.g. (Campbell 2018); however, this is often accompanied by the natural biocontrol, phytoseiids (predatory mites).

In grapevine vigour was reportedly lower in cover crop, compared to no-cover crop alleys (Costello and Daane 2003). Terminal growth was particularly depressed for apple trees with understories of white clover and grass (Haley and Hogue 1990). In addition, in vines, native natural ground cover (compared to tilled areas) had more abundant populations of ants, which protected mealybugs from natural enemies (Serra, Lentini et al. 2006). Consequently, a reliance on resident colonisation of flora may not deliver pest control benefits and may enhance pests.

Leafrollers (e.g. *E. postvittana*) had an increased longevity and egg production fecundity in the presence of alyssum (*L. maritima*) (Irvin, Scarratt et al. 2006). Flower margins may also be suitable habitat for slugs creating a microclimate refugia (Frank 1998, Frank 1998, Frank 1998). In orchards where docks have been allowed to grow, dock sawfly (*Ametastegia glabrata*) can move onto developing apples (pers. obs.) causing fruit damage (Petherbidge 1924). Alternative host species for other pests like plantain (Plantaginaceae) for rosy apple aphid (*Dysaphis plantaginea*) should be avoided. More research is needed to determine the risk of additional pest pressure from these species.

The abundance of earwigs (*Forficula pubescens*) was positively correlated with codling egg predation in regularly mown plots, but negatively correlated orchard plots where grass was left to grow (Marliac, Simon et al. 2015). The authors of this study suggest that earwigs might find an alternative resource in the taller grass cover and that growers could mow at key times in the season to increase foraging on codling moth (Marliac, Simon et al. 2015). This could be predicted using codling moth flight pheromone traps and temperature-based models (e.g. RIMPro). Flower mixes in orchards may change community composition of invertebrates, for example in a study by (Markó and Keresztes 2014) the dominance of one spider species resulted in a lower overall spider diversity.

Pollinators: Another potential detrimental effect of floral margin implementation the distraction of managed pollinators (e.g. honeybees) from pollinating crops. In Scottish raspberry crops, commercially produced bumblebees had 12% and 15% pollen from *Rubus* and *Potentilla*, respectively. The remaining pollen on the bees was from non-target wildflowers (Foulis and Goulson 2014). However, this study did not measure the impact on crop pollination. Another study demonstrated the potential to divert managed bees to crops with the use of caffeine coupled with a reward and the odour of the focus crop (Arnold, Dudenhöffer et al. 2021). In spring crops of open-ended polytunnel grown strawberries provisioned with bumblebees, there was a significant increase in marketable yield compared to strawberry without bumblebee provision (Martin, Fountain et al. 2019). In spring blossoming tree fruit, most sown wildflowers would not be flowering and not encourage competition. However, more studies would be useful to determine the impacts of early wildflower distraction, e.g. dandelion, during pome and stone fruit blossom.

The effects of floral margins can also be inconsistent (Campbell 2018) with interannual differences in the benefits the crops receive. However, these may be transient negative effects, especially in the establishment year, until beneficial insects have established and built-in abundance. Careful selection of plants is important to avoid any risk of enhancing pest populations or offering an alternate host for plant pathogens and other noxious organisms. Ideally, plants should be botanically unrelated to the crop (Pfiffner and Wyss 2004).

## Choice of Floral Resources

Sown wildflower strips (Fig. 17) support higher insect abundances and diversity than cropped habitats, especially pollen- and nectar-rich flower mixtures (Haaland, Naisbit et al. 2011). Although common insect species are the main beneficiaries of agri-environmental schemes (Haaland, Naisbit et al. 2011), there is the potential to optimise floral mixes, depending on the service required, and increase the number of wildflowers at a landscape scale to increase their overall effectiveness (Aviron, Herzog et al. 2011).

To promote natural enemies and pollinators on farms, land managers should aim to 1) Identify where they already have sources of good quality flora and Protect these areas, 2) Enhance and Improve areas that are adequate, but not giving the best service, 3) Connect areas of floral resource (e.g. hedgerows, woodlands and/or meadows) by creating corridors to enable beneficials to move around the landscape and, 4) Create new areas of floral resource on farm areas lacking heterogeneity. These manipulations should always be coupled with other lifecycle requirements of the beneficials including nesting, overwintering, and breeding sites.

Orchards are devoid of flowers post-bloom but need to support insects though the growing season. Because bee diversity is related both to flower cover and diversity (Holzschuh, Steffan‑Dewenter et al. 2007) choosing a floral mix with functional diversity (components of biodiversity that influence how an ecosystem operates or functions) should be considered to encourage higher species diversity and deliver more ecosystem services (Uyttenbroeck, Hatt et al. 2015). Increases in plant species richness and abundance will promote flower visits by bees (Sutter, Jeanneret et al. 2017).



**Figure 17.** Diverse and abundant floral mix of different flower types. Credit Celine Silva.

Floral mixes can be manipulated according to floral traits to target the 'types' of beneficials required (Campbell, Biesmeijer et al. 2012). For example, flowers of buckwheat (*F. esculentum*), cornflower (*C.cyanus*), alyssum (*L. maritima*), coriander (*Coriandrum sativum*), mint (*Mentha spicata*), yarrow (*A. millefolium*), Phacelia (*Phacelia tanacetifolia*), fennel (*Foeniculum vulgare*), Korean liquorice mint (*Agastache rugosa*), wild parsnip (*P. sativa*), corn marigold (*Chrysanthemum segetum*), borage (*Borago officinalis*), wild carrot (*Daucus carota*), hairy white oldfield aster (*Aster pilosus*), camomile (*Matricaria recutita*), mallow (*Malva sylvestris*), cow parsnip (*Heracleum maximum*) and vetch (*Vicia sativa*) are attractive to hoverfly adults (Salveter 1998, Colley and Luna 2000, Tooker, Hauser et al. 2006, van Rijn, Kooijman et al. 2006, Laubertie 2007, Langoya and Van Rijn 2008, Pineda and Marcos-Garcia 2008, Sadeghi 2008, Dunn, Lequerica et al. 2020). Buckwheat and phacelia are sucrose rich (Baker and Baker 1982, Irvin, Scarratt et al. 2006, Irvin, Hoddle et al. 2007, Tompkins, Wratten et al. 2010), whilst borage has a high nectar production (Wykes 1953).

For insects with short mouthparts, forage with easily accessible nectar, particularly Asteraceae, Umbelliferae and Fabaceae are beneficial (Langoya and Van Rijn 2008). Nectar availability can be limiting for parasitoids (Berndt, Wratten et al. 2006) and so flowers with open nectaries are important (Hatt, Uyttenbroeck et al. 2018). This was achieved with plantings of creeping cinquefoil (*Potentilla reptans*), yarrow (*A. millefolium*), white clover (*Trifolium repens*) and common hedge parsley (*Torilis arvensis*) (Dib, Libourel et al. 2012). Hymenopteran parasitoids are also abundant on corn marigold (*C. segetum*) and corn chamomile (*Anthemis arvensis*) (Fitzgerald and Solomon 2004).

Plants like yarrow (*A. millefolium*) and oxeye daisy (*Leucanthemum vulgare*) (Fig. 18) attract multiple beneficial arthropods (Carrié, George et al. 2012). Perennial stinging nettle (*Urtica dioica*) is a reservoir of natural enemies including pirate bugs (Anthocoridae), Miridae and ladybirds (Coccinellidae) (Anderson 1962, Perrin 1975). Anthocorids are also abundant on cornflower (*Centaurea cyanus*) and corn chamomile (*Anthemis arvensis*) (Fitzgerald and Solomon 2004).

Scabious (*Knautia*), knapweed (*Centaurea*), and thistles (*Cirsium*) are regularly visited by bumblebees and butterflies (Haaland and Bersier 2010). Knapweed (*Centaurea*) flower coverage also has a strong positive effect on crop pollination services (Korpela, Hyvönen et al. 2013). Including a range of Umbelliferae, Asteraceae, and Geraniaceae in seed mixes caters for a wide diversity of bee species (Nichols, Goulson et al. 2019). These authors demonstrated that 14 wildflower species across nine families attracted 37 out of the 40 bee species recorded in a farm study (Nichols, Goulson et al. 2019). Kidney vetch (*Anthyllis vulneraria*) and meadow cranesbill (*Geranium pratense*) were highly attractive to bumblebees and smooth hawk's-beard (*Crepis capillaris*), wild mustard (*Sinapsis arvensis*), field bindweed (*Convolvulus arvensis*) and rough chervil (*Chaerophyllum temulum*) were attractive to solitary bees (Nichols, Goulson et al. 2019).

**Figure 18.** Oxeye daisy (*Leucanthemum vulgare*). Credit Celine Silva.

For pollination of apple orchards, floral mixes should be tailored towards species preferred by andrenid bees (Campbell, Wilby et al. 2017, Garratt, de Groot et al. 2021, Carvell, Mitschunas et al. 2022). Evidence suggests that dandelions also enhance andrenid bees so can be managed in alleyways as an early flowering resource (Campbell, Wilby et al. 2017, Son and Jung 2021).

Flower density is a good predictor of insect diversity (Scriven, Sweet et al. 2013) so growers may consider minimising the ratio of grasses to flora where possible. In addition, there are no strict rules on whether sown species should be native with some non-native species capable of extending the flowering season (Salisbury, Armitage et al. 2015). Growers might also consider adding to floral mixes, species which flower more consistently, e.g. clovers (*Trifolium hybridum, T. pratense, T. repens*, *L. corniculatus*), cornflower (*C. montana*), vetches (e.g. *V. cracca, V. sativa*) and wild carrot (*D. carota*) (Campbell, Wilby et al. 2017). Legumes are particularly important for bumblebees (but species with a shorter corolla can be selected to encourage shorter proboscis insects, e.g. hoverflies) (Bryan, Sipes et al. 2021, Cole, Baddeley et al. 2022) in addition to providing a source of nitrogen to orchards (Pavek and Granatstein 2014).

## Establishment and management of floral resource

To establish a perennial wildflower area, ensure that the seedbed is firm, fine, and weed free and sow the seeds on the surface of the soil; broadcast (Nowakowski and Pywell 2016). Ideally wildflowers should be grown with season-longevity in mind. Spring flowers (March to May) are vitally important for nest-founding bees (Fig. 19); tall grass is need for overwintering bumblebees (Nowakowski and Pywell 2016). More details on how to establish wildflower successfully can be found in (Nowakowski and Pywell 2016) and

Plant size influences numbers of beneficials visiting floral resources, for example, increasing plant size of brassicas increased the species richness of insect herbivores, natural enemies, and pollinating insects. Plant heights from 10 to 130 cm led to a 2.7-fold increase in predicted total arthropod species richness (Schlinkert, Westphal et al. 2015). Mowing can have a negative impact on wild bees at landscape scales of 3-5 km (Hellwig, Schubert et al. 2022) and reducing mowing regimes and fewer applications of herbicides will encourage flowering species (Campbell, Wilby et al. 2017) and web-building spiders (Diehl, Mader et al. 2013). The number of aphids per spider web decreased with increasing management intensity from 8.5 ± 4.0 (mean ± SE) aphids at uncut sites to 4.7 ± 1.8 aphids at sites that were managed by cutting (Horton, Broers et al. 2003). Reducing mowing regimes from 2-3, to only once per month, increased the numbers of predators and parasitoids in pear orchards because of an increase in food resources e.g. non-pest aphids, Lygus spp. (Heteroptera: Miridae) and leafhoppers/planthoppers (Horton, Broers et al. 2003). Numbers of spiders and a predatory mirid, *Deraeocoris brevis* were also higher in trees where the ground flora was only mowed once per month (Horton, Broers et al. 2003).



**Figure 19.** Solitary bee nests with exposed tumuli (excavated soil) above ground. Photo credit Konstantinos Tsiolis and NIAB EMR.

By increasing sward architecture, the total biomass of invertebrates can be increased by around 60% providing food for higher trophic levels, such as birds and mammals (Woodcock, Potts et al. 2009). There was no difference in natural enemy abundance, richness or pest control when these were recorded and compared in two wildflower management regimes; a standard single cut in late September or regularly cutting to a height of 20 cm throughout the growing season in cherry alleyways. However, the numbers of predators in the cherry trees were 15% higher compared to standard regularly mown grass alleyways (Mateos-Fierro, Fountain et al. 2021). Cutting half the margin mid-season will also prolong the floral resources available (Nowakowski and Pywell 2016). In addition, high mowing preserves vegetative and flower buds and permits regrowth (Bugg and Waddington 1994, Mateos-Fierro, Fountain et al. 2021). Other management practices to consider in orchard alleyway sowings (Fig. 20) include cutting every other row on a rotation (Uyttenbroeck, Hatt et al. 2015). Another

strategy is to have a selection of floral areas at different stages of succession and/or with different plants to provide habitats for various insect groups (Haaland, Naisbit et al. 2011) and seasonal continuity. To cut down costs, seed mixtures can have a simple composition, if key plant species are provided (Pywell, Meek et al. 2011), however, wildflower strips may need to be resown if flowers begin to decrease (Carvell, Meek et al. 2004).

Wildflower areas will provide 1) alternative prey or hosts when pests become temporarily scarce 2) alternative food sources such as nectar and pollen for adult predators and parasitoids, and 3) shelter or undisturbed habitats as refuges and overwintering sites (Shaw 2006, Lu, Zhu et al. 2014). Unmanaged strips have the potential to give shelter to vertebrate pests, such as rodents, which without control could become a severe problem in orchards (Merwin, Ray et al. 1999).



**Figure 20.** Orchard alleyway sowings with diverse flora and structure for natural enemies and pollinators. Credit Celine Silva.

# Conclusions

Overall, the impact of wildflower sowings on crop production is either benign or positive with either low or under-reported negative impacts (Pardo, Lopes et al. 2020). This review highlights the rather isolated nature of the studies and more large-scale studies are needed to tailor flowering resources to specific crops and landscapes to further advance the science and benefit to fruit growers.

Many studies do not consider the dual nature of insects e.g. pollination and predation from hoverflies (Dunn, Lequerica et al. 2020), or studies are conducted in a restricted time period (Pywell, Heard et al. 2015, Amy, Noel et al. 2018), or do not consider the economic impacts, including increased crop yields, of providing floral resources (Schneider, Krauss et al. 2015). Profitability is primarily driven by spillover of beneficial organisms which contribute to biocontrol (Rand and Louda 2006, Hogg and Daane 2010, Korpela, Hyvönen et al. 2013,

Badenhausser, Gross et al. 2020) and pollination. A higher focus on economic gains would encourage take-up of diversifying agroecosystems to benefit the environment and growers' profit (Amy, Noel et al. 2018).

Fruit crops benefit, in part, from areas of flora to provide enhanced abundance and diversity of pollinating insects and support Integrated Pollinator and Pest Management (Lundin, Rundlöf et al. 2021) of perennial crops through the provision of natural enemies including predators and parasitoids. However, scientists need to work closely with growers to understand the specific requirements of growing systems and the potential negative impacts on the business that implementing and maintaining floral resources might have.

Often fruit growers do not have the time or resources to invest in understanding or implementing such changes and rely on agronomists for advice and evidence from the latest scientific and trialling of new practices. This shifts emphasis one step away from the grower and consequently they can be removed from the benefits that floral provision may provide. Tools for floral establishment, and long-term maintenance are needed alongside long-term monitoring of the benefits that floral resources can bring, so that habitats can be adjusted over time to suit the requirements of the grower and the ecosystem services that are being delivered.

However, there is ample evidence that provisioning florally diverse areas with long-lasting floral resource through the season (Scheper, Bommarco et al. 2015), provides resources to beneficial insects (Woodcock, Edwards et al. 2013, Stanley and Stout 2014, Holzschuh, Dainese et al. 2016). Wildflower areas increase the predator to prey ratio in crops (Langoya and Van Rijn 2008) and designing agricultural areas that integrate land use and ecosystem function is a practical approach for promoting sustainable agriculture practices (Morandin, Winston et al. 2007) promoting less interannual variability between pollinator populations (Senapathi, Frund et al. 2021).

Areas of species rich and abundant floral resources (Holzschuh, Steffan‑Dewenter et al. 2007, Scheper, Bommarco et al. 2015, Tschumi, Albrecht et al. 2016) provide food (pollen nectar, nectar, vegetation, and prey (Salveter 1998), nesting sites, structure to build (e.g. spiders webs, (Schmidt-Entling and Döbeli 2009) and an area of refuge in poor weather and for diapause during the winter. These areas can be kept pesticide free (Otieno, Woodcock et al. 2011) through positioning or through the targeted use of precision agriculture (McKerchar, Potts et al. 2020) and can even impact insect abundances in the wider landscape (Jönsson, Ekroos et al. 2015). Connectedness and age of floral resources are also important for increasing numbers of pollinators (McHugh, Bown et al. 2022) and other beneficial fauna.

Fruit crops lend themselves to floral resource provisions (Bihaly, Kovács-Hostyánszki et al. 2021). Unlike field crops where floral resources are often restricted to the perimeter of crops with limited reach of beneficial insects in from the crop edges, fruit crops are growing in rows (e.g. tree fruit, (Markó, Jenser et al. 2012, Cahenzli, Sigsgaard et al. 2019)) or even on elevated structures (e.g. table-top strawberries). This area of unused land could be put to better use, to benefit the crop (Fig. 19).

Floral resources should be planned with landscape in mind (Blaauw and Isaacs 2014, Bartholomée, Aullo et al. 2020) but include proximity to the crops they are to benefit. For example, it is suggested that they need to be within 500 m of apple orchards for pollination benefits to be realised (Földesi, Kovács-Hostyánszki et al. 2016, Joshi, Otieno et al. 2016, Samnegård, Alins et al. 2018). In addition, floral resources should not be implemented without considering preservation of semi-natural areas in the landscape which are key to provisioning the full life cycles of many insects (Baude, Kunin et al. 2016, Hevia, Carmona et al. 2021). Floral resources should not be implemented in isolation of other beneficial insect needs and can be enhanced by proximity of existing

features (von Königslöw, Mupepele et al. 2021) and inter-connectedness of well-managed habitats that have complementary resources (Cole, Kleijn et al. 2020).

Future studies of floral resources in fruit crops need to tailor floral mixes to the crops to provide the highest benefit whilst reducing any negative impacts. (e.g. introduced pests, diseases or undesirable microclimate).

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