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1 Introduction

Agricultural intensification, or the increase in crop production per unit land area, has resulted in high-input, large-scale monoculture cropping and overall declines in crop diversity in the USA (Aguilar et al., 2015) and greater homogeneity in the crops grown across regions at a global scale (Martin et al., 2019). This has often resulted in agricultural landscapes devoid of the habitat and floral resources needed to sustain pollinators. In addition to a reduction in crop diversity, the intensified use of agrochemical inputs reduces populations of flowering weeds that can provide floral resources for pollinators and introduces compounds into the environment found to be toxic to sensitive pollinator species (van der Slujis et al., 2013). Modern crop production systems are, thus, thought to contribute to declines in pollinator populations that we rely on for the pollination of economically important crops and wild plants.

To address this pressing issue, agriculture must develop practices that diversify the agricultural landscape to enhance the availability of floral resources and habitat within the crop production space. This approach, known as land sharing, is in contrast to the land sparing paradigm where natural lands are set aside for conservation purposes and are distinct management units from agricultural lands (Phalan et al., 2011). The land-sharing paradigm, however, is thought to be a more realistic approach given the demands a growing

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population has placed on agricultural lands and the benefits that increased biodiversity has on agroecosystems and agricultural production (Tscharntke et al., 2005, 2012).

Another chapter discusses in more detail the management of field margins, wildflower strips, or other adjacent and surrounding habitat to crop fields that contribute to landscape diversity and enhanced pollinator resources. In this chapter, the focus is on approaches to enhance plant diversity within the crop production space. Approaches by which this can be achieved include in-field practices such as the planting of flowering cover crops between crop rotations, intercropped with cash crops, or in place of a cash crop, planting of diverse perennial forages that also provide floral resources, and maintaining flowering weed communities if they pose little threat to crop production.

2 Approaches to managing production space for pollinators

2.1 Cover crops

Cover crops play a critical role in providing habitat and floral resources to promote pollinators and pollination within the crop production space or field, i.e. not only field edges or margins as discussed in a previous chapter. Integrating flowering cover crops is challenging due to the need to reduce competition for space and other resources with the primary cash crop. However, there are a number of ways in which this can be achieved, including planting overwintering (cold-hardy) cover crops that provide early-season floral resources prior to a cash crop, planting full-season cover crops in lieu of a cash crop or fallow ground (bare ground not planted to a cash crop), or strip or companion plantings between crop rows or on orchard floors.

Planting overwintering cover crops in the fall for early spring flowering can be an effective way to reduce competition with the primary cash crop while providing floral resources at a time when few are available across the landscape (Bretagnolle and Gaba, 2015). Examples of cold-hardy species that also flower early the subsequent year, which is particularly important in northern growing zones, are winter camelina (*Camelina sativa* L.), winter canola (*Brassica napus* L.), and pennycress (*Thlaspi arvense* L.) (Eberle et al., 2015). Other cover crops that overwinter, though to varying extents depending on planting date and climate, include red clover (*Trifolium pratense* L.) and Austrian winter pea (*Pisum sativum* subsp. *arvense* L.; Ellis and Barbercheck, 2015). In warmer climates or southern growing zones, additional cover crops will likely overwinter, but the timing of flowering may limit their use if impacts on the subsequent cash crop are a primary consideration. Further, if the cover crop is to double as an economic crop (winter camelina and pennycress, for instance, are being

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developed as oilseed crops; Cubins et al., 2019), adjustments to the crop rotation and agronomic management would be necessary to accommodate cover crop seed harvest for a relay- or double-crop system (Patel et al., 2021; Ott et al., 2019; Johnson et al., 2017; Gesch et al., 2014).

Cover crops may be planted as full-season crops for a variety of reasons. They may be planted in fields that would otherwise remain fallow or in fields where adverse conditions such as drought or excess moisture result in a failure to plant an insured crop by a certain date (also known as prevented planting; 2013 Crop insurance handbook, USDA-RMA, 2013). Though not as common, full-season cover crop mixtures may also be integrated into a crop rotation to achieve soil health benefits and provide a forage source for livestock (Housman et al., 2021; Sanderson et al., 2018). With the inclusion of flowering species in full-season cover crop mixtures, season-long floral resources that support both managed and wild pollinators may be achieved, though cover crop species selection and mixture composition will influence the species of pollinators attracted (Mallinger et al., 2019).

Companion planting with flowering cover crops in intercropping systems is another approach that can sustain pollinator communities within crop production fields (Kordbacheh et al., 2020; Norris et al., 2018). In some instances, intercropping with flowering species does not only attract beneficial insects strictly for pollination services, but, as is the case with alyssum (*Lobularia maritima* (L.) Desv.) in organic lettuce (*Lactuca sativa* L.) and broccoli (*Brassica oleracea* L. var. *italica* Plenck) production fields, it may also attract predatory insects such as hoverflies that reduce pest populations (Brennan, 2013, 2016). Intercropping with non-flowering ground covers that release volatile organic compounds such as peppermint (*Mentha* × *piperita*) can also support pollinators and other beneficial insects (Gowton et al., 2021). Further, orchard production systems with cover crop ground covers can also act as a companion planting system to provide a number of benefits including habitat and floral resources for pollinators (Van Sambeek, 2017; Saunders et al., 2013). Companion or intercropping systems should, however, be managed with a holistic approach that reduces reliance on commercial inputs, as pesticide exposure, which is a well-documented source of bee declines, is an ever-present risk to pollinators (Nicholls and Altieri, 2013).

2.2 Flowering weeds for pollinators

Within the production space, floral resources for pollinators can be provided by commercial crops, cover crops, intercrops, and even flowering weeds. Where flowering weeds do not significantly compete with and reduce crop yields, they can be an effective and affordable way to provide pollen and nectar for pollinators. Flowering weeds can supplement the crop plant during crop bloom, as an alternative source of nectar and pollen, or, more importantly, extend the flowering season to provide floral resources for pollinators outside of crop bloom. Weeds often flower in high density and require few inputs, thus offering a cost-effective way to enhance or conserve pollinator communities.

Weed communities within crop fields have shifted with increasing agricultural intensification to favor weeds that are resistant to herbicides or germinate late to escape herbicides, with resulting on-farm weed community simplification (Bretagnolle and Gaba, 2015). Nonetheless, on-farm weeds can provide equal or even better floral resources for pollinators as compared to adjacent natural/semi-natural habitat as the open canopy of crop fields facilitates high flower density (Gemmill-Herren and Ochieng, 2008). Furthermore, weeds are often top nectar and pollen producers, outproducing intentionally grown plant species that are typically present in lower densities (Hicks et al., 2016). For honey bees, in particular, flowering weeds have been found to be a major source of food (Requier et al., 2015).

Flowering weeds can enhance pollination services through increasing crop flower visitation rates via a spillover effect in which pollinators attracted to flowering weeds move over to pollinate the crop plant, or they can enhance pollinator abundance and/or diversity via increased season-long resource availability. In the case of the former, effects on crop pollination could be realized immediately, while in the case of the latter, effects are typically seen 1–3 years following resource enhancement. Examples from sunflower crop fields have illustrated the benefit of weeds for pollinator communities and pollination services. For example, higher on-farm weed diversity in sunflower fields was correlated with a higher diversity of pollinators visiting sunflowers, and seed mass increased with flowering weed species richness. In a different example, the diversity of weed flowers had a positive impact on the species richness of pollinators visiting sunflowers and on sunflower seed set (Carvalheiro et al., 2011). Additionally, the presence of flowering weeds within sunflower fields mitigated some of the negative effects of reduced natural habitat in the surrounding landscape on pollinator diversity (Carvalheiro et al., 2011). These examples from sunflowers illustrate how flowering weeds can benefit not only pollinator communities but pollination services and crop yields as well.

However, weeds can compete with the crop plant for space, nutrients, and water, thereby reducing crop plant densities and overall yields (Sidemo-Holm et al., 2021). They can also compete for pollinators if bloom time overlaps and if they are more attractive than the crop plant. To reduce competition for pollinators, weeds can be mowed or spot treated during bloom, but allowed to flower outside of bloom. Another cost is greater pesticide risk to pollinators; the presence of flowering weeds could increase pollinator exposure to pesticides applied outside of crop bloom with significant negative effects on pollinator populations (Larson et al., 2013). To prevent exposure to pesticides, flowering weeds should be mowed or treated prior to insecticide applications when possible.

2.3 Flowering crops

Large homogeneous row crop systems dominated by corn and soybean, often representative of agriculture in the US Midwest, do not provide the nectar and pollen resources needed to support many pollinator populations. Declines in crop diversity in US cropland (Aguilar et al., 2015) have resulted in fewer flowering crops that sustain pollinator resources. Therefore, diversification strategies are needed to restore plant diversity and re-introduce flowering economic crops into crop rotations that can improve habitat and foraging resources for pollinators (Nicholls and Altieri, 2013).

Crops such as sunflower (*Helianthus annuus* L.), buckwheat (*Fagopyrum esculentum* Moench), flax or linseed (*Linum usitatissimum* L.), canola, and other flowering (forbs) crops can provide floral resources that attract diverse species of pollinators at varying times of the growing season (Mallinger et al., 2019; Campbell et al., 2016; Eberle et al., 2015) and, in some instances, may also benefit from insect pollination (Mallinger et al., 2018; Witter et al., 2015). Forage crops such as alfalfa (*Medicago sativa* L.) and clovers (*Trifolium* spp.) have also been shown to provide floral resources attractive to some pollinator species (Butters et al., 2022; Bryan et al., 2021), though these crops are typically harvested prior to mass bloom events.

Other lesser known but emerging forage crops such as silflower (*Silphium integrifolium* Michx.) and cup plant (*Silphium perfoliatum* L.) support a high abundance of diverse bees when planted as crop borders (Butters et al., 2022), but more work is needed to develop breeding and agronomic management strategies to successfully integrate them into crop production systems (Van Tassel et al., 2017; Lehmkuhler et al., 2007). It is likewise worthy to note the potential for extreme climate scenarios, i.e. drought, to reduce nectar production of crops such as buckwheat and cup plant, thereby reducing the benefit of these flowering crops for pollinators (Rering et al., 2020; Mueller et al., 2020).

2.4 Crop rotations

Rotating crops across growing seasons and years can mean temporally inconsistent resources for pollinators, especially when nectar and pollen-rich crops, such as melons, are rotated with less attractive and resourceful crop such as grains. However, crop rotations can be designed to allow for pollinator populations to persist in heterogeneous and disturbed environments. It may be particularly important to consider how crop rotations affect pollinator population persistence when animal-pollinated crops are used in rotation with non-flowering crops or crops that are wind-pollinated. Examples include oilseed crops such as sunflowers, oilseed rape, and flax, which are typically grown on 3–4-year rotations with wind-pollinated crops including wheat or barley, or with fallow fields. Additionally, pollinator-dependent melons, squash, and other cucurbits are grown on a 3+-year rotation with a variety of crops including many that do not provide significant floral resources for pollinators (e.g. greens, root vegetables, legumes, oats, and wheat) or with fallow fields.

Rotated crops pollinated by specialist pollinators are at particular risk of experiencing reduced pollination services due to inconsistent and small pollinator populations. For example, sunflowers in North America receive significant pollination services from specialist bees including long-horned bees in the tribe Eucerini that rely on sunflowers or other Asteraceae species (Mallinger et. al., 2018). Squash is also pollinated by a few species of specialist squash bees that rely on squash and related Cucurbitaceae plants (Tepedino, 1981). For specialist sunflower and squash bees, the absence of their preferred or required plant hosts in some years may limit population growth and persistence. Unlike with generalist pollinators, these specialists cannot take advantage of other crops in the rotation or flowering weeds in the crop fields. Thus, particular attention needs to be given to designing crop rotations to ensure some resource availability within the specialist pollinator’s foraging range.

Limited research on crop rotation effects on pollinator populations has been conducted, and therefore recommendations are also limited. Rotating crops at the level of individual fields, and staggering rotation cycles across adjacent fields, can achieve the benefits of crop rotations for disease pressure and soil health while still ensuring that the pollinator resources provided by certain crops are present in the broader landscape. Larger-bodied pollinators, including some specialist sunflower and squash bees, may forage a few hundred meters and up to 1 km from their nests (Gathmann and Tscharntke, 2002; Greenleaf et al., 2007), though other studies suggest most bees forage locally within a small radius (Sardiñas et al., 2016). Thus, rotations would need to be designed to ensure resource availability within a few hundred meters, which may not be feasible in many landscapes. However, some studies suggest that consistent and high presence of the focal pollinator-dependent crop in the landscape does not improve pollination services to the focal crop (Andersson et al., 2014). Alternatively, including some flowering forbs in the landscape each year or growing season, especially for generalist pollinators that are able to take advantage of a diversity of floral resources, can reduce negative effects of crop rotations. These floral resources could be provided by other crops in the rotation or by stable, flowering field margins and flower strips. In some studies, generalist pollinator abundance was affected by crop rotation schemes, but

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stable crop boundary features mitigated the negative effects of crop rotations on floral resource availability and pollinator populations. Thus, having larger and more stable areas of pollinator habitat near crop fields may be the best way to ensure temporally consistent resources in rotational landscapes (Marja et al., 2018; Gardner et al., 2021).

2.5 Providing protected nesting areas within the production space

Many pollinators need nesting habitat in addition to floral resources. For example, the majority of bees nest belowground and require soil of suitable texture, slope, and accessibility, and with minimal disturbance (Danforth et al., 2019). For bees that nest aboveground, the majority are considered renters and need hollowed cavities, while a minority will excavate nests in a substrate such as wood (Danforth et al., 2019). While the majority of research, particularly for wild bees, has focused on nest habitat adjacent to the field within field margins or hedgerows, in this section we cover agronomic practices to provide or enhance nest habitat within the production space. In fact, some wild bees, such as specialist squash bees, preferentially nest within crop fields over areas adjacent to the field (Julier and Roulston, 2009).

Agronomic practices that can affect nesting habitat for bee pollinators include irrigation and tillage, inclusion of trap nests for aboveground nesting bees, and manipulation of soil to intentionally create belowground nesting habitat. Squash bees, important solitary bee pollinators of *Cucurbita* spp., have been shown to prefer irrigated soils (Julier and Roulston, 2009), and thus regular irrigation within these fields may enhance their nesting rates. However, little is known about how irrigation affects other bee species. The effects of tillage are better documented, though the focus is largely on squash bees, and results are mixed. In some contexts, squash bee abundance did not vary across farms differing in tillage intensity (Julier and Roulston, 2009), but in other studies, populations were more abundant in no or reduced tillage systems (Shuler et al., 2005; Appenfeller et al., 2020). In a more controlled study, tillage moderately reduced and delayed offspring emergence but did not completely eliminate emergence or destroy nests (Ullmann et al., 2016). However, squash bees also seem to prefer nesting in tilled soils (Skidmore et al., 2019) despite the impacts that tillage may have on future offspring emergence. And, in the lone example conducted in other agricultural systems (perennial vineyards), alternating tillage systems had a positive effect on bee pollinator abundance and diversity as compared to no tillage, suggesting that some amount of soil disturbance can increase nesting rates and bee populations (Kratschmer et al., 2019). These studies suggest overall that there may be benefits to reduced tillage, especially for squash bees and within agroecosystems with significant tillage intensity, though soil accessibility is also important for bee nesting rates and can be achieved through occasional or alternating tillage practices.

Intentionally creating nesting space for wild bees within the production space is not common and limited to a few specific agroecosystems. Perhaps the most well-known example of creating ground-nesting habitat is with the alkali bee, an important pollinator of alfalfa in western North America. While this bee is solitary, it nests in aggregations underground within soil of sufficient alkalinity, texture, and moisture (Danforth et al., 2019). These soil attributes have been successfully manipulated in nest boxes or artificial bee beds at ground level through the addition of soil, salt, and irrigation, and have been shown to increase local populations (Stephen, 1960; Cane, 2008). Another opportunity for providing ground-nesting habitat is for the Southeastern blueberry bee *Habropoda laboriosa*, an important pollinator of blueberries in the Southeastern USA. It has been shown to readily nest in manmade holes in the ground, suggesting that nest habitat could be created but is also highly sensitive to changes in visual cues associated with the nest site (Cane, 1994). Finally, the use of trap nests within the crop field to provide nesting habitat for both wild and managed aboveground cavity nesters has been done in alfalfa for the managed alfalfa leafcutter bee (Pitts-Singer and Cane, 2011), in almonds for the managed orchard mason bee (Boyle and Pitts-Singer, 2019), and in oilseed rape fields for wild bees (Dainese et al., 2018).

3 Case studies

3.1 Annual row crop systems

Increasing plant diversity within row crop production fields can be achieved by integrating cover crops or native species within a crop rotation using four primary strategies: (1) intercropping (mixed, strip, or otherwise) or companion cropping with cover crops, forages, or native species that provide floral resources and habitat for pollinators; (2) strategic placement of flowering cash crops (including forages) across the landscape; (3) replacement of a monoculture cash crop, fallow fields, or in prevented plantings scenarios with cover crops in the rotation; and (4) adding overwintering cover crops that provide floral resources early in the season and do not compete with cash crops. The examples provided in this section will focus on the two latter strategies.

In North Dakota, USA, annual cover crops planted specifically for the purpose of providing full-season ground cover and floral resources were shown to support diverse bee populations (Mallinger et al., 2019). Flowering cover crops such as buckwheat, sunflower, and phacelia were planted in single-species stands, i.e. monocultures, and in mixtures of two, three, and six species (with cowpea, hairy vetch, and kale/mustard). Low-diversity mixtures with phacelia and buckwheat provided season-long floral resources at high densities that supported honey bees and generalist bumble bees. Adding sunflower into the mixture increased visitation by more rare wild bees but reduced visitation by managed and generalist bees due to lower floral density of buckwheat and phacelia flowers. Thus, more diverse mixtures increased bee species richness but resulted in reduced visitation by more common species. In addition, the cover crops evaluated in this study attracted several bee species considered to be in decline, many of which were also recorded in adjacent rangeland (minimally managed grazing areas).

Providing early-season floral resources in crop production fields lacking in plant diversity to sustain pollinators during this critical time of year is also crucial. Planting cold-hardy, overwintering cover crops may play an important role in filling this niche. In Pennsylvania, USA, increasing cover crop diversity to include flowering crops such as canola (an early flowering crop, April–May) can support diverse populations of pollinators including honey bees, native bees, and Syrphid flies (Ellis and Barbercheck, 2015). However, crop rotations restrict the flowering window and effectiveness of other flowering service crops such as red clover and Austrian winter pea that flower later in the season (May–July). This study also demonstrated the importance of fall planting date on winter survival and spring flowering, with cover crops planted earlier (August–September) generally resulting in increased overwintering as well as earlier flowering in the spring. Work in South Dakota and Minnesota, USA, also found variability in winter survival of fall-planted flowering cover crops (Eberle et al., 2015). In this study, pennycress, winter canola, and, in particular, winter camelina provided floral and nectar resources early in the season to support pollinators in a corn-soybean crop rotation. The extent to which these floral resources benefit insect pollinators, however, may be impacted by weather variability, particularly in the spring when conditions are often cool and wet in this region of the USA and may have variable impacts on pollinator populations (Forcella et al., 2020).

3.2 Annual specialty crop systems

Within annual cropping systems, intercropping and on-farm crop diversification are the primary ways in which the production system can be modified for pollinators and pollination services. As compared to perennial systems and annual row crops, there are fewer examples of altering crop management practices within the production space for annual specialty crops, likely because their high value discourages modifications within the production space in favor of modifications adjacent to the crop field (i.e. field margins). Additionally, there is minimal vertical structure to manipulate as in perennial orchard crops, and many specialty annual crops (e.g. vegetable crops) are not pollinator-dependent. Here, we present three examples from annual specialty crops.

In strawberries, intercropping with *Coriandrum sativum* or *Mentha arvensis* increased flower visitor frequency overall within the field but reduced pollinator visitation specifically to strawberry flowers, suggesting that the intercrops competed with the strawberry flowers for pollinators (Hodgkiss et al., 2019). Treatments in which strawberries were intercropped with *C. sativum* or *M. arvensis* did not show improved pollination or yields. However, in a different system, intercropping bell peppers with basil increased pollinator visits to the bell peppers specifically, with resulting increases in pepper fruit and seed production (Pereira et al., 2015). Combined, the research to date suggests mixed effects of intercropping on pollination of annual specialty crops likely dependent on both the attractiveness of the specialty crop and the intercrop. Intercrops should be attractive enough to draw in or enhance pollinator populations, but not significantly more attractive than the specialty crop so as to compete for pollinators. Intercrops with peak bloom time slightly before the peak bloom of the specialty crop may be most effective for facilitating pollination. Finally, in an example of crop diversification, more bees were found on diversified polyculture farms than on monoculture farms, including more specialized bees such as the squash bee, but there was no assessment of how these higher bee abundances affected crop yields (Guzman et al., 2019).

3.3 Perennial orchard systems

While within annual specialty crops, intercropping and on-farm crop diversification were the primary management strategies examined, for perennial orchard systems, research focuses primarily on cover crops or living ground cover with examples from almonds, vineyards, and apples. Flowering ground cover within almond orchards can increase pollinator abundance and richness as well as fruit set. On small farms in Egypt, more abundant and species-rich ground cover provided by both crops and wild plants was associated with a greater abundance and diversity of pollinators within the orchard (Norfolk et al., 2016). Importantly, the abundance and species richness of ground vegetation were also directly associated with increased almond fruit set (Norfolk et al., 2016). In Spanish almond orchards, flower abundance on the orchard floor positively predicted wild pollinator visitation to almonds and pollinator species diversity and was associated with increased almond set both via direct effects and indirect effects mediated through increasing pollinator diversity (Alomar et al., 2018). Finally, in Australia, the richness of ground cover plants in almond orchards was associated with greater native bee abundance (Saunders et al., 2013), though effects on yield were not examined. Additionally, no examples from the primary almond production region (California, USA) link within-orchard vegetation to pollinators, pollination, or yield.

Within European vineyards, greater interrow floral resource availability and percent vegetation cover increased wild pollinator abundance and diversity (Kratschmer et al., 2019), but effects on crop production were not evaluated. Finally, while the aforementioned studies all examined existing gradients in ground cover floral resources, one study found that planting cover crops within vineyards, including a mix of *Phacelia tancetifolia*, *Ammi majus*, and *Daccus carota*, resulted in higher abundance and diversity of wild bees as compared to control plots (Wilson et al., 2018). The abundances of numerous individual wild bee taxa, including *A. mellifera*, *Bombus* spp., *Halictus* spp., and *Lasioglossum* spp., were all higher in vineyard blocks with cover crops as compared to control, though again effects on crop production were not examined (Wilson et al., 2018). Yields in these vineyard studies were likely not examined in part because wine grapes have overall minimal dependence on insect pollinators (Klein et al., 2007), though in some cases insect pollination can improve yields and grape quality (Sampson et al., 2001).

3.4 Perennial forage systems (pastures and rangelands)

Perennial forage systems offer perhaps the greatest opportunity for improving agroecosystems for pollinators due to the large land area that they comprise and the diverse plant communities that they can contain. Perennial forage systems, including pasture and rangeland, are a major land use in North America and globally. Pastures and rangelands constitute approximately 22–26% of global ice-free land surface area and represent more land than is in forest or cropland (Ellis et al., 2010; Ellis and Ramankutty, 2008; Klein Goldewijk and Ramankutty, 2004). Therefore, changes to perennial forage systems could have significant impacts on pollinator communities and pollination services.

Perennial forage systems can be improved for pollinators through plant diversification and alteration of management practices including grazing intensities and regimes. Adding flowering plants to forage systems has been shown to increase the diversity of bees and other pollinators, and with consequences for pollination services provided to wild and crop plants. For example, in a study comparing forage systems with (1) bluestem grass only, (2) bluestem grass mixed with alfalfa, (3) alfalfa only, and (4) mixed native grasses, there was a higher insect pollinator abundance and richness in the plots with alfalfa and native grasses as compared to bluestem only plots, and this trend was driven largely by native sweat bees (Bhandari et al., 2018). Additionally, on working grasslands, increasing plant richness by adding legumes and forbs resulted in increased functional diversity of pollinator communities (Orford et al., 2016). Higher pollinator functional diversity in turn reduced variation in flower visitation rates to two of three sentinel crop species, including strawberry and red campion, that were placed within the pastures (Orford et al., 2016). These results conclusively show the benefits of increased forage plant diversity on pollinator abundance and diversity, with potential benefits for the pollination of adjacent crop fields.

However, one limitation to the adoption of plant diversification for pollinators in perennial forage systems is the perceived lack of benefits for the farmer given that forage system productivity is not generally thought to be pollinator-dependent. There is also limited information on how diverse forage plant communities specifically designed for pollinators could improve animal production or the health and productivity of the pasture. Increased pollinator activity and diversity could improve pollination services to flowering forage species, thereby reducing the need to reseed forage each year, but this has not been well studied. If benefits for either animal production or long-term forage quantity and quality could be demonstrated, the adoption of plant diversification for pollinators within perennial forage systems may be increased.

Along with plant diversification, altering the grazing intensity and stocking levels of pastures can influence floral resource availability and pollinator communities. However, the direction of the relationships between grazing intensity, floral resources, and pollinators is variable. While some studies show that high-intensity grazing can have negative effects on floral resources and bee abundance and diversity (Kearns and Oliveras, 2009; Kruess and Tscharntke, 2002; Xie et al., 2008), other studies show no or even positive effects of high-intensity grazing on flowers and bees (Vulliamy et al., 2006; Wallen, 2010). Some of this variability may be due to variable responses to grazing intensity across bee taxa, with bumble bees showing greater sensitivity to increased grazing intensity, particularly in the early season, as compared to sweat bees (Kimoto et al., 2012). Additionally, the relationship between grazing intensity and floral resources may be hump-shaped, suggesting that intermediate levels of grazing may be optimal for maintaining abundant and diverse pollinator communities (Lázaro et al., 2016). As with plant diversification, modifying pasture management for pollinators is unlikely to be widely adopted unless it can show benefits for animal production or system sustainability.

4 Assessing efficacy of alternative agronomic practices

Assessing the impact of agronomic practices on pollinators and farm productivity is crucial for identifying best management practices and encouraging adoption. However, most studies examined the responses of pollinator abundance and diversity to agronomic practices but did not include crop productivity and yield responses. In notable exceptions to this trend, Norfolk et al. (2016) and Alomar et al. (2018) were able to link increased ground cover diversity and flower abundance to increased almond production via direct effects and indirect effects on increased pollinator abundance and diversity. Other work including yield measures found contrasting conclusions with intercropping having no effect on strawberry production (Hodgkiss et al., 2019) but a positive effect on bell pepper production via increased pollinator activity (Pereira et al., 2015). In all these cases, the focal crop was a pollinator-dependent crop. Examples of agronomic practices for pollinators benefiting crop productivity and yields are more limited for crops perceived to have little to no benefit from insect pollinators, including vineyards (Kratschmer et al., 2019; Wilson et al., 2018) and perennial forage systems. For crops with little to no dependence on pollinators, farmer motivation to conserve or enhance pollinators within the production space may be out of general conservation principles or because such practices provide other tangible benefits to production.

Additionally, the scale at which these agronomic practices were assessed may influence the applicability of study conclusions to real-world agroecosystems. Many of the previously-described studies were conducted in small plots (Hodgkiss et al., 2019; Pereira et al., 2015; Orford et al., 2016; Wilson et al., 2018; Bhandari et al., 2018), and those that were done at the farm scale relied on existing gradients in floral resources, including weeds and intentionally planted species (Norfolk et al., 2016; Saunders et al., 2013; Guzman et al., 2019; Kratschmer et al., 2019). Few to no studies manipulated agronomic practices at the farm scale. These limitations can make it challenging to draw conclusions or make predictions for working farms. When using existing gradients, treatments are not randomly assigned, and variables of interest such as floral resource availability and diversity are likely correlated with other factors that vary across farms. For example, farms with greater cover crop diversity may also have reduced chemical inputs or a greater diversity of crop plants, which could additionally impact pollinator abundance and diversity. In small plot studies, treatments are typically randomly assigned and other variables are better controlled, but these results may not scale up the level of the whole farm. Thus, analyzing the scale at which the study was conducted, and correlations among different agronomic practices, is crucial for developing management recommendations from study results.

5 Conclusion

To summarize, agronomic strategies that seek to diversify crop and forage production to support pollinators and the services they provide continue to be evaluated, but we must be intentional and strategic in how we integrate them. Overall, given the large land area occupied by perennial pasture and rangeland along with their relatively more diverse plant communities (as compared to crop production systems), these areas may provide the greatest opportunity for altering management practices to support pollinators. However, acreage of row crops such as corn and soybean, which typically are characterized by large-scale, monoculture, input-intensive practices, has steadily increased over the last year 30 years (USDA NASS, 2020). In 2021, corn and soybean, along with all types of wheat, were grown on 227 million acres in the USA alone (USDA NASS, 2021), and additional acreage is dedicated to other row crops, specialty crops, and orchard production. Thus, agricultural lands overall represent opportunities to not only reduce adverse impacts on pollinators but also support and sustain pollinator populations through strategic design and management modifications.

One challenge associated with these approaches, particularly where agrochemicals are heavily used, is the exposure of sensitive pollinator species to toxic pesticide residues. Therefore, for these strategies to be effective within the crop production space, use of agrochemical inputs would need to be reduced in order to prevent the agroecosystem from functioning as a population sink. Integrated pest management (IPM) and holistic approaches would need to be implemented more broadly to reduce adverse impacts on diverse pollinator populations. Conversely, IPM approaches that reduce insecticide applications may support greater populations of wild pollinators and maintain or enhance crop yields (Pecenka et al., 2021), contributing to both ecosystem and agronomic resilience.

Certainly, as is the case with other ecosystem services such as carbon markets and water quality credits, payments for pollinator provisioning and habitat conservation services may be one of several approaches integrated into a system that further incentivizes many of the practices discussed in this chapter. Globally, payments for ecosystem services have increased, with hundreds of programs now in existence, but with biodiversity PES lagging behind other sectors (Boetzl et al., 2020; Geppert et al., 2020; Salzman et al., 2018). Programs and structures that support biodiversity would, by default, also promote pollinators. Finally, if crop rotations are to include more flowering, pollinator-dependent crops, crop diversity must simultaneously be maintained to support greater biodiversity, sustained pollination services, and the long-term sustainability of agriculture (Aizen et al., 2019).

6 Future trends in research

Altering agronomic management practices, particularly within the crop production space, is challenging and poses more questions than we currently have answers to. For example, the literature is scant on data that quantifies the agronomic (e.g. yield, return on investment) and ecosystem (biodiversity) tradeoffs involved when implementing the approaches described in this chapter. Can we achieve an optimal state whereby both food production and farm economics are balanced with pollinator habitat and floral resource provisioning? What are the long-term impacts of these practices compared to business as usual (current) farming practices and how do they impact agroecosystem functioning? How do fluctuations in crop commodity prices and the development of new or emerging markets impact farmer willingness to alter their crop management practices? What other ecosystem services can be bundled with pollinator services to increase the use of conservation-focused agronomic practices across the agricultural landscape?

Future research should address these and other relevant questions if we are to transition from conventional production practices to more agroecologically based approaches. Additionally, within the context of different cropping systems and farming practices, research has yet to address how different pollinator populations will respond to these changes under current and future climate scenarios, and how they respond to landscape-level changes beyond the crop production space. These uncertainties can only be addressed and implemented at a transformative level by more transdisciplinary research that bridges disciplines in the biophysical and social sciences and invites co-production of research with farmers and other stakeholders.

7 Where to look for further information

The following articles and guides provide a good overview:

- Sustainable Agriculture Research and Education. (2013). *Managing Cover Crops Profitably: Third Edition*. Available at https://www.sare.org/resources/managing-cover-crops-profitably-3rd-edition/.
- Green, R. E., Cornell, S. J., Scharlemann, J. P. W. and Balmford, A. (2005). Farming and the Fate of Wild Nature, *Science* 307(5709), 550–555.
- Kremen, C. and Merenlender, A. M. (2018). Landscapes That Work for Biodiversity and People, *Science* 362(6412).
- Nicholls, C. A. and Altieri, M. A. (2013). Plant biodiversity enhances bees and other insect pollinators in agroecosystems. A review, *Agronomy for Sustainable Development*, 33, 257–274.
- Phalan, B., Onial, M., Balmford, A. and Green, R. E. (2011). Reconciling food production and biodiversity conservation: Land sharing and land sparing compared, *Science* 333(6047), 1289–1291.
- Potts, S. G., Biesmeijer, J. C., Kremen, C., Neumann, P., Schweiger, O. and Kunin, W. E. (2010). Global pollinator declines: trends, impacts and drivers, *Trends in Ecology & Evolution* 25(6), 345–353.

Key research and resources in this area can be found at the following organizations:

- Food and Agriculture Organization of the United Nations (https://www.fao.org/pollination/en/).

- United States Department of Agriculture (USDA) (www.usda.gov).
- Xerces Society for Invertebrate Conservation (https://www.xerces.org/pollinator-conservation).
- Pollinator Partnership (https://www.pollinator.org/international).

8 References

Aguilar, J., Gramig, G. G., Hendrickson, J. R., Archer, D. W., Forcella, F. and Liebig, M. A. (2015). Crop species diversity changes in the United States: 1978–2012, *PLoS ONE* 10(8), e0136580.

Aizen, M. A., Aguiar, S., Biesmeijer, J. C., Garibaldi, L. A., Inouye, D. W., Jung, C., Martins, D. J., Medel, R., Morales, C. L., Ngo, H., Pauw, A., Paxton, R. J., Sáez, A. and Seymour, C. L. (2019). Global productivity is threatened by increasing pollinator dependence without a parallel increase in crop diversification, *Global Change Biology* 25(10), 3516–3527. doi:10.1111/gcb.14736.

Alomar, D., González-Estévez, M. A., Traveset, A. and Lázaro, A. (2018). The intertwined effects of natural vegetation, local flower community, and pollinator diversity on the production of almond trees, *Agriculture, Ecosystems and Environment* 264, 34–43. doi:10.1016/j.agee.2018.05.004.

Andersson, G. K. S., Ekroos, J., Stjernman, M., Rundlöf, M. and Smith, H. G. (2014). Effects of farming intensity, crop rotation and landscape heterogeneity on field bean pollination, *Agriculture, Ecosystems and Environment* 184, 145–148. doi:10.1016/j.agee.2013.12.002.

Appenfeller, L. R., Lloyd, S. and Szendrei, Z. (2020). Citizen science improves our understanding of the impact of soil management on wild pollinator abundance in agroecosystems, *PLoS ONE* 15(3), e0230007. doi:10.1371/journal.pone.0230007.

Bhandari, K. B., West, C. P., Longing, S. D., Brown, C. P., Green, P. E. and Barkowsky, E. (2018). Pollinator abundance in semiarid pastures as affected by forage species, *Crop Science* 58(6), 2665–2671.

Boetzl, F. A., Krauss, J., Heinze, J., Hoffmann, H., Juffa, J., König, S., Krimmer, E., Prante, M., Martin, E. A., Holzschuh, A. and Steffan-Dewenter, I. (2020). A multitaxa assessment of the effectiveness of agri-environmental schemes for biodiversity management, *Proceedings of the National Academy of Sciences of the United States of America* 118(10), e2016038118. doi:10.1073/pnas.2016038118.

Boyle, N. K. and Pitts-Singer, T. L. (2019). Assessing blue orchard bee (Osmia lignaria) propagation and pollination services in the presence of honey bees (Apis mellifera) in Utah tart cherries (Osmia lignaria), *PeerJ* 7, e7639. doi:10.7717/peerj.7639.

Brennan, E. B. (2013). Agronomic aspects of strip intercropping lettuce with alyssum for biological control of aphids, *Biological Control* 65(3), 302–311.

Brennan, E. B. (2016). Agronomy of strip interropping broccoli with alyssum for biological control of aphids, *Biological Control* 97, 109–119.

Bretagnolle, V. and Gaba, S. (2015). Weeds for bees? A review, *Agronomy for Sustainable Development* 35(3), 891–909.

Bryan, C. J., Sipes, S. D., Arduser, M., Kassim, L., Gibson, D. J., Scott, D. A. and Gage, K. L. (2021). Efficacy of cover crops for pollinator habitat provision and weed suppression, *Environmental Entomology* 50(1), 208–221.

Butters, J., Murrell, E., Spiesman, B. J. and Kim, T. N. (2022). Native flowering border crops attract high pollinator abundance and diversity, providing growers the opportunity to enhance pollination services, *Environmental Entomology* 51(2), 492–504.

Campbell, J. W., Irvin, A., Irvin, H., Stanley-Stahr, C. and Ellis, J. D. (2016). Insect visitors to flowering buckwheat, *Fagopyrum esculentum* (Polygonales: Polygonaceae), in North-Central Florida, *Florida Entomologist* 99(2), 264–268.

Cane, J. H. (1994). Nesting biology and mating behavior of the southeastern blueberry bee, Habropoda laboriosa (Hymenoptera: Apoidea), *Journal of the Kansas Entomological Society* 67(3), 236–241.

Cane, J. H. (2008). A native ground-nesting bee (Nomia melanderi) sustainably managed to pollinate alfalfa across an intensively agricultural landscape, *Apidologie* 39(3), 315–323. doi:10.1051/apido:2008013.

Carvalheiro, L. G., Veldtman, R., Shenkute, A. G., Tesfay, G. B., Pirk, C. W. W., Donaldson, J. S. and Nicolson, S. W. (2011). Natural and within-farmland biodiversity enhances crop productivity, *Ecology Letters* 14(3), 251–259. doi:10.1111/j.1461-0248.2010.01579.x.

Dainese, M., Riedinger, V., Holzschuh, A., Kleijn, D., Scheper, J. and Steffan-Dewenter, I. (2018). Managing trap-nesting bees as crop pollinators: spatiotemporal effects of floral resources and antagonists, *Journal of Applied Ecology* 55(1), 195–204. doi:10.1111/1365-2664.12930.

Danforth, B. N., Minckley, R. L., Neff, J. L. and Fawcett, F. (2019). *The Solitary Bees: Biology, Evolution, Conservation*. Princeton University Press. doi:10.2307/j.ctvd1c929.

Cubins, J. A., Wells, M. S., Frels, K., Ott, M. A., Forcella, F., Johnson, G. A., Walia, M. K., Becker, R. L. and Gesch, R. W. (2019). Management of pennycress as a winter annual cash cover crop: a review, *Agronomy for Sustainable Development* 39(5), 46.

Eberle, C. A., Thom, M. D., Nemec, K. T., Forcella, F., Lundgren, J. G., Gesch, R. W., Riedell, W. E., Papiernik, S. K., Wagner, A., Peterson, D. H. and Eklund, J. J. (2015). Using pennycress, Camelina, and canola cash cover crops to provision pollinators, *Industrial Crops and Products* 75, 20–25.

Ellis, K. E. and Barbercheck, M. E. (2015). Management of overwintering cover crops influences floral resources and visitation by native bees, *Environmental Entomology* 44(4), 999–1010.

Ellis, E. C., Klein Goldewijk, K., Siebert, S., Lightman, D. and Ramankutty, N. (2010). Anthropogenic transformation of the biomes, 1700 to 2000, *Global Ecology and Biogeography* 19.

Ellis, E. C. and Ramankutty, N. (2008). Putting people in the map: anthropogenic biomes of the world, *Frontiers in Ecology and the Environment* 6(8), 439–447.

Forcella, F., Patel, S., Lenssen, A. W., Hoerning, C., Wells, M. S., Gesch, R. W. and Berti, M. T. (2020). Weather and landscape influences on pollinator visitation of flowering winter oilseeds (field pennycress and winter Camelina), *Journal of Applied Entomology* 145(4), 286–294.

Gardner, E., Breeze, T. D., Clough, Y., Smith, H. G., Baldock, K. C. R., Campbell, A., Garratt, M. P. D., Gillespie, M. A. K., Kunin, W. E., McKerchar, M., Potts, S. G., Senapathi, D., Stone, G. N., Wäckers, F., Westbury, D. B., Wilby, A. and Oliver, T. H. (2021). Field boundary features can stabilise bee populations and the pollination of mass-flowering crops in rotational systems, *Journal of Applied Ecology* 58(10), 2287–2304. doi:10.1111/1365-2664.13948.

Gathmann, A. and Tscharntke, T. (2002). Foraging ranges of solitary bees, *Journal of Animal Ecology* 71(5), 757–764. doi:10.1046/j.1365-2656.2002.00641.x.

Gemmill-Herren, B. and Ochieng', A. O. (2008) Role of native bees and natural habitats in eggplant (Solanum melongena) pollination in Kenya, *Agriculture, Ecosystems and Environment* 127(1–2), 31–36. doi:10.1016/j.agee.2008.02.002.

Geppert, C., Hass, A., Földesi, R., Donkó, B., Akter, A., Tscharntke, T. and Batáry, P. (2020). Agri-environment schemes enhance pollinator richness and abundance but bumblebee reproduction depends on field size, *Journal of Applied Ecology* 57(9), 1818–1828.

Gesch, R. W., Archer, D. W. and Berti, M. T. (2014). Dual cropping winter Camelina with soybean in the northern corn belt, *Agronomy Journal* 106(5), 1735–1745.

Gowton, C. M., Cabra-Arias, C. and Carrillo, J. (2021). Intercropping with peppermint increases ground dwelling insect and pollinator abundance and decreases *Drosophila suzukii* in fruit, *Frontiers in Sustainable Food Systems* 5, 700842.

Greenleaf, S. S., Williams, N. M., Winfree, R. and Kremen, C. (2007). Bee foraging ranges and their relationship to body size, *Oecologia* 153(3), 589–596.

Guzman, A., Chase, M. and Kremen, C. (2019). On-farm diversification in an agriculturally-dominated landscape positively influences specialist pollinators, *Frontiers in Sustainable Food Systems* 3, 87. doi:10.3389/fsufs.2019.00087.

Hicks, D. M., Ouvrard, P., Baldock, K. C. R., Baude, M., Goddard, M. A., Kunin, W. E., Mitschunas, N., Memmott, J., Morse, H., Nikolitsi, M., Osgathorpe, L. M., Potts, S. G., Robertson, K. M., Scott, A. V., Sinclair, F., Westbury, D. B. and Stone, G. N. (2016). Food for pollinators: quantifying the nectar and pollen resources of urban flower meadows, *PLoS ONE* 11(6), e0158117. doi:10.1371/journal.pone.0158117.

Hodgkiss, D., Brown, M. J. F. and Fountain, M. T. (2019). The effect of within-crop floral resources on pollination, aphid control and fruit quality in commercial strawberry, *Agriculture, Ecosystems and Environment* 275, 112–122. doi:10.1016/j.agee.2019.02.006.

Housman, M., Tallman, S., Jones, C., Miller, P. and Zabinski, C. (2021). Soil biological response to multi-species cover crops in the Northern Great Plains, *Agriculture, Ecosystems and Environment* 313, 107373.

Johnson, G. A., Wells, M. S., Anderson, K., Gesch, R. W., Forcella, F. and Wyse, D. L. (2017). Yield tradeoffs and nitrogen between pennycress, camelina, and soybean in relay- and double-crop systems, *Agronomy Journal* 109, 2128–2135. doi:10.2134/agronj2017.02.0065.

Julier, H. E. and Roulston, T. H. (2009). Wild bee abundance and pollination service in cultivated pumpkins: farm management, nesting behavior and landscape effects, *Journal of Economic Entomology* 102(2), 563–573. doi:10.1603/029.102.0214.

Kearns, C. A. and Oliveras, D. M. (2009). Environmental factors affecting bee diversity in urban and remote grassland plots in Boulder, Colorado, *Journal of Insect Conservation* 13(6), 655–665. doi:10.1007/s10841-009-9215-4.

Kimoto, C., DeBano, S. J., Thorp, R. W., Taylor, R. V., Schmalz, H., DelCurto, T., Johnson, T., Kennedy, P. L. and Rao, S. (2012). Short-term responses of native bees to livestock and implications for managing ecosystem services in grasslands, *Ecosphere* 3(10), doi:10.1890/ES12-00118.1.

Klein, A. M., Vaissiere, B. E., Cane, J. H., Steffan-Dewenter, I., Cunningham, S. A., Kremen, C. and Tscharntke, T. (2007). Importance of pollinators in change landscapes for world crops, *Proceedings of the Royal Society. Series B,-Biological Sciences* 274, 303–313.

Klein Goldewijk, K. and Ramankutty, N. (2004). Land cover change over the last three centuries due to human activities: the availability of new global data sets, *GeoJournal* 61(4), 335–344.

Kordbacheh, F., Liebman, M. and Harris, M. (2020). Strips of prairie vegetation placed within row crops can sustain native bee communities, *PLoS ONE* 15(10), e0240354.

Kratschmer, S., Pachinger, B., Schwantzer, M., Paredes, D., Guzmán, G., Goméz, J. A., Entrenas, J. A., Guernion, M., Burel, F., Nicolai, A., Fertil, A., Popescu, D., Macavei, L., Hoble, A., Bunea, C., Kriechbaum, M., Zaller, J. G. and Winter, S. (2019). Response of wild bee diversity, abundance, and functional traits to vineyard inter-row management intensity and landscape diversity across Europe, *Ecology and Evolution* 9(7), 4103–4115. doi:10.1002/ece3.5039.

Kruess, A. and Tscharntke, T. (2002). Grazing intensity and the diversity of grasshoppers, butterflies, and trap-nesting bees and wasps, *Conservation Biology* 16(6), 1570–1580. doi:10.1046/j.1523-1739.2002.01334.x.

Larson, J. L., Redmond, C. T. and Potter, D. A. (2013). Assessing insecticide hazard to bumble bees foraging on flowering weeds in treated lawns, *PLoS ONE* 8(6), e66375. doi:10.1371/journal.pone.0066375.

Lázaro, A., Tscheulin, T., Devalez, J., Nakas, G. and Petanidou, T. (2016). Effects of grazing intensity on pollinator abundance and diversity, and on pollination services, *Ecological Entomology* 41(4), 400–412. doi:10.1111/een.12310.

Lehmkuhler, J. W., Ramos, M. H. and Albrecht, K. A. (2007). Cupplant silage as a replacement for corn silage in growing beef cattle diets, *Forage and Grazinglands* 5(1), 1–6.

Mallinger, R. E., Bradshaw, J., Varenhorst, A. J. and Prasifka, J. R. (2018). Native Solitary Bees Provide Economically Significant Pollination Services to Confection Sunflowers (Helianthus annuus L.) (Asterales: Asteraceae) Grown Across the Northern Great Plains, *Journal of Economic Entomology* 112(1), 40–48.

Mallinger, R. E., Franco, J. G., Prischmann-Voldseth, D. A. and Prasifka, J. R. (2019). Annual cover crops for managed and wild bees: optimal plant mixtures depend on pollinator enhancement goals, *Agriculture, Ecosystems and Environment* 273, 107–116.

Marja, R., Viik, E., Mänd, M., Phillips, J., Klein, A.-M. and Batáry, P. (2018). Crop rotation and agri-environment schemes determine bumblebee communities via flower resources, *Journal of Applied Ecology* 55(4), 1714–1724. doi:10.1111/1365-2664.13119.

Martin, A. R., Cadotte, M. W., Isaac, M. E., Milla, R., Vile, D. and Violle, C. (2019). Regional and global shifts in crop diversity through the Anthropocene, *PLoS ONE* 14(2), e0209788.

Mueller, A. L., Berger, C. A., Schittenhelm, S., Stever-Schoo, B. and Dauber, J. (2020). Water availability affects nectar sugar production and insect visitation on the cup plant *Silphium perfoliatum* L. (Asteraceae), *Journal of Agronomy and Crop Science* 206(5), 529–537.

Nicholls, C. I. and Altieri, M. A. (2013). Plant biodiversity enhances bees and other insect pollinators in agroecosystems. A review, *Agronomy for Sustainable Development* 33(2), 257–274.

Norfolk, O., Eichhorn, M. P. and Gilbert, F. (2016). Flowering ground vegetation benefits wild pollinators and fruit set of almond within arid smallholder orchards, *Insect Conservation and Diversity* 9(3), 236–243. doi:10.1111/icad.12162.

Norris, S. T., Blackshaw, R. P., Critchley, C. N. R., Dunn, R. M., Smith, K. E., Williams, J., Randall, N. P. and Murray, P. J. (2018). Intercropping flowering plants in maize systems increases pollinator diversity, *Agricultural and Forest Entomology* 20, 246–254. doi:10.1111/afe.12251.

Orford, K. A., Murray, P. J., Vaughan, I. P. and Memmott, J. (2016). Modest enhancements to conventional grassland diversity improve the provision of pollination services, *Journal of Applied Ecology* 53(3), 906–915. doi:10.1111/1365-2664.12608.

Ott, M. A., Eberle, C. A., Thom, M. D., Archer, D. W., Forcella, F., Gesch, R. W. and Wyse, D. L. (2019). Economics and agronomics of relay-cropping pennycress and Camelina with soybean in Minnesota, *Agronomy Journal* 111(3), 1281–1292.

Patel, S., Lenssen, A. W., Moore, K. J., Mohammed, Y. A., Gesch, R. W., Wells, M. S., Johnson, B. L., Berti, M.T. and Matthees, H. L. (2021). Interseeded pennycress and camelina yield and influence on row crops, *Agronomy Journal* 113, 2629–2647. doi:10.1002/agj2.20655.

Pecenka, J. R., Ingwell, L. L., Foster, R. E., Krupke, C. H. and Kaplan, I. (2021). IPM reduces insecticide applications by 95% while maintaining or enhancing crop yields through wild pollinator conservation, *Proceedings of the National Academy of Sciences of the United States of America* 118(44), e2108429118. doi:10.1073/pnas.2108429118.

Pereira, A. L. C., Taques, T. C., Valim, J. O. S., Madureira, A. P. and Campos, W. G. (2015). The management of bee communities by intercropping with flowering basil (Ocimum basilicum) enhances pollination and yield of bell pepper (Capsicum annuum), *Journal of Insect Conservation* 19(3), 479–486. doi:10.1007/s10841-015-9768-3.

Phalan, B., Onial, M., Balmford, A. and Green, R. E. (2011). Reconciling food production and biodiversity conservation: land sharing and land sparing compared, *Science* 333(6047), 1289–1291.

Pitts-Singer, T. L. and Cane, J. H. (2011). The alfalfa leafcutting bee, Megachile rotundata: the world's most intensively managed solitary bee, *Annual Review of Entomology* 56, 221–237. doi:10.1146/annurev-ento-120709-144836.

Requier, F., Odoux, J. F., Tamic, T., Moreau, N., Henry, M., Decourtye, A. and Bretagnolle, V. (2015). Honey bee diet in intensive farmland habitats reveals an unexpectedly high flower richness and a major role of weeds, *Ecological Applications : a Publication of the Ecological Society of America* 25(4), 881–890. doi:10.1890/14-1011.1.

Rering, C. C., Franco, J. G., Yeater, K. M. and Mallinger, R. E. (2020). Drought stress alters floral volatiles and reduces floral rewards, pollinator activity, and seed set in a global plant, *Ecosphere* 11(9), e03254.

Salzman, J., Bennett, G., Carroll, N., Goldstein, A. and Jenkins, M. (2018). The global status and trends of payments for ecosystem services, *Nature Sustainability* 1(3), 136–144.

Sampson, B., Noffsinger, S., Gupton, C. and Magee, J. (2001). Pollinator biology of the muscadine grape, *Hortscience* 36(1), 120–124.

Sanderson, M., Johnson, H. and Hendrickson, J. (2018). Cover crop mixtures grown for annual forage in a semi-arid environment, *Agronomy Journal* 110(2), 525–534.

Sardiñas, H. S., Tom, K., Ponisio, L. C., Rominger, A. and Kremen, C. (2016). Sunflower (Helianthus annuus) pollination in California's Central Valley is limited by native bee nest site location, *Ecological Applications : a Publication of the Ecological Society of America* 26(2), 438–447. doi:10.1890/15-0033.

Saunders, M. E., Luck, G. W. and Mayfield, M. M. (2013). Almond orchards with living ground cover host more wild insect pollinators, *Journal of Insect Conservation* 17(5), 1011–1025. doi:10.1007/s10841-013-9584-6.

Shuler, R. E., Roulston, T. H. and Farris, G. E. (2005). Farming practices influence wild pollinator populations on squash and pumpkin, *Journal of Economic Entomology* 98(3), 790–795.

Sidemo-Holm, W., Carrié, R., Ekroos, J., Lindström, S. A. M. and Smith, H. G. (2021). Reduced crop density increases floral resources to pollinators without affecting crop yield in organic and conventional fields, *Journal of Applied Ecology* 58(7), 1421–1430. doi:10.1111/1365-2664.13887.

Skidmore, A. R., Short, C. A., Dills, C., Goodell, K. and Bessin, R. T. (2019). Preference of Peponapis pruinosa (Hymenoptera: Apoidea) for tilled soils regardless of soil management system, *Environmental Entomology* 48(4), 961–967. doi:10.1093/ee/nvz052.

Stephen, W. P. (1960). Artificial bee beds for the propagation of the alkali bee, Nomia melanderi, *Journal of Economic Entomology* 53(6), 1025–1030. doi:10.1093/jee/53.6.1025.

Tepedino, V. J. (1981). The pollination efficiency of the squash bee (Peponapis pruinosa) and the honey bee (Apis mellifera) on summer squash (Cucurbita pepo), *Journal of the Kansas Entomological Society* 54(2), 359–377.

Tscharntke,T., Klein, A. M., Kruess, A., Steffan-Dewenter, I. and Thies, C. (2005). Landscape perspectives on agricultural intensification and biodiversity – ecosystem service management, *Ecology Letters* 8(8), 857–874.

Tscharntke, T., Clough, Y., Wanger, T. C., Jackson, L., Motzke, I., Perfecto, I., Vandermeer, J. and Whitbread, A. (2012). Global food security, biodiversity conservation and the future of agricultural intensification, *Biological Conservation* 151(1), 53–59.

Ullmann, K. S., Meisner, M. H. and Williams, N. M. (2016). Impact of tillage on the crop pollinating, ground-nesting bee, Peponapis pruinosa in California, *Agriculture, Ecosystems and Environment* 232, 240–246. doi:10.1016/j.agee.2016.08.002.

United State Department of Agriculture-Risk Management (2013). Agency (USDA-RMA), *Contract Price Addendum, a Risk Management Agency Fact Sheet*. Accessed May 2022, Available at: https://www.rma.usda.gov/pubs/rme/2013revisedorganicsfactsheet.pdf.

United States Department of Agriculture (2020). National Agricultural Statistics Service (USDA-NASS), *Quick Stats*. Accessed April 2022, Available at: https://quickstats.nass.usda.gov/.

United States Department of Agriculture (2021). National Agricultural Statistics Service (USDA-NASS), *Quick Stats*. Accessed April 2022, Available: https://quickstats.nass.usda.gov/.

van der Slujis, J. P., Simon-Delos, N., Goulson, D., Maxim, L., Bonmatin, J.-M. and Belzunces, L. P. (2013). Neonicotinoids, bee disorders and the sustainability of pollinator services, *Current Opinion in Environmental Sustainability* 5(3–4), 293–305.

Van Sambeek, J. W. (2017). Orchard management using cover crops to improve soil health and pollinator habitat in the midwestern United States, *The Nutshell* 71(3), 32–45.

Van Tassel, D. L., Albrecht, K. A., Bever, J. D., Boe, A. A., Brandvain, Y., Crews, T. E., Gansberger, M., Gerstberger, P., Gonzalez-Paleo, L., Hulke, B. S., Kane, N. C., Johnson, P. J., Pestsova, E. G., Picasso Risso, V.D., P., J.R., Ravetta, D. A., Schlautman, B., Sheaffer, C. C., Smith, K. P., Speranza, P. R., Turner, M. K., Vilela, A. E., von Gehren, P. and Wever, C. (2017). Accelerating Silphium domestication: an opportunity to develop new crop ideotypes and breeding strategies informed by multiple disciplines, *Crop Science* 57(3), 1274–1284.

Vulliamy, B., G. Potts, S. and G. Willmer, P. (2006). The effects of cattle grazing on plant-pollinator communities in a fragmented Mediterranean landscape, *Oikos* 114(3), 529–543.

Wallen, K. E. (2010). *Fire, Grazing, and Herbicide: Effects of Rangeland Management on Bee and Floral Communities in Oklahoma*. Oklahoma State University.

Wilson, H., Wong, J. S., Thorp, R. W., Miles, A. F., Daane, K. M. and Altieri, M. A. (2018). Summer flowering cover crops support wild bees in vineyards, *Environmental Entomology* 47(1), 63–69. doi:10.1093/ee/nvx197.

Witter, S., Nunes-Silva, P., Lisboa, B. B., Tirelli, F. P., Sattler, A., Hilgert-Moreira, S. B. and Blochtein, B. (2015). Stingless bees as alternative pollinators of canola, *Journal of Economic Entomology* 108(3), 880–886.

Xie, Z., Williams, P. H. and Tang, Y. (2008). The effect of grazing on bumblebees in the high rangelands of the eastern Tibetan Plateau of Sichuan, *Journal of Insect Conservation* 12(6), 695–703. doi:10.1007/s10841-008-9180-3.