

The Role of Temperate Agroforestry Practices in Supporting Pollinators



Gary Bentrup, Jennifer Hopwood, Nancy Lee Adamson, Rae Powers, and Mace Vaughan

Introduction

Agroforestry is the intentional integration of trees and/or shrubs with herbaceous crops and/or livestock in an agricultural production system. In temperate regions, agroforestry systems include many different practices such as windbreaks, riparian buffers, alley cropping, hedgerows, shelterbelts, silvopasture, and forest farming. Agroforestry practices can deliver a suite of ecosystem services from provisioning, regulating, cultural, and supporting services (Smith et al. 2013). With some exceptions (e.g., pollinator hedgerows), ecosystem services provided by insect pollinators are often not specifically considered in the design and management of agroforestry practices (Udawatta et al. 2019). However, whether using alley cropping or a windbreak, managing a riparian buffer, or forest farming, agroforestry practices can

G. Bentrup (✉)

U.S. Department of Agriculture, U.S. Forest Service, National Agroforestry Center,
Lincoln, NE, USA
e-mail: gary.bentrup@usda.gov

J. Hopwood

Xerces Society for Invertebrate Conservation, Omaha, NE, USA
e-mail: jennifer.hopwood@xerces.org

N. L. Adamson

Formerly with Xerces Society for Invertebrate Conservation
e-mail: nancy@wildbeeplantings.com

R. Powers

Xerces Society for Invertebrate Conservation, Lincoln, NE, USA
e-mail: raeann.powers@xerces.org

M. Vaughan

Xerces Society for Invertebrate Conservation, Portland, OR, USA
e-mail: mace.vaughan@xerces.org

increase the overall diversity of plants and physical structure in landscapes and, as a result, provide habitat for pollinators and other insects beneficial for agriculture such as predators and parasitoids of crop pests and decomposers. Agroforestry plantings can also have indirect benefits for pollinators including habitat connectivity and protection from pesticide exposure. This chapter provides an overview of the current scientific knowledge regarding how agroforestry practices can support pollinators and pollination services.

Importance of Pollinators

Plant pollination by animals is one of the most well-known and important ecosystem services and is essential in both natural and agricultural landscapes (IPBES 2016). An estimated 85% of the world's flowering plants depend on animals—mostly insects—for pollination (Ollerton et al. 2011). Pollination is a mutually beneficial interaction between plants and pollinators. Animals, particularly insects, visit flowers seeking sustenance, and in the process transfer pollen grains from one flower or plant to another, allowing flowering plants to reproduce. Sugary nectar and/or protein-packed pollen grains are food resources for pollinators.

Insect pollination is critical to agricultural production. Eighty-seven of the world's 124 most commonly cultivated crops (70%) are reliant on or benefit from animal pollination, including crops that produce fruits, vegetables, spices, nuts, and seeds (Klein et al. 2007). Additionally, insect-pollinated plants such as alfalfa and clover provide feed for livestock. Roughly 35% of global crop production is dependent on pollination by animals (Klein et al. 2007). The majority of minerals, vitamins, and nutrients needed to maintain human health (such as vitamin C, calcium, and folic acid) come from crop plants that depend partially or fully on animal pollinators (Eilers et al. 2011). The value of crops directly dependent on pollination by insects (e.g., apples, squash) was estimated in 2009 at \$15.1 billion in the United States, and the value of crops indirectly dependent on pollinators (e.g., alfalfa hay, onions) was estimated in 2004 at \$12 billion (Calderone 2012).

Pollinators are a keystone group in most terrestrial ecosystems, necessary for plant reproduction and important for wildlife food webs (Kearns et al. 1998). They sustain wildland plant communities that provide food and shelter for myriad wildlife. Fruits, seeds, and nuts, that result from animal pollination, are food for many insects, birds, and mammals. Pollinators can also be direct prey for wildlife. For example, pollinator larvae are an important part of the diet of many young birds (Buehler et al. 2002). Healthy habitat that supports pollinators often confers other ecosystem services such as reduced soil erosion, enhanced rainwater infiltration, improved water quality, reduced wind velocity, carbon sequestration, recreation spaces for humans, and habitat for a variety of wildlife, including arthropod predators and parasitoids that reduce crop pests.

Important Groups of Pollinators

The great majority of pollinators are insects, including bees, wasps, flies, beetles, butterflies, and moths (Table 1; Allen-Wardell et al. 1998; Kevan 1999; Kearns 2001), but some bird and bat species pollinate as well (Grant 1994; Valiente-Banuet et al. 2004). Bees are considered the most important group of pollinators for agricultural crops (McGregor 1976; Morse and Calderone 2000; Garibaldi et al. 2013) as well as for wild plants in temperate climates (Michener 2007). Bees are such efficient pollinators of many plants because 1) they actively collect both pollen and nectar; 2) they make many trips to flowers as they are foraging to collect nest provisions for their offspring; and 3) they have more flower constancy, i.e., once they find a good forage source they visit that type of flower over and over.

The domesticated European honey bee (*Apis mellifera*) is the most widely recognized bee worldwide and is an important managed crop pollinator. Studies indicate that honey bee pollination accounts for more than \$15 billion in crop production annually in the United States (Morse and Calderone 2000; Calderone 2012).

Based on Ascher and Pickering (2020), there are over 5200 species of native bees in North America, many of which are important crop pollinators. Native bees are important in the production of crops worth an estimated \$3 billion annually to the US economy (Losey and Vaughan 2006), though this may be an underestimate of their contribution. A recent analysis of 41 crop systems worldwide found that managed honey bees do not replace the pollination services provided by a diverse community of native bees (Garibaldi et al. 2013). Native bees provide pollination services in colder, windier weather (Brittain et al. 2013) and are more efficient than honey bees on an individual bee basis at pollinating particular crops, such as squash, berries, and tree fruits (e.g., Tepedino 1981; Bosch and Kemp 2001; Javorek et al. 2002; Garibaldi et al. 2013).

Most native bees live solitary lives, with each female working alone to build her nests and collect and provide food for her offspring. Some solitary bees visit a diversity of flowers to collect pollen, and others collect from flowers of a particular plant species or group of species. Bumble bees and some sweat bees are the only native bees that form social colonies. Their colonies usually have fewer than 200 bees, and are much smaller than a honey bee hive which may house up to 30,000 individuals. Bumble bees are particularly important pollinators. They are able to fly in cooler temperatures and lower light levels than many other bees, which extends their workday and improves the pollination of crops during inclement weather (Corbet et al. 1993). In addition to commercially important crops, bumble bees also play a vital role as generalist pollinators of native flowering plants (Mommott et al. 2004). They and many native bees also possess the ability to “buzz pollinate,” dislodging pollen with a vibration that forces release from poricidal anthers found in flowers such as blueberries, cranberries, tomatoes, and peppers (Buchmann 1983).

Of the other orders of pollinating insects, flies (Diptera) also provide substantial pollination services (Kearns 2001; Larson et al. 2001; Inouye et al. 2015), especially in alpine areas and tundra. Other insects such as beetles (Coleoptera) and

Table 1 Common insect pollinator groups

		
Honey bee Order: Hymenoptera Family: Apidae Genus and species: <i>Apis mellifera</i> The European honey bee (native to Europe, Africa, and Asia) is a domesticated species that lives in large perennial social colonies (hives), with division of labor within the colony. Only the queen reproduces, while others gather nectar and pollen to feed brood (larvae) and store food (honey) for the winter. Feral colonies in the United States are somewhat rare; most hives are managed by beekeepers	Bumble bees Order: Hymenoptera Family: Apidae Genus: <i>Bombus</i> Bumble bees form annual social colonies. Queen bumble bees that mated the previous fall start nests in spring and by mid-summer colonies can have dozens or hundreds of workers. They nest in insulated cavities such as under clumps of bunch grass or in old rodent nests. There are 46 recognized bumble bee species in North America	Ground-nesting bees Order: Hymenoptera Families: Andrenidae, Apidae, Colletidae, Halictidae Most native bees live solitary lives, with each female working alone to build her nests and collect and provide food for her offspring. About 70% of our solitary bee species nest underground, digging slender tunnels in which they build individual cells for each egg and its provisions
		
Tunnel-nesting bees Order: Hymenoptera Families: Apidae, Colletidae, Halictidae, Megachilidae Approximately 30% of solitary bee species nest in tunnels, inside already hollow stems or by chewing into the pithy center of stems, or in existing holes in wood, sometimes man-made. Most tunnel-nesting bees are solitary species	Flower-visiting flies Order: Diptera Families: Anthomyiidae, Bombyliidae, Syrphidae, Tachinidae, others Flower-visiting flies consume nectar and sometimes pollen. Many hover flies (family Syrphidae) resemble bees or wasps in coloration. Larvae of some species are voracious predators of small insects, like aphids	Flower-visiting beetles Order: Coleoptera Families: Cantharidae, Coccinellidae, Scarabaeidae, others Flower-visiting beetles consume nectar and pollen, and may also chew on flower parts. Larvae of some species are predatory, hunting other insects (including crop pests) as food, while others are herbivorous or are decomposers

(continued)

Table 1 (continued)

		
Flower-visiting wasps	Flower-visiting moths	Butterflies
Order: Hymenoptera Families: Sphecidae, Vespidae, Tiphiidae, Scoliidae, others	Order: Lepidoptera Families: Sphingidae, Noctuidae, Arctiidae	Order: Lepidoptera Families: Papilionidae, Hesperiidae, Pieridae, Lycaenidae, Nymphalidae
Predatory wasps, most of which are solitary, hunt for prey to bring back to their nest as food for their young. They build nests in cavities or in the ground, and may utilize pieces of grass, mud, or resin in construction of their nest. Adults maintain their energy by consuming nectar and/or pollen, and in the process may also transfer pollen between flowers	Moths, which are often subdued in color and tend to fly at dusk or night, are less visible than other groups, but many are important specialist pollinators of wild plants, while some also pollinate crops. Moths as a group form a critical food source for other wildlife	With their striking transformation from a chubby plant-chewing caterpillar to a delicate pupa to a graceful nectar-drinking adult, butterflies are some of the most beloved insects. Some species have narrow host plant needs for their caterpillars while others feed on a wide variety of plants

Source: Flower-visiting beetle image by Jennifer Hopwood and remaining images by Nancy Lee Adamson

wasps (Hymenoptera) provide pollination services, though to a lesser extent (e.g., Frankie et al. 1990; Kevan 1999). The contribution of most butterfly and moth species (Lepidoptera) to pollination services is not well known (e.g., Frankie et al. 1990; Allen-Wardell et al. 1998; Westerkamp and Gottsberger 2000; MacGregor et al. 2015), but there are instances where butterflies have been documented pollinating wild plant species, including some flowering plants specially adapted for butterfly pollination (e.g., *Russelia*, *Phlox*, and *Lantana*) (Fallon et al. 2014). Ollerton (2017) estimate that more than 140,000 species of moths and butterflies visit flowers. Many butterfly species fly great distances between flowers and may carry pollen for a long time, and thus they may be effective as dispersers of pollen.

In addition to insect pollinators, there are two groups of nectar-feeding vertebrates that play an important role in pollination: hummingbirds (Trochilidae) and bats (Phyllostomidae). There are 12 species of nectar-feeding bats that are known pollinators in North America (National Research Council 2007). The known ranges for these bats correspond closely with the distribution of columnar cacti (e.g., saguaro [*Carnegieia gigantea*], *Pachycereus* spp., *Stenocereus* spp., *Lophocereus* spp.) and agaves (*Agave* spp.), the main species they are known to pollinate (Valiente-Banuet et al. 2004), primarily in the deserts of Arizona, California, Nevada, New Mexico, and Texas. Hummingbirds, which pollinate about 130 native

plant species with flowers adapted for hummingbird pollination, make long migratory journeys in North America and depend on nectar corridors to sustain their long-distance movements (Nabhan et al. 2004).

Pollinator Status and Threats

Globally, pollinators are in decline (Biesmeijer et al. 2006; National Research Council 2007; Potts et al. 2010; Sánchez-Bayo and Wyckhuys 2019), with some estimates that 40% of invertebrate pollinator species may be at risk of extinction worldwide (IPBES 2016). Threats such as the loss, degradation, and fragmentation of habitat (e.g., Kremen et al. 2002; Williams and Kremen 2007; Potts et al. 2010); introduced species (e.g., Tallamy and Shropshire 2009; Fiedler et al. 2012); use of pesticides (e.g., Dover et al. 1990; Kearns and Inouye 1997; Kevan 1999; Whitehorn et al. 2012); and diseases and parasites (e.g., Altizer and Oberhauser 1999; Colla et al. 2006; Cameron et al. 2011) all contribute to pollinator decline.

In the United States, the number of honey bee colonies has been in decline over the past half-century due to diseases, parasites, lack of floral resources, insecticides, and other factors (National Research Council 2007). Since 2012, beekeepers have experienced record high annual hive losses of 33% or more; an average of 40% of managed colonies were lost in the 2018–2019 season (Bee Informed Partnership 2019).

Much less is known about the status of most of North America's native pollinators, though what data does exist suggests that numerous species are experiencing declines similar to or more severe than the declines seen in honey bees. One-quarter of North America's bumble bees have experienced significant declines (Hatfield et al. 2014), including declines in species that were formerly some of the most common species (Cameron et al. 2011). In 2017, the once common rusty patched bumble bee (*Bombus affinis*) was added to the US Fish and Wildlife list of endangered species (US Fish and Wildlife Service 2019).

In the United States, some butterflies are also in decline. NatureServe assessed all of the country's roughly 800 butterfly species and found that 19% are at risk of extinction (NatureServe 2018). A number of generalist butterfly species have seen significant declines in recent years (Forister et al. 2011). In particular, monarch butterflies (*Danaus plexippus*) in North America are now vulnerable to extinction, according to a recently completed assessment (Semmens et al. 2016). The population of monarchs has dropped by over 80% east of the Rocky Mountains (Rendón-Salinas and Tavera-Alonso 2014) and by over 90% to the west (Schultz et al. 2017). The loss of milkweeds (*Asclepias* spp.), the monarch's larval host plants, has been significant, particularly within agricultural fields (Pleasants and Oberhauser 2012).

The populations of both hummingbirds and nectar-feeding bats throughout the southwestern United States have also experienced declines (National Research Council 2007). Hummingbirds face disruption of migratory routes and loss of

habitat (Calder 2004), while nectar-feeding bats face disturbance of their roost sites and removal of foraging habitat and nectar sources (US Fish and Wildlife Service 2006).

The loss of pollinators negatively affects plant reproduction and plant community diversity (Bawa 1990; Fontaine et al. 2005; Brosi and Briggs 2013). Threats to pollinators may have profound consequences for ecosystem health as well as our food systems (Kearns et al. 1998; Spira 2001; Steffan-Dewenter and Westphal 2008). Concerns about pollinator decline and its repercussions have led to increased efforts to reduce threats to pollinators. Managing existing habitat for insect pollinators and restoring additional habitat have been demonstrated to increase pollinator abundance and diversity (e.g., Fiedler et al. 2012; Klein et al. 2012; Morandin and Kremen 2013). By adding structural and functional diversity in landscapes, agroforestry may provide habitat and other benefits for insect and other pollinators and pollination services.

Agroforestry's Role

Based on a review of available scientific literature, agroforestry practices can confer three key benefits for insect pollinators and pollination services: 1) providing habitat including foraging resources and nesting or egg-laying sites, 2) enhancing site and landscape connectivity, and 3) reducing pesticide exposure (Bentrop et al. 2019). Current research on supporting pollinators in agricultural landscapes has focused primarily on honey bees and native bees but general concepts may apply across other pollinator groups.

Providing Habitat

Foraging Resources

Pollinators require a diversity of flowers to provide nectar and pollen resources to meet their nutritional needs. Nectar is an aqueous solution of sugars, amino acids, and other secondary metabolites that provides a rich source of energy for bees, butterflies, hummingbirds, bats, and some moths, wasps, beetles, and flies. Pollen is a protein-rich resource that is used by native bees, honey bees, and some wasps to feed their brood or to provision their eggs or by some adult flies and beetles as a food source. Agroforestry practices can be important sources of nectar and pollen for pollinators when appropriate plants are used (Table 2). If the agroforestry practice lacks pollinator-suitable floral resources, pollinator use can be limited. For instance, Macdonald et al. (2018) found limited pollinator use of shelterbelts in New Zealand that were predominantly comprised of Monterey pine (*Pinus radiata*

Table 2 North American trees and shrubs that provide abundant nectar and/or pollen^a

Scientific name	Common name	Bloom time ^b	Height ^c	Region ^d
<i>Acer</i> spp. ^e	Maple	Spring to early summer	T	WCE
<i>Amelanchier</i> spp. ^f	Serviceberry	Early spring to summer	SM	WCE
<i>Amorpha</i> spp.	Leadplant, false indigo	Spring to summer	S	WCE
<i>Arbutus</i> spp. ^{a,g}	Madrone	Early spring to summer	MT	WC
<i>Aronia</i> spp. ^f	Chokeberry	Spring to summer	S	C ^h E
<i>Atriplex canescens</i>	Four-wing saltbush	Spring to fall	SM	W
<i>Baccharis</i> spp. ^a	Baccharis	Summer to fall	S	WCE
<i>Callicarpa americana</i>	Beautyberry	Early summer	S	CE ^h
<i>Ceanothus</i> spp.	Native lilac, NJ tea	Early spring to summer	SM	WCE
<i>Cephalanthus occidentalis</i>	Buttonbush	Summer	SM	WCE
<i>Cercis</i> spp.	Redbud	Spring	M	WCE
<i>Chrysothamnus</i> spp.	Rabbitbrush	Summer-fall	SM	W
<i>Clethra alnifolia</i>	Sweet pepperbush	Summer	S	E
<i>Crataegus</i> spp.	Hawthorn	Spring	M	WCE
<i>Dasiphora</i> spp.	Cinquefoil	Spring	S	WCE
<i>Diospyros</i> spp. ^{e,f}	Persimmon	Spring	T	WCE
<i>Ericameria</i> spp.	Rabbitbrush	Summer-fall	SM	WC
<i>Eriogonum</i> spp.	Buckwheat	Summer	S	WC
<i>Gaylussacia</i> spp. ^f	Huckleberry	Early spring	S	CE
<i>Gleditsia</i> spp. ^f	Honey locust	Spring	T	WCE
<i>Halesia</i> spp.	Silverbell	Early spring	MT	E ^h
<i>Holodiscus</i> spp.	Cliff spirea	Summer	S	WC
<i>Hypericum</i> spp.	Shrubby St.-John's-wort	Late spring	S	WCE
<i>Ilex</i> spp. ^{a,g}	Holly, inkberry	Spring	SMT	WCE
<i>Itea virginica</i>	Virginia sweetspire	Spring	S	CE
<i>Krascheninnikovia lanata</i>	Winterfat	Summer	S	W
<i>Liriodendron tulipifera</i> ^c	Tulip tree	Spring	T	CE
<i>Mahonia</i> spp. ^a	Oregon grape	Spring to early summer	S	WCE
<i>Nyssa</i> spp. ^f	Black gum	Spring	MT	CE
<i>Oxydendrum arboreum</i>	Sourwood	Summer	T	E
<i>Parkinsonia</i> spp.	Palo Verde	Spring	M	WCE ^h
<i>Philadelphus</i> spp.	Mock orange	Spring	S	WCE
<i>Physocarpus</i> spp.	Ninebark	Spring to summer	S	WCE
<i>Prunus</i> spp. ^{e,f}	Cherry, plum, peach, apricot	Spring	M	WCE
<i>Purshia tridentata</i>	Antelope bitterbrush	Spring	S	W

(continued)

Table 2 (continued)

Scientific name	Common name	Bloom time ^b	Height ^c	Region ^d
<i>Rhododendron</i> spp. ^a	Rhododendron, azalea	Early spring	SM	WCE
<i>Rhus</i> spp. ^f	Sumac	Spring to summer	M	WCE
<i>Robinia pseudoacacia</i> ^{e,f}	Black locust	Spring	T	E ⁱ
<i>Rosa</i> spp. ^f	Rose	Summer	S	WCE
<i>Rubus</i> spp. ^f	Blackberry, raspberry	Spring to fall	S	WCE
<i>Salix</i> spp. ^f	Willow	Early spring	MT	WCE
<i>Sambucus</i> spp. ^f	Elderberry	Spring to summer	S	WCE
<i>Sassafras albidum</i>	Sassafras	Spring	MT	CE
<i>Shepherdia</i> spp.	Buffaloberry	Spring	SM	WC
<i>Spiraea</i> spp.	Spirea	Summer	S	WCE
<i>Tilia</i> spp. ^c	Basswood	Spring to summer	T	CE
<i>Umbellularia californica</i>	California laurel	Fall to spring	T	W
<i>Vaccinium</i> spp. ^{f,g}	Blueberry, huckleberry	Early spring	S	WCE

^aIncludes some or all evergreen species

^bFlowering times depend on species, location, and environmental conditions, varying from year to year. Consult with local native plant experts to plan for overlapping bloom times

^cShort (S), medium (M), tall (T)

^dWest (W), Central (C), East (E)

^eAdded value as timber

^fAdded value of fruit or other culinary crops

^gAdded value of decorative cut twigs for the floral industry

^hSouthern distribution only

ⁱThis species is invasive in some parts of the country and should not be planted in those regions

Source: Modified from Adamson et al. (2011)

D. Don) and Monterey cypress (*Hesperocyparis macrocarpa* (Hartw.) Bartel) (wind-pollinated exotic species).

Many woody species offer abundant nectar with relatively high sugar contents such as maple (*Acer* spp.), horse chestnut (*Aesculus* spp.), basswood (*Tilia* spp.), willow (*Salix* spp.), brambles (*Rubus* spp.), cherry and plum (*Prunus* spp.), and serviceberry (*Amelanchier* spp.) (Batra 1985; Stubbs et al. 1992; Loose et al. 2005; Ostaff et al. 2015; Baude et al. 2016; Somme et al. 2016; Donkersley 2019). For example, sugar content in horse chestnut (*Aesculus hippocastanum* L.) ranges from 0.58 to 3.57 mg/flower/24 h, while black locust (*Robinia pseudoacacia* L.) ranges from 0.76 to 4.0 mg/flower/24 h (Crane and Walker 1985). For comparison, white clover (*Trifolium repens* L.) ranges from 0.01 to 0.20 mg/flower/24 h and alfalfa (*Medicago sativa* L.) ranges from 0.07 to 0.25 mg/flower/24 h (Crane and Walker 1985).

Willow, maple, cherry and plum, brambles, chestnut (*Castanea* spp.), and ash (*Fraxinus* spp.) are woody species that can provide pollen with high concentrations of amino acids, sterols, trace minerals, and other nutritionally important compounds for bees and other pollinators (Batra 1985; Tasei and Aupinel 2008; Di Pasquale et al. 2013; Ostaff et al. 2015; Russo and Danforth 2017; Filipiak 2019). Some bees are pollen specialists (oligolectic), wholly dependent on specific shrubs and trees in certain families, such as willows, dogwoods (Cornaceae), heaths like blueberry and huckleberry (Ericaceae), buckthorns such as New Jersey tea (Rhamnaceae), and

roses (Rosaceae) (Dötterl and Vereecken 2010; Fowler 2016). These nutritionally rich pollen sources are often sought out by native bees (Stubbs et al. 1992; Ostaff et al. 2015) and have been shown to result in higher reproductive success and better immunity in bumble bees (e.g., Tasei and Aupinel 2008; Di Pasquale et al. 2013).

Tree and shrub plantings with overlapping bloom times provide nectar and pollen resources throughout the growing season and are key for sustaining diverse pollinator populations (Loose et al. 2005; Hannon and Sisk 2009; Miñarro and Prida 2013). Many temperate-zone trees and shrubs flower early in spring and can deliver some of the first pollen and nectar resources of the season, boosting early-season pollinator populations (Table 2) (Dirr 1990; Batra 1985; Ostaff et al. 2015; Somme et al. 2016). In Michigan, United States, Wood et al. (2018) determined that willows, maples, and *Prunus* spp. provided over 90% of the pollen collected in April by social and solitary bees. When forage is available early in the growing season, freshly emerged bumble bee queens are more successful in establishing their colonies (Carvell et al. 2017).

Plantings that include a diversity of flowers of various sizes, shapes, and colors can support a rich and abundant community of bees and other pollinators (Potts et al. 2003; Roulston and Goodell 2011; Nicholls and Altieri 2013). Flower density and subsequent nectar availability can be higher in some tree and shrub species compared to herbaceous species (Crane and Walker 1985; Loose et al. 2005). For example during peak flowering season, gray willow (*Salix cinerea* L.) can produce 334,178 flowers/m² and oneseed hawthorn (*Crataegus monogyna* Jacq.) 19,003 flowers/m² compared to sea aster (*Aster tripolium* L.) 9565 flowers/m² and buttercup (*Ranunculus acris* L.) 688 flowers/m² (Baude et al. 2016). Respectively, nectar productivity for these species is 3612, 584, 169, and 50 kg/ha cover/year. Spatially, agroforestry practices that incorporate a diversity of flowering woody and herbaceous species can deliver a high density of floral resources relative to the land area occupied due to vertical layering (Miñarro and Prida 2013; Morandin and Kremen 2013; Ponisio et al. 2016; Somme et al. 2016; Donkersley 2019). Timberlake et al. (2019) documented approximately two and four times greater nectar per unit area in hedgerows compared to woodlands and pasture, respectively.

Bees also collect resins and oils from trees and other plants (Weislo and Cane 1996; Cane et al. 2007; Policarová et al. 2019). Some tunnel-nesting native bees use tree resins to seal off their nests while honey bees use plant resins mixed with saliva and beeswax to make propolis to seal unwanted holes in their hives. Propolis has antibacterial properties that help prevent disease transmission or pest/parasite invasion (Simone-Finstrom et al. 2017). Poplar trees (*Populus* spp.) are a common source for these resins (Greenaway et al. 1990; Bankova et al. 2000; König 1985; Drescher et al. 2019). Other tree species including pine (*Pinus* spp.), birch (*Betula* spp.), elm (*Ulmus* spp.), alder (*Alnus* spp.), beech (*Fagus* spp.), and horse chestnut can provide resin sources when poplar species are not present (Ghisalberti 1979; König 1985; Drescher et al. 2019).

Pollinator behavior, foraging, and resulting pollination services are strongly influenced by weather conditions (e.g., ambient temperature, wind speed, precipitation) (Corbet 1990; Vicens and Bosch 2000). Temperature and wind speed are two primary weather variables that agroforestry practices can influence.

Windbreaks, alley cropping, and other agroforestry practices can reduce air movement and modify temperatures in the cropped area. Daytime air temperatures are several degrees warmer within a certain distance downwind of windbreaks (8–10 times the windbreak height) (McNaughton 1988). These elevated temperatures can increase pollinator activity and pollination, particularly in vegetable- and fruit-growing regions where air temperatures at pollination time can often be below optimum (Norton 1988). The vertical structure and shaded conditions provided by agroforestry practices can offer niches that allow pollinators to find suitable sites for thermal regulation, which is becoming increasingly important under climate change (Kjølhl et al. 2011). Papanikolaou et al. (2017) found that agricultural landscapes that had a higher proportion of hedgerows and seminatural habitats (i.e., 17% compared to 2%) decreased the detrimental effects of warmer temperatures on native bee species richness and abundance.

Agroforestry plantings can address additional thermoregulation considerations for managed honey bees. Honey bees expend energy to cool themselves and their hives during hot weather. If the hives are shaded, that energy can be diverted to honey production and hive maintenance activities (Nye 1962). Trees and shrubs are useful for shading beehives, especially if the hives are placed on the north or northeast sides of the woody plantings to receive maximum shading during the summer heat (Hill and Webster 1995). Windbreaks and other woody buffers can also provide protection from winter temperatures and winds if the hives are located on the leeward side, helping reduce winter mortality (Haydak 1958). In Kansas, Merrill (1923) documented that populations in overwintered hives can be up to 52% higher when protected by windbreaks.

Foraging in moderate to high winds increases energetic costs for pollinators and reduces pollination efficiency (Vicens and Bosch 2000; Brittain et al. 2013). Agroforestry practices designed to reduce wind speeds can increase pollinator efficiency and allow pollinators to forage during wind events that would normally reduce or prohibit foraging. The protective effect on insect flight extends up to a distance equal to about nine times the height of the windbreak (Pinzauti 1986) and the sheltered zone can contain higher numbers of pollinating insects (Pasek 1988), increasing pollination and fruit set (Norton 1988). Agroforestry practices that reduce winds, such as windbreaks and hedgerows, can enhance pollination by reducing flower shedding and increasing overall flowering (Peri and Bloomberg 2002).

Nesting and Egg-Laying Sites

The availability of nesting and egg-laying sites is also key for successful pollinator conservation (Potts et al. 2005; Steffan-Dewenter and Schiele 2008; Sardiñas et al. 2016b). The short foraging and dispersal distances of many pollinator species require that, along with food resources, nesting resources should be available within a localized area (Gathmann and Tscharncke 2002).

Solitary tunnel-nesting bees build their nests aboveground in hollow tunnels in the soft pithy centers of twigs of some plants, in abandoned wood-boring beetle

tunnels, or in tunnels they excavate themselves into wood, especially rotting logs and snags (e.g., Potts et al. 2005; Cane et al. 2007). Hedgerows and other agroforestry practices that incorporate woody species with soft pithy centers can increase the availability of nesting sites (Table 2) (Morandin and Kremen 2013; Kremen and M'Gonigle 2015). A modeling study calculated a higher nesting potential for cavity-nesting species in landscapes with agroforestry compared to landscapes without agroforestry (Kay et al. 2019). Dead trees and branches left within an agroforestry practice can also provide nesting sites (Brown 2002).

Solitary ground nesters excavate underground tunnels for nesting that can be negatively impacted by tillage in agricultural fields (Shuler et al. 2005; Kim et al. 2006). The presence of trees and shrubs provides protected nesting areas that have limited soil disturbance. Hedgerows have been documented to provide suitable ground-nesting habitat and increase diversity of ground-nesting bees (Morandin and Kremen 2013; Kremen and M'Gonigle 2015; Ponisio et al. 2016); however, another study did not find enhanced nesting rates for ground-nesting bees in hedgerows (Sardiñas et al. 2016a).

Bumble bee queens often hibernate under trees in leaf litter. Upon emerging in early spring, bumble bee queens seek rodent burrows and other insulated cavities in which to start their colonies and rear their brood or offspring. Bumble bees often select nest sites at the interface between fields and linear woody habitat such as hedgerows and windbreaks (Svensson et al. 2000; Kells and Goulson 2003). One study documented bumble bee nest densities twice as great in these linear woody habitats when compared with grassland and other woodland habitats (Osborne et al. 2008b) while another study found hedgerows to be less preferred when compared to herbaceous field margins and grasslands for nest-searching bumble bee queen (Lye et al. 2009). Non-cropped habitat suitable for nesting may also facilitate movement of queens into the wider landscape (Carvell et al. 2017).

Agroforestry practices can provide egg-laying sites, larval host plants, and overwintering sites for lepidopteran (butterfly and moth) species (Dover and Sparks 2000; Maudsley 2000; Merckx et al. 2012). Woody species were found to support ten times more lepidopteran species than herbaceous plants in the US mid-Atlantic region (Tallamy and Shropshire 2009). This work also documented that lepidopteran species used native woody plant species as larval hosts 14 times more than nonnative ornamental woody species. Some of the most highly used plant genera by lepidopteran species include poplar, willows, cherry, plum, birch, and oaks (*Quercus* spp.) (Tallamy and Shropshire 2009; Dumroese and Luna 2016). Lepidopteran species and other pollinators including beetles overwinter under bark and leaf litter found in hedgerows (Dover and Sparks 2000; Maudsley 2000; Pywell et al. 2005).

Enhancing Connectivity

Habitat is becoming increasingly fragmented due to agricultural intensification, urban expansion, and other human activities (Saunders et al. 1991). Pollination services at the farm and landscape scale are impacted by this fragmentation (e.g., Aizen

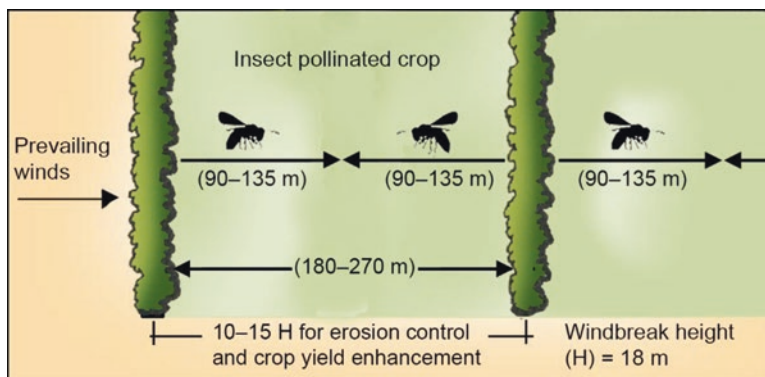


Fig. 1 Windbreaks are typically planted at intervals of 10–15 times windbreak height (H) for reducing erosion and enhancing crop yields through microclimate modification. Using an H of 18 m as an example, the windbreaks would be spaced at 180–270 m across a field. This would place pollinator habitat within 90–135 m from the center of the cropped area, well within the foraging range of most pollinators as well as within the range of predatory and parasitoid insects to prey on crop pests. Within a 1 km² field, a 20 m wide and 18 m tall windbreak could provide 10% non-cropped habitat area to support pollinators

and Feinsinger 1994; Sipes and Tepedino 1995). For example, Garibaldi et al. (2011) estimated fruit set of pollinator-dependent crops decreased by 16% at 1 km distance from the nearest pollinator habitat.

Based on field-level studies and modeling efforts, agroforestry practices can provide pollinator habitat close to crops and at a scale that benefits foraging and crop pollination (e.g., Morandin and Kremen 2013; Kremen and M’Gonigle 2015; Morandin et al. 2016; Sutter et al. 2018; Graham and Nassauer 2019). For example, the spatial distribution of windbreak and alley cropping plantings across fields to achieve other nonpollinator-related services places habitat within the foraging range of many pollinators, including short-distance foragers (Fig. 1) (Gathmann and Tscharntke 2002; Benjamin et al. 2014; Moisan-DeSerres et al. 2015). The benefits of agroforestry practices for pollination services are often higher when this semi-natural habitat is added to structurally simple fields and landscapes (e.g., Carvell et al. 2011; Klein et al. 2012; Ponisio et al. 2016; Ponisio et al. 2019). This distribution of habitat also supports other insect-based services in agricultural fields such as pest management by natural predatory insects. For instance, Morandin et al. (2014) documented pest control by beneficial insects extending 100 m into crop fields from hedgerows while Tscharntke et al. (2002) demonstrated that maintaining diverse habitat on more than 20% of a farm helps ensure effective pest control by predatory and parasitoid insects.

At the landscape scale, habitat connectivity is important for sustaining pollinator diversity, reproduction, and dispersal. Different groups of pollinators respond to habitat fragmentation in different ways (Cane et al. 2006; Brosi et al. 2008; Boscolo et al. 2017). Although some pollinators can complete their entire life cycle within hedgerows or riparian buffers, other pollinators may use agroforestry plantings for

only a portion of their life cycle. Some pollinators can nest or overwinter in one habitat and forage in another if the distances between the patches are within their flight capabilities. Pollinators with limited dispersal capability, such as tiny sweat bees that have foraging ranges of less than 250 m (Greenleaf et al. 2007; Gathmann and Tscharrnke 2002) or butterflies that are poor fliers, may need plantings directly connected to habitat to aid their dispersal. In contrast, bumble bees can forage up to 2 km or more (Osborne et al. 2008a). Habitats with greater connectivity allow pollinators to travel more safely between patches to find resources, disperse to new habitat, and encounter potential mates.

Agroforestry practices can serve as habitat corridors connecting larger patches of habitat that facilitate movement of organisms between habitat fragments, aid in establishing or maintaining populations, promote greater genetic flow among populations, and increase species diversity within isolated areas (Tewksbury et al. 2002). Experimental corridors have been found to increase the movement of pollinators (Haddad 1999) as well as facilitate pollination (Tewksbury et al. 2002; Townsend and Levey 2005). Evidence documenting pollinator use of agroforestry habitat as corridors includes hedgerow-promoted movement of butterflies (Ouin and Burel 2002), moths (Couthard et al. 2016), and bees (Cranmer et al. 2012; Klaus et al. 2015) and butterfly travel along windbreaks (Dover and Fry 2001) and riparian buffers (Meier et al. 2005). Corridors may not always need to directly connect habitat areas to help organisms to disperse (Fried et al. 2005) as patches of habitat can serve as stepping stones between isolated fragments in otherwise inhospitable landscapes (Ottewell et al. 2009).

Agroforestry plantings extending across rural and urban landscapes often contain greater plant diversity than adjacent lands, are longer term in nature, and are generally protected from further development and major disturbances. In developed landscapes, like intensively managed agricultural lands or cities, agroforestry plantings are particularly valuable (Senapathi et al. 2017). Additionally, agroforestry corridors are likely to be particularly beneficial in agricultural landscapes where natural or seminatural habitat benefits pollinator populations (e.g., Klein et al. 2012; McKechnie et al. 2017) as well as crop pollination (Morandin and Winston 2006; Blaauw and Isaacs 2014; Klatt et al. 2014). Hedgerows in intensively managed agricultural landscapes, for example, increase bee, syrphid fly, and other beneficial insect abundance and diversity in adjacent crop fields (Morandin and Kremen 2013; Morandin et al. 2014).

However, agroforestry plantings may act as barriers to some pollinators, inhibiting movement between habitats. Pollen flow can also potentially be reduced across hedgerows (Klaus et al. 2015) and possibly other tree-row plantings. Krewenka et al. (2011) found that bee foraging was not impacted by hedgerows; however, another study found that bombyliid flies had reduced pollen transfer (Campagne et al. 2009). Windbreaks and hedgerows can act as barriers for butterfly movement (Dover and Fry 2001). Hedgerows may channel pollinator movement, which could enhance connectivity but restrict movement across hedgerows, isolating some plant populations (Klaus et al. 2015). The orientation of plant rows may influence hedgerows' abilities to promote movement or act as barriers (Ouin and Burel 2002).

Climate change impacts pollinators and their relationships with plants by driving shifts in the ranges of pollinators or their host plants (Forister et al. 2010; Chen et al. 2011; Kerr et al. 2015), altering plant and pollinator phenology (Parmesan 2007; Bartomeus et al. 2011), decreasing protein concentration in floral pollen (Ziska et al. 2016), and increasing the impacts of other drivers of pollinator decline (Settele et al. 2016). Increasing landscape connectivity is one proposed strategy to reduce negative impacts of climate change on pollinators by enhancing the ability of species to move into new regions as climate shifts (Krosby et al. 2010; Gilchrist et al. 2016). Agroforestry may help enhance connectivity across rural and urban landscapes, thereby helping species extend their ranges and have some resiliency in the face of a changing climate.

Reducing Pesticide Exposure

Pesticides can have acute toxicity leading to pollinator mortality and sublethal effects on growth and development, behavior, and other activities (Stanley and Preetha 2016). Sublethal effects of pesticide exposure at very low concentrations are reported on homing and foraging, larval development and adult emergence, and visual and olfactory learning (Desneux et al. 2007; Sánchez-Bayo and Goka 2014). Among social insects like honey bees and bumble bees, pesticides carried back to the nest may also impact larvae, nestmates, and the queen, and delay emergence of new adults (Wu et al. 2011). Pesticides can also suppress the immune system, making bees (and likely other organisms) more susceptible to disease and parasites (e.g., Sánchez-Bayo et al. 2016; Czerwinski and Sadd 2017; Evans et al. 2018).

On farms and in other landscapes, pollinators may come into contact with pesticides through several exposure pathways (Fig. 2) (e.g., Krupke et al. 2012; Botías et al. 2015; Chagnon et al. 2015; Johnson 2015; Hladik et al. 2016; Long and Krupke 2016; Stanley and Preetha 2016). Pollinators may also be exposed to multiple pesticides over time (with higher cumulative levels of toxicity than an individual pesticide or synergistic effects) (Sánchez-Bayo and Goka 2014). USDA (2014) provides additional information on pesticide exposure pathways and methods for preventing and mitigating potential negative impacts of pesticides on pollinators.

Agroforestry practices can help reduce pollinator exposure to pesticides that are used for managing crop pests and diseases or reducing weed competition (Vaughan et al. 2017). By understanding potential pesticide exposure pathways, farmers and land managers can better design plantings such as windbreaks, hedgerows, and riparian buffers that help reduce or mitigate potential negative impacts of pesticides (Fig. 3). The same agroforestry practices aimed at protecting pollinators can also help reduce pesticide use and associated costs by supporting natural enemies of crop pests, such as predatory and parasitic insects and other arthropods that reduce pest populations (Morandin et al. 2016; Staton et al. 2019).

Windbreaks, hedgerows, and other linear plantings can reduce spray drift by up to 80–90% by reducing wind speeds and trapping particles (Ucar and Hall 2001;

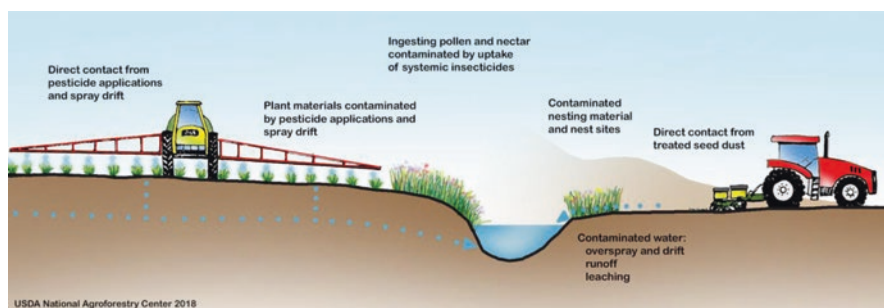


Fig. 2 Potential pesticide exposure pathways encountered by pollinators in an agricultural landscape

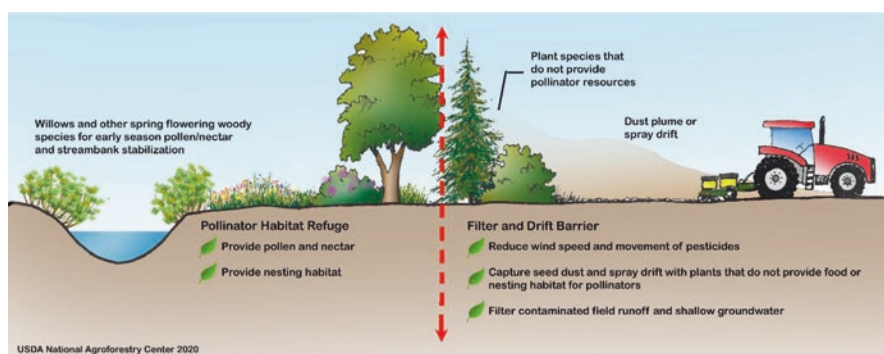


Fig. 3 Using agroforestry practices to mitigate potential negative impacts of pesticides on pollinators

Otto et al. 2015). Buffers slow wind speeds, and the porosity of plant buffers lets wind move through the vegetation (vs. pushing up and over a solid barrier). At slower wind speeds, particles are more likely to fall out and become trapped in foliage. Agroforestry buffers that are 2.5–3 m tall, with 40–50% porosity and fine, evergreen foliage (large surface area), are generally the most effective for drift prevention (Ucar and Hall 2001; Wenneker and Van de Zande 2008; Mercer 2009; Otto et al. 2015; Chen et al. 2017). Yet, even hedgerows with porosity of nearly 75% have been found to be effective in reducing drift by more than 80% (Lazzaro et al. 2008).

In orchards or other crop systems being sprayed early in the growing season, buffers comprised of evergreen species can substantially reduce potential pollinator exposure risk from spray drift (Wenneker and Van de Zande 2008; Felsot et al. 2010). Fine, evergreen, coniferous foliage can capture 2–4 times that of broadleaf species, with the additional benefit of trapping air pollutants in winter (Chen et al. 2017). Leaf roughness, hairiness, waxiness, and other factors can affect foliage capture of particulate matter and some research indicates that the arrangement of a filter strip (with trees, shrubs, and grasses, and of an adequate length) is more important than species composition (Terzaghi et al. 2013; Chen et al. 2016).

Agroforestry buffers can also help capture pesticide runoff, prevent or slow pesticide movement through soil, and help to break down some pesticides (Chaudhry et al.

2005; Jose 2009; Pavlidis and Tsihrintzis 2017). A meta-analysis by Zhang et al. (2010) highlights how sediment captured by vegetative buffers helps improve pesticide removal, particularly those pesticides that are strongly hydrophobic such as pyrethroids and many organophosphates. Based on a review of available studies, Pavlidis and Tsihrintzis (2017) documented a 40–100% reduction of pesticides (including herbicides) in runoff using agroforestry systems. Plants and rhizosphere microorganisms vary in their ability to degrade or immobilize pesticides. Poplar, willow, birch, alder, black locust, and sycamore (*Platanus* spp.) are North American native trees with documented effectiveness in capturing pesticide runoff or immobilizing pesticides within their woody tissue (Pavlidis and Tsihrintzis 2017; Pavlidis and Tsihrintzis 2018).

However, the same factors making agroforestry practices effective buffers can also lead to pesticide accumulation and pose danger for pollinators, particularly from systemic pesticides and those with long residual activity such as neonicotinoids (Krupke et al. 2012; Hopwood et al. 2016). Nectar and pollen of early-flowering tree and shrub species may become contaminated by systemic action of neonicotinoids or through nontarget drift of treated seed-coating dust during crop planting (Long and Krupke 2016). Pesticide droplets and particles or pesticides adhering to dust can also accumulate in the foliage or at the base of agroforestry buffers (Zaady et al. 2018). Pollinators may ingest or carry back to the nest particles contaminated with pesticides (Krupke et al. 2012). If the pesticides or their metabolites have long residual activity and/or are systemically taken up into the plants, the accumulated levels could mean chronic and increased exposure over time. Pesticides accumulating in soil pose higher risks for the approximately 70% of native bees that nest in the ground.

Increasing the proportion of non-cropped habitat in agricultural landscapes has been shown to buffer the effects of pesticide on native bees (Park et al. 2015). Agroforestry practices can provide this habitat, especially when the plantings are protected from pesticide exposure. No-spray buffer zones can be used to protect agroforestry plantings that provide pollinator refuge (Davis and Williams 1990; Ucar and Hall 2001). Spray drift deposition in hedgerows was reduced by 72% when a 12 m no-spray buffer zone was used next to the hedgerows (Kjær et al. 2014). Depending on the cropping systems (and their potential spray regimes), it may be important to use plants that do not provide pollinator forage in the first rows adjacent to a field (Fig. 3).

Crop Pollination Services

Available scientific evidence demonstrates the conservation benefits that agroforestry practices can provide to insect pollinators, including greater pollinator abundance and richness. Although these benefits should translate into enhanced pollination services leading to increased crop yields and quality, few studies have been conducted to document this direct agronomic benefit (Klein et al. 2012; Staton et al. 2019). Studies have shown positive effects on canola (*Brassica napus* L.) yields due to hedgerows (Morandin et al. 2016; Dainese et al. 2017) while another study showed no effects on crop pollination in sunflower (*Helianthus annuus* L.) (Sardiñas and Kremen 2015). In apple orchards, researchers found increased pollinator abundance adjacent to an artificial windbreak, which led to a 20–30% increase in fruit set with no reduction in fruit

size (Smith and Lewis 1972). While the artificial windbreak was created out of coir netting, this study may suggest potential yield increases due to pollinator activity in apple orchards with planted windbreaks.

Many factors are likely to influence the ability of agroforestry practices to promote crop pollination services, including specific pollinator attributes, field size, crop type, plant composition of the agroforestry practice, and landscape context (IPBES 2016). The diversity of interacting variables makes it challenging to conduct studies and develop guidelines for producers. For instance, the ratio of agroforestry practice to crop area in order to supply sufficient pollination service is largely unexplored (Venturini et al. 2017). One study demonstrated that native bees can provide full pollination services for watermelon (*Citrullus lanatus* Thunb.) when around 30% of the land within 1.2 km of a field is in natural habitat (Kremen et al. 2004), which could be an approximate analog to an agroforestry practice. Regarding landscape context, one study found an increase in quality and quantity of strawberries grown adjacent to forest-connected hedgerows, as compared to isolated hedgerows or grass margins (Castle et al. 2019). Plants placed at forest-connected hedgerows produced more high-quality strawberries with 90% classified as “marketable.” In comparison, only 75% of strawberries from plants at isolated hedgerows, 48% of strawberries from plants on grassy margins, and 41% of strawberries from self-pollinated control plants were classified as marketable. Based on market prices of 2016, the increase in economic value between strawberries produced at grassy margins and forest-connected hedgerows amounted to 61% (Castle et al. 2019). Cost-benefit studies that assess the benefits of an agroforestry practice for pollination services compared to the costs of installation and maintenance, opportunity costs, and costs of potential unintended negative effects are also very limited. Morandin et al. (2016) estimated that 7 years would be required for farmers to recover hedgerow implementation costs based on the estimated yield benefits from both pollination and pest control to the crop (Morandin et al. 2016). Future cost-benefit analyses should consider the range of agronomic effects in order to provide comprehensive economic assessment of ecosystem services.

Summary

Agroforestry is a multifunctional land-use approach that provides a range of ecosystem services in support of production and environmental stewardship goals (Nair 2007). Capitalizing on insect-based ecosystem services, agroforestry offers opportunities to benefit pollinators and other beneficial insects and their services including crop pollination and biological pest management. Based on the available scientific literature, agroforestry practices in temperate regions can aid pollinators and pollination services by providing habitat, including foraging resources and nesting or egg-laying sites, enhancing site and landscape connectivity, and mitigating pesticide exposure.

A primary advantage for using agroforestry to support pollinators is that these practices inherently provide some pollinator benefits and with additional considerations during design and management, the effectiveness of agroforestry practices for pollinators

can be enhanced. Due to common landscape settings and spatial configurations, each agroforestry practice provides different options and advantages for providing pollinator habitat, enhancing connectivity, and protecting against pesticides (Table 3).

Table 3 General considerations for promoting pollinators and pollination services for each agroforestry practice

Practice	Considerations for pollinators
Alley cropping (also called tree-based intercropping)	Alley cropping presents an opportunity to grow plants in close proximity that have complementary flowering periods. By paying careful attention to bloom periods and using multiple species, an alley cropping system can provide nearly continuous pollen and nectar forage within a single farmscape. Consider flowering trees like black cherry, black locust, or basswood along with the more typical alley cropping trees of walnut, pecan, or oak. Diverse forbs and shrubs may be planted in rows for cut flowers, berry production, or the nursery market, as well as for pollinators. A legume forage crop between rows will not only fix nitrogen and help manage weeds, but also provide nectar and pollen if allowed to flower
Windbreaks (also includes shelterbelts, hedgerows)	These practices help reduce wind speed, making it easier for pollinators to fly and visit flowers. When planted with diverse flowering shrubs and trees, windbreaks can provide shelter, pollen, and nectar for pollinators. Windbreaks and other linear plantings can serve as buffers against drifting pesticides. Do not use plants that will attract pollinators in windbreaks designed to intercept pesticide drift. Planting wildflowers during establishment can enhance pollinator resources and reduce weed pressure
Riparian forest buffers	Riparian forest buffers are especially important for pollinators during hot summer months when upland plants may not produce nectar or pollen. Early-flowering willows, as well as fruit and nut-bearing shrubs, can provide additional farm income as cut flowers or produce, while also providing reliable food resources for pollinators. Honey bees may also visit muddy shorelines to gather water for cooling their hives. Riparian buffers are important corridors for landscape connectivity from rural to urban areas, facilitating pollinator dispersal
Silvopasture	Silvopastures provide an open understory where a variety of flowering forbs (forage legumes, such as alfalfa or clover, or native wildflowers) can grow. Rotational grazing practices can give these forbs an opportunity to recover from grazing or flower before being eaten. Harvestable flowering trees, such as basswood, black locust, maple, persimmon, or tulip tree, can enhance a silvopasture system. Using thinning and prescribed fire to daylight existing seedbanks can restore natural diversity and promote flowering plants that benefit pollinators
Forest farming (also called multistory cropping)	Many valuable overstory crop trees, like tulip tree, maple, basswood, and black cherry, provide excellent pollinator habitat. Cultivated understory plants, such as ginseng, goldenseal, and black cohosh, may benefit from pollinator visits. For example, diverse bees pollinate black cohosh. Black cohosh does not produce nectar to attract bees, but relies on nearby prolific nectar producers, such as pale touch-me-not or whiteflower leafcup. The pollination needs of many forest-farmed crops are not well understood, but providing diverse habitat niches is the best way to support diverse pollinators. Flies are likely important pollinators since some flies are active in cooler temperatures, when many of the forest crops flower

Source: Modified from Vaughan and Black 2006

Typically, agroforestry practices are planned for sites on individual farms and ranches. Pollinator-friendly agroforestry plantings on a single farm can have important benefits for pollinators. Even greater impact can be achieved through these plantings when planning and design are combined with other nearby farms and ranches which are using pollinator-friendly practices. While it may be uncommon for pollinators and other beneficial insects to be considered in landscape planning efforts (Steingröver et al. 2010), there are many potential benefits from broadening existing large-scale planning efforts to include pollinator issues. Working across site and landscape scales, agroforestry practices can support pollinator abundance and richness, protect biodiversity, enhance pollination, and increase food security.

Acknowledgements We would like to thank Justin Runyon, Judy Wu-Smart, Michele Schoeneberger, Aimee Code, and two anonymous reviewers whose comments and feedback helped to improve the chapter. This work was supported by funding provided by a contribution agreement with the United States Department of Agriculture (USDA)-Natural Resources Conservation Service (NRCS) to the Xerces Society.

References

- Adamson NL, Ward T, Vaughan M (2011) Designed with pollinators in mind. *Inside Agroforestry* 20(1):8–10
- Aizen MA, Feinsinger P (1994) Habitat fragmentation, native insect pollinators, and feral honey bees in Argentine ‘Chaco Serrano’. *Ecol Appl* 4(2):378–392
- Allen-Wardell G, Bernhardt P, Bitner R, Burquez A, Buchmann S, Cane J, Cox P, Dalton V, Feinsinger P, Ingram M, Inouye D, Jones CE, Kennedy K, Kevan P, Koopowitz H, Medellin R, Medellin-Morales S, Nabhan G, Pavlik B, Tepedino V, Torchio P, Walker S (1998) The potential consequences of pollinator declines on the conservation of biodiversity and stability of food crop yields. *Conserv Biol* 12(1):8–17
- Altizer SM, Oberhauser KS (1999) Effects of the protozoan parasite *Ophryocystis elektroscirrha* on the fitness of monarch butterflies (*Danaus plexippus*). *J Invertebr Pathol* 74:76–88
- Ascher JS, Pickering J (2020) Discover life bee species guide and world checklist (Hymenoptera: Apoidea: Anthophila). http://www.discoverlife.org/mp/20q?guide=Apoidea_species Accessed (27 Feb 2020)
- Bankova VB, De Castro SL, Marcucci MC (2000) Propolis: recent advances in chemistry and plant origin. *Apidologie* 31(1):3–15
- Bartomeus I, Ascher JS, Wagner DL, Danforth BN, Colla S, Kornbluth S, Winfree R (2011) Climate-associated phenological advances in bee pollinators and bee-pollinated plants. *Proc Natl Acad Sci U S A* 108(51):20645–20649
- Batra SWT (1985) Red maple (*Acer rubrum* L.), an important early spring food resource for honey bees and other insects. *J Kans Entomol Soc* 58(1):169–172
- Baude M, Kunin WE, Boatman ND, Conyers S, Davies N, Gillespie MA, Morton RD, Smart SM, Memmott J (2016) Historical nectar assessment reveals the fall and rise of floral resources in Britain. *Nature* 530(7588):85–88
- Bawa KS (1990) Plant-pollinator interactions in tropical rain forests. *Annu Rev Ecol Syst* 21:399–422
- Bee Informed Partnership (2019) Colony Loss 2018-2019: Preliminary Results. https://beeinformed.org/wp-content/uploads/2019/11/2018_2019-Abstract.pdf. Accessed 30 Jan 2020

- Benjamin FE, Reilly RJ, Winfree R (2014) Pollinator body size mediates the scale at which land use drives crop pollination services. *J Appl Ecol* 51(2):440–449
- Bentrop G, Hopwood J, Adamson NL, Vaughan M (2019) Temperate agroforestry systems and insect pollinators: a review. *Forests* 10(11):981. <https://doi.org/10.3390/f10110981>
- Biesmeijer JC, Roberts SPM, Reemer M, Ohlemüller R, Edwards M, Peeters T, Schaffers AP, Potts SG, Kleukers R, Thomas CD, Settele J, Kunin WE (2006) Parallel declines in pollinators and insect-pollinated plants in Britain and the Netherlands. *Science* 313(5785):351–354
- Blaauw BR, Isaacs R (2014) Flower plantings increase wild bee abundance and the pollination services provided to a pollination-dependent crop. *J Appl Ecol* 51:890–898
- Bosch J, Kemp WP (2001) How to manage the blue orchard bee as an orchard pollinator. <http://agris.fao.org/agris-search/search.do?recordID=US201300072439>. Accessed 30 Jan 2020
- Boscolo D, Tokumoto PM, Ferreria PA, Ribeiro JW, dos Santos JS (2017) Positive responses of flower visiting bees to landscape heterogeneity depend on functional connectivity levels. *Persp Ecol Conserv* 15(1):18–24
- Botías C, David A, Horwood J, Abdul-Sada A, Nicholls E, Hill E, Goulson D (2015) Neonicotinoid residues in wildflowers, a potential route of chronic exposure for bees. *Environ Sci Technol* 49(21):12731–12740
- Brittain C, Kremen C, Klein AM (2013) Biodiversity buffers pollination from changes in environmental conditions. *Glob Chang Biol* 19(2):540–547
- Brosi BJ, Briggs HM (2013) Single pollinator species losses reduce floral fidelity and plant reproductive function. *Proc Natl Acad Sci U S A* 110(32):13044–13048
- Brosi BJ, Daily GC, Shih TM, Oviedo F, Duran G (2008) The effects of forest fragmentation on bee communities in tropical countryside. *J Appl Ecol* 45(3):773–783
- Brown TK (2002) Creating and maintaining wildlife, insect, and fish habitat structures in dead wood. In: Proceedings of the symposium on the ecology and management of dead wood in western forests. PSW-GTR-181. USDA Forest Service, Pacific southwest Research Station, Albany, p 883–892
- Buchmann SL (1983) Buzz pollination in angiosperms. In: Jones CE, Little RJ (eds) *Handbook of experimental pollination biology*. Van Nostrand Reinhold, New York, pp 73–113
- Buehler DM, Norris DR, Stutchbury BJM, Kopysh NC (2002) Food supply and parental feeding rates of hooded warblers in forest fragments. *Wilson Bull* 114(1):122–127
- Calder WA (2004) Rufous and broad-tailed hummingbirds—pollination, migration, and population biology. In: Nabhan P (ed) *Conserving migratory pollinators and nectar corridors in Western North America*. University of Arizona Press, Tucson, AZ, pp 59–79
- Calderone NW (2012) Insect pollinated crops, insect pollinators and US agriculture: trend analysis of aggregate data for the period 1992–2009. *PLoS One* 7(5):e37235. <https://doi.org/10.1371/journal.pone.0037235>
- Cameron SA, Lozier JD, Strange JP, Koch JB, Cordes N, Solter LF, Griswold TL (2011) Patterns of widespread decline in North American bumble bees. *Proc Natl Acad Sci U S A* 108(2):662–667
- Campagne P, Affre L, Baumel A, Roche P, Tatoni T (2009) Fine-scale response to landscape structure in *Primula vulgaris* Huds.: does hedgerow network connectedness ensure connectivity through gene flow? *Popul Ecol* 51(1):209–219
- Cane JH, Griswold T, Parker FD (2007) Substrates and materials used for nesting by North American *Osmia* bees (Hymenoptera: Apiformes: Megachilidae). *Ann Entomol Soc Am* 100(3):350–358
- Cane JH, Minckley RL, Kervin LJ, Roulston TH, Williams NM (2006) Complex responses within a desert bee guild (Hymenoptera: Apiformes) to urban habitat fragmentation. *Ecol Appl* 16(2):632–644
- Carvell C, Bourke AF, Dreier S, Freeman SN, Hulmes S, Jordan WC, Redhead JW, Sumner S, Wang J, Heard MS (2017) Bumblebee family lineage survival is enhanced in high-quality landscapes. *Nature* 543(7646):547–549
- Carvell C, Osborne JL, Bourke AFG, Freeman SN, Pywell RF, Heard MS (2011) Bumble bee species' responses to a targeted conservation measure depend on landscape context and habitat quality. *Ecol Appl* 21(5):1760–1771

- Castle D, Grass I, Westphal C (2019) Fruit quantity and quality of strawberries benefit from enhanced pollinator abundance at hedgerows in agricultural landscapes. *Agric Ecosyst Environ* 275:14–22
- Chagnon M, Kreutzweiser D, Mitchell EA, Morrissey CA, Noome DA, Van der Sluijs JP (2015) Risks of large-scale use of systemic insecticides to ecosystem functioning and services. *Environ Sci Pollut R* 22(1):119–134
- Chaudhry Q, Blom-Zandstra M, Gupta SK, Joner E (2005) Utilising the synergy between plants and rhizosphere microorganisms to enhance breakdown of organic pollutants in the environment. *Environ Sci Pollut R* 12(1):34–48
- Chen I-C, Hill JK, Ohlemüller R, Roy DB, Thomas CD (2011) Rapid range shifts of species associated with high levels of climate warming. *Science* 333(6045):1024–1026
- Chen L, Liu C, Zhang L, Zou R, Zhang Z (2017) Variation in tree species ability to capture and retain airborne fine particulate matter (PM_{2.5}). *Sci Rep* 7:3206. <https://doi.org/10.1038/s41598-017-03360-1>
- Chen L, Liu C, Zou R, Yang M, Zhang Z (2016) Experimental examination of effectiveness of vegetation as bio-filter of particulate matters in the urban environment. *Environ Pollut* 208:198–208
- Colla SR, Otterstatter MC, Gegear RJ, Thomson JD (2006) Plight of the bumble bee: pathogen spillover from commercial to wild populations. *Biol Conserv* 129:461–467
- Corbet SA (1990) Pollination and the weather. *Isr J Bot* 39:13–30
- Corbet SA, Fussell M, Ake R, Fraser A, Gunson C, Savage A, Smith K (1993) Temperature and the pollinating activity of social bees. *Ecol Entomol* 18(1):17–30
- Couthard E, McCollin D, Littlemore (2016) The use of hedgerows as flight paths by moths in intensive farmland landscapes. *J Insect Conserv* 20:345–350
- Crane E, Walker P (1985) Some nectar characteristics of certain important honey sources. *Pszczel Zesz Naukowe* 29:29–45
- Cranmer L, McCollin D, Ollerton J (2012) Landscape structure influences pollinator movements and directly affects plant reproductive success. *Oikos* 121(4):562–568
- Czerwinski MA, Sadd BM (2017) Detrimental interactions of neonicotinoid pesticide exposure and bumblebee immunity. *J Exp Zool Part A* 327(5):273–283
- Dainese M, Montecchiari S, Sitzia T, Sigura M, Marini L (2017) High cover of hedgerows in the landscape supports multiple ecosystem services in Mediterranean cereal fields. *J Appl Ecol* 54:380–388
- Davis BNK, Williams CT (1990) Buffer zone widths for honeybees from ground and aerial spraying of insecticides. *Environ Pollut* 63(3):247–259
- Desneux N, Decourtye A, Delpuech JM (2007) The sublethal effects of pesticides on beneficial arthropods. *Annu Rev Entomol* 52:81–106
- Di Pasquale G, Salignon M, Le Conte Y, Belzunces LP, Decourtye A, Kretzschmar A, Suchail S, Brunet JL, Alaux C (2013) Influence of pollen nutrition on honey bee health: do pollen quality and diversity matter? *PLoS One* 8(8):e72016. <https://doi.org/10.1371/journal.pone.0072016>
- Dirr MA (1990) Manual of woody landscape plants: their identification, ornamental characteristics, culture, propagation and uses. Stipes Publishing Co., Champaign
- Donkersley P (2019) Trees for bees. *Agric Ecosyst Environ* 270–271:79–83
- Dötterl S, Vereecken NJ (2010) The chemical ecology and evolution of bee–flower interactions: a review and perspectives. *Can J Zool* 88:668–697
- Dover JW, Fry GLA (2001) Experimental simulation of some visual and physical components of a hedge and the effects on butterfly behaviour in an agricultural landscape. *Entomol Exp Appl* 100(2):221–233
- Dover J, Sparks T (2000) A review of the ecology of butterflies in British hedgerows. *J Environ Manag* 60(1):51–63
- Dover J, Sotherton N, Gobett K (1990) Reduced pesticide inputs on cereal field margins: the effects on butterfly abundance. *Ecol Entomol* 15(1):17–24

- Drescher N, Klein AM, Schmitt T, Leonhardt SD (2019) A clue on bee glue: new insight into the sources and factors driving resin intake in honeybees (*Apis mellifera*). PLoS One 14:e0210594. <https://doi.org/10.1371/journal.pone.0210594>
- Dumroese K, Luna T (2016) Growing and marketing woody species to support pollinators: an emerging opportunity for forest, conservation, and native plant nurseries in the Northeastern US Tree Planters' Notes 59(2):49–60 <https://www.fs.usda.gov/treesearch/pubs/52882>. Accessed 30 Jan 2020
- Eilers EJ, Kremen C, Greenleaf SS, Garber AK, Klein AM (2011) Contribution of pollinator-mediated crops to nutrients in the human food supply. PLoS One 6(6):e21363. <https://doi.org/10.1371/journal.pone.0021363>
- Evans AN, Llanos JE, Kunin WE, Evison SE (2018) Indirect effects of agricultural pesticide use on parasite prevalence in wild pollinators. Agric Ecosyst Environ 15(258):40–48
- Fallon C, Black SH, Shepherd M (2014) Butterflies and moths as pollinators. Wings 37(2). The xerces Society for Invertebrate Conservation
- Felsot AS, Unsworth JB, Linders JB, Roberts G, Rautman D, Harris C, Carazo E (2010) Agrochemical spray drift; assessment and mitigation—a review. J Environ Sci Heal B 46(1):1–23
- Fiedler AK, Landis DA, Arduser M (2012) Rapid shift in pollinator communities following invasive species removal. Restor Ecol 20(5):593–602
- Filipiak M (2019) Key pollen host plants provide balanced diets for wild bee larvae: a lesson for planting flower strips and hedgerows. J Appl Ecol 56:1410–1418
- Fontaine C, Dajoz I, Meriguet J, Loreau M (2005) Functional diversity of plant–pollinator interaction webs enhances the persistence of plant communities. PLoS Biol 4(1):e1. <https://doi.org/10.1371/journal.pbio.0040001>
- Forister ML, Jahner JP, Casner KL, Wilson JS, Shapiro AM (2011) The race is not to the swift: Long-term data reveal pervasive declines in California's low-elevation butterfly fauna. Ecology 92(12):2222–2235
- Forister ML, McCall AC, Sanders NJ, Fordyce JA, Thorne JH, O'Brien J, Waetjen DP, Shapiro AM (2010) Compounded effects of climate change and habitat alteration shift patterns of butterfly diversity. PNAS 107(5):2088–2092
- Fowler J (2016) Specialist bees of the northeast: host plants and habitat conservation. Northeast Nat 23:305–320
- Frankie GW, Vinson SB, Newstrom LE, Barthell JF, Haber WA, Frankie JK (1990) Plant phenology, pollination ecology, pollinator behaviour and conservation of pollinators in Neotropical dry forest. In: Bawa KS, Hadley M (eds) Reproductive ecology of tropical forest plants. Parthenon Publishing Group, Paris, pp 37–47
- Fried JH, Levey DJ, Hogsette JA (2005) Habitat corridors function as both drift fences and movement conduits for dispersing flies. Oecologia 143(4):645–651
- Garibaldi LA, Steffan-Dewenter I, Kremen C, Morales JM, Bommarco R, Cunningham SA, Carvalheiro LG, Chacoff NP, Dudenhöffer JH, Greenleaf SS, Holzschuh A (2011) Stability of pollination services decreases with isolation from natural areas despite honey bee visits. Ecol Lett 14(10):1062–1072
- Garibaldi LA, Steffan-Dewenter I, Winfree R, Aizen MA, Bommarco R, Cunningham SA, Kremen C, Carvalheiro LG, Harder LD, Afik O, Bartomeus I (2013) Wild pollinators enhance fruit set of crops regardless of honey bee abundance. Science 339(6127):1608–1611
- Gathmann A, Tschamtk T (2002) Foraging ranges of solitary bees. J Anim Ecol 71(5):757–764
- Ghisalberti EL (1979) Propolis: a review. Bee World 60:59–84
- Gilchrist A, Barker A, Handley JF (2016) Pathways through the landscape in a changing climate: the role of landscape structure in facilitating species range expansion through an urbanised region. Landsc Res 41(1):26–44
- Graham JB, Nassauer JI (2019) Wild bee abundance in temperate agroforestry landscapes: assessing effects of alley crop composition, landscape configuration, and agroforestry area. Agrofor Syst 93:837–850

- Grant V (1994) Historical development of ornithophily in the western North American flora. *Proc Natl Acad Sci U S A* 91:10407–10411
- Greenaway W, Scaysbrook T, Whatley FR (1990) The composition and plant origins of propolis: a report of work at Oxford. *Bee World* 71(3):107–118
- Greenleaf SS, Williams NM, Winfree R, Kremen C (2007) Bee foraging ranges and their relationship to body size. *Oecologia* 153(3):589–596
- Haddad NM (1999) Corridor and distance effects on interpatch movements: a landscape experiment with butterflies. *Ecol Appl* 9:612–622
- Hannon LE, Sisk TD (2009) Hedgerows in an agri-natural landscape: potential habitat value for native bees. *Biol Conserv* 142(10):2140–2154
- Hatfield RG, Colla SR, Jepsen S, Richardson LL, Thorp RW (2014) International Union for the Conservation of nature (IUCN) assessments for North American *Bombus* spp. for the North American IUCN bumble bee specialist group. The Xerces Society for Invertebrate Conservation, Portland. <https://xerces.org/sites/default/files/publications/14-065.pdf>. Accessed 6 Feb 2020
- Haydak MH (1958) Wintering of bees in Minnesota. *J Econ Entomol* 51(3):332–334
- Hill DB, Webster TC (1995) Apiculture and forestry (bees and trees). *Agrofor Syst* 29(3):313–320
- Hladik ML, Vandever M, Smalling KL (2016) Exposure of native bees foraging in an agricultural landscape to current-use pesticides. *Sci Total Environ* 542:469–477
- Hopwood J, Code A, Vaughan M, Biddinger D, Shepherd M, Black SH, Lee-Mäder E, Mazzacano, C (2016) How neonicotinoids can kill bees. Xerces Society for Invertebrate Conservation, Portland. <http://www.xerces.org/neonicotinoids-and-bees>. Accessed 30 Jan 2020
- IPBES (2016) Assessment report on pollinators, pollination and food production. Intergovernmental science-policy platform on biodiversity and ecosystem services, Bonn, Germany. <https://ipbes.net/assessment-reports/pollinators>. Accessed 30 Jan 2020
- Inouye DW, Larson BM, Szymank A, Kevan PG (2015) Flies and flowers III: ecology of foraging and pollination. *J Pollinat Ecol* 16(16):115–133
- Javorek SK, Mackenzie KE, Vander Kloet SP (2002) Comparative pollination effectiveness among bees (Hymenoptera: Apoidea) on lowbush blueberry (Ericaceae: *Vaccinium angustifolium*). *Ann Entomol Soc Am* 95:345–351
- Johnson RM (2015) Honey bee toxicology. *Annu Rev Entomol* 60:415–434
- Jose S (2009) Agroforestry for ecosystem services and environmental benefits: an overview. *Agrofor Syst* 76(1):1–10
- Kay S, Kühn E, Albrecht M, Sutter L, Szerencsits E, Herzog F (2019) Agroforestry can enhance foraging and nesting resources for pollinators with focus on solitary bees at the landscape scale. *Agrofor Syst* 94(2):379–387. <https://doi.org/10.1007/s10457-019-00400-9>
- Kearns CA (2001) North American dipteran pollinators: assessing their value and conservation status. *Conserv Ecol* 5(1):5. <http://www.consecol.org/vol5/iss1/art5/>. Accessed 30 Jan 2020
- Kearns CA, Inouye DW (1997) Pollinators, flowering plants, and conservation biology. *Bioscience* 47(5):297–307
- Kearns CA, Inouye DW, Waser NM (1998) Endangered mutualisms: the conservation of plant–pollinator interactions. *Annu Rev Ecol Syst* 29:83–113
- Kells AR, Goulson D (2003) Preferred nesting sites of bumblebee queens (Hymenoptera: Apidae) in agroecosystems in the UK. *Biol Conserv* 109(2):165–174
- Kerr JT, Pindar A, Galpern P et al (2015) Climate change impacts on bumblebees converge across continents. *Science* 349(6244):177–180
- Kevan PG (1999) Pollinators as bioindicators of the state of the environment: species, activity and diversity. *Agric Ecosyst Environ* 74(1–3):373–393
- Kim J, Williams N, Kremen C (2006) Effects of cultivation and proximity to natural habitat on ground-nesting native bees in California sunflower fields. *J Kansas Entomol Soc* 79(4):309–320
- Kjær C, Bruus M, Bossi R, Løfstrøm P, Andersen HV, Nuytens D, Larsen SE (2014) Pesticide drift deposition in hedgerows from multiple spray swaths. *J Pestic Sci* 39(1):14–21
- Kjøhl M, Nielsen A, Stenseth NC (2011) Potential effects of climate change on crop pollination. Food and Agriculture Organization of the United Nations, Rome

- Klatt BKA, Holzschu A, Westphal C, Clough Y, Smit I, Pawelzik E, Tschardt T (2014) Bee pollination improves crop quality, shelf life and commercial value. *P Roy Soc B-Biol Sci* 281:20132440. <https://doi.org/10.1098/rspb.2013.2440>
- Klaus F, Bass J, Marholt L, Mulle B, Klatt B, Kormann U (2015) Hedgerows have a barrier effect and channel pollinator movement in the agricultural landscape. *J Landsc Ecol* 8(1):22–31
- Klein AM, Brittain C, Hendrix SD, Thorp R, Williams N, Kremen C (2012) Wild pollination services to California almond rely on semi-natural habitat. *J Appl Ecol* 49(3):723–732
- Klein AM, Vaissière BE, Cane JH, Steffan-Dewenter I, Cunningham SA, Kremen C, Tschardt T (2007) Importance of pollinators in changing landscapes for world crops. *P Roy Soc B-Biol Sci* 274:303–313
- König B (1985) Plant sources of propolis. *Bee World* 66(4):136–139
- Kremen C, M'Gonigle LK (2015) Small-scale restoration in intensive agricultural landscapes supports more specialized and less mobile pollinator species. *J Appl Ecol* 52(3):602–610
- Kremen C, Williams NM, Bugg RL, Fay JP, Thorp RW (2004) The area requirements of an ecosystem service: crop pollination by native bee communities in California. *Ecol Lett* 7(11):1109–1119
- Kremen C, Williams NM, Thorp RW (2002) Crop pollination from native bees at risk from agricultural intensification. *Proc Natl Acad Sci U S A* 99(26):16812–16816
- Krewenka KM, Holzschuh A, Tschardt T, Dormann CF (2011) Landscape elements as potential barriers and corridors for bees, wasps and parasitoids. *Biol Conserv* 144(6):1816–1825
- Krosby M, Tewksbury J, Haddad NM, Hoekstra J (2010) Ecological connectivity for a changing climate. *Conserv Biol* 24(6):1686–1689
- Krupke CH, Hunt GJ, Eitzer BD, Andino G, Given K (2012) Multiple routes of pesticide exposure for honey bees living near agricultural fields. *PLoS One* 7(1):e29268. <https://doi.org/10.1371/journal.pone.0029268>
- Larson BMH, Kevan PG, Inouye DW (2001) Flies and flowers: taxonomic diversity of anthophiles and pollinators. *Can Entomol* 133(4):439–465
- Lazzaro L, Otto S, Zanin G (2008) Role of hedgerows in intercepting spray drift: evaluation and modelling of the effects. *Agric Ecosyst Environ* 123(4):317–327
- Long EY, Krupke CH (2016) Non-cultivated plants present a season-long route of pesticide exposure for honey bees. *Nat Commun* 7:11629. <https://doi.org/10.1038/ncomms11629>
- Loose J, Drummond F, Stubbs C, Woods S, Hoffman S (2005) Conservation and management of native bees in cranberry. Tech bull 191. Maine agricultural and Forest Experiment Station, Orono ME
- Losey JE, Vaughan M (2006) The economic value of ecological services provided by insects. *Bioscience* 56:311–323
- Lye G, Park K, Osborne J, Holland J, Goulson D (2009) Assessing the value of rural stewardship schemes for providing foraging resources and nesting habitat for bumblebee queens (Hymenoptera: Apidae). *Biol Conserv* 142(10):2023–2032
- Macdonald KJ, Kelly D, Tylanakis JM (2018) Do local landscape features affect wild pollinator abundance, diversity and community composition on Canterbury farms? *N Z J Ecol* 42:262–268
- Macgregor CJ, Pocock MJ, Fox R, Evans DM (2015) Pollination by nocturnal Lepidoptera, and the effects of light pollution: a review. *Ecol Entomol* 40(3):187–198
- Maudsley MJ (2000) A review of the ecology and conservation of hedgerow invertebrates in Britain. *J Environ Manag* 60(1):65–76
- McGregor SE (1976) Insect pollination of cultivated crop plants. Agricultural Research Service, Washington, DC. <https://naldc.nal.usda.gov/download/CAT76674944/PDF#page=11>. Accessed 30 Jan 2020
- McKechnie IM, Thomsen CJM, Sargent RD (2017) Forested field edges support a greater diversity of wild pollinators in lowbush blueberry (*Vaccinium angustifolium*). *Agric Ecosyst Environ* 237:154–161
- McNaughton KG (1988) Effects of windbreaks on turbulent transport and microclimate. *Agric Ecosyst Environ* 22(23):17–40

- Meier K, Kuusemets V, Luig J, Mander U (2005) Riparian buffer zones as elements of ecological networks: case study on *Parnassius mnemosyne* distribution in Estonia. *Ecol Eng* 24:531–537
- Memmott J, Waser NM, Price MV (2004) Tolerance of pollination networks to species extinctions. *Proc Roy Soc Lond B Bio* 271:2605–2611
- Mercer GN (2009) Modelling to determine the optimal porosity of shelterbelts for the capture of agricultural spray drift. *Environ Model Softw* 24:1349–1352
- Merckx T, Marini L, Feber RE, Macdonald DW (2012) Hedgerow trees and extended-width field margins enhance macro-moth diversity: implications for management. *J Appl Ecol* 49(6):1396–1404
- Merrill JH (1923) Value of winter protection for bees. *J Econ Entomol* 16(2):125–130
- Michener CD (2007) The bees of the world. John Hopkins University Press, Baltimore, MD
- Miñarro M, Prida E (2013) Hedgerows surrounding organic apple orchards in north-west Spain: potential to conserve beneficial insects. *Agric For Entomol* 15(4):382–390
- Moisan-DeSerres J, Chagnon M, Fournier V (2015) Influence of windbreaks and forest borders on abundance and species richness of native pollinators in lowbush blueberry fields in Québec, Canada. *Can Entomol* 147(4):432–442
- Morandin LA, Kremen C (2013) Hedgerow restoration promotes pollinator populations and exports native bees to adjacent fields. *Ecol Appl* 23(4):829–839
- Morandin LA, Winston ML (2006) Pollinators provide economic incentive to preserve natural land in agroecosystems. *Agric Ecosyst Environ* 116(3):289–292
- Morandin LA, Long RF, Kremen C (2014) Hedgerows enhance beneficial insects on adjacent tomato fields in an intensive agricultural landscape. *Agric Ecosyst Environ* 189:164–170
- Morandin LA, Long RF, Kremen C (2016) Pest control and pollination cost–benefit analysis of hedgerow restoration in a simplified agricultural landscape. *J Econ Entomol* 109(3):1020–1027
- Morse RA, Calderone NW (2000) The value of honey bees as pollinators of US crops in 2000. *Bee Cult* 128:1–15
- Nabhan GP, Brusca RC, Holter L (eds) (2004) Conserving migratory pollinators and nectar corridors in western North America. University of Arizona Press, Tucson
- Nair PR (2007) The coming of age of agroforestry. *J Sci Food Agric* 87:1613–1619
- National Research Council (2007) Status of pollinators in North America. National Academies Press, Washington, DC
- NatureServe (2018) Conservation status. <http://explorer.natureserve.org/ranking.htm>. Accessed 30 Jan 2020
- Nicholls CI, Altieri MA (2013) Plant biodiversity enhances bees and other insect pollinators in agroecosystems: a review. *Agron Sustain Dev* 33(2):257–274
- Norton RL (1988) Windbreaks: benefits to orchard and vineyard crops. *Agric Ecosyst Environ* 22(23):205–213
- Nye WP (1962) Extra supering and shading as factors in honey production in northern Utah. *Glean Bee Cult* 90(5):396–399
- Ollerton J, Winfree R, Tarrant S (2011) How many flowering plants are pollinated by animals? *Oikos* 120:321–326
- Ollerton J (2017) Pollinator diversity: distribution, ecological function, and conservation. *Annu Rev Ecol Evol Syst* 48:353–376
- Osborne JL, Martin AP, Carreck NL, Swain JL, Knight ME, Goulson D, Hale RJ, Sanderson RA (2008a) Bumble bee flight distances in relation to the forage landscape. *J Anim Ecol* 77(2):406–415
- Osborne JL, Martin AP, Shortall CR, Todd AD, Goulson D, Knight ME, Hale RJ, Sanderson RA (2008b) Quantifying and comparing bumblebee nest densities in gardens and countryside habitats. *J Appl Ecol* 45(3):784–792
- Ostaf DP, Mosseler A, Johns RC, Javorek S, Klymko J, Ascher JS (2015) Willows (*Salix* spp.) as pollen and nectar sources for sustaining fruit and berry pollinating insects. *Can J Plant Sci* 95(3):505–515
- Ottewell KM, Donnellan SC, Lowe AJ, Paton DC (2009) Predicting reproductive success of insect-versus bird-pollinated scattered trees in agricultural landscapes. *Biol Conserv* 142(4):888–898

- Otto S, Loddo D, Baldoin C, Zanin G (2015) Spray drift reduction techniques for vineyards in fragmented landscapes. *J Environ Manag* 162:290–298
- Ouin A, Burel F (2002) Influence of herbaceous elements on butterfly diversity in hedgerow agricultural landscapes. *Agric Ecosyst Environ* 93(1-3):45–53
- Papanikolaou AD, Kühn I, Frenzel M, Schweiger O (2017) Semi-natural habitats mitigate the effects of temperature rise on wild bees. *J Appl Ecol* 54(2):527–536
- Park MG, Blitzer EJ, Gibbs J, Losey JE, Danforth BN (2015) Negative effects of pesticides on wild bee communities can be buffered by landscape context. *Proc R Soc B* 282(1809):20150299. <https://doi.org/10.1098/rspb.2015.0299>
- Parmesan C (2007) Influences of species, latitudes and methodologies on estimates of phenological response to global warming. *Glob Change Biol* 13(9):1860–1872
- Pasek JE (1988) Influence of wind and windbreaks on local dispersal of insects. *Agric Ecosyst Environ* 22:539–554
- Pavlidis G, Tsihrintzis VA (2017) Pollution control by agroforestry systems: a short review. *Eur Water* 59:297–301
- Pavlidis G, Tsihrintzis VA (2018) Environmental benefits and control of pollution to surface water and groundwater by agroforestry systems: a review. *Water Res Manage* 32(1):1–29
- Peri PL, Bloomberg M (2002) Windbreaks in southern Patagonia, Argentina: a review of research on growth models, windspeed reduction, and effects on crops. *Agrofor Syst* 56(2):129–144
- Pinzauti M (1986) The influence of the wind on nectar secretion from the melon and on the flight of bees: the use of an artificial wind-break. *Apidologie* 17(1):63–72
- Pleasant JM, Oberhauser KS (2012) Milkweed loss in agricultural fields because of herbicide use: effect on the monarch butterfly population. *Insect Conserv Divers* 6(2):135–144
- Polcarová J, Cardinal S, Martins AC, Straka J (2019) The role of floral oils in the evolution of apid bees (Hymenoptera: Apidae). *Biol J Linn Soc* 128:486–497
- Ponisio LC, M'gonigle LK, Kremen C (2016) On-farm habitat restoration counters biotic homogenization in intensively managed agriculture. *Glob Chang Biol* 22(2):704–715
- Ponisio LC, de Valpine P, M'Gonigle LK, Kremen C (2019) Proximity of restored hedgerows interacts with local floral diversity and species' traits to shape long-term pollinator metacommunity dynamics. *Ecol Lett* 22:1048–1060
- Potts SG, Biesmeijer JC, Kremen C, Neumann P, Schweiger O, Kunin WE (2010) Global pollinator declines: trends, impacts and drivers. *Trends Ecol Evol* 25(6):345–353
- Potts SG, Vulliamy B, Dafni A, Ne'eman G, Willmer P (2003) Linking bees and flowers: how do floral communities structure pollinator communities? *Ecology* 84(10):2628–2642
- Potts SG, Vulliamy B, Roberts S, O'Toole C, Dafni A, Ne'eman G, Willmer P (2005) Role of nesting resources in organizing diverse bee communities in a Mediterranean landscape. *Ecol Entomol* 30(1):78–85
- Pywell RF, James KL, Herbert I, Meek WR, Carvell C, Bell D, Sparks TH (2005) Determinants of overwintering habitat quality for beetles and spiders on arable farmland. *Biol Conserv* 123(1):79–90
- Rendón-Salinas E, Tavera-Alonso G (2014) Monitoreo de la superficie forestal ocupada por las colonias de hibernación de la mariposa Monarca en diciembre de 2013. Alianza WWF-Telcel/CONANP
- Roulston TAH, Goodell K (2011) The role of resources and risks in regulating wild bee populations. *Annu Rev Entomol* 56:293–312
- Russo L, Danforth B (2017) Pollen preferences among the bee species visiting apple (*Malus pumila*) in New York. *Apidologie* 48:806–820
- Sánchez-Bayo F, Goka K (2014) Pesticide residues and bees—a risk assessment. *PLoS One* 9(4):e94482. <https://doi.org/10.1371/journal.pone.0094482>
- Sánchez-Bayo F, Goulson D, Pennacchio F, Nazzi F, Goka K, Desneux N (2016) Are bee diseases linked to pesticides?—a brief review. *Environ Int* 89:7–11
- Sánchez-Bayo F, Wyckhuys KA (2019) Worldwide decline of the entomofauna: a review of its drivers. *Biol Conserv* 232:8–27

- Sardiñas HS, Kremen C (2015) Pollination services from field-scale agricultural diversification may be context-dependent. *Agric Ecosyst Environ* 207:17–25
- Sardiñas HS, Ponisio LC, Kremen C (2016a) Hedgerow presence does not enhance indicators of nest-site habitat quality or nesting rates of ground-nesting bees. *Restor Ecol* 24(4):499–505
- Sardiñas HS, Tom K, Ponisio LC, Rominger A, Kremen C (2016b) Sunflower (*Helianthus annuus*) pollination in California's Central Valley is limited by native bee nest site location. *Ecol Appl* 26(2):438–447
- Saunders DA, Hobbs RJ, Margules CR (1991) Biological consequences of ecosystem fragmentation – a review. *Conserv Biol* 5:18–32
- Schultz CB, Brown LM, Pelton E, Crone EE (2017) Citizen science monitoring demonstrates dramatic declines of monarch butterflies in western North America. *Biol Conserv* 214:343–346
- Semmens BX, Semmens DJ, Thogmartin WE, Wiederholt R, López-Hoffman L, Diffendorfer JE, Pleasants JM, Oberhauser KS, Taylor OR (2016) Quasi-extinction risk and population targets for the eastern, migratory population of monarch butterflies (*Danaus plexippus*). *Sci Rep* 6:23265
- Senapathi D, Goddard MA, Kunin WE, Baldock KC (2017) Landscape impacts on pollinator communities in temperate systems: evidence and knowledge gaps. *Funct Ecol* 31(1):26–37
- Settele J, Bishop J, Potts SG (2016) Climate change impacts on pollination. *Nat Plants* 2(7). <https://doi.org/10.1038/nplants.2016.92>
- Shuler RE, Roulston TH, Farris GE (2005) Farming practices influence wild pollinator populations on squash and pumpkin. *J Econ Entomol* 98:790–795
- Simone-Finstrom M, Borba RS, Wilson M, Spivak M (2017) Propolis counteracts some threats to honey bee health. *Insects* 8(2):46. <https://doi.org/10.3390/insects8020046>
- Sipes SD, Tepedino VJ (1995) Reproductive biology of the rare orchid, *Spiranthes diluvialis*: breeding system, pollination, and implications for conservation. *Conserv Biol* 9(4):929–938
- Smith BD, Lewis T (1972) The effects of windbreaks on the blossom-visiting fauna of apple orchards and on yield. *Ann Appl Biol* 72(3):229–238
- Smith J, Pearce BD, Wolfe MS (2013) Reconciling productivity with protection of the environment: is temperate agroforestry the answer? *Renew Agr Food Syst* 28(1):80–92
- Somme L, Moquet L, Quinet M, Vanderplanck M, Michez D, Lognay G, Jacquemart AL (2016) Food in a row: urban trees offer valuable floral resources to pollinating insects. *Urban Ecosyst* 19(3):1149–1161
- Spira TP (2001) Plant-pollinator interactions: a threatened mutualism with implications for the ecology and management of rare plants. *Nat Area J* 21(1):78–88
- Stanley J, Preetha G (2016) Pesticide toxicity to non-target organisms. Springer, Dordrecht
- Staton T, Walters RJ, Smith J, Girling RD (2019) Evaluating the effects of integrating trees into temperate arable systems on pest control and pollination. *Agric Syst* 176:102676
- Steffan-Dewenter I, Schiele S (2008) Do resources or natural enemies drive bee population dynamics in fragmented habitats. *Ecology* 89(5):1375–1387
- Steffan-Dewenter I, Westphal C (2008) The interplay of pollinator diversity, pollination services and landscape change. *J Appl Ecol* 45(3):737–741
- Steingröver EG, Geertsema W, van Wingerden WK (2010) Designing agricultural landscapes for natural pest control: a transdisciplinary approach in the Hoeksche Waard (The Netherlands). *Landsc Ecol* 25(6):825–838
- Stubbs CS, Jacobson HA, Osgood EA, Drummond FA (1992) Alternative forage plants for native (wild) bees associated with lowbush blueberry, *Vaccinium* spp., in Maine. *Tech Bull* 148. Maine Agricultural Experiment Station, Orono
- Sutter L, Albrecht M, Jeanneret P (2018) Landscape greening and local creation of wildflower strips and hedgerows promote multiple ecosystem services. *J Appl Ecol* 55:612–620
- Svensson B, Lagerlöf J, Svensson BG (2000) Habitat preferences of nest-seeking bumble bees (Hymenoptera: Apidae) in an agricultural landscape. *Agric Ecosyst Environ* 77(3):247–255
- Tallamy DW, Shropshire KJ (2009) Ranking lepidopteran use of native versus introduced plants. *Conserv Biol* 23(4):941–947

- Tasei JN, Aupinel P (2008) Nutritive value of 15 single pollens and pollen mixes tested on larvae produced by bumblebee workers (*Bombus terrestris*, Hymenoptera: Apidae). *Apidologie* 39(4):397–409
- Tepedino VJ (1981) The pollination efficiency of the squash bee (*Peponapis pruinosa*) and the honey bee (*Apis mellifera*) on summer squash (*Cucurbita pepo*). *J Kansas Entomol Soc* 54(2):359–377
- Terzaghi E, Wild E, Zacchello G, Cerabolini BE, Jones KC, Di Guardo A (2013) Forest filter effect: role of leaves in capturing/releasing air particulate matter and its associated PAHs. *Atmos Environ* 74:378–384
- Tewksbury JJ, Levey DJ, Haddad NM, Sargent S, Orrock JL, Weldon A, Danielson BJ, Brinkerhoff J, Damschen EI, Townsend P (2002) Corridors affect plants, animals, and their interactions in fragmented landscapes. *Proc Natl Acad Sci U S A* 99(20):12923–12926
- Timberlake TP, Vaughan IP, Memmott J (2019) Phenology of farmland floral resources reveals seasonal gaps in nectar availability for bumblebees. *J Appl Ecol* 56:1585–1596
- Townsend PA, Levey DJ (2005) An experimental test of whether habitat corridors affect pollen transfer. *Ecology* 86(2):466–475
- Tscharntke T, Steffan-Dewenter I, Kruess A, Thies C (2002) Contribution of small habitat fragments to conservation of insect communities of grassland–cropland landscapes. *Ecol Appl* 12(2):354–363
- Ucar T, Hall FR (2001) Windbreaks as a pesticide drift mitigation strategy: a review. *Pest Manag Sci* 57(8):663–675
- Udawatta RP, Rankoth LM, Jose S (2019) Agroforestry and biodiversity. *Sustainability* 11:2879
- USDA (2014) Preventing or mitigating potential negative impacts of pesticides on pollinators using IPM and other conservation practices. US Department of Agriculture, Washington, DC. https://www.nrcs.usda.gov/Internet/FSE_DOCUMENTS/stelprdb1261468.pdf. Accessed 30 Jan 2020
- US Fish and Wildlife Service (2006) Lesser long-nosed bat (*Leptonycteris curasoae yerbabuenae*) 5-year review: summary and evaluation. US fish and wildlife service. Phoenix, Arizona
- US Fish and Wildlife Service (2019) Rusty patched bumble bee listed as endangered. <https://www.fws.gov/midwest/endangered/insects/rpbb/FAQsFinalListing.html>. Accessed 30 Jan 2020
- Valiente-Banuet A, Molina-Freaner F, Torres A, Arizmendi MC, Casas A (2004) Geographic differentiation in the pollination system of the columnar cactus *Pachycereus pecten-aboriginum*. *Am J Bot* 91:850–855
- Vaughan M, Black SH (2006) Improving forage for native bee crop pollinators. *Agroforestry Notes* #33. USDA National Agroforestry Center, Lincoln
- Vaughan M, Adamson N, MacFarland K (2017) Using agroforestry practices to reduce pesticide risks to pollinators & other agriculturally beneficial insects. *Agroforestry Notes* #35. USDA National Agroforestry Center, Lincoln
- Venturini EM, Drummond FA, Hoshida AK, Dibble AC, Stack LB (2017) Pollination reservoirs for wild bee habitat enhancement in cropping systems: a review. *Agroecol Sustain Food Syst* 41:101–142
- Vicens N, Bosch J (2000) Weather-dependent pollinator activity in an apple orchard, with special reference to *Osmia cornuta* and *Apis mellifera* (Hymenoptera: Megachilidae and Apidae). *Environ Entomol* 29(3):413–420
- Wcislo WT, Cane JH (1996) Floral resource utilization by solitary bees (Hymenoptera: Apoidea) and exploitation of their stored foods by natural enemies. *Annu Rev Entomol* 41:257–286
- Wenneker M, Van de Zande JC (2008) Spray drift reducing effects of natural windbreaks in orchard spraying. *Asp Appl Biol* 84:25–32
- Westerkamp C, Gottsberger G (2000) Diversity pays in crop pollination. *Crop Sci* 40:1209–1222
- Whitehorn PR, O'Connor S, Wackers FL, Goulson D (2012) Neonicotinoid pesticide reduces bumble bee colony growth and queen production. *Science* 336(6079):351–352
- Williams NM, Kremen C (2007) Resource distribution among habitats determine solitary bee off-spring production in a mosaic landscape. *Ecol Appl* 17:910–921

- Wood TJ, Kaplan I, Szendrei Z (2018) Wild bee pollen diets reveal patterns of seasonal foraging resources for honey bees. *Front Ecol Evol* 6:210. <https://doi.org/10.3389/fevo.2018.00210>
- Wu JY, Anelli CM, Sheppard WS (2011) Sub-lethal effects of pesticide residues in brood comb on worker honey bee (*Apis mellifera*) development and longevity. *PLoS One* 6:e14720. <https://doi.org/10.1371/journal.pone.0014720>
- Zaady E, Katra I, Shuker S, Knoll Y, Shlomo S (2018) Tree belts for decreasing aeolian dust-carried pesticides from cultivated areas. *Geosciences* 8:286
- Zhang X, Liu X, Zhang M, Dahlgren RA, Eitzel M (2010) A review of vegetated buffers and a meta-analysis of their mitigation efficacy in reducing nonpoint source pollution. *J Environ Qual* 39(1):76–84
- Ziska LH, Pettis JS, Edwards J, Hancock JE, Tomecek MB, Clark A, Dukes JS, Loladze I, Polley HW (2016) Rising atmospheric CO₂ is reducing the protein concentration of a floral pollen source essential for North American bees. *Proc Roy Soc B-Biol Sci* 283(1828):20160414