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Abstract: In this chapter, we argue that while pesticides can be harmful to pollinators, when they are used in an integrated pest and pollinator management (IPPM) context both pest management and pollinator protection can be achieved. This can be done by implementing non-pesticidal pest management practices, changing pesticide types and timing as well as incorporating other pollinator species into commercial practice.

Highlights

- Pesticide use in crops can be harmful to pollinators, but each pesticide type differentially affects various pollinator species including honey bees, bumble bees and solitary bees.
- Expanding integrated pest management (IPM) to integrated pest and pollinator management (IPPM) will incorporate pollinator protection into the pest management and pesticide use decision framework.
- Changes in research and education policy, regulatory actions, corporate practices and consumer education are necessary to support IPPM adoption.

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In this chapter we argue that while pesticides can be harmful to pollinators, when they are used in an integrated pest and pollinator management (IPPM) context, both pest management and pollinator protection may be achieved. Our growing knowledge of the impacts of pesticides on honey bees as well as bumble bees and solitary bees allows us to use the latitude we have in pest management including non-pesticidal pest management practices, changing pesticide types and incorporating other, less susceptible pollinator species into commercial practice. Pollinator health should be a central component of integrated pest management research, education and extension to produce viable IPPM approaches.

Pesticides and the Current Pollinator Crisis

Insecticides, by definition and design, kill insects including pollinators if sufficient dosage and exposure levels are met. Plant systemic neonicotinoid insecticides in particular may affect bee health and may contribute to the decline of some species [1]. In 2013, the European Commission imposed a two year moratorium on the use of some of these compounds [2] based on laboratory studies that demonstrated sublethal effects on honey bees or bumble bees [3]. Polemics for and against neonicotinoid bans concentrate on extremes, but the solution lies somewhere in between. Neonicotinoid types are not equally toxic [1, 11], and not all bee species are equally susceptible [5]. Rather than banning neonicotinoids (or other pesticide types) as a class, we argue that we should modify pest management practices to include considerations for pollinator health.

While laboratory-based studies can provide some information [4], appropriate field–realistic concentrations and formulations, as well as evaluating relevant short- and long-term exposures and impacts are the best indicators of pollinator impacts [1, 3, 5]. Acute exposures of only a few days also conflict with growing evidence for more subtle, sublethal effects on growth, reproduction and behavior from long-term chronic exposure at low doses [6]. For example, the chitin inhibitor, novaluron, applied during bloom in almonds is not toxic to adult bees, but has sublethal effects on *Osmia* and honey bee reproduction [57]. The “field relevancy” of some of the laboratory studies that led to the European Union ban of some neonicotinoids is hotly debated [3, 7] and is difficult to gauge because most studies use a single dose rather than a range of doses to generate a response curve [7]. Other considerations should include synergy of insecticides with fungicides and other mixtures [5, 9] and the impact of acaricides and antimicrobial drugs used against hive pests. It is these products which are the most frequently found contaminants in honey bee hives and have also been shown to also affect bee reproduction and health [10]. .

Importance of Neonicotinoids

Any pesticide has benefits and costs associated with it. Neonicotinoids were developed partly because of the Food Quality Protection Act (FQPA), which restricted organophosphate, organochlorine, and carbamate pesticides on public health grounds [12]. The generally vertebrate-safe neonicotinoids also contributed to pesticide resistance management by offering a different mode of action. But actions to ameliorate the perceived costs, such as the well-intentioned EU neonicotinoid ban, were based on the Substitution Principle (one set of compounds is replaced by newer, safer alternatives [13]), furthers the ‘pesticide treadmill’ [14], and could force growers to revert to the remaining older compounds, which have largely unknown pollinator impacts. Used judiciously, targeting pests at critical timings as in the following example in apple production, neonicotinoids can be effective while sparing pollinators as well as other beneficial organisms in conservation biological control programs [15].

Integrated Pest Management and Pollinators

Integrated Pest Management (IPM) is a long standing, science based, decision making process whose ecological roots lie in the use of multiple biological, cultural, physical, and chemical tactics to protect crops in a way that minimizes economic, health, and environmental risks. IPM can address any pest complex (insect, disease, weed, vertebrate, etc.) and can be adapted to any agricultural production goals including conventional, sustainable and organic. In addition, IPM can evolve to meet new production demands such as pesticide use reduction, incorporation of ecosystem services and food safety [16]. Likewise, IPM can be adjusted to protect pollinator health just as it is adjusted to protect other beneficial organisms such as predators and parasitoids. Indeed, the IPM paradigm, already understood by growers, will facilitate adoption of pollinator protection practices.

While well understood, relatively easy to maintain, mobile in large numbers, and can rapidly communicate food source locations [17], honey bees are not the best pollinators for all crops [18, 19]. Sole reliance on honey bees can be risky. North American beekeepers lost 1/3 of their colonies due to Colony Collapse Disorder (CCD) [20] and other factors [21] including a general 40% decline since 1947 [22]. Recent colony scarcity increased rental costs three-fold prompting consideration of alternative pollinators in Pennsylvania tree fruit [23]. **So, the IPPM challenge is integration in two dimensions: Integrating alternative pollinators into crop production and integrating the welfare of all pollinators into the IPM crop protection programs, which often include pesticide use.**

The importance of pollinators in apple production

In southern Pennsylvania, apple farms are nestled in the rolling Appalachian Mountains among a patchwork of forest land and diverse agriculture. All cultivars require cross-pollination to ensure commercial, fresh market crops in which size and shape of the fruit is as important as yield, in contrast with other crops (eg. almonds) where yield is maximized [24]. Unlike some apple production regions, mid-Atlantic U.S. apple pollination needs can be met by native bee species that occur in the landscape, and over half of Pennsylvania and New York apple growers do not rent honey bees [25,26].

Reliance on non-honey bee, wild pollinators requires multiple species to provide the biological insurance for sustainable pollination. However knowledge of species’ distributions, pollination effectiveness, nutritional requirements, alternate food sources and nesting sites is needed in order to modify usually oversimplified agricultural landscapes. Of the 3,500 bumble bee and solitary bee (or pollen bee) species in the US that are potential crop pollinators [27,28], the value of pollen bees alone is at least $3 billion annually [27]. Wild and managed pollen bees can supplement or replace honey bees, with each wild pollinator species within a crop pollination guild having its own life history traits, flower preferences and pollination usefulness. The early bloom of tree fruits (eg. plum, apple, etc) requires species that overwinter as adults. For apples these include univoltine, solitary species (eg. *Osmia*) and multivoltine species (eg. *Bombus*) [26]. Of the 371 known bee species in Pennsylvania [29], over 180 occur in orchards during the growing season and 52 pollinate apple. Some such as *Osmia* can be 80 times more effective than honey bees [30].

Roles of landscape and floristic diversity in support of apple pollinators. The reliability of wild pollinators depends on habitat suitability, both in the orchard and in the surrounding countryside [31]. In the Pennsylvania Appalachian mountains, orchards have steep slopes, well drained soils and a landscape matrix of approximately 8% orchards, 24% arable and pasture land, 9% developed area and 56% forests [32] and a continental climate [33]. The average two to four ha orchards are bordered by undeveloped scrub, forest, or fence rows where floristic diversity is correlated with pollinator communities. The forest edge/orchard border is the most species rich (169 out of 228 plant species recorded) and a significant predictor of bee species richness and abundance in the orchard [31, 34-36]. This floristic diversity is also attractive to beneficial predators and parasitoids [37].

IPM, pesticides and pollinators in apple

During the apple growing season, more than a dozen insect and mite pests [38, 39], 8 to10 fungal and bacterial diseases, and several vertebrate pests can attack the fruit and the trees [38]. Pennsylvania tree fruit IPM is an efficient and profitable combination of host plant resistance, biological control, sophisticated pest monitoring, and model-based pest predictions resulting in specifically-timed management practices [38]. Apple IPM has been modified to protect living IPM tools (biological control agents) [40-44], and can be further modified to protect pollinators giving rise to IPPM.

Pesticide applications may include multiple types of insecticides, fungicides, bactericides, herbicides, surfactants and others, each having a toxicity profile and impact on various insect species. Bee health is affected by field exposure to pesticides. Most studies consider only short–term acute contact exposure to adult bees in the laboratory using technical product in acetone [6, 5]. Lab assays can be poor predictors of field performance [49, 50]. Up to 100–fold toxicity differences were found comparing commercial formulations in water with technical products in acetone [5, 11]. In addition, pesticide combinations sometimes add unexpected pollinator mortality [5, 46-49.

Importantly, neonicotinoids control multiple sucking pests and are safer to biocontrol agents [38]. Not all neonicotinoids are equally toxic to bees [11]; specific active ingredients can be toxic to a particular pollinator species or not and may become more toxic when mixed with fungicides [5]. Eliminating neonicotinoids would necessitate using less effective alternative pesticides, increase secondary pests and production costs and aggravate pest resistance problems. Neonicotinoid insecticides can be used to manage pests in apples, and through an IPPM approach, pollinators can be protected from them.

Since insecticides are not applied during the short apple bloom, direct contact of surface residues by bees is not likely. The mostly likely route of exposure is through the ingestion of contaminated pollen and nectar from systemic insecticides and fungicides applied before bloom. Ingestion bioassays are rare for bees other than the honeybee and some *Bombus* species, as are studies of exposure levels when bees encounter low doses in multiple flower visits over time [1, 11]. The neonicotinoid, thiamethoxam, sprayed at the pink bud stage of apple at a typical 100 ppm field rate is reduced by translocation in the plant tissues; thus 5 days after a pre-bloom application, only 1–4 ppb is present in the nectar and pollen at 25% bloom [51]. Bee consumption rates of nectar and pollen are important in determining toxicity, but except for the honeybee, such consumption rates are largely unknown.

Pesticide recommendations in apple IPM to protect pollinators

An important advantage of IPM is that the pest management practices can be adjusted to accommodate new factors such as pollinator protection. Information on pesticide effects on non-honeybees is for the most part lacking, but certain groups such as the megachilids (including *Megachile* and *Osmia*) appear less susceptible on average than honeybees [5, 52].This varies among species and pesticides even within the same pesticide class [5]. Using the honeybee as proxy for all pollinator species (as is presently done) is not an accurate predictor for other species like *Osmia* [5], leafcutter bees, or bumblebees, since susceptibility varies by bee species and pesticide [52]. For example, the Japanese orchard bee (*Osmia cornifrons*) was 26 times less susceptible to imidacloprid than the honeybee, but 12 times more susceptible to acetamiprid [5]. Present tree fruit IPM recommendations for pollinators are based on minimizing pesticide impact on honey bees rather than protecting wild pollinators. Pesticide recommendations for honeybees include no insecticide applications during bloom or when hives are present (except for insecticides that are non-toxic to honeybees (eg lepidopteran insect growth regulators [26, 49]), and apply bloom fungicides at night or early morning. Pesticide restrictions are lifted when hives are removed; sometimes well before the end of bloom and without regard to wild bees that may still be foraging.

While systemic pesticides are regarded as biocontrol-friendly since the pesticides are absorbed into the plant tissues where they were accessible only to plant feeders [53], the potential movement into the nectar and pollen from pre bloom sprays may make them toxic to bees. While neonicotinoids have harmed bees in some agricultural systems [54,55], these pesticides may be integrated into agriculture to preserve their pest management aspects as long as precautions are taken to minimize their impacts on non-targets such as pollinators and other beneficial insects. For example, the rosy apple aphid (*Dysaphis plantaginea*),which is resistant to organophosphates, carbamates and pyrethroids, and for which no alternative control methods (including biological control) exists [56], is killed by a neonicotinoid application made just before bloom. Simply, adjusting the pesticide's application time to 10 days before bloom controls the aphids and drastically reduces pesticide residues in nectar and pollen (Biddinger, pers. comm.). Solutions like this should be investigated in all crops serviced by pollinators. A complete ban of this pesticide class would cause a) a reversion to the older, more toxic compounds they were meant to replace, b) exacerbation of pest resistance by removing a rotation partner, c) a switch to broad spectrum pyrethroid sprays which would destroy existing IPM programs by eliminating most biological control agents, or d) the complete loss of control of pests like the rosy apple aphid.

Even fungicides, long thought relatively harmless to pollinators and therefore safe to spray during bloom, are now indicted as potential pollinator threats [10, 58]. Bloom-sprayed fungicides break crop disease cycles early in the season reducing many sprays later in the season. While most fungicides alone still appear safe, the simultaneous application of some fungicides (ergosterol biosynthesis inhibitors, DMI) may synergize neonicotinoid toxicity [5, 9] and possibly that of other insecticides such as the pyrethroids [59]. A single lab study [9] using a technical neonicotinoid product dissolved in acetone, found synergism of 105– to 1,141–fold to honeybees by contact with acetamiprid and thiacloprid when mixed with two different DMI fungicides. However, synergism of other neonicotinoid insecticides with DMI fungicides was not found. Formulated versions of acetamiprid and imidacloprid with field rates of a formulated DMI fungicide in water tested on both honeybees and *Osmia cornifrons* revealed synergism that was barely significant at a 5–fold level with acetamiprid, and insignificant for imidacloprid in the lab [5]. Field trials with formulated product of both the insecticide and fungicide showed similar results [60]. Rightly or wrongly, almost all fungicides, except the older contact fungicides, are considered bee-safe even in combinations [38,48,56,61]. These older fungicides have some insecticidal properties that can affect larval development through chronic exposure during nectar and pollen feeding [61, 62]. Even fungicides acceptable in organic agriculture, sulfur and lime sulfur, are restricted during bloom because the odor is repellant to bees for up to 48 hours [63,64].

IPM recommendations for conserving wild pollen bees for tree fruit pollination

Tree fruit IPM programs can be adjusted to provide both pest control and pollinator health protection in an IPPM framework if we can better understand the relative levels of susceptibility of various bees species to both acute and chronic exposures to pesticides and the sources and levels of exposure in the field over time. With this information, we can inform farmers on how to adjust their spray programs to choose pesticides that are less toxic to bees while still controlling pests, or how to adjust the timing of toxic pesticides to minimize exposure levels just as we have done for over 40 years in biological control programs to conserve predatory mites and other beneficial arthropods. Since neonicotinoid residues in plant tissue does not carry over the winter (Biddinger pers comm), only prebloom applications have to be adjusted in tree fruit. In addition, while wild bees have great pollinator potential, they are also susceptible to pesticides and other factors such as lack of alternate forage and nesting sites. These other factors can also be part of the overall IPPM approach by expanding orchard management to include the surrounding landscape as well as siting nesting sites and hive placement in orchard interiors to accommodate species-specific foraging ranges [65]. This same approach can be applied to other crops.

The recognition of honeybee decline and a rising reliance on wild, pollen bees has started to be included in public policy, providing increased funding for research and education on this topic. The Food, Conservation, and Energy Act of 2008 (aka The Farm Bill) acknowledged the great importance of pollen bees for agriculture by providing funding for farmers to increase and protect pollinator habitat on farm land. Farmers are encouraged to seed strips of wildflowers along their property to encourage bee visitation to their crops, or to leave part of their property fallow to increase pollinator habitat [66, 67]. USDA/NRCS provides conservation payments that underwrite pollinator–friendly farm practices.

While some may say that we are in a pollinator crisis mainly based on honeybee declines, we assert that in addition to honey bee protection, we need to encourage and make use of the myriad other pollinator species and, by properly adjusting crop IPM practices to create IPPM that will protect all the pollinator species. Going forward we need to:

- Include pollinator protection in IPM education.
- Expand pesticide toxicity testing to include other pollinator species in addition to honey bees.
- Encourage federal and state agencies to fund research and extension programs that integrate pollinator health into IPM, yielding IPPM.
- Encourage USEPA and other regulatory bodies to include pollinator protection in pesticide use regulations.
- Encourage conservation bodies such as USDA/NRCS to incentivize farm practices that preserve pollinator health.
- Work with the private sector (commodity groups, agricultural input companies, food retailers, etc.) to incorporate pollinator protection into their businesses.
- Provide public education so consumers can choose products produced with good pollinator protection standards.

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