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Indirect Effects of Pesticides on Natural Enemies

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1. Introduction

Pesticides including insecticides and miticides are primarily used to regulate arthropod (insect and mite) pest populations in agricultural and horticultural crop production systems. However, continual reliance on pesticides may eventually result in a number of potential ecological problems including resistance, secondary pest outbreaks, and/or target pest resurgence [1,2]. Therefore, implementation of alternative management strategies is justified in order to preserve existing pesticides and produce crops with minimal damage from arthropod pests. One option that has gained interest by producers is integrating pesticides with biological control agents or natural enemies including parasitoids and predators [3]. This is often referred to as ‘compatibility,’ which is the ability to integrate or combine natural enemies with pesticides so as to regulate arthropod pest populations without directly or indirectly affecting the life history parameters or population dynamics of natural enemies [2,4]. This may also refer to pesticides being effective against targeted arthropod pests but relatively non-harmful to natural enemies [5,6].

Pesticides vary in their activity, which not only impacts how they kill arthropod pests but also how they may indirectly influence natural enemy populations. Pesticides may be classified as contact, stomach poison, systemic, and/or translaminar [7,8]. In addition, the application method—foliar vs. drench or granular—may determine the extent of any indirect effects on natural enemies [9] as well as the pesticide mode of action. The type of natural enemy—parasitoid or predator—may be influenced differently based on the factors mentioned above. Furthermore, the type of pesticide may substantially contribute to any indirect effects on natural enemies. For example, broad-spectrum, nerve toxin pesticides such as most of the older pesticides in the chemical classes, organophosphate (acephate and chlorpyrifos), carbamate (carbaryl and methiocarb), and pyrethroid (bifenthrin and cyfluthrin) may be both directly and indirectly more harmful to natural enemies than non-nerve toxin type pesticides (often referred to a “selective pesticides”) including insect growth regulators (kinoprene and pyriproxyfen), insecticidal soaps (potassium salts of fatty

acids), horticultural oils (petroleum or neem-based), selective feeding blockers (flonicamid and pymetrozine), and microbials (entomopathogenic fungi and bacteria, and other microorganisms) [10]. The non-nerve toxin pesticides are generally more specific or selective in regards to arthropod pest activity with broader modes of action than nerve toxin pesticides [3].

The effects of pesticides on natural enemies are typically associated with determining direct effects such as mortality or survival over a given time period (24 to 96 hours) [11]. While evaluations associated with the direct effects of pesticides on natural enemies are important, what are actually more relevant are the indirect or delayed effects of pesticides because this provides information on the long-term stability and overall success of a biological control program when attempting to integrate the use of pesticides with natural enemies [12-16].

Any indirect effects, which are sometimes referred to as sub-lethal, latent, or cumulative adverse effects may be associated with interfering with the physiology and behavior of natural enemies by inhibiting longevity, fecundity, reproduction (based on the number of progeny produced or eggs laid by females), development time, mobility, searching (foraging) and feeding behavior, predation and/or parasitism, prey consumption, emergence rates, and/or sex ratio [2,13,16,17-22].

2. Indirect effects of pesticides on natural enemies

In this book chapter, the term ‘indirect’ will be used for consistency. The indirect effects of pesticides on natural enemies (Table 1) have not been studied as extensively compared to direct effects, and those studies associated with indirect effects of pesticides have primarily involved evaluating fecundity and longevity [23-27].

* Longevity	* Reproduction
* Fecundity and/or fertility	* Development time (egg to adult or specific instars)
* Mobility	* Prey searching efficiency and feeding behavior
* Predation and/or parasitism	* Sex ratio
* Emergence rates	* Prey consumption
* Population growth/reduction	* Repellency
* Orientation behavior	* Prey acceptance (for oviposition by female parasitoids)

Modified from [2, 18].

Table 1. List of potential indirect effects of pesticides (insecticides, miticides, and fungicides) on the physiology and behavioral parameters of natural enemies (parasitoids and predators).

Although indirect effects may be more subtle or chronic compared to direct effects [14, 28-29] any indirect effects may inhibit the ability of natural enemies to establish populations; suppress the capacity of natural enemies to utilize prey; impact parasitism (for parasitoids) or consumption (for predators) rates; decrease female reproduction; reduce prey

availability; inhibit ability of natural enemies to recognize prey; influence the sex ratio (females: males); and reduce mobility, which could impact prey-finding [3, 27, 30-31]. In addition, more than one physiological and/or behavioral parameter may be indirectly affected after exposure to a pesticide. Furthermore, understanding the indirect effects of different concentrations of pesticides on fecundity, fertility, reproduction, adult and larva longevity, and prey consumption is important in successfully integrating natural enemies with pesticides and avoiding any indirect consequences on population dynamics [16,32].

The important physiological and behavioral parameters presented above are responsible for allowing natural enemies to regulate arthropod pest populations. Some factors affiliated with natural enemies that may influence the indirect effects of pesticides include natural enemy age, type of natural enemy (parasitoid vs. predator), life stages (immature vs. adult) exposed to pesticides, and sex (male vs. female) [9,33]. In addition, the type of pesticide (nerve toxin vs. non-nerve toxin) as well as the pesticide application method (foliar vs. systemic) may have significant consequences and thus impact the extent of any indirect effects on natural enemies based on exposure (immediate vs. chronic). For example, foliar applications of pesticides, which in most cases, represents immediate exposure, that do not directly harm natural enemies may have indirect effects. Another indirect affect may be related to residues remaining after a foliar application, which could inhibit the emission of volatile cues from plants that are utilized by certain natural enemies to detect prey location (prey patches) from long distances within plant communities, thus impacting foraging behavior and searching efficiency [34-37]. Moreover, any residues remaining after application may indirectly affect parasitoids by inhibiting adult emergence [38].

Furthermore, natural enemies, particularly parasitoids, may be indirectly affected by feeding on contaminated honeydew excreted by phloem-feeding insect prey [39,40], which could significantly affect their performance. Certain pesticides (insecticides and fungicides) may also exhibit repellent activity [16,41-46] or alter host plant physiology [13,47] thus indirectly affecting the ability of natural enemies to regulate existing arthropod pest populations [48].

This book chapter will now focus specifically on the indirect effects on natural enemies associated with different categories of pesticides including systemic insecticides, insect growth regulators, selective feeding blockers, microbials, miticides, and fungicides.

3. Systemic insecticides

Systemic insecticides, when applied as drenches or granules to the soil/growing medium, have been promoted to be relatively non-toxic to natural enemies due to lack of any direct exposure [49-51]. However, this may not be the case as systemic insecticides may exhibit indirect effects on natural enemies via several mechanisms including elimination of prey, contamination of floral parts by the active ingredient, consumption of the active ingredient while ingesting plant fluids, and contamination of prey ingesting either lethal or sub-lethal concentrations of the active ingredient [52-54]. Systemic insecticides, when applied to the soil or growing medium, may have minimal direct effects on aboveground natural enemies

(both parasitoids and predators); however, they may indirectly influence natural enemies if mortality of prey populations is high (>90%). This results in a reduction or potential elimination of available prey that serve as a food source for natural enemies [55-57], making it difficult for natural enemies to locate any remaining individuals. This would then lead to a decline in natural enemy populations either through starvation or dispersal thus suppressing establishment [1,55,58-59]. However, this effect is dependent on the foraging efficiency of the specific natural enemy. Furthermore, this may reduce the quantity or density of available prey or reduce their quality such that they are unacceptable as a food source for predators (both larvae and adults) or female parasitoids may not lay eggs. As such, reproduction, foraging behavior, fecundity, and longevity may all be indirectly affected [3].

The distribution of the systemic insecticide active ingredient into flower parts (petals and sepals) may indirectly impact natural enemies that feed on plant pollen or nectar as a nutritional food source including several species of predators such as minute pirate bug, *Orius* spp., which may feed on plants sometime during their life cycle [60-61] and certain parasitoids [62]. For example, adults of the parasitoid, *Anagyrus pseudococci* were indirectly affected after feeding on nectar of buckwheat (*Fagopyrum esculentum*) plants that had been treated with a soil application of a systemic insecticide [53]. Stapel et al. (2000) [11] found that foraging ability and longevity of the parasitoid, *Microplitis croceipes* was reduced after feeding on the extrafloral nectaries of cotton (*Gossypium hirsutum*) plants that had been treated with systemic insecticides. It was also noted that the application method (soil vs. foliar) and possibly timing of application (spatially and temporally) may influence any indirect effects on parasitoids that feed on flower pollen and nectar as a food source. In addition, foraging behavior may be altered depending on the exposure time and concentration of active ingredient present in floral portions of plants. As such, indirect effects associated with systemic insecticides may reduce the overall success of parasitoids in regulating arthropod pest populations under field conditions [11]. Translocation of systemic insecticides into flowers may indirectly affect natural enemies by altering foraging behavior as has been shown with the pink lady beetle, *Colemegilla maculata*, the green lacewing, *Chrysoperla carnea*, and the parasitoid, *A. pseudococci* [53,63-64]. Nevertheless, the ability of systemic insecticides, when applied to the soil or growing medium as a drench or granule, to move into floral parts may be contingent on water solubility, application rate, and plant type [9,65].

In addition, the metabolites of certain systemic insecticides, which in general, may be more water soluble and toxic to arthropod pests, could be more concentrated in pollen and nectar than the actual active ingredient [66]. This might have a significant indirect effect on natural enemies. In fact, the metabolites associated with certain systemic insecticides have been implicated to indirectly affect natural enemies, primarily by contaminating flower pollen or extrafloral nectaries as the active ingredient is translocated and distributed throughout plant parts [9]. Furthermore, any natural enemies feeding on prey that have fed upon plants and have ingested concentrations of the systemic insecticide active ingredient may be indirectly affected [67-68]. This is associated with prey contamination, which can lead to subtle and long-term indirect effects on parasitoids and/or predators [5,69].

Any indirect effects of systemic insecticides may also be associated with alterations in prey quality or induced changes in host plants [1,70-71], which may reduce the attractiveness of plants to parasitoids [13]; thus impacting the foraging behavior and searching efficiency of natural enemies [13,72]. The indirect effects of systemic insecticides, particularly on predators, may vary depending on feeding habits. For example, hemipteran predators, which may feed on plants as a supplemental food source, would likely be more indirectly affected than coccinellid predators that only feed on prey [2,5,73-76]. Furthermore, any odors associated with treated plants, may result in an avoidance response, which could inhibit the performance and thus effectiveness of natural enemies [11].

Exposure via both contact and oral-ingestion to systemic insecticides at variable concentrations indirectly affected both foraging ability and parasitization (parasitizing ability) of the parasitoid, *Anagrus nilaparvatae* [72]. Another indirect effect was a decrease in the ability of the parasitoid to perceive host-plant volatiles after being exposed to various concentrations of a systemic insecticide [72]. In addition, applications of certain systemic insecticides have been demonstrated to reduce reproduction of vedalia beetle, *Rodolia cardinalis* females and inhibit development from larvae to adult [67]. However, in a study in which nymphs and adults of the plant bug, *Deraeocoris brevis* were exposed to a systemic insecticide, there were no indirect effects on development or reproduction [72], which indicates variability associated with any indirect effects due to natural enemy type and species.

4. Insect growth regulators

Insect growth regulators are compounds that are active directly on the immature stages (larvae or nymphs) of certain insect pests, and there are three distinct categories of insect growth regulators: juvenile hormone mimics, chitin synthesis inhibitors, and ecdysone antagonists [78-79]. Insect growth regulators have been presumed to be compatible, with minimal indirect affects on natural enemies [80-83], and numerous studies have evaluated the indirect effects of insect growth regulators on natural enemies, both parasitoids and predators, under laboratory and field conditions. However, there is distinct variability regarding the indirect effects of insect growth regulators on natural enemies, which is primarily associated with natural enemy type (parasitoid or predator), kind of insect growth regulator, life stage evaluated, and timing of application (spatially and temporally).

4.1. Pyriproxyfen

The insect growth regulator pyriproxyfen, a juvenile hormone mimic [84-85] was demonstrated to have no indirect harmful effects on adult female oviposition and egg viability of the green lacewing, *C. carnea* [86]. Similarly, pyriproxyfen exhibited no indirect effects on development time, female longevity, and fertility of an *Orius* sp. after exposure under laboratory conditions [86]; however, these results may be inconclusive as control mortality was nearly 70%. Pyriproxyfen did not negatively affect parasitism capacity of the

parasitoid, *Aphytis melinus* and there were no indirect effects on the sex ratio of the progeny whereas female *Coccophagus lycimnia* failed to produce any progeny [87]. However, exposure to pyriproxyfen delayed development and decreased the parasitization rate of the parasitoid, *Hyposoter didymator* [88]. In addition, pyriproxyfen has been demonstrated to substantially alter the development time of *Chrysoperla rufilabris* immatures [89] whereas pyriproxyfen did not indirectly impact *Delphastus catalinae* female fecundity after adults had fed upon treated eggs of the sweet potato whitefly, *Bemisia tabaci* [83]. In another study, exposure of *Podisus maculiventris* fifth instars to pyriproxyfen did not result any indirect effects on reproduction [5]. The parasitoid species may influence any indirect effects as both *Encarsia pergandiella* and *Encarsia transvena* were not indirectly affected after exposure to pyriproxyfen whereas *Encarsia formosa* exhibited reduced emergence rates, increased development time, and decreased parasitization when exposed to different concentrations of pyriproxyfen [90]. This demonstrates that the parasitoid species, natural enemy type, and developmental life stage may influence the extent of any indirect effects of insect growth regulators.

4.2. Kinoprene

Another juvenile hormone mimic insect growth regulator, kinoprene [7], has been shown to be indirectly harmful to natural enemies by inhibiting adult emergence of the leafminer parasitoid, *Opius dimidiatus* [91] and the aphid parasitoid, *Aphidius nigripes* [92]. Although directly harmful to the parasitoid, *Leptomastix dactylopii*, kinoprene did not indirectly affect percent parasitoid emergence from citrus mealybug (*Planococcus citri*) mummies [93]. Nevertheless, kinoprene may inhibit adult emergence when applied to prey parasitized with larval or pupal stages of certain parasitoids [92].

4.3. Fenoxycarb

Fenoxycarb is a juvenile hormone analog [79,94-95] that has shown to be indirectly harmful to certain natural enemies. For example, different concentrations of fenoxycarb delayed the development time from pupae to adult of *C. rufilabris* [95], and significantly delayed development of third instar larvae but not first instar larvae. In addition, female reproduction was inhibited when second and third instars were initially exposed to fenoxycarb [96]. Grenier and Plantevin (1990) [97] demonstrated that fenoxycarb (at various concentrations) increased duration of larval development of the tachinid parasitoid, *Pseudoperichaeta nigrolineata*, and Bortolotti et al (2005) [98] observed a similar response (increased longevity) for the third instar larvae of *C. carnea*. In addition, exposure to fenoxycarb indirectly affected female longevity and fecundity of the predator, *Micromus tasmaniae* [99].

4.4. Cyromazine

Cyromazine is an insect growth regulator that disrupts molting by affecting cuticle sclerotization through increasing cuticle stiffness in insects [79], and has been shown to

exhibit indirect effects on the reproduction of *Phytoseiulus persimilis* females [100] whereas no indirect effects, associated with adult emergence rates, were exhibited after the parasitoid, *Chrysocharis parksi* was exposed to cyromazine [101]. Furthermore, exposure to cyromazine did not indirectly affect longevity and reproduction of the leafminer parasitoids, *Hemiptarsenus varicornis* and *Diglyphus isaea* [57].

4.5. Diflubenzuron

Another insect growth regulator, diflubenzuron, which is a chitin synthesis inhibitor [79], has been shown, in general, to have minimal indirect impact on natural enemies—both parasitoids and predators—under laboratory and field conditions [10,102]. However, exposure to diflubenzuron decreased female longevity and reduced the parasitization rate of the endoparasitoid, *Hyposoter didymator* [88] and reproduction of the parasitoid, *Eulophus pennicornis* [103]. It was reported by [99] that *M. tasmaniae*, when exposed to diflubenzuron, resulted in indirect affects on reproduction, sex ratio (female bias), and longevity. In contrast, diflubenzuron exhibited no indirect effects on the reproduction of *Podisus maculiventris* adults [5]. Additionally, diflubenzuron displayed minimal indirect effects on the parasitoid, *Macrocentrus ancylivorus* [104]. Similar to other insect growth regulators, any indirect effects of diflubenzuron are likely associated with the natural enemy type, timing of application (spatially and temporally), and exposure time.

4.6. Buprofezin

Buprofezin, a chitin synthesis inhibitor [79,105], has been shown to sterilize certain natural enemies [106], and reduce the number of progeny produced per female and alter sex ratios [87]. In addition, feeding on buprofezin-treated sweet potato whitefly (*B. tabaci*) eggs resulted in a decrease in female fertility and fecundity, and sterilized the males of the predatory coccinellid, *Delphastus catalinae* [83] indicating no compatibility with this insect growth regulator. However, buprofezin did not negatively affect development (nymph to adult) of the predatory bug, *Orius tristicolor* [107] or inhibit female reproduction of the predatory mite, *P. persimilis* [100]. In addition, buprofezin demonstrated no indirect affects on oviposition and foraging behavior of certain parasitoids including *Eretmocerus* sp., and *Encarsia luteola* [108]. Buprofezin, when applied at three different concentrations (100, 500, and 1,000 mg active ingredient per liter), did not indirectly affect egg viability and subsequent development of *C. rufilabris*. However, the higher rates (500 and 1,000 mg active ingredient per liter) when applied to first instars did prolong overall development to adult whereas second and third instars and pupae were not affected [109]. This indicates that the specific life stage exposed to insect growth regulators may vary in susceptibility with early instars tending to be more susceptible than later instars and adults to chitin synthesis inhibiting insect growth regulators [108,110-111]. In addition, the concentration in which natural enemies are exposed to may influence any indirect effects to these types of insect growth regulators. Furthermore, any indirect effects on natural enemies associated with buprofezin may be due to volatility of the compound as buprofezin is known to be volatile and display vapor activity against certain insect pests [112].

4.7. Azadirachtin

Azadirachtin is an ecdysone antagonist [78,113-114], which may exhibit variability regarding any indirect effects on natural enemies [115]. It was reported by [116], for example, that azadirachtin inhibits oviposition of the green lacewing, *C. carnea* and indirectly affected both fertility and fecundity [117]. In addition, exposure to azadirachtin decreased longevity and predation rates, and inhibited prey finding. Furthermore, the sex ratio was male biased ([88]. Three different formulations (0.3%, 4.5%, and 1.6%) of azadirachtin were reported to indirectly affect the fecundity of *Macrolophus caliginosus* females [118]. Reproduction of the aphid predator, *Aphidoletes aphidimyza* was not indirectly affected after exposure to azadirachtin [119], and azadirachtin did not indirectly affect the fecundity of the parasitoid, *Aphidius colemani* [120]; longevity and foraging ability of the parasitoids, *Cotesia plutellae* and *Diadromus collaris* and sex ratio of progeny [6]; nor reproduction of the predatory mite, *Neoseiulus californicus* [121]. Cloyd et al. (2009) [122] found, under laboratory conditions, that exposure to azadirachtin did not inhibit prey consumption (fungus gnat larvae) of rove beetle, *Atheta coriaria* adults. However, it was reported by [123] that first instar larvae of *Harmonia axyridis*, when exposed to azadirachtin, exhibited increased development time whereas there was no indirect effect on adult female fecundity.

Similar to buprofezin, this demonstrates that any indirect effects of insect growth regulators such as azadirachtin may be more prevalent on the early instars than the later instars of certain natural enemies [123]. Likewise, as also demonstrated by [124], development time of *Coccinella septempunctata* larvae was indirectly affected in a dose-dependent manner with fourth instar larvae more sensitive to azadirachtin than first instar larvae, which suggests that any indirect effects may be stage and age specific. As such, azadirachtin may be more indirectly harmful to nymphs and larval instars than adults under laboratory conditions whereas under semi-field or field conditions any indirect effects associated with these life stages are nullified [115].

5. Selective feeding blockers

Selective feeding blockers, which include flonicamid and pymetrozine, inhibit the feeding activity of piercing-sucking insects (aphids and whiteflies) after initial insertion of their stylets into plant tissues and interfere with neural regulation of fluid intake through the mouthparts resulting in starvation [125-130]. It was reported by [130] that both flonicamid and pymetrozine, did not negatively affect the development time, fertility, and parasitism of a variety of natural enemies including the hoverfly, *Episyrphus balteatus*; the carabid beetle, *Bembidion lampros*; the parasitoid, *Aphidius rhopalosiphi*; the ladybird beetle, *Adalia bipunctata*; and the rove beetle, *Aleochara bilineata* under laboratory conditions. In general, pymetrozine exhibited minimal indirect effects on the reproduction of *N. californicus* under laboratory conditions [121]. Cloyd and Dickinson (2006) [131] found that flonicamid did not indirectly affect parasitism, the sex ratio, and adult emergence of the parasitoid, *L. dactylopii*. Overall, minimal research has been conducted to determine the indirect effects of these types of

pesticides on natural enemies; however, in general, they appear to be compatible, which is likely associated with their mode of action.

6. Microbials

Although entomopathogenic fungi and bacteria (*Bacillus thuringiensis*) are, in general, not indirectly harmful to natural enemies, this may vary depending on concentration, natural enemy type, life stage exposed, timing of application (spatially and temporally), and environmental conditions (temperature and relative humidity) [3,132]. Furthermore, any indirect effects may take longer to be expressed compared to other types of pesticides [133] as well as the fact that indirect effects may not be immediately associated with either the entomopathogenic fungi or bacteria, but may be due to altering the availability of the food source or killing prey before parasitoid immatures have completed development [134]. The bacterium, *B. thuringiensis* has been shown to have indirect effects on certain parasitoids although this is dependent on the formulation [135].

Natural enemies may ingest fungal conidia when grooming (cleaning themselves) or when feeding on contaminated hosts [10,104]; however, the extent of any indirect effects primarily depends on the concentration of spores present [136]. In addition, entomopathogenic fungi may indirectly affect certain natural enemies when feeding on prey that have been sprayed (contaminated prey). For example, larvae of the mealybug destroyer, *Cryptolaemus montrouzieri* were killed (50% mortality) after consuming mealybugs that had been sprayed with *Beauveria bassiana* [133]. Moreover, exposure to *B. bassiana* reduced the fecundity of *N. californicus* females [121] whereas the fungus *Cephalosporium lecanii* exhibited no indirect effects on longevity of the leafminer parasitoid, *Diglyphus begini* [137]. In another study, conducted under laboratory conditions, [122] reported that exposure to *Metarhizium anisopliae* had no indirect effect on prey consumption (fungus gnat larvae) of rove beetle, *A. coriaria* adults. It was shown by [132] that exposure to *Isaria* (= *Paecilomyces*) *fumosoroseus* at a low relative humidity (55%) resulted in no indirect effects on foraging behavior and longevity of the aphid parasitoid, *Aphelinus asychis* whereas both parameters were significantly reduced when exposed to a high ($\geq 95\%$) relative humidity, which could impact the ability of the parasitoid to regulate aphid populations. In addition, ovipositing females may avoid prey that are infected by entomopathogenic fungi [132].

The micro-organism spinosad has been demonstrated to be indirectly harmful to a variety of predatory insects including the green lacewing, *C. carnea* [138]; ladybird beetle, *Hippodamia convergens*; minute pirate bug, *Orius laevigatus*; big-eyed bug, *Geocoris punctipes*; and the damsel bug, *Nabis* sp. [139-140]. For example, it was determined by [141] that exposure to spinosad extended development time from first instar to adult and decreased fertility of *Harmonia axyridis* females. Nevertheless, exposure to spinosad did not inhibit foraging behavior and reproduction of *P. persimilis* females [142]. It has been shown by [143-144] that parasitoids may be indirectly affected by spinosad based on decreased reproduction and reduced longevity. However, exposure to spinosad did not indirectly affect the sex ratio of

the parasitoids, *Aphytis melinus* and *L. dactylopii*, and there was no significant effect on reproduction and longevity of *L. dactylopii* females [87].

7. Miticides

Miticides, similar to other pesticides, may demonstrate variability in regards to any indirect effects on natural enemies depending on the type of miticide and predatory mite species [145]. It was reported by [145] that the miticide fenpyroximate did not negatively affect prey consumption of *Neoseiulus* (= *Amblyseius*) *womersleyi* on twospotted spider mite (*Tetranychus urticae*) eggs compared to the miticide pyridaben. However, both miticides indirectly affected reproduction of *N. womersleyi* and *P. persimilis* females. Egg viability of *P. persimilis* was not affected by either miticide but was for *N. womersleyi*. Furthermore, the population growth, based on reproduction and egg viability, of *N. womersleyi* was indirectly affected more so by pyridaben than fenpyroximate. Overall, fenpyroximate appeared to be more compatible with both predatory mite species. Similarly, [146] found that exposure to different concentrations of fenpyroximate did not indirectly affect female reproduction, immature development time, fecundity, and the sex ratio of progeny associated with *N. womersleyi*. Nevertheless, exposure to variable concentrations of fenpyroximate indirectly affected longevity and fecundity of *P. plumifer* females [147]. In another study, pyridaben inhibited reproduction of *Galendromus occidentalis* [148] whereas [149] reported no indirect effects associated with sex ratio and prey consumption of *P. persimilis*.

The miticides bifentazate, etoxazole, acequinocyl, chlorfenapyr, and fenbutatin oxide were shown to exhibit no indirect effects on the reproduction of *P. persimilis* females under laboratory conditions, and adult females that fed upon prey treated with the miticides were not indirectly affected based on sex ratio of progeny, prey consumption, and female reproduction [150]. This indicates that these miticides are in fact compatible with this predatory mite. In another study, [22] found that exposure to bifentazate did not reduce fecundity, longevity, or prey consumption of adult female *P. persimilis* or *N. californicus*. Moreover, exposure to bifentazate, etoxazole, acequinocyl, and chlorfenapyr under laboratory conditions did not indirectly affect fecundity or reproduction of *N. womersleyi* females. In addition, females that fed upon treated prey were in no way indirectly affected [151]. Overall, the miticide bifentazate appears to be compatible with a variety of predatory mite species.

8. Fungicides

Although, in general, fungicides may be considered less harmful to natural enemies than insecticides and miticides [18] it is still critical to determine any indirect effects and thus compatibility with natural enemies since fungicides are extensively used in agricultural and horticultural production systems and as such it is justifiable to evaluate their indirect effects on natural enemies. It may be that the fungicide type will determine compatibility with natural enemies as 'older' fungicides could be more indirectly harmful to natural enemies than 'newer' fungicides, which may be associated with the mode of action or any

metabolites. Although similar to other pesticides, this may depend on the natural enemy type and species, timing of application (spatially and temporally), and life stage exposed. For example, mancozeb was shown to negatively affect fecundity and reproduction of the predatory mites, *Amblyseius andersoni*, *G. occidentalis* [42,152] and *Euseius victoriensis* [45] under laboratory and field conditions and benomyl indirectly inhibited reproduction of female *Amblyseius fallacis* [153] and *G. occidentalis* [148]. However, mancozeb did not indirectly affect longevity or reproduction of two leafminer parasitoids, *Hemiptarsenus varicornis* and *Diglyphus isaea* [57].

It was determined that the 'newer' fungicides, azoxystrobin and fosetyl-aluminum did not inhibit prey consumption (fungus gnat larvae) of rove beetle, *A. coriaria* adults under laboratory conditions [122]. Bostanian et al. (2009) [154] reported that none of the fungicides evaluated including myclobutanil, propiconazole, fenhexamid, and pyraclostrobin, had any indirect effects on the fecundity of the predatory mite, *G. occidentalis*, and the fungicides captan, mancozeb, and myclobutanil did not indirectly affect longevity and fecundity of *A. fallacis* females [155]. Exposure to the fungicides boscalid and kresoxim-methyl, which are relatively 'newer' fungicides did not indirectly affect fecundity of both *E. victoriensis* and *G. occidentalis* [45]; and [148] found that exposure to the fungicides myclobutanil and trifloxystrobin resulted in no indirect effects on fecundity of *G. occidentalis*.

9. Additional factors associated with indirect effects of pesticides on natural enemies

It is important to exercise caution when attempting to translate laboratory evaluations associated with indirect effects into predictions related to field performance of natural enemies [156-159]. Laboratory assays, for example, may fail to take into account the indirect effects of pesticides, which could underestimate their overall impact [18]. In addition, long-term evaluations conducted under field conditions provide more applicable information regarding pesticide-pest-natural enemy interactions [159] including how pesticides indirectly interfere with the synchrony between natural enemies and their prey [99]. Furthermore, field exposure is assumed to be less severe and more variable than laboratory exposure because of factors such as plant architecture (arrangement of leaves and branches), spray application coverage, pesticide degradation, and potential for recolonization [45]. In addition, the methodology used to evaluate indirect effects of pesticides on natural enemies may influence the results obtained [87].

Another potential issue to be considered is that any indirect effects of pesticides on natural enemies may not necessarily be affiliated with the active ingredient but due to inert ingredients in the commercial formulation [2,160-164]. It is possible that formulations such as emulsifiable concentrates (EC) and soluble powders (SP) may contain additives such as adjuvants, surfactants, solvents and/or carriers that are indirectly harmful to natural enemies [45,165]. Studies associated with how inert ingredients affect natural enemies are necessary in order to better understand the actual indirect impact of pesticides on natural enemies.

10. Summary

This book chapter has demonstrated the feasibility of combining or integrating natural enemies with certain pesticides including systemic insecticides, insect growth regulators, selective feeding blockers, microbials, miticides, and fungicides. The information presented clearly indicates that combining pesticides with natural enemies is not straight-forward [2,18] and that compatibility of natural enemies with pesticides depends on a range of factors including class of pesticide applied, natural enemy type (parasitoid or predator), natural enemy species, pesticide formulation, concentration in which natural enemies are exposed to, exposure time, timing of application (spatially and temporally), and developmental life stage (early vs. later instars) exposed to pesticide. In addition, more than one physiological or behavioral parameter (longevity, reproduction, fecundity, and/or searching efficiency) of a given natural enemy may be indirectly affected by pesticides. As such, there are three primary means by which natural enemies may be integrated with pesticides including pesticide selection (using non-nerve toxin or “selective” pesticides), spatial separation (applying pesticides to localized areas of infestation) of natural enemies and pesticides, and temporal discontinuity (applying pesticides when natural enemies are absent or when tolerable life stages are present) between natural enemies and pesticides [2,132].

As [27] indicated, any indirect effects must be evaluated to determine if pesticides are compatible with natural enemies so as not to compromise long-term success of biological control programs. However, many pesticide manufacturers and suppliers make unsubstantiated claims that pesticides are safe to natural enemies without any references to testing methodology, which fails to take into consideration that results obtained associated with any indirect effects may vary depending on concentration, natural enemy species, pesticide exposure time, developmental life stage(s) evaluated, and the influence of residues and repellency [45]. Therefore, compatibility of natural enemies with pesticides is important if both these management strategies are to be integrated into programs designed to regulate arthropod pest populations and minimize plant damage.

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