Compatibility of Insecticides with Natural Enemies to Control Pests of Greenhouses and Conservatories[1]

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Abstract Natural enemies used as biological control agents may not always provide adequate control of plant-feeding insects in greenhouses and conservatories. Research continues to assess the utilization of natural enemies in conjunction with biorational insecticides including insect growth regulators, insecticidal soaps, horticultural oils, feeding inhibitors, and microbial agents (entomogenous bacteria and fungi, and related microorganisms); and the potential compatibility of both strategies when implemented together. A variety of factors influence the ability of using natural enemies with insecticides. These include whether the natural enemy is a parasitoid or predator, the species of the natural enemy, life stage sensitivity, rate and timing of insecticide application, and mode of action of the insecticide. Insecticides may impact natural enemies by affecting longevity (survival), host acceptance, sex ratio, reproduction (fecundity), foraging behavior, emergence, and development. Despite the emphasis on evaluating the compatibility of natural enemies with insecticides, it is important to assess if this is a viable and acceptable pest management strategy in greenhouses and conservatories.

Key words biological control, insecticides, compatibility, integrated pest management, natural enemies

Greenhouse crops and conservatory plantings are susceptible to attack by a wide range of insect pests including aphids, whiteflies, thrips, mealybugs, scales, and leafminers (Haseman and Jones 1934, Pritchard 1949, Osborne and Oetting 1989, Kole and Hennekam 1990). Biological control, involving the use of natural enemies including parasitoids, predatory insects and mites, and/or entomogenous bacteria, fungi, and nematodes provides an alternative to insecticides for managing insect pests (Van Driesche and Heinz 2004) in greenhouses and conservatories. However, the sole use of biological control may not always be sufficient to control phytophagous insect populations in greenhouses (van Lenteren 1987, Medina et al. 2003, Hassan and Van de Veire 2004). As a result, research has explored the possibility of using so-called "biorational" or "reduced risk" insecticides, in conjunction with natural enemies to determine if there is compatibility when both management strategies are implemented together. Those insecticides that are classified as biorational or reduced risk include insect growth regulators, insecticidal soaps and horticultural oils, feeding inhibitors, and microbial agents including entomogenous bacteria and fungi, and related microorganisms.

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Biorational or reduced risk insecticides are considered to be compatible with natural enemies when compared with most conventional broad-spectrum insecticides because they are active on a narrow range of target sites or systems than the conventional insecticides (Croft 1990). In fact, several commercially available biorational insecticides claim to not disrupt beneficial insects and mites. However, research conducted worldwide has shown that biorational insecticides may, in fact, be harmful to certain natural enemies. Although biorational insecticides may not be directly or immediately toxic to a specific natural enemy there may be indirect or sublethal effects, such as delayed development of the host and the natural enemy, delayed adult emergence of the natural enemy, and/or decreased natural enemy survival (Croft 1990). Parrella et al. (1999) noted that the harmful effects of biorational insecticides may be due to direct contact, host elimination, residual activity, or indirect effects. Examples of each are:

Direct effects. Directed sprays of biorational insecticides may kill natural enemies or, in the case of parasitoids, they maybe killed while developing within hosts.

Host elimination. Biorational insecticides may kill hosts, which may lead to natural enemies dying or leaving the vicinity because they are unable to locate additional hosts.

Residual activity. Although spray applications of biorational insecticides may not directly kill natural enemies, any residues may have repellent activity thus influencing the ability of parasitoids or predators to locate a food source.

Indirect effects. Biorational insecticides may not directly kill a natural enemy, but may affect reproduction such as sterilizing females, reducing the ability of females to lay eggs, or impact the sex ratio. Additionally, foraging behavior may be modified thus influencing the ability of a parasitoid or predator to find a host (Elzen 1989). Also, those parasitoids that host feed, such as the greenhouse whitefly parasitoid, *Encarsia formosa* Gahan may inadvertently consume residues on hosts after a spray application. This may make a host unacceptable to a parasitoid or predator.

Differences in natural enemy susceptibility to biorational insecticides may be due to a number of factors including (1) whether the natural enemy is a parasitoid or predator, (2) species of the natural enemy, (3) life stage (i.e., egg, larva, pupa, and adult) sensitivity, (4) developmental stage of the host, (5) rate of application, (6) timing of application, and (7) mode of action of the biorational insecticide. All these differences are complex primarily due to the differential interactions that may occur among the aforementioned factors and the variability in natural enemy sensitivity. A further complication is that harmful effects from biorational insecticides may not be associated with the active ingredient but due to the inert ingredients such as carriers or surfactants (Stevens 1993, Imai et al. 1995, Wood et al. 1997, Cowles et al. 2000).

Biorational insecticides are generally more specific in pest activity and more physiologically selective to natural enemies than conventional insecticides (Croft 1990). A number of biorational insecticides used in greenhouses and conservatories have been evaluated for both their direct and indirect effects on natural enemies. The work presented herein is a review of descriptive research-based examples of the compatibility of biorational insecticides with various natural enemies. This review will address the impact of various insecticides on natural enemies of insect pests found in greenhouses and conservatories.

Effects of Insecticides on Natural Enemies

Insect growth regulators. Insect growth regulators that have been evaluated for both their direct and indirect effects on natural enemies include the juvenile hormone mimics pyriproxyfen and kinoprene, the chitin synthesis inhibitors diflubenzuron and buprofezin, and the ecdysone antagonists tebufenozide and azadirachtin.

In laboratory studies, pyriproxyfen was nontoxic to the larval and adult stages of the green lacewing, *Chrysoperla carnea* Stephens (Medina et al. 2003), and predatory bugs, *Orius* spp., and had no harmful effects on adult female oviposition and egg viability (Nagai 1990). Pyriproxyfen also was not lethal to the predatory bug, *Orius laevigatus* L., via ingestion and residual contact (Delbeke et al. 1997). Although not toxic to certain predatory insects, pyriproxyfen was lethal to immature parasitoids developing inside nymphs of silverleaf whitefly, *Bemisia argentifolii* Bellows and Perring (Hoddle et al. 2001). Natural enemy species may influence compatibility as demonstrated with pyriproxyfen, which repeatedly is nontoxic to the silverleaf whitefly parasitoid, *Eretmocerus eremicus* Rose and Zolnerowich (Hoddle et al. 2001), and *Encarsia pergandiella* Howard, but is lethal to *Encarsia formosa* Gahan (Liu and Stansly 1997). Rothwangl et al. (2004) found pyriproxyfen to be slightly toxic to the citrus mealybug parasitoid, *Leptomastix dactylopii* Howard, under laboratory conditions. Pyriproxyfen is harmful to the larval stage of coccinellids including the mealybug destroyer, *Cryptolaemus montrouzieri* Mulsant, (Hattingh and Tate 1995) and the vedalia beetle, *Rodalis cardinalis* Mulsant (Grafton-Cardwell and Gu 2003). However, pyriproxyfen is not harmful to *C. montrouzieri* adults (Cloyd and Dickinson, unpubl. data). Cabrera et al. (2004) reported that pyriproxyfen, when applied to growing medium, was not lethal to the soil-predatory mite, *Stratiolaelaps scimitus* Womersley.

Kinoprene is an insect growth regulator that is consistently harmful to certain natural enemies, especially parasitoids. As described above, the rate used may influence natural enemy susceptibility. For example, kinoprene reduced adult emergence of the leafminer parasitoid, *Opius dimidiatus* Ashmead (Lemma and Poe 1978), and the aphid parasitoid, *Aphidius nigripes* Ashmead (McNeil 1975), at all rates tested. Kinoprene may inhibit adult emergence when applied to hosts parasitized with larval and pupal stages of certain parasitoids (McNeil 1975). Kinoprene is extremely toxic to *L. dactylopii* adults (Rothwangl et al. 2004), and the aphid parasitoid, *Aphidius colemanii* Vierek, when exposed to direct sprays and 1-day-old residues (Olson and Oetting 1996). Furthermore, residues on kinoprene-treated poinsettia (*Euphorbia pulcherrima* Willd. ex Klotzsch) leaves are harmful to *E. eremicus* 6 and 96 h after treatment (Hoddle et al. 2001). Although lethal to parasitoids, kinoprene is less toxic to certain predators and different life stages. For example, applications of kinoprene did not negatively affect ladybird beetle eggs (Kismali and Erkin 1984).

Diflubenzuron has minimal impact on natural enemies either directly or indirectly when evaluated under laboratory conditions. However, the life stage (egg, larvae, pupae, and adult) treated influences the effects of this chitin-synthesis inhibitor. For example, diflubenzuron is harmful to the early larval instars of the green lacewing, *C. carnea*; whereas, older larvae are not affected (Niemczyk et al. 1985, Medina et al. 2003). Young larvae of the mealybug destroyer, *C. montrouzieri*, when treated with diflubenzuron, fail to develop into adults; whereas, diflubenzuron has minimal impact on *L. dactylopii* (Mazzone and Viggiani 1980). Diflubenzuron appears to have no direct effect on the twospotted spider mite, *Tetranychus urticae* Koch, predatory mite, *Phytoseiulus persimilis* Athias-Henriot, based on both laboratory and field evaluations (Blumel and Stolz 1993).

Buprofezin is toxic to the larval stage of predatory ladybird beetles (Grafton-Cardwell and Gu 2003, James 2004); however, it is less harmful to adult ladybird beetles (Smith and Papacek 1990, Cloyd and Dickinson, unpubl. data), although it may have a sterilizing effect on some species (Hattingh and Tate 1995). Buprofezin was nontoxic to other predators as demonstrated in laboratory studies where direct applications did not negatively influence development (nymph to adult) of the predatory bug, *Orius tristicolor* White (James 2004), or female reproduction of the predatory mite, *P. persimilis* (Blumel and Stolz 1993). In general, buprofezin is less toxic to parasitoids (Jones et al. 1998). For example, buprofezin does not affect oviposition of the two whitefly parasitoids, *Eretmocerus* sp. and *Encarsia luteola* Howard when the larvae or adults are exposed to spray residues. Additionally, buprofezin has no effect on the foraging behavior of adult *Eretmocerus* sp. (Gerling and Sinai 1994).

In laboratory studies, tebufenazide was not harmful to the green lacewing, *C. carnea* (Medina et al. 2003). This insect growth regulator, which is primarily used against lepidopteran larvae, does not affect adult green lacewing female reproduction (Medina et al. 2003).

Medina et al. (2003) reported that azadirachtin inhibits oviposition of the green lacewing, *C. carnea*. However, azadirachtin was not toxic to the egg and adult stages of the predatory mite, *P. persimilis* and the western flower thrips, *Frankliniella occidentalis* Pergande predatory mite, *Neoseiulus* (= *Amblyseius*) *cucumeris* Oudemans when exposed to treated bean leaves (Spollen and Isman 1996). Futhermore, the number of eggs laid by the aphid predator, *Aphidoletes aphidimyza* Rondani are not affected by azadirachtin (Spollen and Isman 1996). Rothwangl et al. (2004) reported that direct sprays of azadirachtin are nontoxic to adult *L. dactylopii*.

Insecticidal soap and horticultural oil. Direct spray applications (wet sprays) and short-term residues of insecticidal soap and horticultural oil are toxic to most natural enemies, especially parasitoids. However, once the residues have dissipated, they are less harmful. Studies with the predatory mite, *N. cucumeris*, indicate that this mite is more sensitive to horticultural oil than insecticidal soap (Oetting and Latimer 1995). Direct applications of horticultural oil are lethal to the predatory mite; however, 1-2% concentrations were less toxic. Although insecticidal soap appears to be minimally harmful to the predatory mite, sprays of a 4% insecticidal soap were very toxic (90% mortality after 48 h) (Oetting and Latimer 1995). Direct spray applications of insecticidal soap are extremely toxic (100% mortality) to the predatory mite, *P. persimilis*; whereas, there were no harmful effects 3 d after release (Osborne and Petitt 1985).

Feeding inhibitors. Feeding inhibitors are a relatively new group of insecticides that hinder insects from feeding by interfering with neural regulation of fluid intake via the mouthparts (Kayser et al. 1994, Fuog et al. 1995, Fuog et al. 1998). Pymetrozine was nontoxic to the larval stages of the ladybird beetle, *Coccinella septempunctata* L. (Sechser et al. 2002), and the parasitoids, *E. eremicus* (Hoddle et al. 2001) and *E. formosa* (Hassan and Van de Viere 2004). Flonicamid, a recently introduced feeding inhibitor, is not harmful to the adult stage of the mealybug destroyer *C. montrouzieri*, and *L. dactylopii*. This insecticide also does not affect the ability of *L. dactylopii* to parasitize the citrus mealybug, *Planococcus citri* Risso (Cloyd and Dickinson, unpubl. data).

Entomogenous bacteria. In general, sprays of *Bacillus thuringiensis* (Bt) Berliner are safe to most predators including ladybird beetles, green lacewing, and certain predatory hemipterans. However, initial sprays may delay the development of certain natural enemies. The effects of Bt on different life stages of natural enemies are reportedly highly variable (Croft 1990). Additionally, the effects of Bt may take longer to impact natural enemies compared with other biorational insecticides. The larval stage of certain natural enemies, such as green lacewing (*Chrysoperla* sp.), and ladybird beetles, appear to be more susceptible to Bt sprays than adults (Kiselek 1975). It is important to note that any direct or indirect effects may not be immediately associated with the bacteria, but may be a result of altering the available food source or killing hosts before they complete development (Marchal-Segault 1975).

Entomogenous fungi. Entomopathogenic fungi vary in how they impact natural enemies depending on whether sprays directly affect natural enemies or they consume conidia on plant surfaces. Natural enemies may ingest fungal conidia when either grooming (cleaning themselves) or when feeding on a contaminated host or food source. The fungi *Metarhizium anisopliae* Metsch., and *Beauveria bassiana* (Balsamo) Vuillemin can infect ladybird beetles. Direct sprays of *M. anisopliae* and *B. bassiana* resulted in 97% and 95% mortality, respectively, of adult ladybird beetles; however, the severity of the effect was dependent on the concentration of spores applied (James and Lighthart 1994).

Applications of entomopathogenic fungi may indirectly affect predators that feed on hosts that have been sprayed. For example, 50% of mealybug destroyer, *C. montrouzieri*, larvae died when they consumed mealybugs that were sprayed with a *B. bassiana* commercial product. However, the product was nontoxic to the adult (Kiselek 1975). Adults of the aphid parasitoid, *A. colemani* are highly susceptible to infection by *B. bassiana* conidia (Ludwig and Oetting 2001), but this same fungus displayed no toxic effects to the predatory mite, *N. cucumeris* (Jacobson et al. 2001). Direct applications of the fungus, *Cephalosporium lecanii* Zimm., had no impact on the longevity of the leafminer parasitoid, *Diglyphus begini* Ashmead (Bethke and Parrella 1989). In contrast, direct sprays of this same fungus were determined to be harmful, based on infection by conidia, to the aphid parasitoid, *Aphidius matricariae* Haliday (Scopes 1970), and the greenhouse whitefly parasitoid, *E. formosa* (Ekbom 1979).

Spinosad. The impact of spinosad on natural enemies has been extensively studied since its development as direct applications (wet sprays) of spinosad are extremely toxic to parasitoids (Williams et al. 2003) including *A. colemani* and *E. formosa*; however, any toxic effects generally decrease as the spray residues age (Miles et al., unpubl. data) although spray residues are toxic to *E. formosa* even 28 d after treatment (Jones et al. 2005). Spinosad applications were toxic to the eggs and larvae of *Trichogramma* spp. (Consoli et al. 2001). Applications of spinosad exhibited toxic effects to *E. formosa* and *O. laevigatus* shortly after treatment; however, populations of both were not seriously affected after 2-3 wks. Spinosad had no effect on larvae of the aphid predatory midge, *A. aphidimyza* (Miles et al., unpubl. data).

Spinosad appears to be very compatible with many predatory insects and mites (Williams et al. 2003). Studies demonstrated that spinosad had no direct or indirect effects on the green lacewing, (*C. carnea*) (Medina et al. 2001), ladybird beetle (*Hippodamia convergens* Guerin-Meneville), minute pirate bug (*O. laevigatus*), big-eyed bug (*Geocoris punctipes* Say), and damsel bug (*Nabis* sp.) (Thompson et al. 2000, Copping 2001). Additionally, spinosad did not directly harm predatory mites including *A. californicus*, *P. persimilis*, *Hypoaspis miles* Berlese (Miles and Dutton 2003), and *A. cucumeris* (Miles and Dutton 2003, Jones et al. 2005) at the rates tested.

Conclusions

Many studies referred to above were conducted under laboratory conditions. This represents a "worse-case scenario" in that if there are no harmful effects under these conditions, then it is likely that the biorational insecticide will not be harmful when used in greenhouses or conservatories. In addition, the concentration or application rate also influence whether biorational insecticides will negatively impact natural enemies. To avoid any harmful effects to natural enemies, it is recommended to make releases several days after an application, although applying biorational insecticides may still decrease host quality thus increasing parasitoid or predator mortality. For example, parasitoid females may not lay eggs in unsuitable hosts, and predators may not consume hosts that are an inadequate food source. Applications of biorational insecticides also may kill a majority of the hosts, thus reducing the number of available hosts for natural enemies. Finally, the fact that many biorational insecticides may need to be applied frequently (depending on the pest population) to obtain sufficient control of insect pests increases the likelihood that natural enemies will be exposed to sprays or spray residues. This may have a deleterious effect on foraging behavior or reproduction.

The compatibility of natural enemies with biorational insecticides in integrated pest management programs is highly variable. Interactions are based on the type of biorational insecticide, whether the natural enemy is a parasitoid or predator, and the stage of development. Biorational insecticides are effective for controlling many types of insect pests and are generally less harmful to natural enemies than conventional insecticides, which suggests that they are more likely to be compatible with natural enemies. In general, the use of insecticides in conjunction with natural enemies is more likely to occur in systems that sustain long-term crops such as greenhouse-grown cut flowers or large-scale plantings that are typically established in conservatories. As such, it is important to know the compatibility of biorational insecticides with natural enemies to avoid disrupting successful biological control programs.

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