Review

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Impact of neonicotinoid insecticides on natural enemies in greenhouse and interiorscape environments

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Abstract

The neonicotinoid insecticides imidacloprid, acetamiprid, dinotefuran, thiamethoxam and clothianidin are commonly used in greenhouses and/or interiorscapes (plant interiorscapes and conservatories) to manage a wide range of plant-feeding insects such as aphids, mealybugs and whiteflies. However, these systemic insecticides may also be harmful to natural enemies, including predators and parasitoids. Predatory insects and mites may be adversely affected by neonicotinoid systemic insecticides when they: (1) feed on pollen, nectar or plant tissue contaminated with the active ingredient; (2) consume the active ingredient of neonicotinoid insecticides while ingesting plant fluids; (3) feed on hosts (prey) that have consumed leaves contaminated with the active ingredient. Parasitoids may be affected negatively by neonicotinoid insecticides because foliar, drench or granular applications may decrease host population levels so that there are not enough hosts to attack and thus sustain parasitoid populations. Furthermore, host quality may be unacceptable for egg laying by parasitoid females. In addition, female parasitoids that host feed may inadvertently ingest a lethal concentration of the active ingredient or a sublethal dose that inhibits foraging or egg laying. There are, however, issues that require further consideration, such as: the types of plant and flower that accumulate active ingredients, and the concentrations in which they are accumulated; the influence of flower age on the level of exposure of natural enemies to the active ingredient; the effect of neonicotinoid metabolites produced within the plant. As such, the application of neonicotinoid insecticides in conjunction with natural enemies in protected culture and interiorscape environments needs further investigation.

Keywords: imidacloprid; acetamiprid; thiamethoxam; dinotefuran; clothianidin; parasitoids; predators

1 INTRODUCTION

Systemic insecticides are widely used in interiorscape environments such as greenhouses, conservatories and interiorscapes to deal with the multitude of phloem-feeding insects, including aphids, whiteflies, mealybugs and certain scale insects.[1] Systemic insecticides may be applied to the plant as a foliar spray where the active ingredient directly penetrates plant tissues (leaves and stems), or to the growing medium as a drench or granular application for uptake via the roots and distribution throughout the plant by means of the vascular system (xylem and phloem). During feeding, insects imbibe the active ingredient and are killed if concentrations of the active ingredient are sufficient.[1]

2 NEONICOTINOID INSECTICIDES

The neonicotinoid systemic insecticides that may be used in greenhouse and/or interiorscape environments include imidacloprid [Marathon (OHP, Inc., Mainland, PA) and Merit (Bayer Environmental Science, Research Triangle, NC)], acetamiprid [TriStar (Cleary Chemical Comp., Dayton, NJ)], thiamethoxam [Flagship and Meridian (Syngenta Professional Products, Greensboro, NC)], dinotefuran [Safari (Valent USA, Walnut Creek, CA)] and clothianidin [Arena (Valent USA, Walnut Creek, CA) and Celero (Arysta LifeScience North America Corp., San Francisco, CA); however, Celero has been discontinued]. All neonicotinoid insecticides have a similar chemical structure and mode of action. Common characteristics include the following: (1) they bind to the post-synaptic nicotinic acetylcholine receptors (mode of action); (2) they are primarily used to target phloem-feeding insects such as aphids, whiteflies and mealybugs and certain leaf-chewing beetles; (3) they have positive effects on phytophagous mites and both positive and negative effects on predatory mites; (4) they may be applied, depending on the particular product, as a foliar spray, drench or as a granule to the soil or growing medium, or as trunk injections or sprays; (5) they have both systemic and translaminar properties; (6) they have 12 h or less restricted entry intervals (REIs).[2–6]

Although the neonicotinoid insecticides, as a chemical class, have similar chemical structures, they vary greatly in certain characteristics that influence movement into plants, including water solubility and two physical estimated properties: pK_a and $\log P_{oct}$.[7–9] pK_a is the acid dissociation constant and indicates the strength of an acid. For example, the larger the pK_a value, the weaker is the acid. $\log P_{oct}$ stands for the octanol–water partition coefficient and is related to the lipophilicity of compounds.

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Table 1. Water solubility, acid dissociation constant (p*K*a), octanol-water partition coefficient (log P_{oct}), volatility (vapor pressure), and soil half-life (days or years) of the neonicotinoid insecticides available for use in protected culture and interiorscapes that may be applied either to the foliage or the growing medium (drench or granule)

Active ingredient	Trade name	Application type	Water solubility (mg L^{-1})	pK_a	log P_{oct}	Volatility (vapor pressure)	Soil half-life[a]
Acetamiprid	TriStar	Foliar	2950	0.7	0.8	1.0×10^{-6} Pa[b]	1–8 days[g]
Clothianidin	Celero	Foliar and drench	327	11.1	0.7	3.8×10^{-11} Pa[c]	148–1155 days[h]
Dinotefuran	Safari	Foliar and drench	39 830	12.6	−0.64	1.7×10^{-6} Pa[d]	138 days[i]
Imidacloprid	Marathon	Foliar and drench	500	–	0.57	1.3×10^{-6} Pa[e]	>1 year[j]
Thiamethoxam	Flagship	Foliar and drench	4100	N/A	−0.13	6.6×10^{-9} Pa[f]	25–32 days[k]

[a] Based on aerobic soil metabolism.
[b] http://mwinchem.en.made-in-china.com/product/DbNEqjFPJlh/China-Acetamiprid.html
[c] http://www.arystalifescience.us/usa/files/documents/ARN-009%20Arena%20TIB.pdf
[d] http://www.epa.gov/opprd001/factsheets/dinotefuran.pdf
[e] http://extoxnet.orst.edu
[f] http://www.syngentaprofessionalproducts.com/Env_Stewardship/futuretopics/ThiamethoxamEnvirofacts_7-19-05.pdf
[g] www.epa.gov/opprd001/factsheets/acetamiprid.pdf
[h] www.epa.gov/opprd001/factsheets/clothianidin.pdf
[i] www.epa.gov/opprd001/factsheets/dinotefuran.pdf
[j] npic.orst.edu/factsheets/imidacloprid.pdf
[k] http://www.syngenta-us.com/Env_Stewardship/ThiomethoxamEnvirofacts_7-19-05.pdf

Lipophilicity refers to the ability of compounds to dissolve in fats, oils and lipids. Compounds that are lipophilic (log $P_{oct} > 4$) are generally not systemic, whereas those compounds that are considered moderately or intermediately lipophilic have a log P_{oct} value between 0.5 and 3.5. These compounds travel through the xylem to plant shoots. Uptake by the roots is greater when compounds are more lipophilic.[10,11] Table 1 presents the water solubility, pK_a, log P_{oct} and soil half-life (residual activity or longevity) of neonicotinoid insecticides.

Another potentially important difference may be how neonicotinoid systemic insecticides impact natural enemies or biological control agents such as predators and parasitoids (parasitic wasps). This review will focus on the impact of foliar and drench or granular applications of the neonicotinoid insecticides on predators and parasitoids released and/or sustained in greenhouses, conservatories and interiorscapes. First, a brief introduction outlining the potential effects of systemic insecticides on natural enemies will be given, followed by a discussion of the impact of neonicotinoid systemic insecticides on predatory insects and mites, and then parasitoids, and finally the authors' final thoughts regarding the impact of neonicotinoid insecticides on natural enemies will be set out.

3 EFFECTS OF SYSTEMIC INSECTICIDES ON NATURAL ENEMIES

There are two methods of applying systemic insecticides such as the neonicotinoids to herbaceous plants: foliar sprays and applications to the soil or growing medium (drenches and granular). This results in different exposure scenarios for natural enemies. As such, the extent of insecticide toxicity is governed by intrinsic factors, which may be measured by basic dose–response tests through deliberate exposure of natural enemies, and extrinsic factors that influence the degree of exposure.[12] This includes interactions between operational factors (how systemic insecticides are applied) and insect behavior, which could result in systemic insecticides being more selectively toxic to target insect pests than to natural enemies.[12]

It has been proposed that, when systemic insecticides, in this case the neonicotinoids, are applied as a drench or granule to the soil or growing medium, this reduces toxicity to natural enemies.[4] However, systemic insecticides, as a consequence of initially suppressing populations of hosts (prey), may in fact be detrimental to the establishment and extended survival of natural enemies.[13] So how may applications of the neonicotinoid insecticides impact natural enemies? First, neonicotinoid insecticides may reduce survival by direct contact, which occurs when directed sprays or any residues kill natural enemies or, in the case of parasitoids, kill individuals while developing inside hosts.[14] Second, foliar, drench or granular applications may reduce establishment of natural enemies by killing substantial numbers of hosts. Applications of neonicotinoid insecticides may also result in sublethal effects on reproduction, foraging behavior, fecundity and longevity.[14] For example, foliar residues (both wet and dry) may inhibit volatile cues emitted by hosts, which are used by certain natural enemies to detect host location within plants.[15–17] This may influence foraging behavior and the time required to find hosts. Sublethal effects may also inhibit the ability of natural enemies to establish populations, suppress the ability of natural enemies to utilize a host, impact parasitism (for parasitoids) or consumption (for predators) rates, decrease longevity and progeny production rate, reduce host availability, inhibit ability to recognize hosts and influence the sex ratio (females : males).[18–20]

Drench or granular applications to the soil or growing medium of neonicotinoid systemic insecticides may have a minimal effect on aboveground predators, although there may be effects if mortality of the host population is high (>90%), thus reducing the availability of viable hosts serving as a food source for any predators.[13] For example, applications to the soil or growing medium may kill a large proportion of hosts that natural enemies use as a food source and, as such, make it difficult to locate remaining individuals, although this may be dependent on foraging efficiency. Furthermore, this may also reduce the density or quantity of available viable hosts or reduce the quality of hosts such that they are not acceptable as a food source for predators, or parasitoid females may not lay eggs. Natural enemies feeding on hosts or prey that have fed upon plants and have ingested the active ingredient may be affected.[21] If the active ingredient is

Table 2. A listing of the neonicotinoid insecticides (active ingredients) and the natural enemies (predators and parasitoids) to which the insecticides have demonstrated direct toxicity under either laboratory or field conditions

Active ingredient	Natural enemy	Method of evaluating direct toxicity[a]	Reference
Acetamiprid	*Orius* spp.	LA	19
	Hippodamia convergens	FD	42
	Chrysoperla carnea	FD	42
	Geocoris spp.	FD	42
	Encarsia formosa	LA	19
	Encarsia formosa	LA	47
	Eretmocerus eremicus	LA	47
	Leptomastix dactylopii	LA	39
	Cryptolaemus montrouzieri	LA	39
Clothianidin	*Leptomastix dactylopii*	LA	39
	Atheta coriaria	LA	43
Dinotefuran	*Leptomastix dactylopii*	LA	39
	Atheta coriaria	LA	43
Imidacloprid	*Orius* spp.	LA	55
	Hippodamia convergens	LA	4
	Chrysoperla carnea	LA	4
	Geocoris spp.	LA	55
Thiamethoxam	*Orius* spp.	LA	19
	Encarsia formosa	LA	19
	Atheta coriaria	LA	43

[a] LA: laboratory bioassays using either petri dishes or 473 mL deli squat containers; FD: field evaluation.

distributed into flower parts (petals and sepals), this may directly or indirectly negatively impact natural enemies.[22]

Natural enemies feeding on plant pollen or nectar may also ingest the active ingredient. Furthermore, any repellent properties, based on vapor activity or volatility (Table 1), may prevent natural enemies from entering or recolonizing habitats; however, any behavioral effects that may be observed are likely due to deterrency and sublethal effects associated with direct exposure to the active ingredient.[14] Moreover, it should be noted that there is insufficient quantitative information regarding this phenomenon associated with neonicotinoids. Finally, natural enemies foraging on plant surfaces may be exposed to concentrations of neonicotinoids present in the guttation (dew drops) or droplets of xylem fluid on leaf margins, even when neonicotinoids are applied to the soil or growing medium.[23] There are additional factors that may influence the impact of neonicotinoid insecticides on natural enemies, including life stage (egg, larvae, pupae or adult) exposed, rate applied and formulation. A generalized listing of the neonicotinoid insecticides and commonly used natural enemies (both predators and parasitoids) in which direct toxic effects have been demonstrated is presented in Table 2.

4 IMPACT OF NEONICOTINOID INSECTICIDES ON NATURAL ENEMIES

4.1 Predatory insects and mites

Predatory insects and mites may be negatively affected by neonicotinoid systemic insecticides under the following circumstances: (1) when they feed on pollen or nectar, or plant tissue contaminated with the active ingredient; (2) when they consume the active ingredient while ingesting plant sap; (3) when they feed on hosts that have consumed leaves contaminated with the active ingredient; (4) when they consume hosts that have ingested the active ingredient.[24] Most of the initial and current research investigating the impact of the neonicotinoid insecticides on natural enemies has been with imidacloprid, which was the first active ingredient released in 1995 for commercial use in both agriculture and ornamental cropping systems.[9,25] It was determined by Sclar *et al*.[25] that the minute pirate bug, *Orius tristicolor* (White), was negatively affected after feeding on the leaves of marigold (*Tagetes erecta* L.) plants treated with a soil or growing medium application of imidacloprid. However, in this study, the insects were confined so that they had to feed on the plants, which may not be representative of what would occur in an indoor environment. Moreover, the concentration of imidacloprid in the marigold leaves was not assessed.

In laboratory bioassays, a diverse group of arthropods (lacewings, mites, ladybird beetles, plant bugs and spiders) varied in their susceptibility to imidacloprid,[26] with spiders and predatory mites being less susceptible to imidacloprid than the predaceous insects evaluated. Similarly, under laboratory conditions, imidacloprid was toxic to the adults of *Deraeocoris nebulosus* (Uhler), *Hippodamia convergens* (Guerin-Meneville), *Geocoris punctipes* (Say) and *Chrysoperla rufilabris* (Burmeister), although mortality was dependent on the concentration of imidacloprid applied. However, imidacloprid displayed no harmful effects to the adults of the predatory mites *Neoseiulus collegae* (De Leon) and *Phytoseiulus macropilis* (Banks).[4]

It has been suggested that both exposure method (laboratory versus field) and life stage (larva or nymph versus adult) may influence the level of mortality. For example, Studebaker and Kring[27] determined that imidacloprid was more harmful to *Orius insidiosus* (Say) under laboratory conditions (petri dish bioassays) than under greenhouse conditions. Imidacloprid was shown negatively to influence the longevity of *Chrysoperla carnea* (Stephens) larvae and adults.[28] Elbert *et al*.[29] reported that exposure of *C. carnea* larvae to imidacloprid resulted in a 40% reduction in the population under field conditions. Imidacloprid was determined to be extremely harmful to *C. carnea* third-instar larvae, and inhibited adult emergence as well as killing a high proportion of newly emerged adults.[30] Delbeke *et al*.[31] found that imidacloprid was toxic via contact and ingestion to the nymphal and adult stages of *Orius laevigatus* (Fieber), with fifth-instar nymphs more susceptible than adults.

In a greenhouse study, Rogers *et al*.[32] demonstrated that *C. carnea* survival was reduced after feeding on the nectar of buckwheat, *Fagopyrum esculentum* Moench, and Mexican milkweed, *Asclepias curassavica* L., plants that received a soil application of imidacloprid at both the recommended label rate (6.0 g ha^{-1}) and twice the label rate (12.0 g ha^{-1}). Furthermore, the applications appeared to result in translocation into flowers, leading to a decline in the survival of adult *C. carnea* after feeding on nectar. It was discovered that imidacloprid was present in flowers at concentrations of 0 ppb (untreated plants) and 15 ppb in the nectar of plants treated at the label rate.[32] However, the water solubility of imidacloprid, which is 0.51 g L^{-1} at 20 °C, suggests that it may not be able to translocate efficiently or takes longer to be distributed into the floral parts (petals, sepals, pollen and nectar) of plants, whereas those with greater water solubility such as dinotefuran (39.8 g L^{-1}) may be more readily translocated into floral parts.[33] Moreover, only low levels (0.005–0.01 mg kg^{-1}) of the imidacloprid metabolites, olefine and 4- and 5-hydroxy, have been detected in the pollen and nectar of corn, *Zea mays* L., and sunflower, *Helianthus* spp., plants.[9]

It should be noted that the relevance of this study is questionable, as neither of these plant types is commercially grown in greenhouses.[32] In addition, using twice the label rate on these plants may be unrealistic, as well as an off-label use. Furthermore, green lacewings were confined to feeding just on these plants. Although this study provides important data on the potential impact and translocation of imidacloprid in flowering plants, it may be inappropriate to generalize on the basis of a single study and just a few plant species. In reality, green lacewing adults would likely feed on the pollen and nectar from many different flower types (if available) and flowers of different ages, which may impact their actual exposure to imidacloprid residues in flowers. Long *et al*.[34] demonstrated that *C. carnea* moves 6–100 ft within a habitat and feeds on a variety of different flowering plants that are in bloom during certain times of the year. It was reported that applying rubidium (Rb) to plants may be a means to determine the feeding preferences of *C. carnea* on the basis of the floral resources available.[34]

In another study, pink lady beetle, *Coleomegilla maculata* (DeGeer), adults experienced reduced mobility and 38% mortality when confined to the flowers of sunflower, *Helianthus annuus* L., chrysanthemum, *Chrysanthemum morifolium* Ramat., and dandelion, *Taraxacum officinale* Wiggers, plants treated with a drench application of imidacloprid,[35] indicating that imidacloprid had translocated into the flowers. As with Rogers *et al*.[32] and Sclar *et al*.[25], the confining of natural enemies may not be representative of what occurs in greenhouses and conservatories, as natural enemies may feed on diverse plant types at different growth or flowering stages. In fact, the toxic effects of imidacloprid may be dependent on the development stage, length of exposure and properties of the product, such as formulation and concentration of active ingredient.[29] In addition, it is just as essential to assess any sublethal effects of the neonicotinoid insecticides. A final consideration is the age of the natural enemy, which may also influence the level of susceptibility to either foliar residues or drench or granular applications to soil or growing medium.

Foliar applications, in general, are likely to be more harmful to natural enemies than drench or granular applications made to soil or growing medium. For example, foliar applications of imidacloprid reduced progeny production and survival of vedalia beetle, *Rodolia cardinalis* Mulsant, adults and inhibited development of larvae to adult.[21] However, it is known that certain natural enemies will in fact feed on plant tissues to supplement their diet by feeding directly on plant parts (leaves or stems) or consuming pollen or nectar in flowers.[22] As such, the translocation of the active ingredient of neonicotinoid insecticides into flowers may impact on natural enemies via ingestion or by means of repellency or volatility. Moreover, a reduction in mobility could influence prey-finding by natural enemies.[14]

It is important to mention that exposure to imidacloprid may not always lead to negative effects. In laboratory bioassays, topical applications of imidacloprid were not toxic to the predatory mite *Anystis baccarum* (L.) after 48 h.[36] Furthermore, exposure to imidacloprid has been shown to increase egg production of the predatory mite *Amblyseius victoriensis* Womersley,[37] with treated females producing 1.9–2.0 eggs per day compared with the 1.3–1.6 eggs laid per day by untreated females. Moreover, wet residues of imidacloprid may act as a repellent or stimulate locomotion of this mite.[37]

Overall, the quantity of research conducted with the other neonicotinoid insecticides such as acetamiprid, clothianidin, dinotefuran and thiamethoxam is relatively less than with imidacloprid. However, in studies with the plant bug, *Deraeocoris brevis* (Uler), the neonicotinoid insecticide acetamiprid did not affect egg hatch, but residues were toxic to newly hatched nymphs. Acetamiprid, when topically applied to nymphs and adults, did not influence development or reproduction.[38] Nonetheless, it has been shown that acetamiprid, clothiandin and dinotefuran, at labeled rates, when applied as a foliar spray, are toxic to the adult stage of the coccinellid predator *Cryptolaemus montrouzieri* (Mulsant).[39] Studies have also shown that acetamiprid is toxic to or depresses populations of certain predatory insects, including *G. punctipes, O. tristicolor, C. carnea, H. convergens, Stethorus japonicus* Kamiya and *Harmonia axyridis* (Pallas).[40–42] In laboratory bioassays, van de Veire and Tirry[19] ascertained that both acetamiprid and thiamethoxam were harmful to *O. laevigatus, Macrolophus caliginosus* (Wagner) and *Amblyseius californicus* (McGregor). Similarly, acetamiprid and thiamethoxam residues were determined to be directly toxic and also inhibited feeding of the spined soldier bug, *Podisus maculiventris* (Say), with the residues of both insecticides more harmful to the nymphs than the adults.[24] In another study, topical applications of acetamiprid and thiamethoxam, in laboratory bioassays, were non-toxic to the predatory mite *A. baccarum* after 48 h exposure.[36]

The impact on natural enemies feeding on hosts that have consumed the active ingredient of neonicotinoid insecticides has also been investigated. For example, vedalia beetle larvae that fed on cottony cushion scale, *Icerya purchasi* Williston, that had ingested acetamiprid, imidacloprid or thiamethoxam were negatively affected, although direct contact via foliar applications tended to be more toxic to adults than feeding on cotton cushion scales that had ingested the active ingredient.[21] Adult survival was negatively impacted by foliar applications of both acetamiprid and imidacloprid, whereas applications to the soil were less detrimental, especially to the adults. Larvae appeared to be more susceptible than adults to exposure to foliar applications. This demonstrates that predators may be exposed to neonicotinoid insecticides by feeding on hosts that have ingested and accumulated concentrations of the active ingredient. In addition, this study also suggests that stage susceptibility may be a factor that influences the impact of both foliar and/or soil (growing medium) applications of neonicotinoid insecticides.

Cloyd *et al.*[43] found clothianidin, dinotefuran and thiamethoxam to be toxic to rove beetle, *Atheta coriaria* Kraatz, adults when applied to the growing medium; however, toxicity was less pronounced when adults were released at least 96 h after application.

4.2 Parasitoids

There are fewer studies evaluating the impact of neonicotinoid insecticides on parasitoids than for predators, which may be due to the complexity of the experimental designs. Wet sprays of any insecticide are toxic to most parasitoids; however, there may be sublethal effects on the rate of parasitism, host feeding and foraging efficiency. For example, foliar, drench or granular applications to the soil or growing medium of neonicotinoid insecticides may decrease host quality, and, as such, parasitoid females may not lay eggs. Although certain armored-scale parasitoids developing underneath the scale coverings may be protected from foliar applications of neonicotinoid insecticides,[44] these parasitoids may be exposed to foliar residues through preening or consuming residues when chewing holes through scale covering during emergence.[45]

It has been reported that foliar applications of imidacloprid may impair survival and parasitoid activity. For example, the parasitoid *Microplitis croceipes* (Cresson) experienced a 25% reduction in longevity and 77% decrease in host-finding efficiency when exposed to the nectar of plants treated with a foliar application of imidacloprid.[46] Acetamiprid, clothianidin and dinotefuran were shown to be harmful to the citrus mealybug, *Planococcus citri* Risso, parasitoid, *Leptomastix dactylopii* Howard, 24 h after exposure.[39] Rill *et al.*[45] determined that acetamiprid residues were non-toxic to immatures, but were very toxic to newly emerged adults of the scale parasitoid, *Aphytis melinus* DeBach. Residues also inhibited adult emergence and negatively affected adult survival. In laboratory bioassays, which involved spraying glass plates in a spray chamber (1.5 mL spray volume cm^{-2}) at recommended label rates, both acetamiprid and thiamethoxam were detrimental to *E. formosa* adults.[19] Acetamiprid was shown to be toxic to both *Gonatocerus ashmeadi* Girault and *A. melinus*, but was not harmful to *E. formosa* and *Eretmocerus eremicus* Rose & Zolnerowich 24 h after exposure using petri dish bioassays. However, there was variability in susceptibility after 48 h exposure.[47] Medina *et al.*[48] reported that direct applications of imidacloprid were not harmful to the endoparasitoid *Hyposoter didymator* (Thunberg), although adult emergence was reduced from the larvae of *Spodoptera littoralis* (Boisduval) that had ingested residues of imidacloprid, which is associated with the fact that developing parasitoid larvae were killed during development. This demonstrates that endoparasitoids may be exposed to the active ingredient of neonicotinoid insecticides while developing inside the host body.[49] Soil-applied applications of imidacloprid may negatively affect parasitoids when feeding on nectar. For example, there was a reduction in survivorship of the parasitoid *Anagyrus pseudococci* (Girault) after feeding on the nectar of buckwheat, *F. esculentum*, plants treated with soil applications of imidacloprid.[50]

5 SUMMARY

Based on what has been presented in this paper, it is essential to assess the impact of neonicotinoid insecticides on natural enemies. Furthermore, research results should be associated with the application of neonicotinoid insecticides under realistic conditions. For example, it must be noted that 100% coverage of the insecticides is obtained in laboratory assays when using leaf disks, whereas on whole plants in greenhouses, conservatories and interiorscapes this is usually not the case. If natural enemies find locations where there are no residues, they may avoid any direct effects and can continue development and reproduction.[51] Additionally, the testing or evaluation procedures (methodology) may impact the results obtained.[52] The substrate used in laboratory bioassays (plastic versus glass), for example, may influence the activity of a specific insecticide.[53,54] Moreover, standard laboratory bioassays may fail to take into account the various direct and sublethal effects of insecticides, resulting in an underestimation of their total impact.[54] As such, in order to simulate actual greenhouse and interiorscape environments, the authors recommend that replicated studies be conducted using large-scale screening cages (similar to those used in field crop studies) and include a variety of plant species.

Further investigation is warranted to determine what types of plant and flower accumulate active ingredient and at what concentrations. In addition, flower age may influence not only the level of exposure of natural enemies but also the concentration of active ingredient that amasses. There could be a dilution effect when comparing recently opened flowers with flowers that are senescing. As such, it may be necessary to time the releases of natural enemies either before or after flowering, or to initiate releases when only a certain proportion of plants are in flower. However, this may be dependent on determining which flowers accumulate lethal concentrations of the active ingredient. Nonetheless, even if concentrations of the active ingredient are not directly lethal, they may be repellent (antifeedant) or disrupt the feeding activity of natural enemies.

It is also possible that plant and flower morphology may influence the movement of the active ingredient into floral parts (petals, sepals, pollen and nectar) and the concentration present in nectar that natural enemies are exposed to; however, this needs to be investigated further. Therefore, appropriate interpretation of results obtained in the laboratory to what is likely to occur in greenhouses or conservatories is essential, as there may be either over- or underestimations associated with effects on natural enemies. Furthermore, results from topical assays conducted in the laboratory have limits when extrapolated to interiorscape environments.[52] Another factor to consider is that commercially available predators that are shipped as adults without a supplemental food source may be starved, so they will consume and ingest large quantities of pollen and nectar when first released, thus increasing their exposure to concentrations of the neonicotinoid active ingredient that may have accumulated in flowers.

Finally, the impact of metabolites with different water solubility and toxicity to natural enemies than the parent compound has not been investigated. A number of active ingredients are converted into metabolites that may be more water soluble and toxic to natural enemies than the actual active ingredient. For example, imidacloprid is converted to a number of metabolites within certain plants including cotton, *Gossypium hirsutum* L., eggplant, *Solanum melongena* var. *esculentum* Ness., and potato, *Solanum tuberosum* L.[9] The use of natural enemies in conjunction with neonicotinoid insecticides in interiorscape environments may be too complex, based on factors presented in this paper, to be readily understood through a reductionistic approach, because many factors may contribute to the relative toxicity of neonicotinoid insecticides to the target pest(s) and their natural enemies. As such, life table studies of both insect pest and natural enemy populations under realistic conditions may be required to understand whether neonicotinoid insecticides can be successfully integrated with biological control.

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