FORUM

Limitations to Use of Topical Toxicity Data for Predictions of Pesticide Side Effects in the Field

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J. Econ. Entomol. 88(5): 1081–1088 (1995)

ABSTRACT We consider ways in which laboratory-derived toxicity data might be used to predict the safety of insecticides to beneficial invertebrates. A model test system consisting of a predator, the convergent lady beetle, *Hippodamia convergens* Guérin-Méneville (larvae and adults); a parasitoid, *Aphidius ervi* Haliday; and the bee species *Apis mellifera* L., *Megachile rotundata* (F.), and *Nomia melanderi* (Cockerell) was tested with diazinon, imidacloprid, and RH-7988 [ethyl (3-*tert*-butyl-1-dimethyl carbamoyl-1*H*-1,24-triazol-5-ylthio) acetate]. We also tested the pea aphid, *Acyrthosiphon pisum* (Harris), to calculate selectivity ratios for these beneficial species, which coexist with the aphid pest in Washington State pea and alfalfa ecosystems. Topical toxicity was estimated for all species and ranged 0.0002–0.45 micrograms per insect for diazinon, 0.000031–0.04 micrograms per insect for imidacloprid, and 0.0015–6.11 micrograms per insect for RH-7988. Selectivity ratios based on these values spanned 0.02–47.4, 12.9–1,290.3, and 13.3–4,073 for diazinon, imidacloprid, and RH-7988, respectively. Risk assessment indices based on probit substitution (estimate of mortality of beneficial species at LD_{90} for the pest) and 2 standard methods for bees, a sequential testing scheme and a hazard index gave variable predictions of the compatibility of these compounds with integrated pest management. We conclude that predictive methods must advance to consider relative exposure rates to pesticides, aspects of chemical fate, and behavior of the organisms concerned if they are to be useful. Above all, predictions must be validated with field data.

KEY WORDS risk assessment, selective insecticides, topical toxicity

MANY OF THE insecticides commonly used today are devastating to populations of biological control organisms (Croft 1990) and pollinators (Johansen 1977) in that they hinder the implementation and effectiveness of integrated pest management (IPM) (NRC 1989, Poehling 1989). One direction in chemical insect control that might alleviate this situation is the development and use of selective insecticides. Such chemicals may offer an opportunity for integration of chemical and biological control in a more sustainable way. However, scientific methods must advance so that the risks posed by insecticides to natural enemies and pollinators can be predicted reliably. These methods could be applied as one of the steps in registration of agrochemicals or after release and marketing to determine the chemicals value for specific IPM programs. In Europe, for example, standardized test procedures to determine the hazards of pesticides to beneficial invertebrates are now part of the pesticide regulatory protocol (Jepson 1993a). In the United States, compatibility of insecticides with IPM tends to be determined after a pesticide is registered.

A pesticide is considered selective when it is more toxic to a pest than to a beneficial species. Selectivity can be expressed in both physiological and ecological terms (Pickett 1988, Van Emden 1988, Croft 1990). Physiological selectivity results from differences in uptake, detoxification processes, and excretion that exist between different arthropod species; this type of selectivity is rare in IPM (Croft 1990). Ecological selectivity is more complicated because it arises through differences in exposure to pesticides, with the natural enemy being exposed to less pesticide per individual than the pest species. Ecological selectivity may result from differences in behavior and biology, or be a function of pesticide distribution, spray timing, differences in bioavailability achieved by formulation, or physiochemical properties (Graham-Bryce 1987, Croft 1990, Jepson et al. 1995).

In the past, selectivity ratios (LD_{50} of a beneficial species ÷ LD_{50} of a pest species) based on topical toxicity data have been considered sufficient to make decisions about the use of pesticides in IPM programs. Although physiological selectivity is theoretically important, extrapolating topical toxicity data to field effects may not be as straightforward as it may seem. These data are used in all

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0022-0493/95/1081–1088$02.00/0

aspects of pest control from the screening of new insecticides to the assessment of resistance and formulation of resistance management strategies. However, the problems of extrapolation from the laboratory to the field, which trouble the whole of ecotoxicology as a discipline, have not penetrated the crop protection literature to date.

In this article, we calculate several risk assessment indices with beneficial invertebrates based on topical diversity data. We consider the potential limitations of each of these and explore the scientific basis for extrapolation of risks from the laboratory to the field. For our model system we chose the pea aphid, *Acyrthosiphon pisum* (Harris) (Homoptera: Aphididae), which is a pest of crops including peas and alfalfa, and a complex of beneficial arthropods that are associated with these crops. The pesticides we tested, diazinon, imidacloprid, and RH-7988 [ethyl (3-*tert*-butyl-1-dimethyl carbamoyl-1*H*-1,24-triazol-5-ylthio) acetate], are candidate treatments for this system because the 2 more widely used insecticides, ethyl parathion and phosdrin, were recently banned.

Materials and Methods

Insects. Pea aphid, *A. pisum,* the convergent lady beetle, *Hippodamia convergens* Guérin-Méneville (Coleoptera: Coccinellidae), and the aphid parasitoid, *Aphidius ervi ervi* Haliday (Hymenoptera: Aphidiidae), were all obtained from cultures maintained at Washington State University, Puyallup Research and Extension Center, Puyallup, WA, for the past 3 yr. *A. pisum* was raised on broad bean, *Vicia faba* var. Banner XM 980. The honey bee, *Apis mellifera* L. (Hymenoptera: Apidae), and the alfalfa leaf cutting bee, *Megachile rotundata* (F.) (Hymenoptera: Megachilidae), were obtained from colonies maintained at Washington State University, Prosser Irrigated Agriculture Research and Extension Center, Prosser, WA. The alkali bee, *Nomia melanderi* (Cockerell) (Hymenoptera: Halictidae), was collected from the field before treatment. All species were maintained in environmental chambers at 25 ± 1°C and 78 ± 5% RH with a photoperiod of 16:8 (L:D) h. The beneficial species were chosen to span a taxonomic and body weight range that was representative of nontarget species in the pea and alfalfa agroecosystem. Ideally, we also would have included ground-based polyphagous predators such as Carabidae or Linyphiidae.

Chemicals. The insecticides tested were: diazinon (technical grade, 88.3% pure) provided by Ciba, Greensboro, NC; imidacloprid (technical grade, 95.8% pure) provided by Miles, Kansas City, MO; and RH-7988 (technical grade, 96.3% pure) provided by Rohm & Haas, Philadelphia, PA. Diazinon is a nonsystemic organophosphate insecticide. Imidacloprid is a new systemic insecticide which has a mode of action similar to nicotine, but is much less toxic to mammals (Anonymous 1992). RH-7988 represents a new class of neurotoxins that are inhibitors of cholinesterase. This product is also systemic and is reported to be selective against aphids (Anonymous 1989).

Topical Toxicity. All test solutions were formulated in acetone (reagent grade or better). Groups of 10 adult pea aphid (24–48 h old) were anesthetized briefly with CO_2 and treated topically with a Hamilton repeating syringe (Hamilton, Reno, NV) by applying 0.5-μl drops of insecticide solution to the thoracic dorsum. After initial range-finding tests, a series of between 5 and 7 logarithmically spaced concentrations were used that resulted in mortality of between 10 and 90%. Groups of 10 adult and 10 3rd instar *H. convergens* (24–48 h old) and adult *A. ervi* (24–48 h old) were also treated as described above, except that *A. ervi ervi* were treated with 0.2-μl drops of insecticide solution. The bee species were also treated as described above except that *M. rotunda* and *N. melanderi* were anesthetized by chilling for 5 min in a refrigerator (4°C) before treatment and all 3 bee species were treated with 1-μl drops of insecticide solution. Mortality was recorded 24 h after treatment. Each topical application test was replicated at least 3 times with different generations of insects.

Toxicity data were expressed per insect and per unit body weight. Significant differences in the ranking of toxicity between species with these may indicate that penetration rates, detoxification mechanisms, or excretion vary between taxa (Stark and Sherman 1989). For completeness, explorations of pesticide intrinsic toxicity should include data expressed per insect and per unit body weight (Wiles and Jepson 1993).

Risk Assessment. Four methods of risk assessment for pesticides were used to make example recommendations about the practical use of these products in IPM. First, we estimated *selectivity ratios* as

$$\text{selectivity ratio} = \text{LD}_{50} \text{ of } X \div \text{LD}_{50} \text{ of } Y \quad (1)$$

where X = the beneficial species (μg per insect) and Y = the pest species (μg per insect). Values >1 indicate lower toxicity to the beneficial species.

Next, we used *probit substitution* (see equation 2) to determine relative toxicities of beneficial species at particular levels of pest mortality. This method involved substituting the log LD_{90} (micrograms per insect) and its 95% FL for the pest species, *A. pisum,* into modified probit equations (Finney 1971) for each insecticide and beneficial species. For probit programs that estimate probabilities (for example, SAS Probit procedure), equation (2) is used.

$$Y = 5 + m(x - [\log \text{LD}_{50} \text{ of beneficial species}]) \quad (2)$$

where Y = probit value, m = the slope of the probit line for the beneficial species, x = log LD_{90} or log of the fiducial limits for the LD_{90} of the pest

Table 1. Toxicity of diazinon to pea aphid and several beneficial insect species

Species	*n*	Slope ± SEM	Mean body w, mg	LD_{50} (95% FL), μg/g	LD_{50} (95% FL), μg/insect	Selectivity ratio[a]
A. pisum	180	3.21 ± 0.67	2.67	3.56 (3.02–4.20)	0.0095 (0.0081–0.0112)	—
H. convergens						
3rd instars	220	5.15 ± 1.23	8.30	19.53 (10.72–26.54)	0.16 (0.089–0.220)	16.8
Adults	140	2.88 ± 0.67	17.33	9.87 (6.71–12.31)	0.17 (0.12–0.21)	17.9
A. ervi ervi	120	3.08 ± 0.67	0.67	0.30 (0.23–0.38)	0.0002 (0.0002–0.0003)	0.02
A. mellifera	150	7.67 ± 0.76	127.5	1.79 (1.33–2.50)	0.23 (0.17–0.32)	24.2
M. rotundata	150	8.04 ± 1.00	30.1	3.98 (1.99–6.31)	0.12 (0.06–0.19)	12.6
N. melanderi	150	6.10 ± 0.58	86.4	5.22 (4.29–5.80)	0.45 (0.37–0.50)	47.4

[a] Selectivity ratio = LD_{50} of beneficial species (micrograms per insect)/LD_{50} of *A. pisum* (micrograms per insect).

species (the pea aphid in this study). Solving for *Y* gives a probit value which is then converted to percentage of mortality using a conversion table (Finney 1971).

For probit programs that transform percentage of mortality to probits (for example, maximum likelihood program [Ross 1987]), equation (3) can be used.

$$Y = mx + b \quad (3)$$

where *Y* = probit value, *m* = the slope of the probit line for the beneficial species, *x* = log LD_{90} or log of the fiducial limits for the LD_{90} of the pest species, and *b* = the intercept of the probit line for the beneficial species. Solving for *Y* gives a probit value, which is then converted to percentage of mortality with a conversion table (Finney 1971).

We used equation (2); it was solved 3 times for the LD_{90} value and its upper and lower fiducial limits. Use of probit substitution in this manner results in topical mortality estimates for the beneficial species at a dose that would kill 90% of the pest species. The 90% mortality level of the pest species provides an indication of the potential for mortality in nontarget species at a dose likely to result in effective pest control, assuming exposure levels to be equivalent. Doses other than the LD_{90} could also have been used in the equation as well as any other pest and beneficial species.

Next, we used step 1 of the *sequential testing scheme* for bees and pesticides developed by Johansen and Mayer (1990) to make predictions about pesticide hazard. In this scheme, hazard is determined by the LD_{50} as: LD_{50} (micrograms per insect) > 100 micrograms per bee = nontoxic product, no further testing required; LD_{50} (micrograms per insect) = 11–100 micrograms per bee = slightly toxic product, continue with bioassay of field-weathered residue; LD_{50} (micrograms per insect) = 2–10.9 micrograms per bee = moderately toxic product, continue with bioassay of field-weathered residue; LD_{50} (micrograms per insect) < 2 micrograms per bee = highly toxic product that is unacceptable for use. Although developed for bees, we used this method and resultant values and the hazard ratio method described below for the predator and parasitoid species as well as for bees.

Finally, we calculated *hazard ratios* (equation 4), which determine the theoretical number of toxic doses per unit area (Smart and Stevenson 1982, Felton et al. 1986).

$$\text{Hazard ratio} = \text{recommended field rate} \cdot (\text{g[AI]/ha})/LD_{50} \cdot (\text{micrograms per insect}) \quad (4)$$

In the United Kingdom, insecticides with hazard ratios to bees of <50 are considered harmless and 50–2,500 are slightly to moderately toxic; when the ratio is >2,500, the pesticide is considered dangerous (Felton et al. 1986). Many products or product combinations have been shown to be toxic by use of this approach (for example Pilling and Jepson 1993). The recommended field rates for control of *A. pisum* in peas are 466 g (AI)/ha for diazinon and 50 g (AI)/ha for imidacloprid. A range of field rates (70–140 g [AI]/ha) for RH-7988 are recommended for pea aphid control (Anonymous 1989).

Statistical Analyses. Dose–mortality regressions were estimated by probit analysis (SAS Institute 1985). Abbott's (1925) formula was used to correct for control mortality. Differences in toxicity were considered significant when fiducial limits did not overlap. Pearson correlations between LD_{50} (micrograms per insect) and insect weight (milligrams) were estimated (Wiles and Jepson 1992) with SAS (SAS Institute 1985).

Results

Toxicity. The order of susceptibility to diazinon at LD_{50} (μg/g) from most susceptible to least was *A. ervi ervi* > *A. mellifera* > *A. pisum* = *M. rotundata* = *N. melanderi* > adult *H. convergens* = larval *H. convergens*, where > indicates a significant difference in median toxicity at $P \leq 0.05$ (Table 1). When toxicity was expressed as micrograms per insect (a more practical estimate for extrapolation to the field), the parasitoid *A. ervi* was again the most susceptible species followed by *A. pisum*. The toxicity of diazinon at the LD_{50} (micrograms per insect) did not differ significantly among *H.*

Table 2. Toxicity of Imidacloprid to pea aphid and several beneficial insect species

Species	*n*	Slope ± SEM	Mean body w, mg	LD_{50} (95% FL), μg/g	LD_{50} (95% FL), μg/insect	Selectivity ratio[a]
A. pisum	180	2.36 ± 0.57	3.36	0.0094 (0.0074–0.013)	0.000031 (0.000025–0.000044)	
H. convergens						—
3rd instars	160	2.52 ± 0.56	7.10	0.11 (0.09–0.15)	0.00078 (0.00064–0.0011)	25.2
Adults	200	4.35 ± 0.82	15.30	0.68 (0.56–0.77)	0.010 (0.0086–0.012)	322.6
A. ervi ervi	100	1.04 ± 0.26	0.52	0.76 (0.16–1.84)	0.0004 (0.00008–0.0010)	12.9
A. mellifera	150	1.55 ± 0.04	127.5	0.34 (0.24–0.49)	0.04 (0.03–0.06)	1,290.3
M. rotundata	150	1.48 ± 0.06	30.1	1.39 (1.06–2.16)	0.04 (0.03–0.07)	1,290.3
N. melanderi	150	1.52 ± 0.06	86.4	0.46 (0.23–0.93)	0.04 (0.02–0.08)	1,290.3

[a] Selectivity ratio = LD_{50} of beneficial species (micrograms per insect)/LD_{50} of *A. pisum* (micrograms per insect).

convergens larvae and adults, *A. mellifera* and *M. rotundata*. *N. melanderi* was the least susceptible species.

Imidacloprid was 379-fold more toxic to *A. pisum* than diazinon (Table 2). This chemical was also more toxic to *H. convergens* (both larvae and adults), *A. mellifera*, and *N. melanderi* than was diazinon, whereas *A. ervi ervi* and *M. rotundata* were equally susceptible to both insecticides (Table 2). *A. pisum* was the most susceptible species to this product, with the order of susceptibility from most to least susceptible being *A. pisum* > larval *H. convergens* > *A. ervi* = *A. mellifera* = *N. melanderi* = adult *H. convergens* > *M. rotundata*.

In terms of μg per insect, *A. pisum* was again the most susceptible species, followed by larval *H. convergens*, *A. ervi ervi*, and adult *H. convergens* (Table 2). Of the beneficial species, the bees were the least susceptible to imidacloprid; they were all equally susceptible to this product at the LD_{50}.

RH-7988 was ≈7-fold more toxic to *A. pisum* than diazinon and 55-fold less toxic than imidacloprid (Table 3). This insecticide was much less toxic to all of the beneficial species tested than diazinon and was also less toxic to the beneficial species than imidacloprid. The order of susceptibility at LD_{50} (μg/g) was *A. pisum* > *A. ervi ervi* > larval *H. convergens* = adult *H. convergens* > *A. mellifera* > *N. melanderi* > *M. rotundata*. When LD_{50}s were expressed in terms of micrograms per insect, the order of susceptibility did not change.

The relationship between body weight and susceptibility varied as might be expected for such chemically different insecticides and physiologically different insects. We detected a weak correlation between LD_{50} and body weight ($r = 0.71$, $P = 0.074$) for diazinon when all species were compared. For imidacloprid, the correlation between body weight and LD_{50} was significant and positive ($r = 0.82$, $P = 0.025$), indicating that heavier insects were less susceptible than lighter ones to this insecticide. The correlation between body weight and LD_{50} was not significant ($r = 0.56$, $P = 0.19$) for RH-7988.

Risk Assessment. Selectivity ratios indicated that at the LD_{50}, diazinon is a marginally selective insecticide that is more toxic to *A. pisum* than to all of the beneficial species tested, except *A. ervi ervi* (Table 1). Imidacloprid was more selective than diazinon whereas RH-7988 was the most selective insecticide tested (Tables 2 and 3). *A. ervi* exhibited equivalent selectivity ratios for both imidacloprid and RH-7988, although it was far more susceptible to imidacloprid. If the selectivity ratio method was used as the only method of evaluation, all 3 insecticides might be recommended for use in IPM programs, with imidacloprid and RH-7988 showing the most promise (Table 4).

Probit substitution demonstrated that mortality in all beneficial species except *A. ervi ervi* would be ≤1%. However, doses that caused 90% mortality in *A. pisum* were predicted to cause 100% mortality of *A. ervi ervi* for diazinon, 21–51% mortality for imidacloprid, and 5–29% for RH-7988 (Table 5). If probit substitution was used to make recommendations for selection of these insecticides in IPM programs, only imidacloprid and RH-7988 would be recommended (Table 4) because of the potential importance of hymenopteran parasitoids

Table 3. Toxicity of RH-7988 to pea aphid and several beneficial insect species

Species	*n*	Slope ± SEM	Mean body w, mg	LD_{50} (95% FL), μg/g	LD_{50} (95% FL), μg/insect	Selectivity ratio[a]
A. pisum	220	2.36 ± 0.49	2.84	0.52 (0.39–0.62)	0.0015 (0.0011–0.0018)	—
H. convergens						
3rd instars	240	1.95 ± 0.26	8.30	238.70 (188.68–314.70)	1.98 (1.57–2.61)	1,320
Adults	280	1.60 ± 0.25	12.06	114.48 (85.44–156.98)	1.38 (1.03–1.89)	920
A. ervi ervi	140	2.38 ± 0.76	0.62	30.21 (13.89–42.79)	0.02 (0.009–0.027)	13.3
A. mellifera	150	3.36 ± 0.24	127.5	26.21 (21.61–31.75)	3.36 (2.77–4.07)	2,240
M. rotundata	150	4.04 ± 0.50	30.1	202.85 (191.90–232.73)	6.11 (5.78–7.01)	4,073.3
N. melanderi	150	3.89 ± 0.38	86.4	58.23 (48.14–64.03)	5.02 (4.15–5.52)	3,346.7

[a] Selectivity ratio = LD_{50} of beneficial species (micrograms per insect)LD_{50} of *A. pisum* (micrograms per insect).

Table 4. Comparison of the recommendations of several risk assessment methods

Risk assessment method	Recommendation for use in IPM program		
	Diazinon	Imidacloprid	RH-7988
Selectivity ratio	Perhaps	Yes	Yes
Probit substitution	No	Yes	Yes
Sequential testing scheme	No	No	More testing required
Hazard ratio	No	No	Yes

in aphid population limitation (Wratten and Powell 1991).

The sequential testing scheme of Johansen and Mayer (1990) predicted that diazinon and imidacloprid would be highly toxic to all of the beneficial species in the field because the topical LD_{50} (micrograms per insect) of each chemical was <2 μg per insect. RH-7988 is predicted to be highly toxic to *H. convergens* and *A. ervi ervi* and moderately toxic to the 3 bee species. If the sequential testing scheme was used to make recommendations for IPM, none of these insecticides would be recommended.

Hazard ratios predicted that diazinon was hazardous to all beneficial species except *A. mellifera* and *N. melanderi* at the currently recommended field rate (Table 6). Ratios indicated that imidacloprid would be hazardous to larval and adult *H. convergens* and *A. ervi ervi,* but not to the bee species. RH-7988 was predicted to be the least hazardous product that we evaluated. This product should be harmless to *H. convergens* larvae and adults at the low field rate, and slightly toxic at the higher field rate. RH-7988 should also be harmless to all of the bee species; however, our results predicted this chemical would be dangerous to *A. ervi ervi.* If the hazard ratio method was chosen to make recommendations for IPM, only RH-7988 would be recommended (Table 4).

Discussion

Our study indicated a range of physiological selectivity exists between diazinon, imidacloprid, and RH-7988, with diazinon being the least selective product and RH-7988 the most selective. Selectivity ratios as high as those for RH-7988 have rarely been reported before for arthropod species (see Croft 1990).

Susceptibility to the insecticides that we tested was a result of species-specific factors rather than simply to differences in body weight between the species. Robertson and Preisler (1992) indicate that body weight is not always correlated with susceptibility. Although Wiles and Jepson (1992) evaluated the susceptibility of a range of natural enemies of the cereal aphid, *Sitobion avenae* (F.), and found that, in general, the susceptibility ranking closely followed body weight, this relationship was most apparent within closely related taxa (Coleoptera or Carabidae alone). Our data indicate that generalizations between species or active ingredients are impossible until the research into their effects over a wide taxonomic range is undertaken. Testing procedures must therefore evaluate effects against a taxonomic range that represents the cropping system in question (Jepson 1993a).

Recommendations of the use of insecticides in IPM programs have been made in the past based on topical toxicity data, particularly by using selectivity ratios (for example, Bartlett 1958, Bull and Ridgeway 1969, Abdel-Aal et al. 1979, Lecorne and Smilowitz 1980, Syrett and Penman 1980, Chang 1981, Respicio and Forgash 1984, Purcell et al. 1994). Physiological selectivity is very important and perhaps necessary for the successful integration of chemical and biological controls in IPM. However, physiological selectivity based exclusively on topical toxicity data may not provide sufficient information from which to make recommendations about the use of a product for IPM. The range of recommendations that arise from the 4 different methods of risk assessment that we used must be of concern; each would clearly need to be validated if it were to be used as a decision-making tool in pest management.

Several factors must be considered when trying to predict the effects that a pesticide might have in the field (termed *risk* by ecotoxicologists). The 1st is the innate susceptibility of a species to a particular pesticide. Innate susceptibility indicates which population of organisms will be depleted the most, but only if all populations are equally exposed to the active ingredient. Exposure is, however, very unlikely to be similar between species.

Table 5. Predicted mortality of beneficial arthropods at the dose resulting in 90% mortality (LD_{50}) of the pea aphid (Probit substitution method)

Species	Predicted % mortality (95% FL)		
	Diazinon	Imidacloprid	RH-7988
H. convergens			
3rd instars	0 (0–0.03)	1 (0.2–22.4)	0
Adults	0.7 (0.2–5.2)	0	0 (0–0.15)
A. ervi ervi	100 (100–100)	28 (21–51)	9 (4.6–28.7)
A. mellifera	0	0 (0–0.1)	0
M. rotundata	0	0 (0–0.2)	0
N. melanderi	0	0 (0–0.02)	0

Table 6. Hazard ratios for several beneficials and several insecticides

Insecticide (recommended field rate)	Diazonin (466 g [AI]/a)	Imidaclo-prid (50 g [AI]/ha)	RH-7988 (70–140 g [AI]/ha)
Species	Hazard ratio[a]		
H. convergens			
3rd instars	2,913	64,102	35–70
Adults	2,742	5,000	51–101
A. ervi ervi	2,330,500	125,000	3,500–7,000
A. mellifera	2,027	1,250	21–42
M. rotundata	3,884	1,250	11–23
N. melanderi	1,036	1,250	14–28

[a] Hazard ratio is recommended field rate (g [AI]/ha)/LD_{50} (micrograms per insect). A ratio greater than 2,500 indicates a hazardous product for bees (smart and Stevenson 1982).

Some species will be exposed more than others, based on their location and patterns of activity (Jepson 1989, 1993b). These differences also determine the most likely route of exposure (Jepson 1989). For example, ground beetles (Coleoptera: Carabidae) that spend much of their time on the soil surface are less likely to be exposed than organisms such as Coccinellidae which reside in the top of the crop canopy (Unal and Jepson 1991, Cilgi and Jepson 1992). The ground contact area and the activity levels of an organism (Wiles and Jepson 1993), the time when an organism is active and differential behavior patterns in different agroecosystems (Stark et al. 1994, Stark 1995) will also influence exposure to pesticides. These and many other intrinsic (for example, Salt and Ford 1984, Jepson et al. 1990) and chemical factors lead to differences in exposure, uptake, and toxic effect, that cannot be predicted from laboratory topical application data alone. We do not therefore have confidence in any method based solely on such data.

The effect that a pesticide will have on a beneficial species in the field is a complex process involving both susceptibility and exposure, with exposure being a multidimensional process. Selectivity ratios, probit substitution, and step 1 of the bee sequential testing scheme are based solely on topical toxicity data, whereas the hazard ratio method is based on field application rates and thus incorporates a rough estimate of field exposure.

Both the selectivity ratio and the probit substitution method are therefore flawed in terms of determining effects in the field because they do not take into account the key physical, chemical, operational, and biological factors that determine bioavailability and exposure (Mullié and Everts 1992, Jepson et al. 1993a). Both methods assume equal exposure of all organisms by the direct route. The multitiered risk assessment methods developed for bees (hazard ratio and sequential testing scheme) are a positive step toward risk assessment based on laboratory data because they have been validated. For example, the hazard ratio method has been demonstrated to predict pesticide hazards for bees in the field (Aldridge and Hart 1994). However, bees may represent an unusually simple case for validation because of their behavior. For example, they return to hives to die and, therefore one can measure mortality at the population level directly. Hazard thresholds will be far more variable for dispersive and widely distributed beneficial species, for which mortality at the population level may only be inferred from reduced capture rates in traps (for example, Jepson and Thacker 1990, Stark 1992). Therefore, the hazard ratio method may not be so effectively predictive for species other than bees but it may provide good general guidance concerning the potential for harm.

More research is obviously needed in developing risk assessment methods for other beneficial arthropod species (Jepson 1993a). The International Organization for Biological and Integrated Control of Noxious Animals and Plants/Working Group "Pesticides and Beneficial Organisms" has been one of the major proponents of the development of tiered risk assessment methods (IOBC/WPRS 1992). The principle of the IOBC approach is to ensure maximum exposure at a single rate to provide a worst case assessment of toxic effects, based on residual deposits on inert surfaces. This conservative approach may be far more useful as a starting point than the method of determining susceptibility by topical application; it too is flawed (Jepson 1993a).

If we are to make progress in integrating biological and chemical controls, development of more accurate risk assessment methods for pesticides and beneficial species is needed, particularly if we are to encourage the use of new and more selective insecticides. Field studies may always be necessary to validate the effects that pesticides have on beneficial arthropods in agroecosystems; however, risk prediction models for groups of beneficial species that can accurately forecast effects in the field from laboratory data are a necessity to make decisions in IPM.

Acknowledgment

This research was funded in part by a Leverhulme Trust grant to P.C.J.

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Received for publication 8 December 1994; accepted 22 May 1995.