AN ABSTRACT OF THE THESIS OF

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Title: The SELCTV Database: The Susceptibility of Arthropod Natural Enemies of Agricultural Pests to Pesticides.

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Abstract approved: ______________________

Documentation of the side effects of pesticides on arthropod natural enemies has expanded rapidly since the 1950's as part of an increase in non-target side effects literature. Most reviews have been based on empirical analysis of selected literature. The SELCTV database was developed to make a larger information base accessible for characterization and analysis. The feasibility of such a database is a function of improving microcomputer technology and database management software. Record structure and scope of the SELCTV database included 40 information fields covering natural enemy biology, pesticide chemistry, toxicology and literature citations.

SELCTV was assembled from over 900 published papers, believed to constitute 80-90% of available literature through the early 1980's. Currently, some 12,600 records contain taxonomic, biological, toxicological, reference and summary information for over 600 species of natural enemies in 88 families. Research was conducted in 58 countries around the world and included predators and parasitoids associated with 60 agricultural commodities. All major classes of pesticides are represented, including microbial insecticides. The impact of over 400 agricultural chemicals on natural enemies by means of one of ten basic test types has been distilled into SELCTV.

Many different types of natural enemy responses were reported in the literature. In addition to recording these as documented, measurements were translated to a scale ranging from 1 (0% effect) to 5 (90-100% effect). This toxicity rating scale formed the basis for most SELCTV analysis. Selectivity ratios, resistance ratios and sublethal effects were other types of data which were recorded when possible.

Lethal and sublethal effects were evaluated for many species, pesticide and test method data groupings. Results showed that predators were less susceptible and more variable in responses to pesticides than parasitoids. Relative susceptibility was computed for important natural enemy species. Among the most tolerant were *Lycosa pseudoannulata*, *Cryptolaemus montrouzieri* and *Chrysopa carnea*. Insecticides were the most toxic of pesticide classes, followed by herbicides, acaricides and fungicides, respectively. Among insecticide classes, a trend of increasing toxicity to natural enemies was demonstrated from the early inorganics to synthetic pyrethroids. More recent microbials and IGR's were less toxic and more selective.

In addition to characterizing the natural enemy-pesticide impact literature and conducting selected analyses, several case studies were compiled to demonstrate application of SELCTV to decision making in pest management. Another compares results of SELCTV with a large standardization testing program from Europe.

Increased size and degree of specificity of the information base were among research trends elucidated through chronological searches of SELCTV. Specific natural enemies, pesticides and test methods as assessment components have fluctuated relative to pesticide use, as well as testing and pest management philosophies. The study of diverse natural enemy responses to pesticides has

led to the identification of unique factors that influence natural enemies in different ways or to a greater or lesser degree than pests. Differences in the susceptibility of pests, predators and parasitoids are discussed.

The SELCTV Database:
The Susceptibility of Arthropod Natural Enemies to Agricultural Pests to Pesticides

by

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TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

THE SELCTV DATABASE: THE SUSCEPTIBILITY OF ARTHROPOD NATURAL ENEMIES OF AGRICULTURAL PESTS TO PESTICIDES

INTRODUCTION

Since the advent of agricultural pesticides in the late 19th century, their impact on arthropod natural enemies of pests has only slowly been recognized (Debach 1964). Today, few are aware of the high levels of biological control that go on unaided until natural enemies are affected by chemical pesticides. Documentation of the deleterious effects of pesticides on arthropod predators and parasitoids, which first appeared in the early 1900's, has grown into a global literature base of at least 2000 publications (Croft, personal communication). Studies of pesticide side effects on natural enemies have evolved slowly and sometimes tangentially to similar studies with pest arthropods (Croft 1987).

Before DDT, pesticides were commonly less effective, of lower potency and less widely used in US agriculture (Perkins 1982). Unilateral dependence upon them was the exception rather than the rule. Early pesticides were inorganic, heavy metals or derivatives of natural toxins (Van den Bosch and Stern 1962). Many acted as stomach poisons, primarily affecting plant feeding species; this conferred some behavioral or ecological selectivity to natural enemies (Ripper 1956).

Synthetic organic pesticides radically improved crop protection, allowing yields not previously possible. However, this efficacy was not without greater negative contingencies to biological control (Stern et al. 1959).

Early studies showed that the composition of arthropod community structure was altered by extensive synthetic pesticide use (Pimentel 1961). Natural enemy populations were temporarily decimated and highly susceptible species sometimes disappeared (Lord 1949, Ripper 1956, MacPhee and Sanford 1961). Following pesticide applications, natural enemy re-establishment lagged behind pests. This was due partly to consistent availability of pest food supplies compared to natural enemies, whose dependence on pest populations for food limited their recolonization (Bartlett 1964). Selection for pesticide resistance was accelerated by heavy reliance on pesticides (Ripper 1956). Still, the broad spectrum efficacy of synthetic organic pesticides was unparalleled. Expansion of acreage under intensive pesticide treatment continued. Over time, the rate and frequence of application increased as pests were released from their natural controls (Metcalf and Luckmann 1982).

Pest resistance, resurgence and secondary outbreaks caused by synthetic pesticide use began to rise toward the end of the 1950's (Van den Bosch and Stern 1962). Integration of chemical and biological control became necessary when some pest populations could no longer be chemically limited (Ripper 1956). As a result, integrated pest management (IPM) was promulgated as a crop protection philosophy (Stern et al. 1959). Implementation of IPM was limited, in part, by the lack of selective chemical pesticides (Newsom et al. 1976, Gruys 1980, Mullin and Croft 1985). Additionally, the rate at which new broad spectrum compounds became available did not encourage conservative pesticide use. Overuse and eventual pesticide failure became sufficiently widespread to generate new scientific studies. Questions arose regarding the intrinsic susceptibility of natural enemies relative to pests. How might we spare natural enemies while killing pests? Studies undertaken to assess the acute and chronic affects of pesticides on natural enemies began to increase in the early 1960's, in an upward trend that continues today (Croft 1977).

Early reviews of pesticide impact on natural enemies featured toxicity summaries, identified deleterious ecological effects and discussed ways of achieving ecological selectivity (Ripper 1956, van den Bosch and Stern 1962, Bartlett 1964). Several comprehensive reviews of pesticide impact on arthropod natural enemies were published in the mid 1970's (e.g., Kirknel 1974), most recently by Croft and Brown (1975). The breadth of their review reflected the evolving status and specialization of pesticide impact studies on natural enemies in the 1960's and 1970's. Their discussion spanned from direct toxic effects of pesticides on natural enemies to indirect effects, such as sublethal and ecological influences, to pesticide resistance in natural enemies. Selectivity needs for pest management were outlined with newer pesticides including microbial insecticides and insect growth regulators. They concluded that improved selectivity with these agents was likely.

The shortage of physiologically selective pesticides plagued IPM in the 1970's. Ecological selectivity remained the major means of preferentially sparing natural enemies, as it is today (Newsom et al. 1976, Hull and Beers 1985). Newsom's review of selectivity is one of the first to focus on more specialized aspects of the overall topic of natural enemy response to pesticides. Contemporary reviews have largely followed this trend, summarizing natural enemy response to pesticides: regionally (e.g., in the USSR, Kurdyukov 1980), by commodity (apple, Croft and Whalon 1982, Niemczyk et al. 1981; cotton, Sukhoruchenko et al. 1977), or by individual pesticide groups (e.g., synthetic pyrethroid insecticides, Croft and Whalon 1982, Niemczyk et al. 1981; microbial pesticides, Flexner et al. 1986; insect hormone analogues, Beckage 1985). Other reviews have focused on standardized side effects testing (von Franz 1974, Croft 1977, Bogenschutz 1979, Franz et al. 1980, Hassan et al. 1983), modes of pesticide uptake (Croft 1977), physiological and ecological selectivity (Newsom et al. 1976, Gruys 1980, Hull and Beers 1985, Mullin and Croft 1985), resistance development (Croft and Strickler 1983, Fournier et al. 1986), genetic improvement of resistant strains (Roush 1979, Hoy 1985) and their use in biological control (Croft and Hoyt 1983, Hoy 1984).

The literature base on natural enemy/pesticide interactions has expanded rapidly (Croft and Brown 1975, Croft 1977), having approximately doubled in the last decade (see Results). Evaluations have become more specific and methods more precise over this period (Croft 1987). As previously demonstrated, reviews published since the 1970's tend to focus on subdivisions within the subject area such as susceptibility testing, sublethal effects or pesticide selectivity. Because the literature of pesticide effects on natural enemies has become so vast, comprehensive summation by empirical or traditional methods alone has become less feasible.

Modern microcomputer technology and database management software makes possible the development of searchable databases from large information sets. In this thesis, data published over the past 40 years documenting pesticide side effects on natural enemies of agricultural pests are summarized in the form of a large database (SELCTV). This database provides a means to count, index, sort and search for key assessments made on a wide variety of natural enemies (609 species). Currently, the total literature includes 933 published papers from 58 countries. SELCTV contains toxicity assessment data for over 400 agricultural chemicals, including fungicides, herbicides, insecticides, acaricides, feeding repellents, insect and plant growth regulators and others.

The principal objectives of this thesis were 1) to develop and assemble a database on the impact of pesticides on arthropod natural enemies of agricultural pests, 2) to characterize database contents by many attributes, including features of the natural enemy, the pesticide, the assessment method and test results, and 3) to use SELCTV to address scientific questions or hypotheses regarding the overall topic. For example, toxicity assessment summaries from SELCTV were developed using a variety of pest/crop/pesticide combinations. Selectivity tables for natural enemies in several cropping systems were assembled and a number of case history searches of SELCTV were performed to demonstrate uses of the database in problem solving. It was anticipated that construction of the database would provide an improved means for summarizing information on the effects of pesticides on arthropod predators and parasitoids. In addition, a structure and method would be provided for dealing with future publications and reviews of this topic.

MATERIALS AND METHODS

Hardware/software

The SELCTV database was originally developed on a Digital Rainbow 100 microcomputer (CP/M operating system) and Winchester 10 megabyte hard disk using dBASE II/86 version 2.4 (Ashton-Tate 1982), a relational database management system. Because of space and speed limitations, the database was transferred to an AT&T 6300 microcomputer (MS-DOS operating system) with a 20 megabyte hard disk. Software was upgraded to dBASE III PLUS, version 1.0 (Ashton-Tate 1985). At this time reference citations were moved and expanded in a separate database called REFER. SELCTV and REFER are related on a key field, REFNUM (reference number), and are henceforth referred to collectively as SELCTV. A menu driven, compiled version of SELCTV is currently under development to circumvent the need for dBASE III PLUS literacy to query, append to or edit SELCTV (for further information on this program, contact B. A. Croft).

Record Structure

SELCTV and REFER record structures (Table 1) were determined by consideration of attributes of the natural enemy tested, the pesticide used, testing methods employed and the literature reference for each data entry. These requirements were balanced against the consistent availability of data elements from one literature publication to the next.

A total of 40 fields were selected to accomodate data, comprising the structure or template for each record. Four distinct groupings of database fields emerged and were organized accordingly in the record structure: 1) biological, 2) chemical, 3) test and summary, 4) reference citation (see Table 1 for detailed explanation of the contents for each field). Field

Table 1. Record structure and field descriptions for SELCTV and REFERENCE databases of documented pesticide impact on arthropod natural enemies.

SELCTV Subdivision: Biological

GENUS: taxonomic genus of the natural enemy being tested, e.g., *Chrysopa*.

SPECIES: taxonomic species of the natural enemy being tested, e.g., *carnea*.

FAMILY: taxonomic family of the natural enemy being tested, e.g., Chrysopidae.

NE:ATTRIBU: coded field of 5 biological attributes of the tested natural enemy:
1) ORDER: taxonomic order of the natural enemy.
2) NE:TYPE: predator (d), parasitoid (r) or both (b).
3) SEX: female (f), male (m) or unspecified (u).
4) SOURCE: where the test natural enemies were obtained, (l)ab reared or (f)ield collected.
5) SUSCEPTIBILITY STATUS: resistant (r), tolerant (t), or neither (n).

STAGE: lifestage of the natural enemy at the time of pesticide impact evaluation, e.g., egg(e), larva(l).

PROD:UNIT: crop or production unit with which natural enemy is commonly associated, e.g., corn (cn), alfalfa (al), bean (bn), etc.

LOCI: location where the research was conducted, e.g., USA-OR, Australia, Canada-BC, etc.

HOST:PREY: scientific or common name of host/prey of the tested natural enemy, e.g., *Myzus persicae*.

HP:TOX:DAT: was toxicity for the host or prey included in the publication? yes(y), no(n).

SELCTV Subdivision: Chemical

CPD:NAME: experimental or common chemical name of the toxicant tested, e.g., carbaryl, demeton.

Table 1 Continued

FORMULATN: concentration of active ingredient and/or type of preparation for use, e.g., 25%wp (wettable powder), 50%ec (emulsifiable concentrate).

CHEM:CLASS: pesticide class to which the compound belongs belongs, e.g., fungicide(f), insecticide(i).

CHEM:GROUP: chemical catagory by primary functional group or structure, e.g., organochlorine (oc), synthetic pyrethroid (sp).

CHEM:RATE: manner of application, e.g., dose (d), field(f), concentration (c), residue (r).

CR:UNITS: units by which application was measured, e.g. grams ai/ac, lb/100liter, etc.

CR:VALUE: numeric value associated with rate units.

SC:AI: standard concentration in %ai.

SELCTV Subdivision: Test and Summary

DUR:EXP: amount of time natural enemy is in actual contact with the toxicant.

TST:METHD: method used for susceptibility assessment, e.g., contact with fresh, dry film (c), dip (d), field (f).

EVAL:TIME: time elapsed from initial pesticide exposure to assessment of impact, e.g., 48h (hours).

RESP:TYPE: response that is being measured, e.g., LC, LD, mortality, longevity, etc.

RESP:UNITS: response units, e.g., %+, %-, or units associated with LD, LC, LT assays.

RESP:VALUE: numerical value associated with RESP:UNITS.

RR:RATIO: LD_{50} or LC_{50} of resistant strain divided by that of the susceptible strain.

TOX:RATING: common scale of ranking natural enemy response, ranging from 0 (no effect) to 5 (90-100% mort).

Table 1 Continued

DAT:RATING: a two part index; the first digit is a relative indicator of precision, ranging from 1 (best) to 4 (worst). The second digit indicates presence (1) or absence (2) of statistics to support inference.

SUBLETHAL: effects of non-lethal doses, e.g. fecundity (fec) or longevity (long), rated on the same scale as toxicity.

SLECTRATIO: LC_{50} or LC_{50} of host or prey divided by the LD_{50} or LD_{50} of associated natural enemy (values < 1 indicate selective compounds).

COMMENTS: any other relevant features of the paper that are that are not included in database fields.

REFERENCE Subdivision: Reference Citation

REF:NUM: unique number assigned to each reference, which allows citations to be related to appropriate records in SELCTV.

AUTHOR: author(s) of publication from which the data is extracted.

PUB:DATE: year of publication.

TITLE: title of the publication.

JOURNAL: scientific or technical journal of pubication.

VOLUME: volume and number of journal.

PAGES: page numbers of publication.

LANGUAGE: language paper was published in.

ABSTRACT: coded field indicating type of literature, e.g. abstract only, or paper and abstract, etc.

RECORDS: number of records extracted from publication.

KEYWORDS: abbreviations which correspond to subjects of interest in natural enemy susceptibility assessment, e.g. physiological selectivity p-sel), etc.

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lengths were set by anticipating needs for space based on possible field contents. Data type designations included character, numeric and logical, as allocated in dBASE. Data type was dictated in part by the degree of specificity needed in the field and by whether or not numerical computations were to be made on the information in a particular field. Nested groupings of fields were created for natural enemy and pesticide information to build in levels of search specificity. These combinations included ORDER/ FAMILY/ GENUS /SPECIES fields and CHEM:CLASS (pesticide class)/ CHEM:GROUP (chemical group)/ CPD:NAME (compound name) fields, respectively.

Inputting Data

Publications entered in SELCTV were obtained from B. A. Croft, who maintains an extensive collection of literature pertaining to the side effects of pesticides on arthropod natural enemies. This literature base was used previously for the review published by Croft and Brown (1975). It was initiated and has been updated by means of computerized library searches of abstract databases such as BIOSIS, CAB and Agricola, and by cross checks of bibliographies from acquired publications. In addition, periodic searches of the Review of Applied Entomology have produced relevant literature. Collected literature is believed to be essentially complete for the United States and most western countries. However, SELCTV is limited with respect to eastern European, Russian and far eastern literature. This information was generally less available due to language barriers and literature inaccessibility. However, abstracts have been obtained for much of this literature and data gleaned from them as possible.

Data were input into SELCTV by extracting relevant information from a publication and filling each record as completely as possible. A new record was appended for every unique documentation of a natural enemy's response to any pesticide and formulation at a given dose on a particular crop using a specific test method, exposure time and evaluation time. The number of records extracted from a publication was highly variable, ranging from 1 to 600 (for tabulations of toxicity from reviews). Because the form of information in the literature did not always coincide with SELCTV structure, an element of interpretation was occasionally introduced. While unavoidable, this subjectivity is believed to be relatively minor over the entire database. Care was taken to preserve data integrity and to maintain consistency within SELCTV. To date, 933 publications have been distilled into the database and SELCTV will be expanded as data become available.

Characterization and Analysis

After completion of data entry, the contents of each field were screened to correct errors and insure consistency. Fields were then characterized. This involved programming in dBASE for required counts or listings, usually on indexed fields. Fields with a limited number of possible entries were characterized using simple counting routines, while indexing and sorting field contents were used to simplify summation on fields with many possible entries. Programs were then designed to list unique field entries and their frequencies. All fields were similarly characterized.

More complex characterization was then undertaken by creating multiple field indexes and more complex programs. For example, the frequency of natural enemy genera by crop was examined by indexing SELCTV on PROD:UNIT (production unit) as a primary key and GENUS as a secondary key. A program was then written to list and count data by crop, and within each crop by genus of natural enemy.

Publication date was used to identify trends in research priorities and response data over time. Field contents were partitioned over 5 year increments and results displayed using line charts.

Most SELCTV analyses involved calculations and comparisons of average toxicity ratings (TOX:RATING) and associated variance components for data grouped by selected criteria. These calculations provided a means to examine factors which affect natural enemy responses. Data were ordered by building indexes on single or multiple keys. Average toxicity and variance values were then calculated using programs written in dBASE. Additional analyses were performed on other numeric indices within the database, such as resistance ratios (RR:RATIO), selectivity ratios (SLECTRATIO) and sublethal effects ratings. Computations were then performed on data grouped by various criteria such as pesticide or natural enemy attributes.

The collected literature of pesticide impact on arthropod natural enemies is sufficiently complete to be considered a population (see above and later discussion of how comprehensive SELCTV might be with respect to the global literature). On the basis of this assumption, the use of statistical methods for inference was not appropriate. Rather, descriptive statistics such as histograms or scatterplots have been employed to represent data.

All response data were translated to a unitless scale (TOX:RATING) ranging from 1 to 5, which allowed a common rating of severity to be imposed upon many different types of natural enemy responses to pesticides. Toxicity ratings on a scale of percent mortality or effect were not linearly incremented. Extremes in effects were considered most important to document as these indicate cases of preferential selectivity or of high hazard to natural enemies. Hence, ratings were more heavily assigned at scale extremes. While the range of possible analyses in SELCTV was broadened considerably by using a common scale, computed variance values were altered. These computed variance values represent a relative approximation of variability about the true mean because SELCTV calculations were performed on a different scale (TOX:RATING) than the original response measurement.

High variance indicated a greater frequency of extreme values on the toxicity scale, whereas means alone gave no indication of the spread of data points. In some cases, variance was not biologically meaningful. In part, variance reflects the number of different investigators, test methods, natural enemies, pesticides and doses present in the mean toxicity value computed from a data grouping. Additionally, where toxicity means are high on the scale (4-5), the range of variability is limited by the upper end of the toxicity scale. Variance may be underestimated in these cases, principally reflecting variation below the mean.

Confidence associated with SELCTV analyses is primarily dependent upon: 1) the size (n) of specific data groupings, 2) numerical differences between means based on the specificity of the search or computation and 3) the number of fields or data elements spanned by an average value. There also may be hidden data trends or research biases which influence mean values. These components are identified and their impact estimated in the discussion section.

The biological relevance of means and variances in SELCTV is relative at a broad level of analysis. Here, SELCTV indicates trends in natural enemy research, biology or ecology. Trends or differences which persist across several to many parameters (e.g., species and/or pesticide and/or test method) may be biologically significant, and merit further experimental investigation. As search criteria become more general, the number of parameters incorporated in the mean increases as does the number (n) of data points which satisfy these more general search criteria. Extremes are assumed to balance each other at a broad level of generalization. Higher variance expected for means of broad data groupings is offset somewhat by a larger number of data points (n).

With specific comparisons or calculations, results can be interpretted more literally. The number of records which satisfy these criteria and the number of parameters spanned by means become small. These mean values have more direct and precise application to the field or testing conditions specified. However, means of small data subsets or groupings are strongly influenced by results from individual studies. Caution must be used in interpreting analysis based on small data sets. Variance of small data sets is a good indicator of the consistency or range spanned by data points.

RESULTS

Contents of the SELCTV database were initially characterized for each of the 40 fields of the record structure (Table 1). This included the current 12,593 records in SELCTV and the related 933 records in REFERENCE. Following a discussion of PUB:DATE, AUTHOR, JOURNAL, LANGUAGE and KEYWORDS fields, the remaining fields were treated in the order of their appearance (Table 1). Because the study of pesticide impact on natural enemies is an evolving field, time trend curves were used to show how documentation of different aspects has progressed. Analysis of the database was based on numerical computations on the TOX:RATING (Toxicity rating), RR:RATIO (Resistance ratio), SLECTRATIO (Selectivity ratio) and SUBLETHAL (Sublethal effects) fields. Analysis follows characterization of SELCTV in the Results section of this thesis. Finally, four historical cases of analysis were prepared to illutrate uses of SELCTV. These included a comparison of the susceptibility of natural enemies from 4 crops to insecticide chemical groups (CHEM:GROUP), a selectivity table for 8 important genera of natural enemies found on cotton and a case study of the impact of synthetic pyrethroids on apple and cotton natural enemies. Finally, SELCTV results have been compared with those compiled from a major European study of pesticide impact on arthropod natural enemies, which featured the development of standardized assessment techniques.

Characterization of the Database

By Reference Attributes

The distribution of published research over time (PUB:DATE) was examined from several perspectives. Initially, frequency histograms were constructed for the number of records and number of publications on a yearly basis. Both varied considerably from year to year. Therefore, representations were grouped into classes of 5 year periods were plotted (see Fig. 1 and 2).

The number of records per period in SELCTV (Fig. 1) began to rise after 1945, with a sharp upturn in slope after 1955. This rate of increasing research has been maintained thereafter, with the exception of 1965-1970. A decrease in records per year occurred in the 1981-1985 period. This was believed to be an artifact of incomplete literature acquisition for the recent past, and applies to all time trend figures (see later discussion). The maximum records generated during any one year was 896 in 1983.

The distribution of publications over time (Fig. 2) revealed a similar trend with publication rate as seen with records. Three distinct rate phases were distinguished. In the first, lasting from 1940 to 1955, the number of publications increased at a barely discernible rate. From 1955 to 1970, the publication rate increased moderately and steadily. After 1970, there was a near exponential increase in the number of pesticide impact studies published for arthropod natural enemies. Again, the decrease in publication rate after 1980 was attributed to ongoing literature acquisition for the most recent past. The maximum number of publications in SELCTV for a given year was 77 in 1979.

Records for chemical pesticides and microbial pesticides were maintained separately in SELCTV. Thirty-two publications contained both chemical and microbial pesticide assessments. Hence, while there were 843 chemical pesticide and 123 microbial pesticide citations, the number of unique publications in SELCTV was 933 (Complete literature citations in appendix A). Most

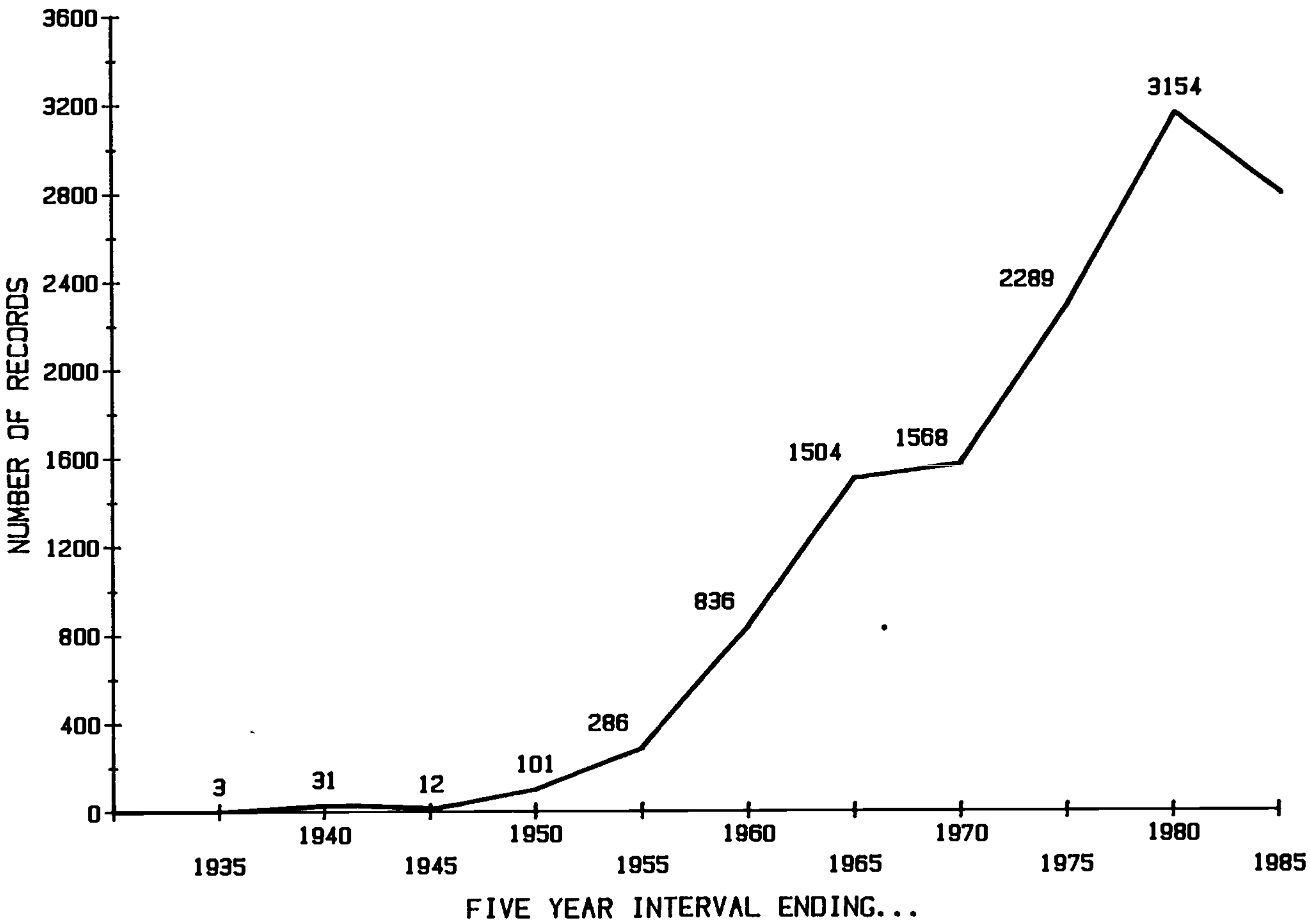


Figure 1. Incidence of records of pesticide impact on arthropod natural enemies over time from the SELCTV database.

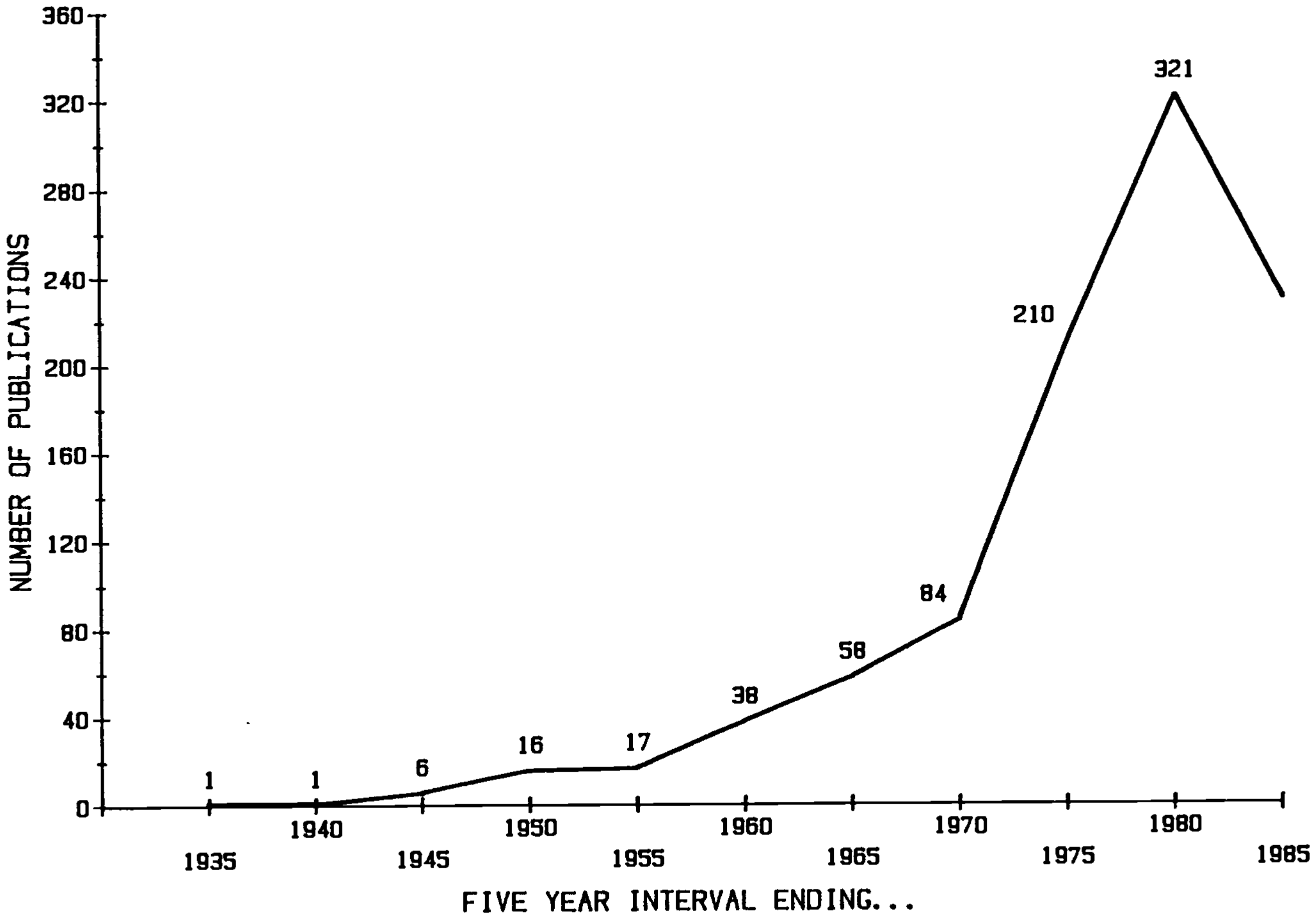


Figure 2. Incidence of publications documenting pesticide impact on arthropod natural enemies over time from the SELCTV database.

prolific first authors by number of publications were B. A. Croft (12 publications), M. A. Hoy (10), S. A. Hassan (9), H. K. Kaya (8) and E. Niemczyk and S. K. Wiackowski with 6 each. First authors by number of records in SELCTV included K. H. Sanford (625 records), B. R. Bartlett (535), S. A. Hassan (406), A. W. MacPhee (339) and W. E. Ripper (282). The latter group of authors published reviews of pesticide impact on natural enemies (Ripper 1956, MacPhee and Sanford 1961, Bartlett 1964, Hassan 1982, Hassan et al. 1983). These included extensive toxicity summaries which generated many records.

Papers containing data input into SELCTV were cited from 275 scientific journals, reviews, technical publications and congress or symposium proceedings published in 19 languages. Journals most common in bibliographic citations included: J. Econ. Entomol. (156 citations), Environ. Entomol. (97), Can. Entomol. (30), Z. Angew. Entomol. (30) and Entomophaga (24). Literature was most often published in English, followed by German, Russian and French, respectively. Twelve percent of records were extracted from abstracting journals or English summaries of papers in foreign languages.

Keywords (KEYWORDS) were assigned to each publication as applicable by subject area. The most frequently assigned keyword was that for physiological selectivity of pesticides to natural enemies (Table 2). Physiological selectivity was discussed in many publications as a desirable pesticide feature for use in IPM. However, documentation of physiological selectivity to natural enemies has been far less common than implied by KEYWORDS counts. Next, in decreasing order of frequency were keywords indicating factors influencing susceptibility, mode of pesticide uptake, methods development for susceptibility assessment, general pesticide selectivity, ecological selectivity and resistance documentation.

Table 2. Frequency of keywords from the SELCTV database describing aspects of arthropod natural enemy susceptibility or resistance to pesticides.

Symbol	Topic	No.Records
p-sel	Physiological selectivity	7081
fi	Factors affecting susceptibility (S)	2360
md-s	Methods development-susceptibility (S)	913
sel	General selectivity	669
e-sel	Ecological selectivity	594
r-doc	Documented pesticide resistance (R)	561
fctx	Food chain toxicity	350
ec	Ecological effects	339
mu	Mode of pesticide uptake	227
r-crss	Cross resistance (R) to pesticides	128
tb	Toxicology or biochemistry (S)	125
rm-gi	(R) management-genetic improvement	104
r-tg	(R)-Toxicology or genetics	63
rm-i	(R) management-introduced strains	63
md-r	Methods development-resistance (R)	29
rm-t	(R) management-theory	9
rm-e	(R) management-endemic strains	3

Table 3. Distribution of SELCTV database records of pesticide impact on arthropod natural enmeis grouped by order.

Order	No. Records	% Total Records
Hymenoptera	3431	27.24
Coleoptera	2763	21.94
Acari	2420	19.23
Hemiptera	1772	14.07
Neuroptera	1096	8.70
Diptera	585	4.64
Aranae	320	2.54
Thysanoptera	160	1.27
Dermaptera	16	.14
Leptidoptera	9	.07
Scorpiones	3	.02
Orthoptera	3	.02
Odonata	3	.02

By Natural Enemy Attributes

Five levels of natural enemy identification were built into SELCTV record structure (Table 1). First, natural enemies were classified by type, i.e. predators or parasitoids. Predators accounted for 8993 records or just over 71% of SELCTV. Parasitoids made up 3591 records or approximately 29%. In 4 records, natural enemies were designated as "both" on a continuum between parasitoid and predator.

Taxonomic characterization was initiated at the most general level. SELCTV pesticide impact data spanned thirteen orders of arthropod natural enemies (Table 3); 10 were in the class Insecta and 3 in the Arachnida. Hymenoptera was the most common order, accounting for over 27% of records. Coleoptera made up nearly 22% of SELCTV by record, followed by predaceous mites (Acari 19.2%), Hemiptera (14.1%) and the Neuroptera (8.7%). Natural enemies in SELCTV included some of the most important known biological control agents (Huffaker and Messenger 1976, Ridgway and Vinson 1977, Hoy and Herzog 1985, Helle and Sabelis 1986).

Pesticide side effects in SELCTV spanned 88 families of arthropods. Of the 20 most numerous families three predators and one parasitoid comprised those most commonly tested for pesticide impact (i.e., predators include the phytoseiids, coccinellids and chrysopids). Thirteen of the top 20 families represented in SELCTV were generalist or mite predators. The Braconidae, Aphelinidae, Ichneumonidae and Trichogrammatidae, respectively, were the most commonly studied parasitoid families.

Family composition within each order varied considerably. Hymenoptera was represented by 21 families in SELCTV, Coleoptera by 14, and Hemiptera and Araneae by 12 each. Data were extracted from the literature for 8 families of Acari and 7 of Diptera. The remaining 7

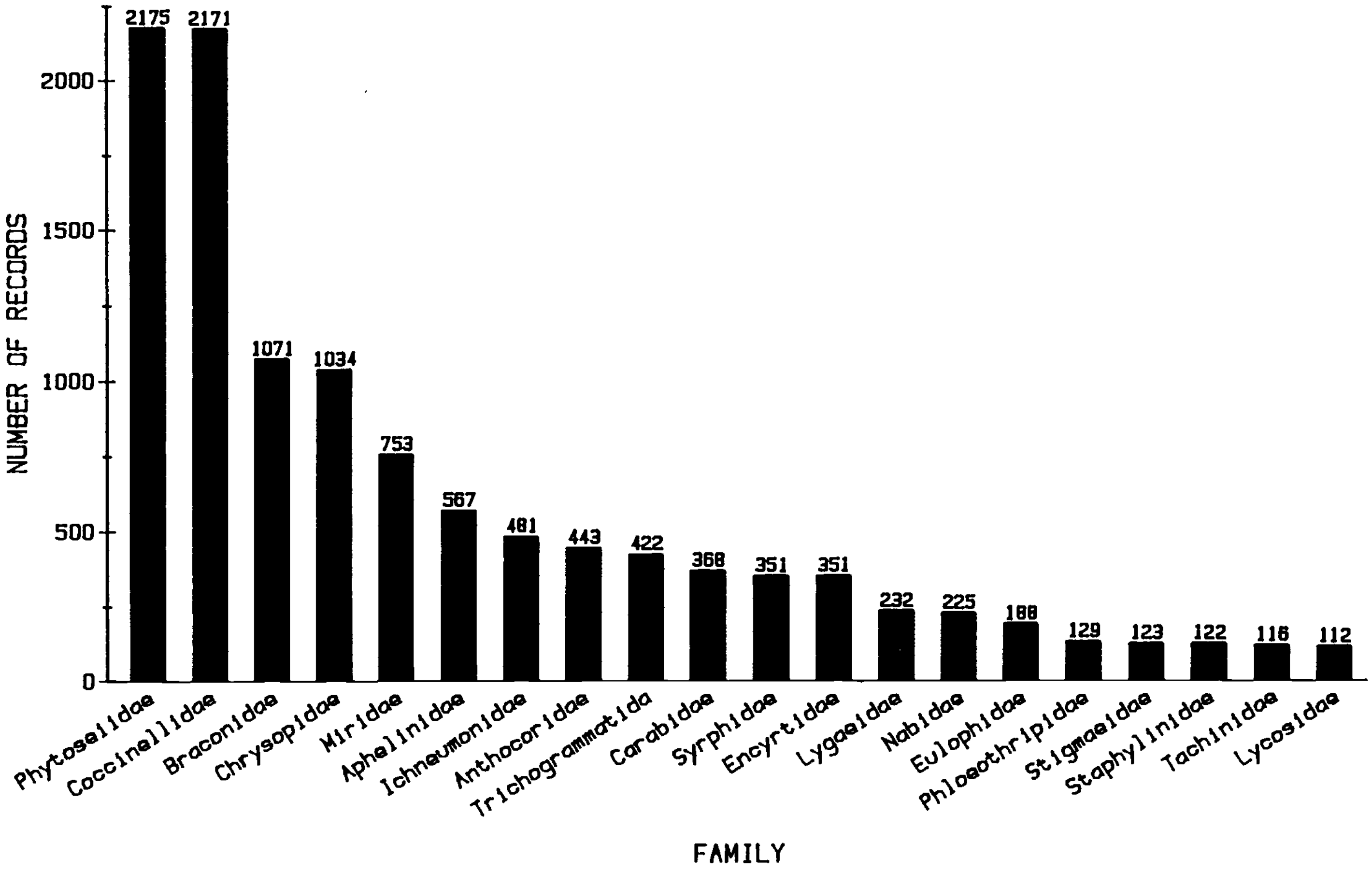


Figure 3. Distribution of SELCTV database records of pesticide impact on arthropod natural enemies for the 20 most commonly tested families.

orders contained 3 or fewer families. These proportions become important when generalizing about susceptibility among natural enemies. For example, over 90% of acarine records detailed pesticide impact on the Phytoseiidae. The remaining 7 families made up only 9.6% of acarine records. Similarly, data for Coleoptera were 80% composed of the family Coccinellidae. In contrast, none of the 21 hymenopteran families accounted for more than about 30% of this order.

SELCTV contained 342 unique genera (GENUS). *Amblyseius* made up 8% of database records (Table 4). Again, the 5 most frequently studied natural enemies, which accounted for nearly 30% of records, were either generalist or mite predators. The latter species have been documented as important biological control agents on a wide variety of high value crops (Croft and McGroarty 1977, Hoy et al. 1979, Berendt 1980, Penman and Chapman 1980, Cranham and Solomon 1981, Helle and Sabelis 1986). *Trichogramma*, *Encarsia*, *Apanteles*, *Opius* and *Aphytis* were the most commonly studied parasitoids. In comparison, these 5 parasitoid genera comprised less than 10% of SELCTV records.

The 5 most commonly studied species were generalist or mite predators, led by *Chrysopa carnea* (Table 5). Ten of the ranked top 20 species were either predatory phytoseiids or coccinellids. *Encarsia formosa*, 6th ranked by species, was the most prevalent parasitoid in SELCTV. *E. formosa* has been managed in greenhouse IPM programs, and has been extensively tested for susceptibility to relevant pesticides (e.g. Beglyarov and Maslienko 1978, Zseller and Budai 1982, Hassan et al. 1983, Hoogcarspel and Jobsen 1984). Only 6 of the 22 most common species were parasitoids, all of the order Hymenoptera. The remainder were generalist or mite predators. At this level of classification, a spider (*Lycosa pseudoannulata*)

Table 4. Distribution of SELCTV database records of pesticide impact on arthropod natural enemies for the 20 most commonly tested genera.

Genus	Family	No.Records
Amblyseius	Phytoseiidae	1009
Chrysopa	Chrysopidae	986
Typhlodromus	Phytoseiidae	629
Coccinella	Coccinellidae	571
Hippodamia	Coccinellidae	441
Trichogramma	Trichogrammatidae	398
Stethorus	Coccinellidae	379
Orius	Anthocoridae	235
Encarsia	Encyrtidae	233
Geocoris	Lygaeidae	232
Apanteles	Braconidae	222
Nabis	Nabidae	212
Opius	Braconidae	183
Aphytis	Aphelinidae	179
Anthocoris	Anthocoridae	174
Deraeocoris	Miridae	169
Campoletis	Ichneumonidae	147
Leptomastix	Encyrtidae	139
Phygadeuon	Ichneumonidae	124
Syrphus	Syrphidae	117

Table 5. Distribution of SELCTV database records of pesticide impact on arthropod natural enemies for the 22 most commonly tested species.

Species	Family	No.Records
Chrysopa carnea	Chrysopidae	591
Amblysieus fallacis	Phytoseiidae	574
Coccinella septempunctata	Coccinellidae	440
Hippodamia convergens	Coccinellidae	375
Phytoseiulus persimilis	Phytoseiidae	323
Typhlodromus occidentalis	Phytoseiidae	268
Encarsia formosa	Aphelinidae	232
Typhlodromus pyri	Phytoseiidae	213
Trichogramma cacoeciae	Trichogrammatidae	158
Chrysopa oculata	Chrysopidae	137
Stethorus punctum	Coccinellidae	134
Metasyrphus corollae	Syrphidae	134
Phygadeuon trichops	Ichneumonidae	124
Leptomastix dactylopii	Encyrtidae	117
Cryptolaemus montrouzieri	Coccinellidae	114
Coleomegilla maculata	Coccinellidae	103
Hyaliodes harti	Miridae	102
Amblyseius hibisci	Phytoseiidae	90
Trichogramma evanescens	Trichogrammatidae	86
Opius concolor	Braconidae	85
Lycosa pseudoannulata	Lycosidae	85
Anthocoris nemorum	Anthocoridae	82

made the list of prevalent species.

In laboratory assessments of pesticide side effects where greater precision was possible, sex of the natural enemy was occasionally specified. Where referred to in the literature, sex was catalogued in NE:ATTRIBU (Natural enemy attributes). Sex is unspecified in over 90% of the records in SELCTV. In 8% of records, the test organisms were female. Slightly less than 2% of records document pesticide side effects on male natural enemies. Source of tested natural enemies was also entered in NE:ATTRIBU. Test organisms were either field collected (70%) or lab reared (25%).

Susceptibility status (in NE:ATTRIBU) was assigned based on apparent pesticide toxicity to the natural enemy. The status was assigned as susceptible when natural enemy mortality was greater than 10%, accounting for about 71% of the database. Approximately 26% of records in SELCTV demonstrated tolerance, wherein natural enemies sustained only 10% mortality or less. Natural enemies which exhibited a 5-fold or greater survival ratio when exposed to a pesticide as compared to a known susceptible strain were termed resistant. Resistant natural enemies accounted for less than 3% of SELCTV or 347 records. Some level of resistance has been shown for selected species from the Aphelinidae, Braconidae, Carabidae, Cecidomyiidae, Coccinellidae, Encyrtidae, Lygaeidae, Phytoseiidae and Trichogrammatidae. However, some of these cases might have been more appropriately considered tolerance.

Individual life stage (STAGE) was specified in over 65% of records in SELCTV (Fig. 4). Egg and pupal stages accounted for about 2% of records each. Susceptibility of immatures (larvae and nymphs) was documented in 1832 records (14.5%). Adults were most commonly tested at 46.7% of SELCTV records. In 32% of records, lifestage was

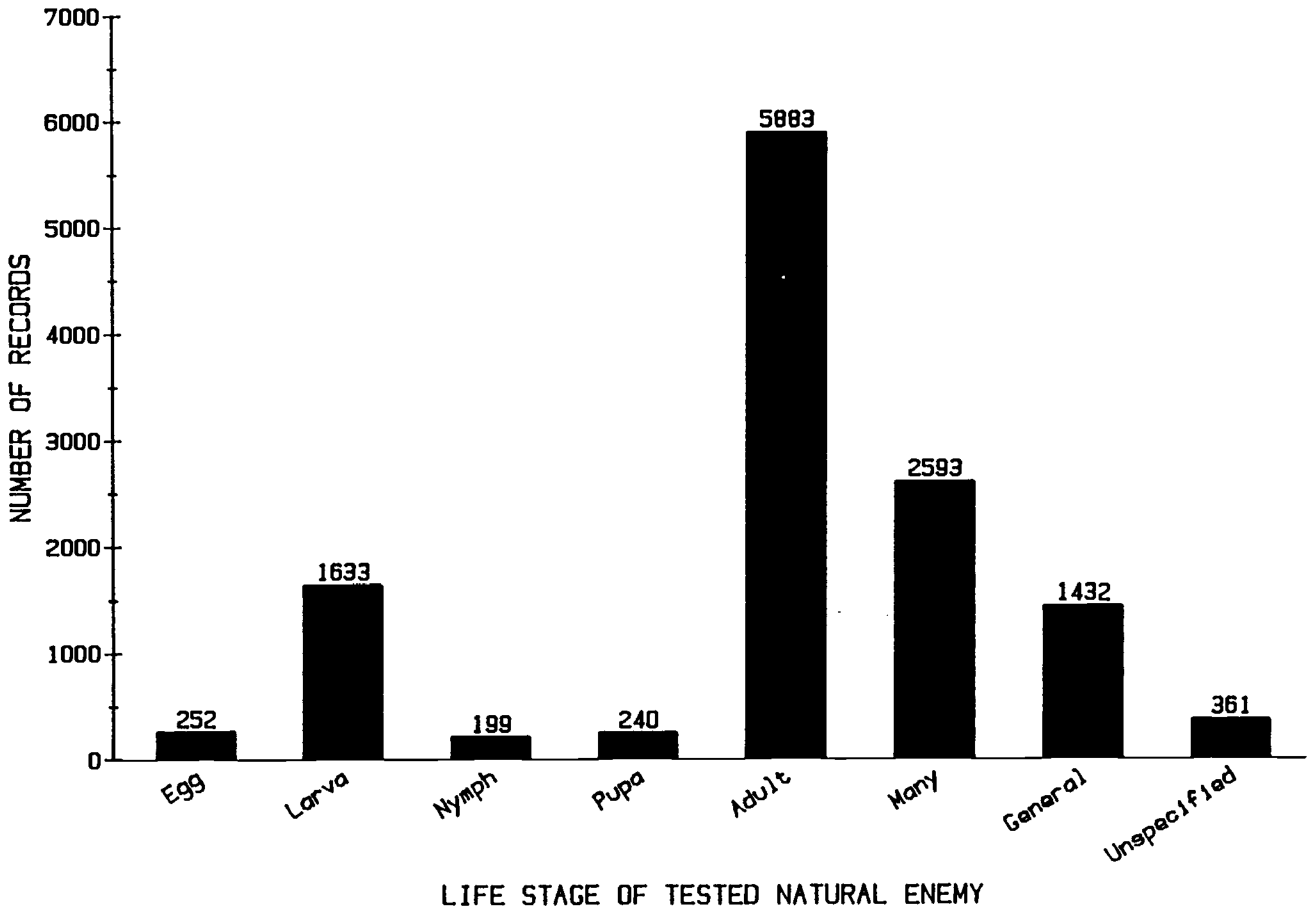


Figure 4. Distribution of SELCTV database records of pesticide impact on arthropod natural enemies grouped by life stage.

not cited specifically due to treatment of many stages (general and many-see Table 1 for definitions). This applied mostly to field tests.

A two letter code was assigned in PROD:UNIT (production unit) to identify the crop with which the natural enemy was most commonly associated. SELCTV contained a total of 60 different crop designations. Natural enemies from apple, cotton, citrus, alfalfa and greenhouse cropping systems were most frequently the subjects of pesticide susceptibility tests (Fig. 5). For 19% of records, largely those pertaining to laboratory testing or more basic research, the common habitat or crop of origin was not mentioned in the literature.

The three most commonly tested genera of natural enemies by crop (Table 6) primarily included predators of indirect or induced pests in intensively sprayed cropping systems such as apple, cotton or citrus. Pesticide side effects on phytophagous mite and aphid predators have been most extensively studied in alfalfa, cereal grains, citrus and greenhouse production units (PROD:UNIT). However, in forest ecosystems, impact studies on parasitoids of lepidopterous pests were most common. <u>Encarsia</u> and <u>Trichogramma</u> spp. predominated in greenhouse studies where they have been released and managed for control of whiteflies and several lepidopteran pests (Ridgway and Vinson 1977, Kurdyukov 1980, van Lenteren et al. 1980, Iacob et al. 1981).

The geographic location at which research was conducted was entered in LOCI (location). Country was the limit of resolution for location with the exception of states for the United States and provinces of Canada. Of 58 locations, the greatest number of studies on pesticide impact on arthropod natural enemies have been conducted in the United States, in California, Texas, New York and Michigan in descending order. Natural enemy testing in

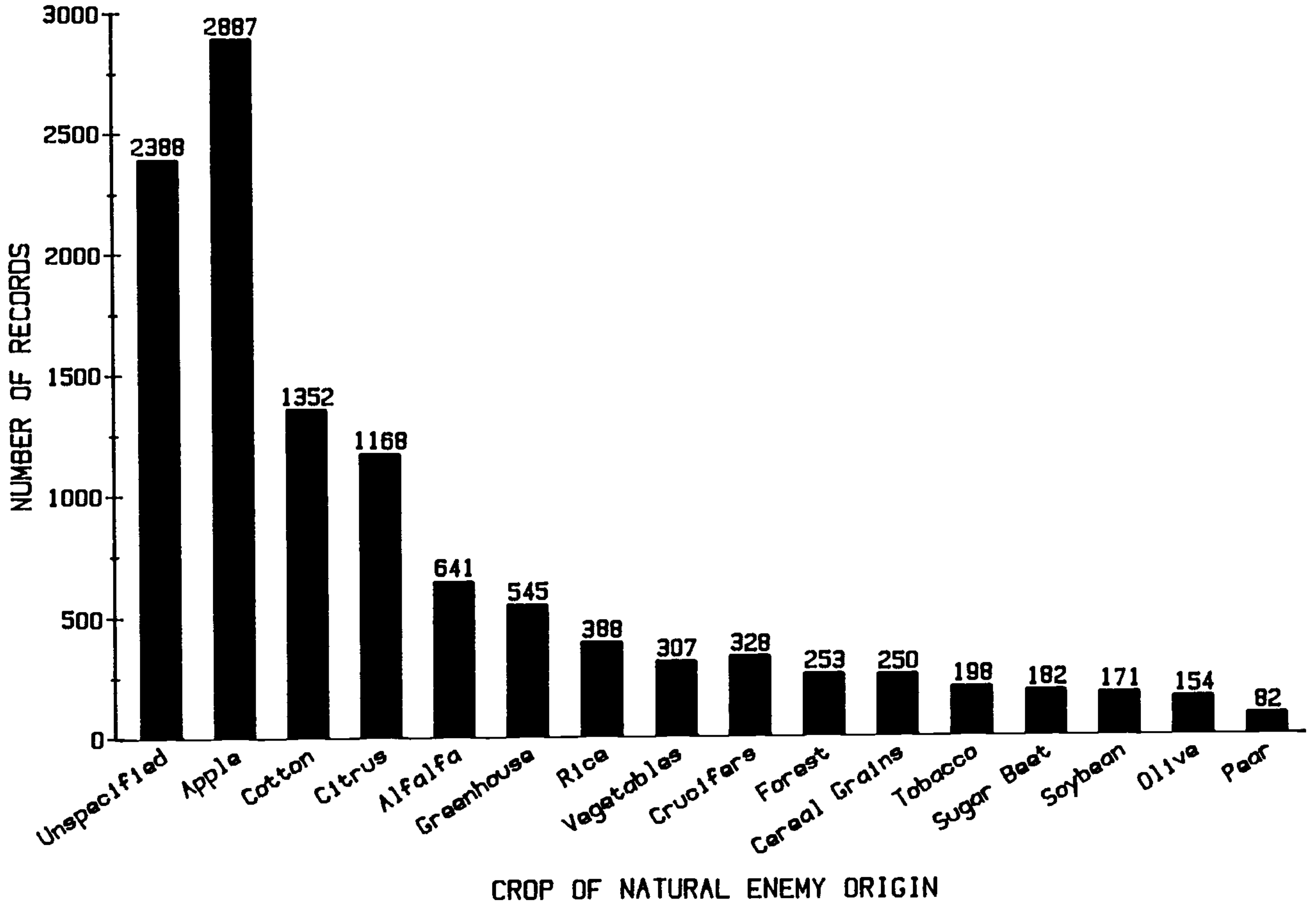


Figure 5. Distribution of SELCTV database records of pesticide impact on arthropod natural enemies for the 16 most common crop categories.

Table 6. Three natural enemy genera most cvommonly tested for pesticide side effects on each of the 10 most prevalent crops from the SELCTV database.

Crop	Predominant Genera		
Apple	Amblyseius a/ (701)	Typhlodromus (446)	Trichogramma (53)
Cotton	Chrysopa (193)	Geocoris (144)	Orius (113)
Citrus	Amblyseius (148)	Aphytis (134)	Chrysopa (94)
Alfalfa	Chrysopa (80)	Hippodamia (79)	Orius (71)
Greenhouse	Phytoseiulus (234)	Encarsia (202)	Trichogramma (35)
Rice	Lycosa (86)	Cyrtorhinus (51)	Oedothorax (27)
Crucifers	Apanteles (63)	Coccygomimus (39)	Brachymeria (27)
Forest	Apanteles (39)	Coccygomimus (23)	Brachymeria (17)
Cereal Grains	Feronia (19)	Hippodamia (16)	Pterostichus (16)
Soybeans	Geocoris (21)	Chrysopa (20)	Nabis (14)

a/ (#) = Number of Records

Table 7. Relative distribution of SELCTV database records by host or prey associated with arthropod natural enemies tested for pesticide impact.

Host or Prey Classification	% Total Records
Phytophagous mites	18.6
Aphids	17.7
Lepidoptera-general	11.4
Homoptera-general	11.9
Mealybugs (3.2)	
Scales (2.7)	
Whiteflies (2.6)	
Diptera-general	4.1
Leafminers	1.7
Coleoptera-general	1.6
Several or many	11.6
None specified	21.8

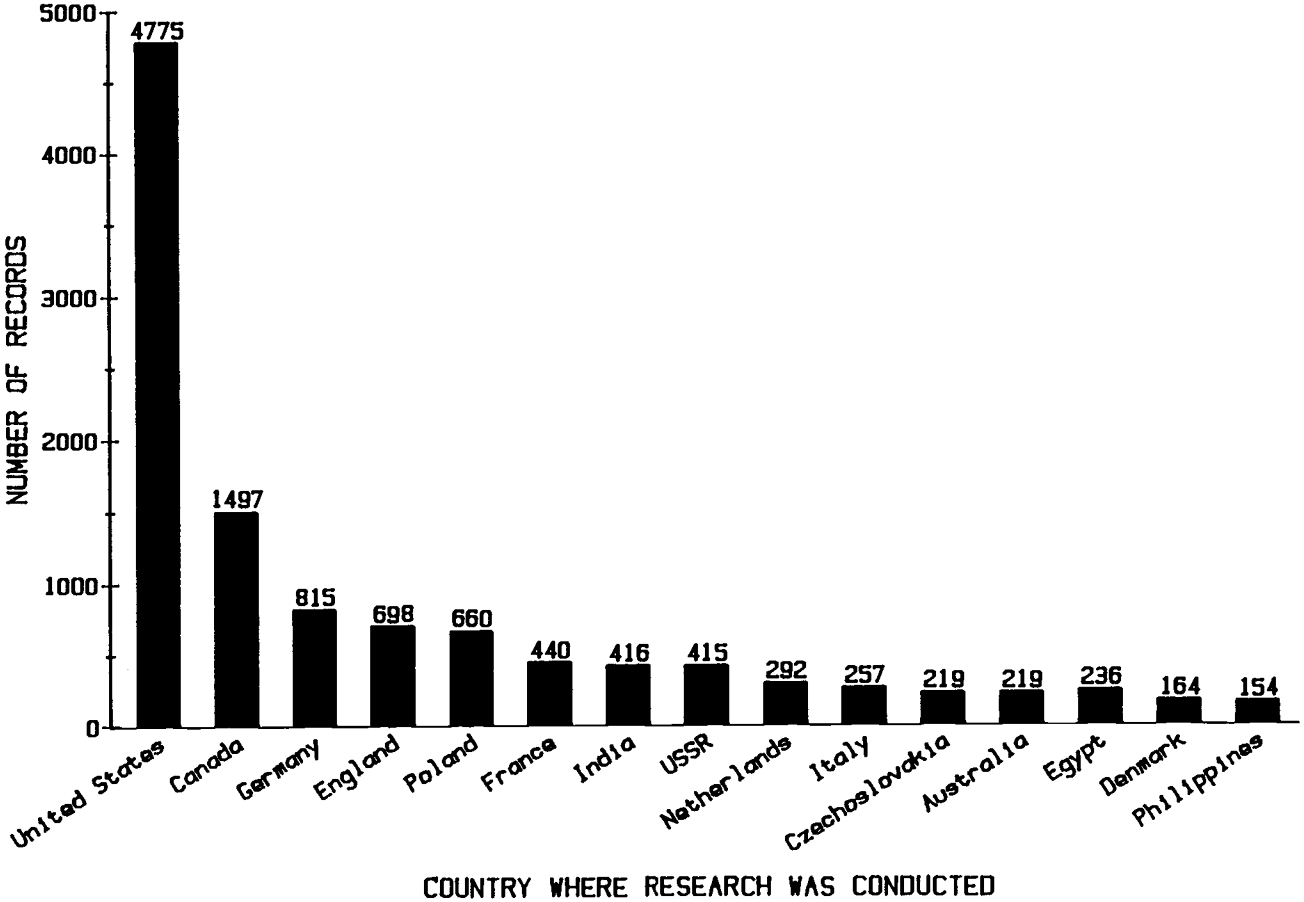


Figure 6. Distribution of SELCTV database records of pesticide impact on arthropod natural enemies grouped by research location.

the United States accounted for nearly 40% of SELCTV records, followed by Canada, West Germany, and England (Fig. 6). Eastern European, Asian and far Eastern countries were most extensively represented by Poland, USSR and Czechoslovakia.

When identified in the literature, the primary host or prey (HOST:PREY) of the tested natural enemy was entered in each record. HOST:PREY contained 250 unique entries which were distributed among 9 general catagories (Table 7). Nearly 22% of records had no specified host or prey. Another 11% listed a pest complex for a given crop. Phytophagous mites and aphids were the most common HOST:PREY at 18.6% and 17.7% of records, respectively. The Homoptera (excluding aphids), which included scales, mealybugs, psyllids and whiteflies, comprised another 12%. Many of the hosts or prey identified in natural enemy/pesticide impact literature were induced or indirect pests. In general, biological control agents for these species are more effective than for primary pests of agriculture (Hoyt and Simpson 1979, Hoyt and Tanigoshi 1983). Among the pest Lepidoptera, Coleoptera and Diptera listed in SELCTV are a few key pests whose natural enemies may provide substantial natural control (Mosievskaya and Nakarov 1974, Brettell 1979, Ascerno et al. 1980, Somchoudhury and Dutt 1980).

Pest susceptibility data were sometimes presented in publications in addition to natural enemy assessments. Presence or absence of this comparative data was indicated in HP:TOX:DAT (Host or prey toxicity data). Approximately 30% of records were extracted from publications which provided some type of host/prey toxicity data, while 70% did not.

Table 8. Frequency and classification of the 30 most commonly studied pesticides in the SELCTV database of pesticide impact on arthropod natural enemies.

Compound Name	Pesticide Class	Chemical Group	No. Records
Carbaryl	[a/] I	Carbamate	494
DDT	I	DDT Derivative	476
Malathion	I	Organophosphate	436
Parathion	I	Organophosphate	430
Dimethoate	I	Organophosphate	390
Azinphosmethyl	I	Organophosphate	373
Diazinon	I	Organophosphate	266
Permethrin	I	Syn. Pyrethroid	239
Demeton	I	Organophosphate	237
Trichlorfon	I	Organophosphate	224
Endosulfan	I	Organochlorine	210
Oxydemeton-methyl	I	Organophosphate	204
Methyl parathion	I	Organophosphate	203
Pirimicarb	I	Carbamate	200
Fenvalerate	I	Syn. Pyrethroid	184
Methomyl	I	Carbamate	175
Toxaphene	I	Organochlorine	155
Dicofol	A	DDT Derivative	155
Fenitrothion	I	Organophosphate	154
Deflubenzuron	I	Chitin Inhibitor	143
Phosmet	I	Organophosphate	139
Carbophenothion	I	Organophosphate	129
Lindane	I	Organochlorine	129
Phosalone	I	Organophosphate	125
Phosphamidon	I	Organophosphate	125
Lead arsenate	I	Inorganic	121
Carbofuran	I	Carbamate	119
Monocrotophos	I	Organophosphate	115
Captan	F	Misc. Organic	113
Cyhexatin	A	Organotin	112

a/ A = Acaricide, F = Fungicide, I = Insecticide

Table 9. Relative distribution of SELCTV database records of pesticide impact on arthropod natural enemies grouped by pesticide formulation type.

Formulation	% Total Records
Emulsifiable Concentrate	36.9
Wettable Powder	28.6
Technical Grade	22.9
Granular	5.0
Soluble or Dispersible Powder	3.4
Flowable	1.9
Dust	1.4

By Pesticide Attributes

Names or designations of pesticides tested on natural enemies were entered in CPD:NAME (Compound name). Among 430 unique entries were common chemical names, experimental compound designations and microbial species names. As a general rule, pesticide mixtures were not entered into SELCTV. Table 8 contains the top 30 ranked compounds, as well as the pesticide class (CHEM:CLASS) and group (CHEM:GROUP) to which they belong (see below). Records of these 30 compounds comprise over 50% of SELCTV. Over half of these were organophosphates, the largest and most widely used group of insecticides. Dicofol and cyhexatin (acaricides) and captan (fungicide) were the only non-insecticides in this listing.

The type of pesticide formulation and amount of active ingredient were entered in FORMULATN (Formulation). Slightly more than half the records in SELCTV contained quantitative formulation data. If available, trade names were used when formulation was not specified. Table 9 shows the distribution of records among 7 general categories of pesticide formulation. Emulsifiable concentrates and wettable powders were the most widely used formulations in agriculture and for natural enemy impact assessments. Minor use formulations included granular, solubles, flowables and dusts. Approximately 10% of records documented side effects of technical grade pesticides on natural enemies. Technical grade refers to unformulated active ingredient, often used in laboratory tests.

Pesticide class (CHEM:CLASS) was determined for most compounds in SELCTV. Of 8 class differentiations, not all were specifically pesticides but included agricultural chemicals which could have an effect on natural enemies. Insecticides have been most extensively studied for side effects on natural enemies (82% of records). Fungicides and acaricides were the only other classes of compounds whose side effects had been studied to any degree, at 9% and 7% of records, respectively. Herbicides accounted for only 1.4% of records. The remaining 60 records contained impact data for feeding repellents, fumigants, nutrient sprays and plant growth regulators.

Incidence of records by pesticide class was plotted over time by number of records beginning in 1940 (Fig. 7). As indicated above, research by pesticide class was heavily skewed toward insecticides. Only in the past decade have impact studies begun to include other pesticides and agricultural chemicals (not included in this figure due to limited data) with any regularity. Herbicide and fungicide testing was conducted at similarly low levels, while herbicide testing remained neglible. The negative slope of lines after 1980 reflects incomplete data collection for this period.

Pesticides were further categorized (CHEM:GROUP) by chemical structure, origin or taxonomy (microbial insecticides). Twenty-eight unique chemical groupings of pesticides were differentiated within SELCTV (Table 10). Some CHEM:GROUP designations apply to more than one CHEM:CLASS, e.g., carbamate fungicides, herbicides and insecticides. Together, organophosphates and carbamates comprised over half of the database. Other common CHEM:GROUPs included organochlorines, DDT derivatives and synthetic pyrethroids, all of which are insecticides. Microbial insecticides accounted for 4% of SELCTV.

Trends in testing by insecticide CHEM:GROUP (chemical group) were demonstrated by examining records by insecticide chemical group over 5 year intervals (Fig. 8). The botanical and inorganic insecticides were relied upon more heavily before organosynthetics became available. Testing of these compounds increased, as did all others, with interest in finding selective pesticides for use in

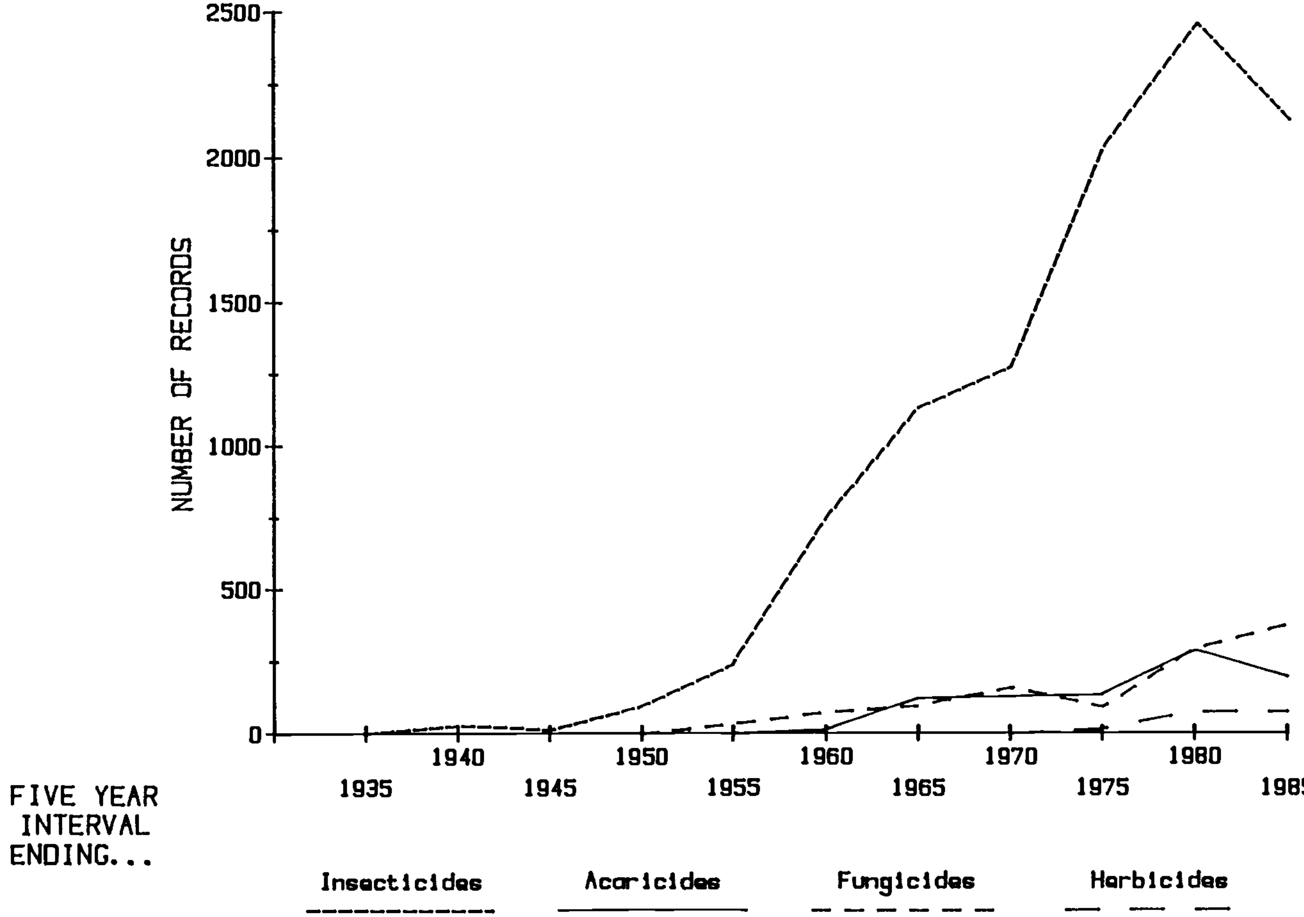


Figure 7. Incidence over time of pesticide impact research on arthropod natural enemies for each major pesticide class from the SELCTV database.

Table 10. Distribution of SELCTV database records of pesticide impact on arthropod natural enemies sorted by pesticide chemical group.

Chemical Group	Symbol	No.Records
Organophosphate	op	5093
Carbamate	ca	1593
Organochlorine	oc	893
DDT Derivative	dd	878
Synthetic Pyrethroid	sp	701
Miscellaneous Organic	or	680
Inorganic	io	419
Botanical	bt	319
Bacterial Insecticide	mpb	314
Juvenile Hormone Mimic	jhm	297
Other	o	287
Sulfur Based Acaricide	sul	228
Organotin	ot	207
Nitrophenol Derivative	npd	180
Chitin Inhibitor	ici	162
Viral Insecticide	mpv	79
Fungal Insecticide	mpf	38
Nitrogen Heterocyclic	nh	35
Not ascertainable	???	34
Urea Derivative	ur	29
Entomophagous Nematode	mpn	22
Protozoan Insecticide	mpp	20
Microbial By-product	mbp	18
Organometallic	om	14
Phenoxy Herbicide	po	12
Plant Growth Regulator	pgr	12
Insect Growth Reg.- Miscellaneous	igr	6

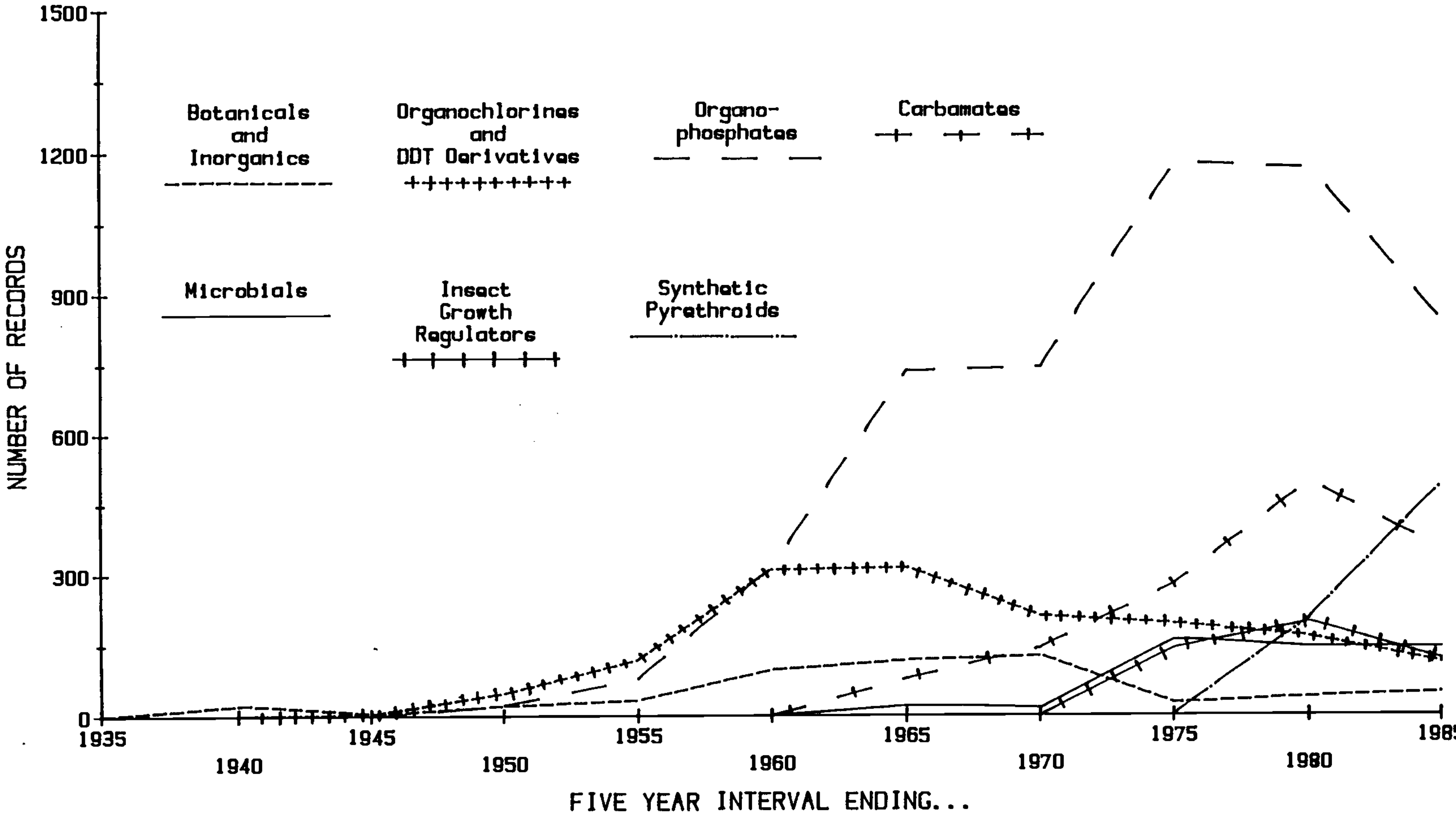


Figure 8. Incidence over time of insecticide impact research on arthropod natural enemies for major insecticide groupings from the SELCTV database.

IPM. However, after 1970 screening with botanicals and inorganics decreased to very low levels. Testing of organochlorine/DDT derivative side effects began when control problems with these compounds alone arose during the late 1950's and early 1960's. Organophosphates made up the majority of insecticide impact records, accurately representing the most widely used group of insecticides.

Chemical rate (CHEM:RATE) refers to the rate at which the pesticide was applied. Four different rate types were assigned. Over 50% of database records contained toxicity data for pesticides applied at recommended field rate. Natural enemies were exposed to pesticides applied at a given concentration in 22% of records, to a specific dose in 2% of cases and to a residual deposit in 6% of SELCTV records. Chemical rate was not assigned to records of LC_{50} or LD_{50} assays.

The units at which an application was made were entered into CR:UNITS (Chemical rate units). Application units were most often reported as % formulation (20% records), pounds of formulated pesticide per volume of water (11%) or % active ingredient (6%). Over 150 different rate units were entered into SELCTV. CR:UNITS apply to the numbers entered in CR:VALUE (Chemical rate value). In order to make global comparisons throughout the database based on dosage, SC:AI (Standard concentration in % active ingredient) was created to accommodate all rate units in terms of percent active ingredient. A limited number of conversion factors have been worked out, allowing entries in this field for only 25% of SELCTV.

By Testing and Summary Attributes

The length of time that the natural enemy was in contact with the toxicant was entered in DUR:EXP (Duration of Exposure). Nine categories were developed from the 68 different exposure time entries in SELCTV (Fig. 9). The most common exposure time catagory was 24 hours or less, accounting for 18% of records. The number of records for longer exposure times declined as the duration of exposure increased. Nearly 40% of SELCTV records documented susceptiblity testing in which the exposure period and evaluation time were the same, but the time period was variable or not specified. This condition would apply, for example, to parasitoids treated in some manner and evaluated at emergence. Exposure time was not specified for 22% of records.

Ten test methods were distinguished in SELCTV (Fig. 10). Field tests and contact tests (contact with a fresh, dry deposit of pesticide) accounted for about 30% of records each. Tests in which pesticides were sprayed, applied topically, contacted as aged residues or used as dips for natural enemies each accounted for another 6-7% of records. Data for pesticides administered to natural enemies orally, by injection or in tests where the mode of uptake was variable were contained in another 5% of SELCTV. A special designation was reserved for tests in which the host of an endoparasitoid was treated with a microbial insecticide prior to or following parasitization. This designation was used for less than 1% of records.

The frequency of six common test methods over time indicated that laboratory contact tests have surpassed field tests as the preferred method for assessing pesticide impact on natural enemies (Fig. 11). Curves for topical, residue and dip tests showed similar trends of rapid increase from 1965 to 1975, but then level off approaching 1980. Spray testing was maintained at a fairly steady rate over the last 15 years, slightly below that of the others.

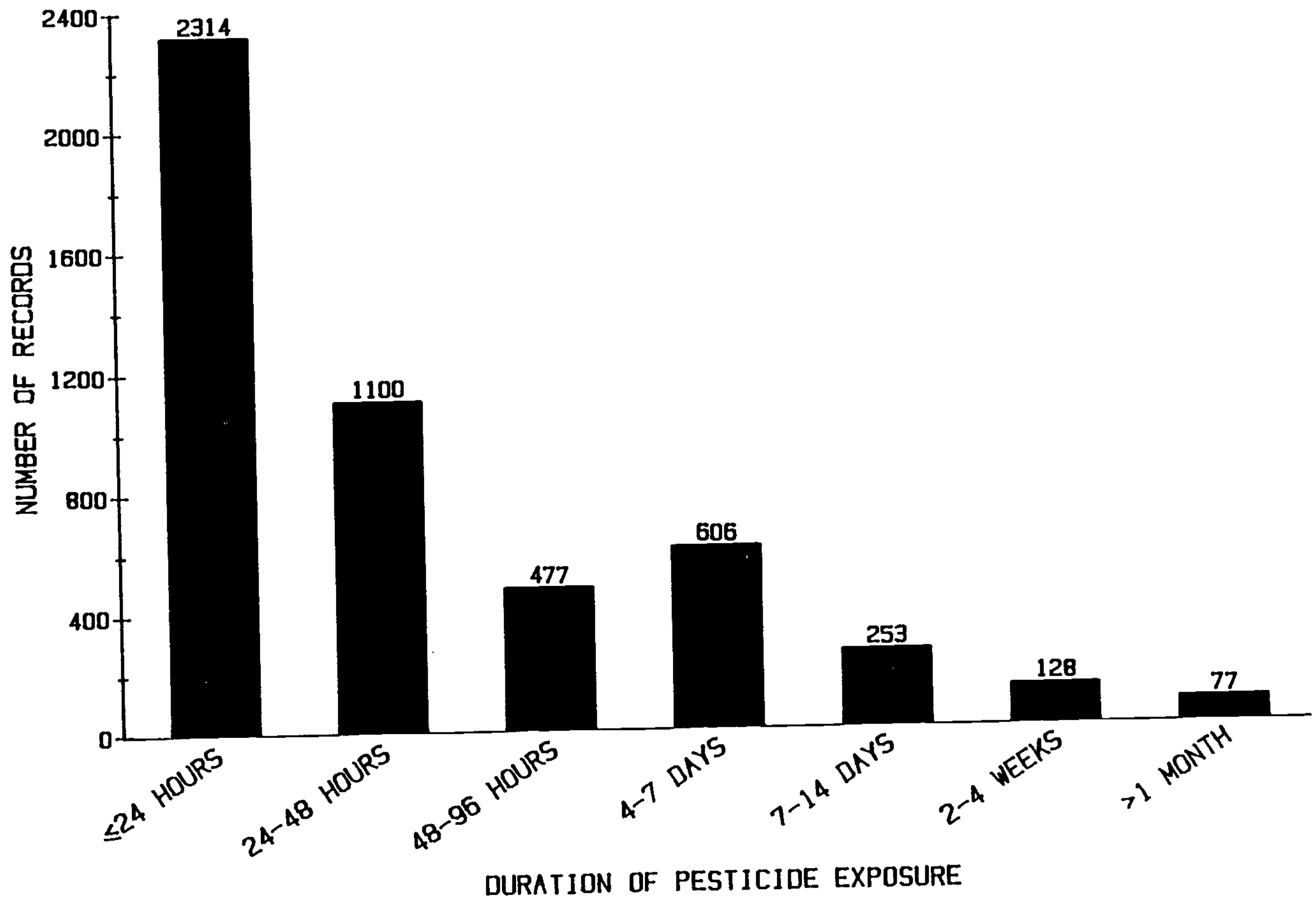


Figure 9. Distribution of SELCTV database records of pesticide impact on arthropod natural enemies by pesticide exposure time.

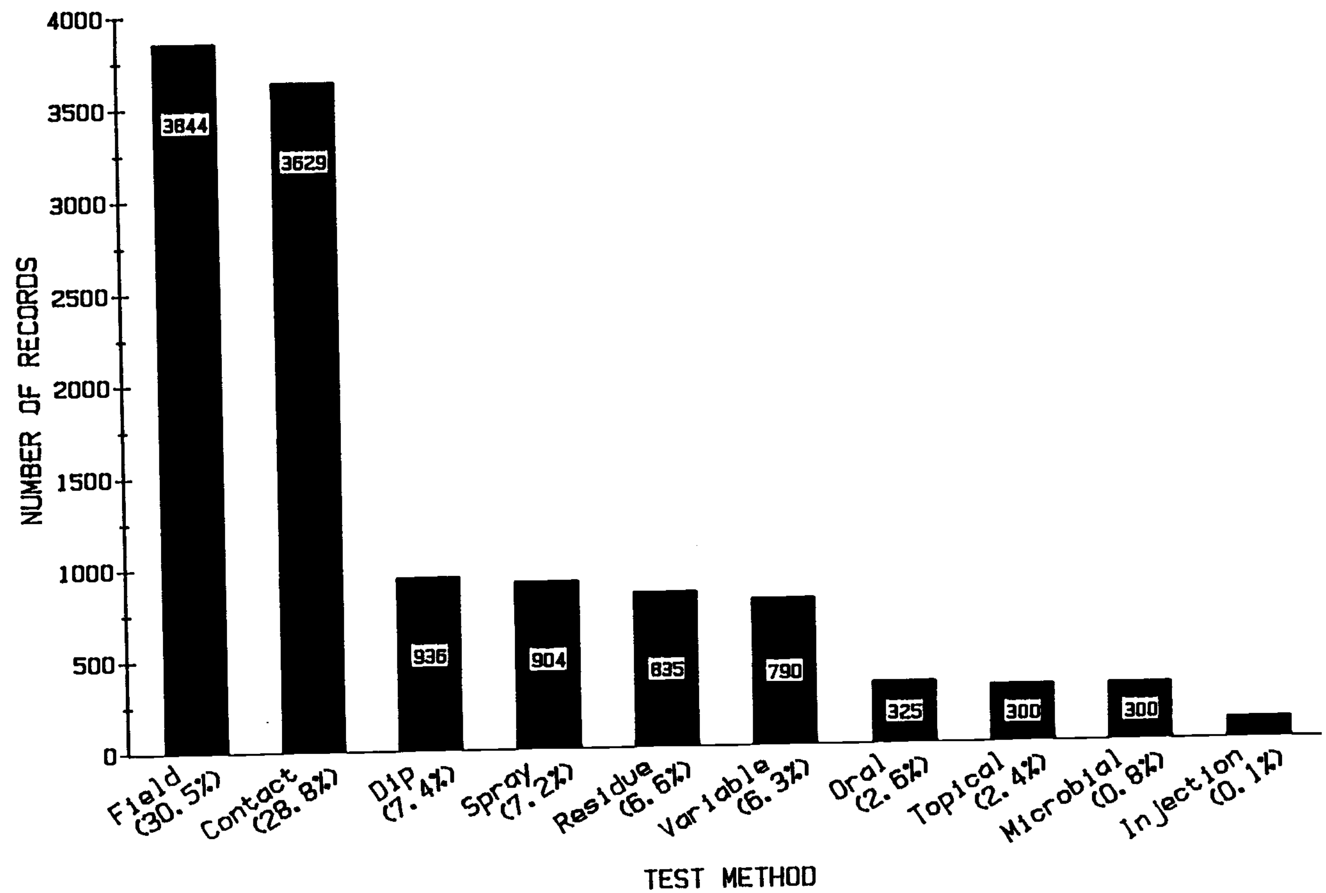


Figure 10. Distribution of SELCTV database records of pesticide impact on arthropod natural enemies grouped by test method.

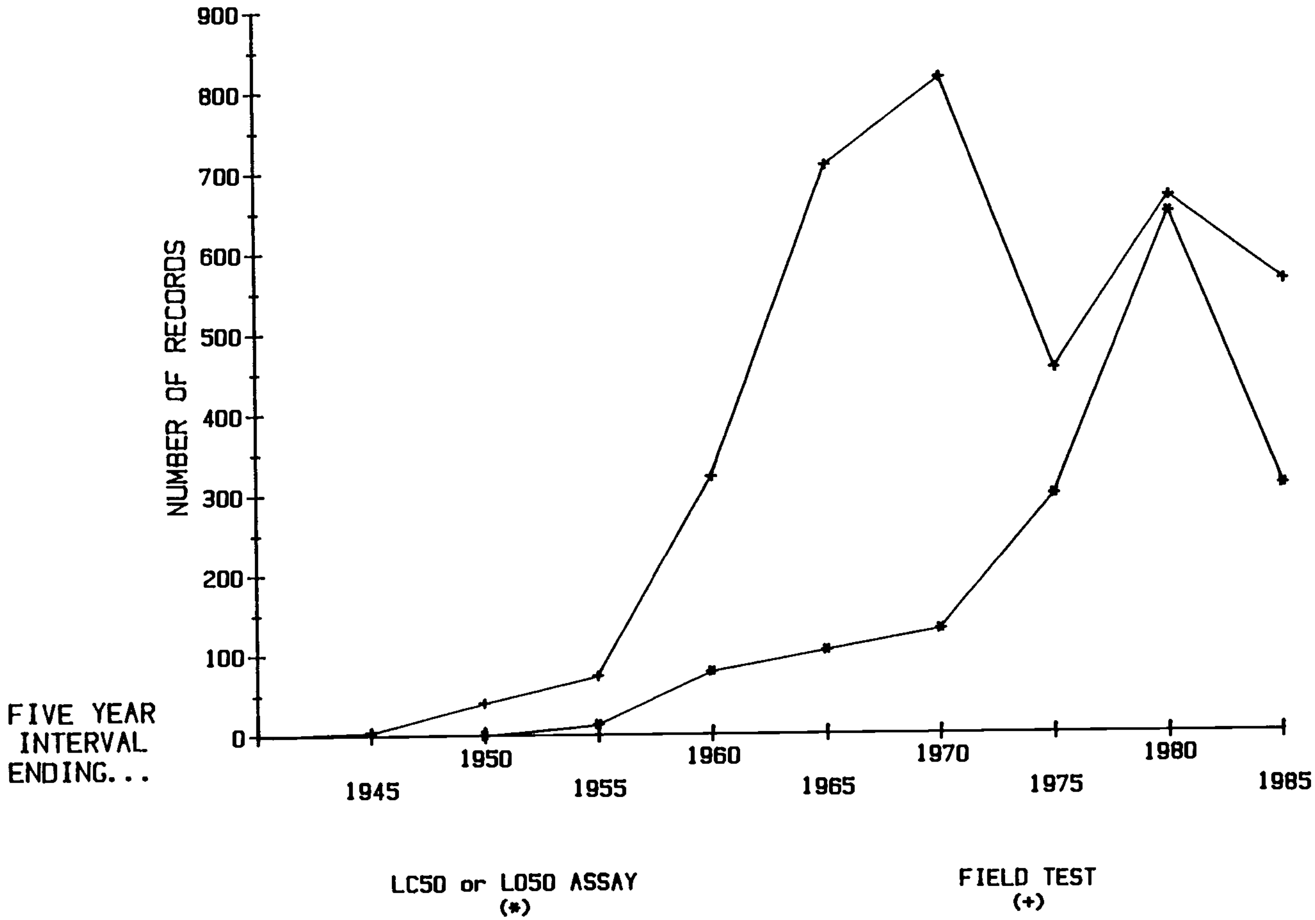


Figure 11. Changes in precision associated with pesticide impact assessment on arthropod natural enemies measured in records of field vs. median lethal assays over time from the SELCTV database.

Changes in the precision with which natural enemy susceptibility were assessed was examined by comparing field assessments of pesticide toxicity and LC_{50} or LD_{50} assays over time (Fig. 12). These two types of testing were chosen as exemplifying extremes in precision. Field tests dominated early studies, increasing after 1955 and peaking by 1970. Median lethal assays began a more gradual increase around 1955. After 1970, the use of this type of assay for evaluating side effects of pesticides on natural enemies increased rapidly. Field assessments may now be declining slowly in proportion to all records and have probably been succeeded in frequency by median lethal assays.

Evaluation time (EVAL:TIME) refers to the elapsed time from initial pesticide exposure to evaluation of impact. Most tests of pesticide side effects on natural enemies were conducted in 48 hours or less (Fig. 13). Fewer records were found for the longer evaluation times, as with exposure time (Fig. 9). Many EVAL:TIME field entries were not specifically time increments. Five percent of records document lethal time of exposure required to cause 50% mortality (LT_{50}). Another 5% of records were assessments of parasitoids which were treated subsequent to emergence from their hosts, and evaluated at emergence. Evaluation time was not specified in over 20% of records.

Response measurements encompassed 3 fields in SELCTV record structure (see Table 1): RESP:TYPE, RESP:UNITS and RESP:VALUE. RESP:TYPE (Response type) identified the measured response of a natural enemy to a pesticide. Of 27 types of responses listed in SELCTV, mortality was measured in over 75% of records. Median lethal dose, concentration or time were measured in another 20% of records. The remaining responses included such sublethal

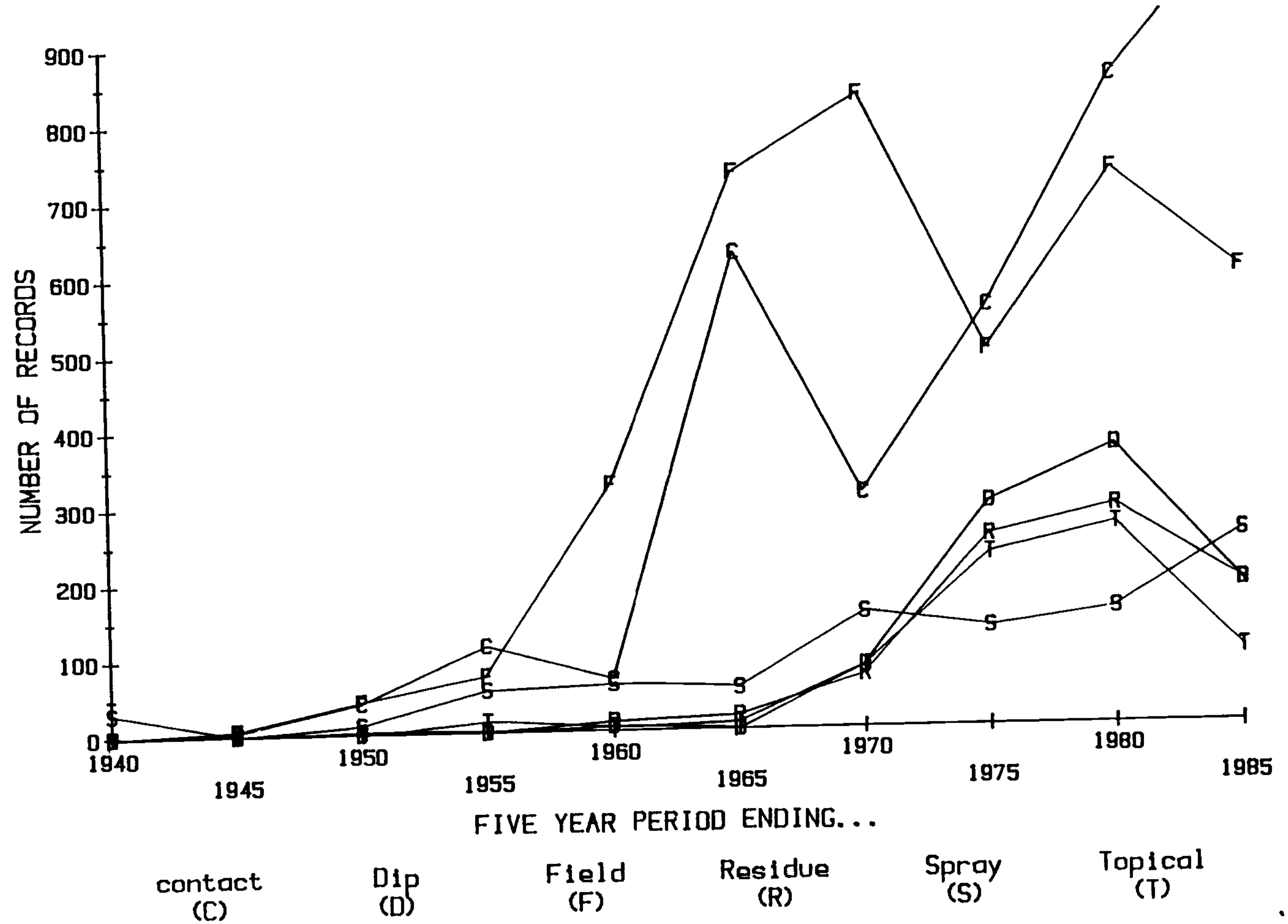


Figure 12. Incidence of predominant test methods used to assess natural enemy susceptibility to pesticides in number of records over time from the SELCTV database.

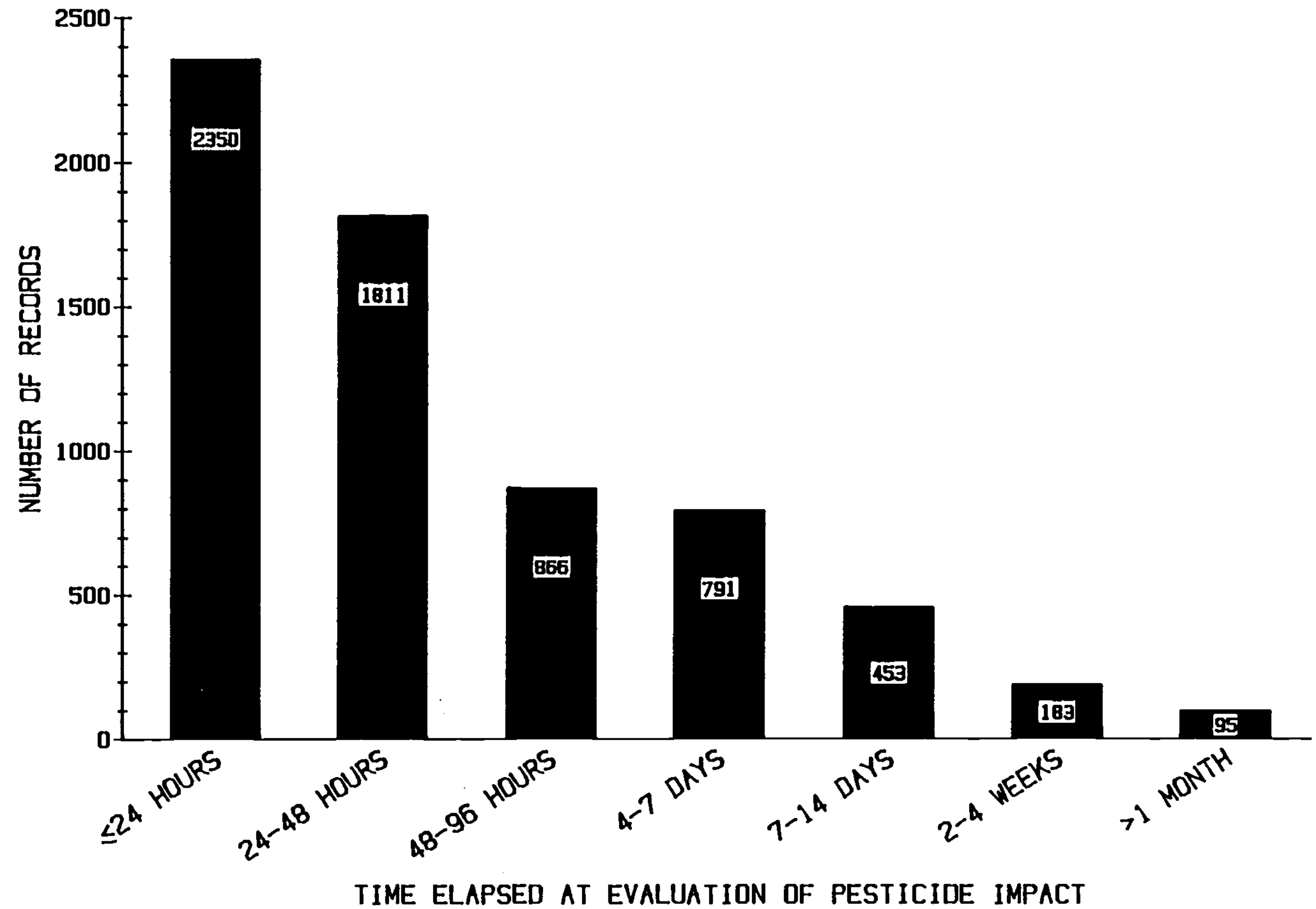


Figure 13. Distribution of SELCTV database records of pesticide impact on arthropod natural enemies grouped by evaluation time period.

responses as changes in consumption, ability to diapause, fecundity, oviposition and developmental time. In a few cases, biochemical conversion of a pesticide to its metabolite(s) was measured.

RESP:UNITS (Response units) apply to phenomena listed in RESP:TYPE. Most (80%) units are percentage increase or decrease, referring to mortality or the change in natural enemy biology caused by a sublethal pesticide dose. The remaining 53 response units apply to quantities measured in lethal concentration, dose or time (LC, LD, or LT), e.g. % active ingredient, % formulated pesticide and micrograms of toxicant per insect. Most LT_{50} values were expressed in hours. RESP:VALUE (Response value) refers to the numerical value of the measured response.

Resistance ratios (RR:RATIO) were computed or cited from the literature. Ratios consist of the LC_{50} or LD_{50} of the natural enemy divided by that of a known susceptible strain, and were entered in only 149 records or just over 1% of SELCTV. This low value reflects the paucity of documentation of resistance in natural enemy species (Croft and Brown 1975, Hoy 1982, Croft and Strickler 1983). Ratios ranged from a low of 2 to a high of nearly 80,000 for Amblyseius fallacis with azinphosmethyl (Motoyama et al. 1970). Most resistance ratios were calculated for phytoseiid mites (71%) (Croft and Strickler 1983, Hoy 1985). Braconid and aphelinid parasitoids accounted for about 11% of ratios (e.g., Pielou and Glasser 1952, Abdelrahman 1972, Schoones and Giliomee 1982, Rosenheim and Hoy 1986) while resistant coccinellids composed another 6% (Mohamad 1974, Head et al. 1977, Hull and Starner 1983). By insecticide group, organophosphates predominate natural enemy cases of resistance, folllowed by carbamates, synthetic pyrethroids and DDT derivatives, respectively.

Toxicity ratings (TOX:RATING) were assigned from a 1-5 scale allowing comparison of many different response types (see RESP:TYPE and RESP:UNITS this section; Fig. 14). Over half of SELCTV records fell into the higher toxicity categories of 4 or 5. Zero was assigned if no response data could be extracted from an abstract or publication. Most of the SELCTV analysis was based on the averages calculated on the toxicity rating scale.

In an effort to rank pesticide impact studies on natural enemies by quality or level of precision, a data rating (DAT:RATING) system was imposed (Fig. 15). This standard was not used to sort data for thesis analysis. Some types of analysis might warrant using data rating as a search criterion, such as computations omitting data from abstracts or summaries. While such a scientific rating contains a qualitative element, the capacity to specifiy a precision level for data analysis has utility.

The first digit of the two part code indicated the relative level of precision on the response measurement. Presence (1) or absence (2) of summary statistics was reflected by the second digit. Historically, laboratory tests without statistical analysis were the most common types of assessments conducted with natural enemies on a per record basis (Fig. 16). Next in frequency were LC_{50} or LD_{50} assays with probit analysis.

Sublethal effects of pesticides (SUBLETHAL) were recorded for 8% of SELCTV records, some of which contained multiple reports of sublethal responses for a particular pesticide/natural enemy combination. A 2-way table shows the frequency of sublethal effects measurements by order (Table 11). Changes in fecundity were evaluated twice as often as any other sublethal effect, accounting for 30% of reports. Consumption, morphological deformation, developmental time, fertility, longevity and parastism were examined in approximately 10% of records each.

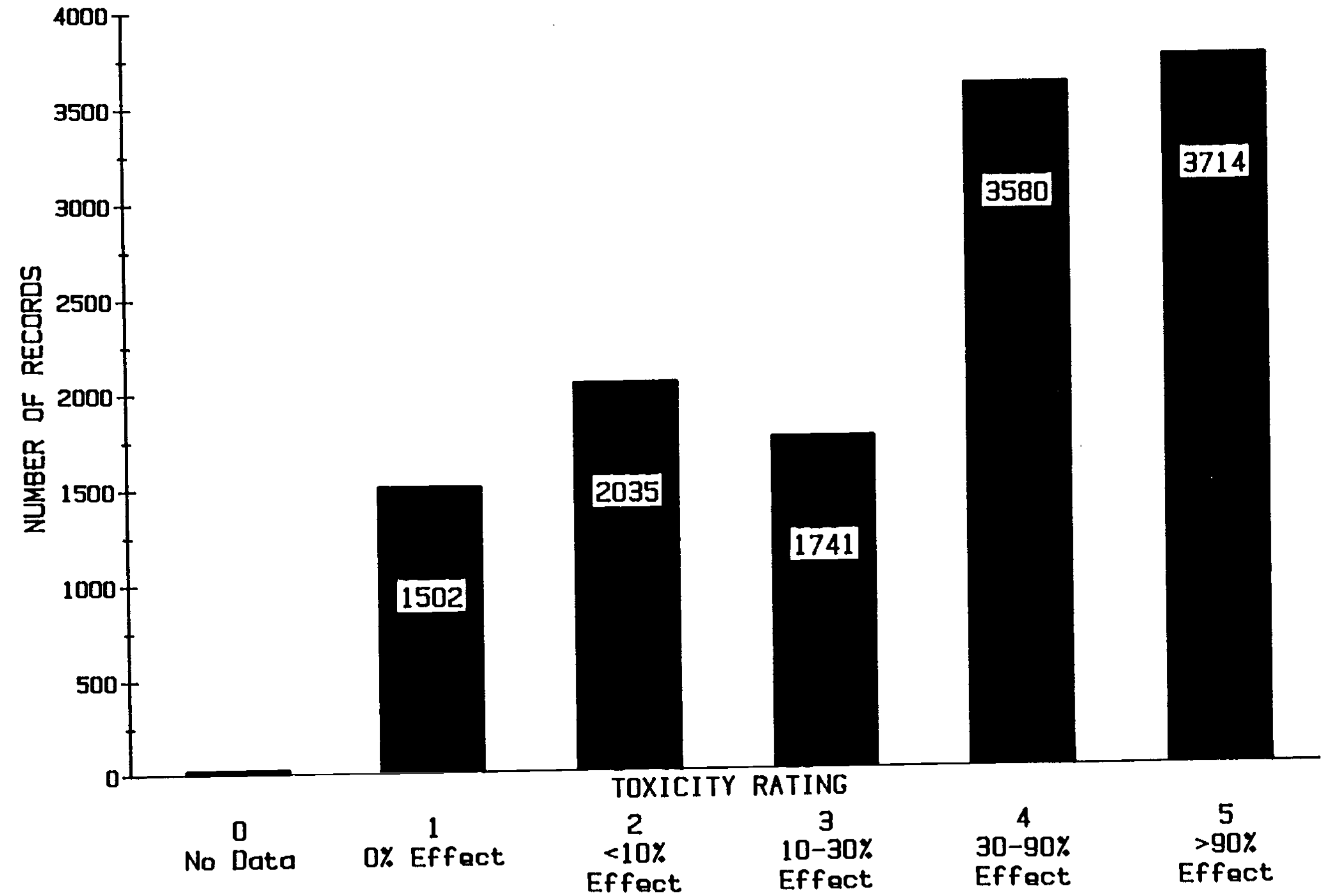


Figure 14. Distribution of SELCTV database records of pesticide impact on arthropod natural enemies grouped by toxicity rating.

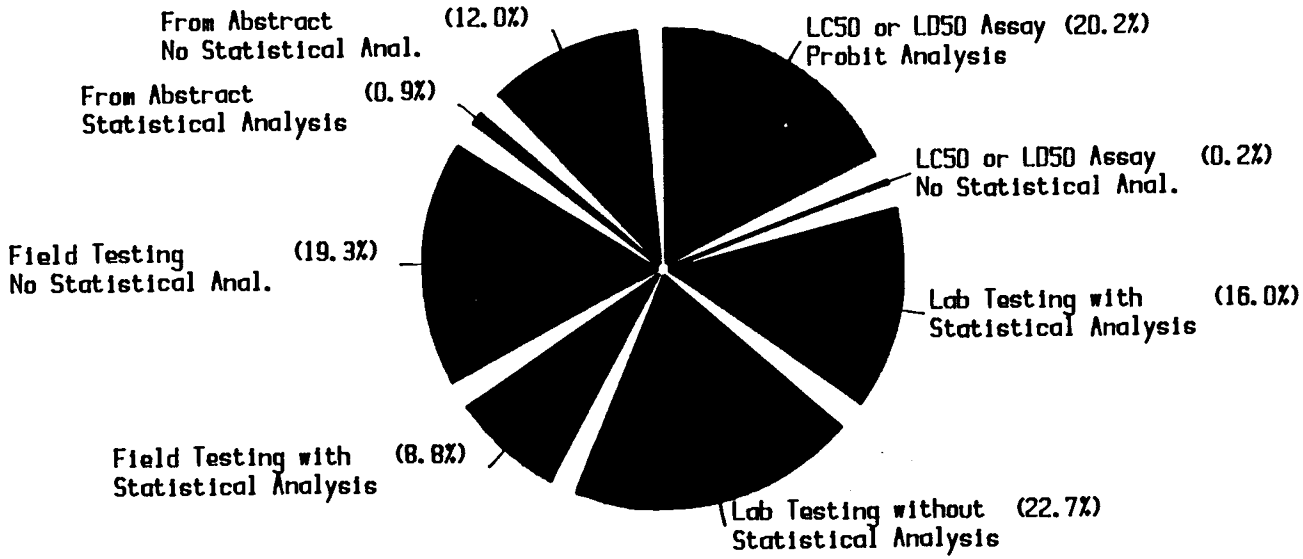


Figure 15. Distribution of SELCTV database records of pesticide impact on arthropod natural enemies grouped by data rating.

Table 11. Documented sublethal pesticide side effects and their distribution among natural enemy orders from the SELCTV database.

Sublethal Effect (No. Recprds)	Order[a/] Y	A	C	H	N	D	S	L	O
Fecundity (397)	133	165	28	58	11	2	0	0	0
Developmental Time (150)	75	40	1	5	21	8	0	0	0
Parasitism (140)	114	0	18	0	0	8	0	0	0
Consumption (138)	0	49	39	10	18	6	14	0	2
Longevity (115)	84	5	11	9	0	2	0	4	0
Deformation (101)	30	0	22	3	29	17	0	0	0
Fertility (94)	5	10	2	47	30	0	0	0	0
Oviposition (64)	22	29	9	4	0	0	0	0	0
Repellency (63)	39	18	1	0	0	5	0	0	0
Reproduction (40)	9	30	1	0	0	0	0	0	0
Locomotion (30)	4	5	21	0	0	0	0	0	0
Order Totals	515	351	153	136	109	48	14	4	2

a/ Y = Hymenoptera, A = Acari, C = Coleoptera,
H = Hemiptera, N = Neuroptera, D = Diptera,
S = Araneae, L =Lepidoptera, O = Orthoptera

Pesticide induced sublethal effects were studied across 9 orders of natural enemies: Hymenoptera (40%), Acari (26%), Coleoptera (10%), Hemiptera (10%), Neuroptera (8%) and 4 others (6%).

Records documenting sublethal effects increased exponentially in number after 1960 (Fig. 16). Because all records in SELCTV were rising, sublethal effects data were also expressed as % of total records. The incidence of sublethal response measurements increased slowly relative to total records. A small peak in sublethal assessments for 1940-1945 may reflect interest in the effects of agricultural chemicals on natural enemies, possibly related to the field failure of lead arsenate. However, with the higher efficacy of newly introduced synthetic organic pesticides, this type of research diminished until the 1960's. Since then, a small but steady increase in sublethal effects research has been maintained. Some more recent studies document these effects in carefully designed and sometimes unconventional experiments (Dumbre and Hower 1976, Babikir 1979, Bogenschutz 1979, Ascerno et al. 1980, Perera 1982, Moosbeckhofer 1983, Hoy and Dahlsten 1984, Grafton-Cardwell and Hoy 1985, O'Brien et al. 1985).

Selectivity ratios (SLECTRATIO) were calculated by dividing the LC_{50} or LD_{50} of the host or prey by that of the natural enemy. This comparative information was sporadically available in the literature, resulting in ratio calculations for only 870 records. Selectivity ratios ranged from 0.0001 to over 3000, spanning 8 orders of magnitude. In order to compute meaningful averages on SLECTRATIO, ratios were assigned values from a logarithmic scale (the SR:INDEX) ranging from 1 to 9. A value of 5 represents equal impact on pest and natural enemy (Table 12). Nearly 80% of selectivity ratios were computed for predators and their prey, and 20% for parasitoid-host

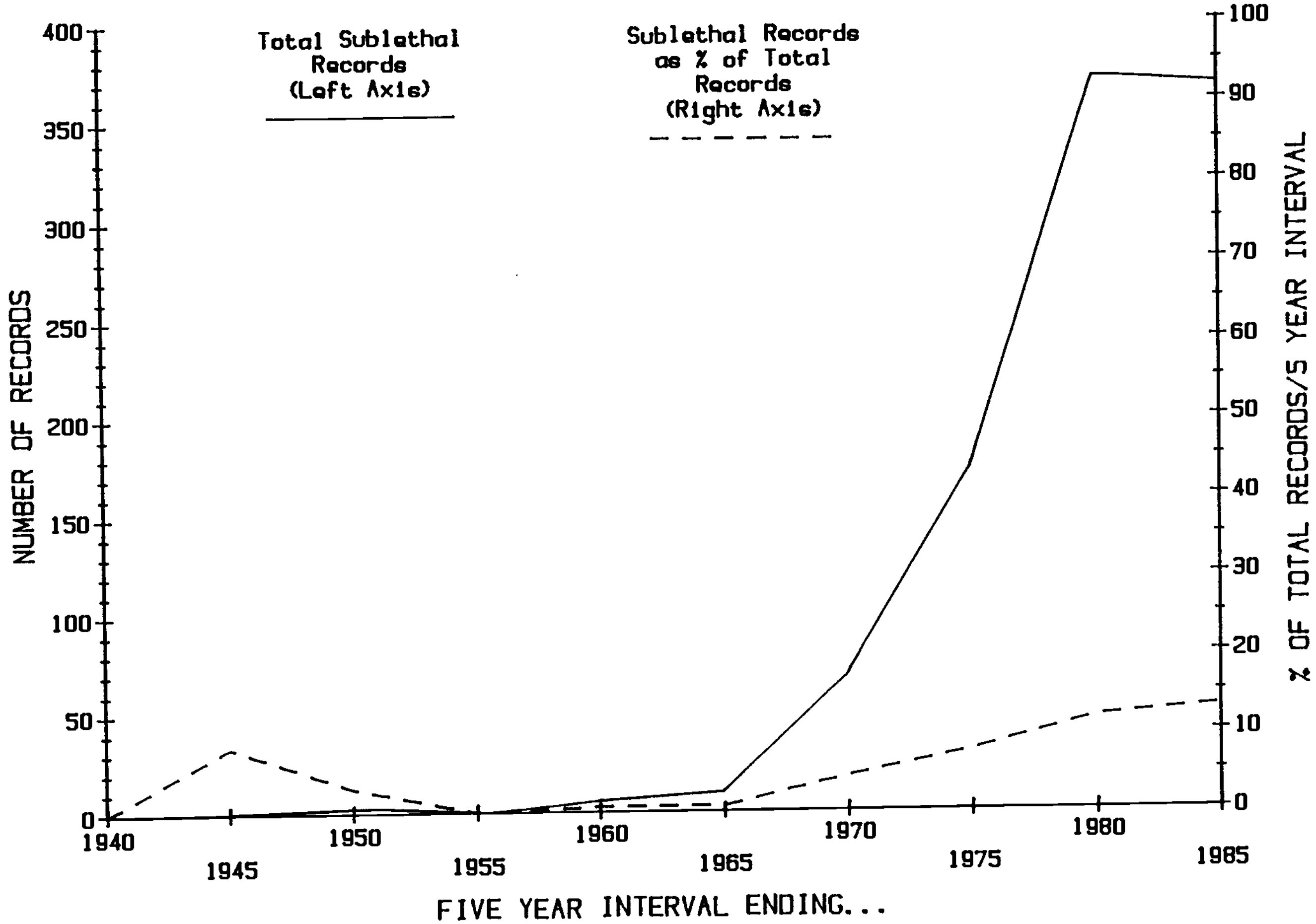


Figure 16. Incidence over time of documented sublethal side effects of pesticides on arthropod natural enemies from the SELCTV database.

Table 12. Frequency of selctivity ratios and assigned selectivity ratio index values indicating comparative pest/natural enemy pesticide susceptibility from the SELCTV database.

Range of SLECTRATIO	SR:INDEX	No.Records
<0.00051	1	10
0.00051-0.0050	2	44
0.0051-0.0500	3	85
0.0501-0.5000	4	193
0.5001-5.0000	5	355
5.0001-50.0000	6	131
50.0001-500.0000	7	38
500.0001-5000.0000	8	14
>5000.0000	9	0

data. By order, ratios were calculated predominantly for Coleoptera (29%), Acari (20%), Hymenoptera (20%) and Araneae (11%). The majority of SLECTRATIOs equated natural enemy and pest susceptibility for insecticides, specifically for organophosphates. (See Analysis section for more detailed examination of SLECTRATIO).

Analysis of the Database

SELCTV analysis was based primarily on TOX:RATING (toxicity rating) computations and to a lesser degree on SLECTRATIO (Selectivity ratio), RR:RATIO (Resistance ratio) and SUBLETHAL (Sublethal). Means were calculated from numeric data grouped by various criteria from character fields. Variance associated with toxicity rating averages was usually computed, but was not always meaningful due to the breadth of information sources and focal points of studies in SELCTV.

Toxicity Rating Analysis

By Natural Enemy Attributes

Predator, parasitoid and all natural enemy responses to the primary pesticide classes (CHEM:CLASS) and to all compounds were compiled in Table 13. Lower predator susceptibility to pesticides was indicated by lower average toxicity ratings (TOX:RATING) for most pesticide classes. Susceptibility to fungicides was approximately equal for both natural enemy types. In most cases, parasitoids exhibited a less variable response to pesticides than predators. Insecticides were most toxic to natural enemies, followed by herbicides, acaricides and fungicides respectively. Several authors (Huffaker 1971, Croft and Morse 1979) have commented on possible causes for these toxicity differences between predators and parasitoids. Factors such as genetic variability,

Table 13. Average toxicity ratings and variances of pesticide classes to all arthopod natural enemies, predators and parasitoids from the SELCTV database.

Pesticide Class	Predators Mean	Predators Variance	Parasitoids Mean	Parasitoids Variance	All Mean	All Variance
Insecticide	3.61	1.78	3.74	1.74	3.65	1.77
	(7326)[a]		(2989)		(10315)	
Fungicide	2.59	1.51	2.58	1.45	2.59	1.49
	(781)		(357)		(1138)	
Acaricide	2.76	1.81	2.83	1.50	2.77	1.76
	(747)		(144)		(891)	
Herbicide	2.83	1.73	3.10	1.77	2.95	1.76
	(92)		(84)		(176)	
All Pesticides	3.43	1.92	3.57	1.86	3.47	****
	(8968)		(3583)		(12551)	

a/ (#) = No. Records

detoxification and resistance differences have been implicated (see Discussion).

Average toxicity values (TOX:RATING) for the 15 most common families (FAMILY) in SELCTV for pesticide classes and to all compounds were computed (Table 14). Miridae, Ichneumonidae and Chrysopidae were least susceptibile to pesticides on the average. The hemipteran families, Miridae, Lygaeidae and Anthocoridae were fairly tolerant to each of the pesticide classes listed. Syrphidae, a family containing important aphid predators, were highly susceptible to most pesticides. Their sensitivity is a widely documented though largely unexplained phenomenon (Niemczyk et al. 1981, Hassan et al. 1983, Horn 1983, David and Horsburgh 1985). Most parasitoid families (e.g., Trichogrammatidae, Encyrtidae, Braconidae and Eulophidae) were more susceptible than families of predators.

The apparent tolerance of the Ichneumonidae was notable. More detailed examination of records indicated that this value was an artifact of the test types run for this group. Many ichneumonid records originated from tests where pesticides were applied to parasitized hosts (e.g., Smilowitz et al. 1976, Kaya and Hotchkin 1981), which tend to show lower toxicities than direct exposure tests. Also, a disproportionate number of ichneumonid tests measured side effects of the more innocuous IGR's (e.g., Smilowitz et al. 1976, von Naton 1978, Secher and Varty 1978, Bogenschutz 1979, Franz et al. 1980), fungicides (e.g., von Naton 1978, Bogenschutz 1979) and microbial pesticides (e.g., Ticehurst et al. 1982, Hotchkin and Kaya 1983, Salama and Zaki 1983). The low mean toxicity for ichneumonids was not the anomaly it appeared to be, as quite a few studies documented the harmful effects of conventional pesticides on this group of parasitoids (e.g., Abu and Ellis 1977, Plapp and Vinson

Table 14. Average toxicity ratings of pesticide classes to the 15 most commonly tested natural enemy families from the SELCTV database.

Family	Fungi-cide[a/]	Herbi-cide	Insecti-cide	Acari-cide	Pesti-cide
Miridae	2.06	-	3.57	2.23	3.21
Ichneumonidae	2.33	2.77	3.46	2.64	3.23
Chrysopidae	2.29	2.30	3.39	2.16	3.24
Lygaeidae	2.00	2.00	3.50	2.25	3.31
Anthocoridae	2.26	2.00	3.53	2.33	3.31
Aphelinidae	2.36	2.88	3.93	2.73	3.47
Nabidae	-	-	3.56	1.50	3.48
Carabidae	-	-	3.49	-	3.49
Coccinellidae	2.36	2.44	3.67	2.25	3.53
Phytoseiidae	2.86	3.64	3.84	3.25	3.53
Trichogram-matidae	3.56	3.67	3.68	4.07	3.65
Encyrtidae	2.07	3.69	3.97	2.61	3.69
Braconidae	2.56	2.88	3.75	3.00	3.70
Eulophidae	2.20	-	3.89	4.00	3.85
Syrphidae	3.08	3.86	3.93	3.83	3.89

a/ All means are based on 5 or more data points.

1977, Otvos and Raske 1980, Rajakulendran and Plapp 1982, Hassan et al. 1983).

Scatterplots and linear regression were used to show the relationship between mean insecticide toxicity and variance for families of parasitoids (Fig. 17) and families of predators (Fig. 18). Parasitoids were slightly more susceptible to insecticides than predators, indicated by the position of scatter centers in each plot. The response of parasitoids to insecticides was less variable than that of predators, represented by the tighter vertical spread of points in Figure 17. For both natural enemy types (Figs. 17 and 18), a linear relationship existed between susceptibility and variability in response. Negative slopes indicated a proportional decrease in variation as mean susceptibility by family increased. Three outliers lowered both the slope value and the correlation coefficient (r) for predators; otherwise, both regression lines had similar slopes and r values.

An examination of outliers in figures 17 and 18 was undertaken to see if high variance was dependent on a low number of database records/family. Families represented by fewer than 50 records were circled in the figures. No pattern was evident among circled families, as they occurred across the entire range of toxicity and variance elicited by natural enemy families. Therefore, no skewing effects were noted between variability and the number of records/family.

The 22 most common species (GENUS + SPECIES) in SELCTV were ranked in order of their increasing susceptibility to pesticides (Table 15). A spider, <u>Lycosa pseudoannulata</u>, was most tolerant of the prevalent species. Three generalist predator species followed, a coccinellid, a chrysopid and a mirid, respectively. Of the phytophagous mite predators, <u>Phytoseiulus persimilis</u>,

Figure 17. Mean insecticide toxicity ratings versus variance for 12 families of parasitoids in the SELCTV database.

<u>KEY to families:</u> {No. on figure = Family (No. of Obs.)}

1 = Tachinidae (89)	* 7 = Platygasteridae (25)
* 2 = Chalcididae (30)	8 = Pteromalidae (66)
* 3 = Scelionidae (42)	9 = Aphelinidae (382)
4 = Trichogrammatidae (326)	10 = Braconidae (1016)
5 = Ichneumonidae (365)	11 = Encyrtidae (280)
* 6 = Eupelmidae (27)	12 = Eulophidae (181)

(* = circled values on figure; fewer than 50 records.)

<u>Regression parameters:</u>

$y = -1.2x + 6.3$

$r = -0.72$

mean $x = 3.74$

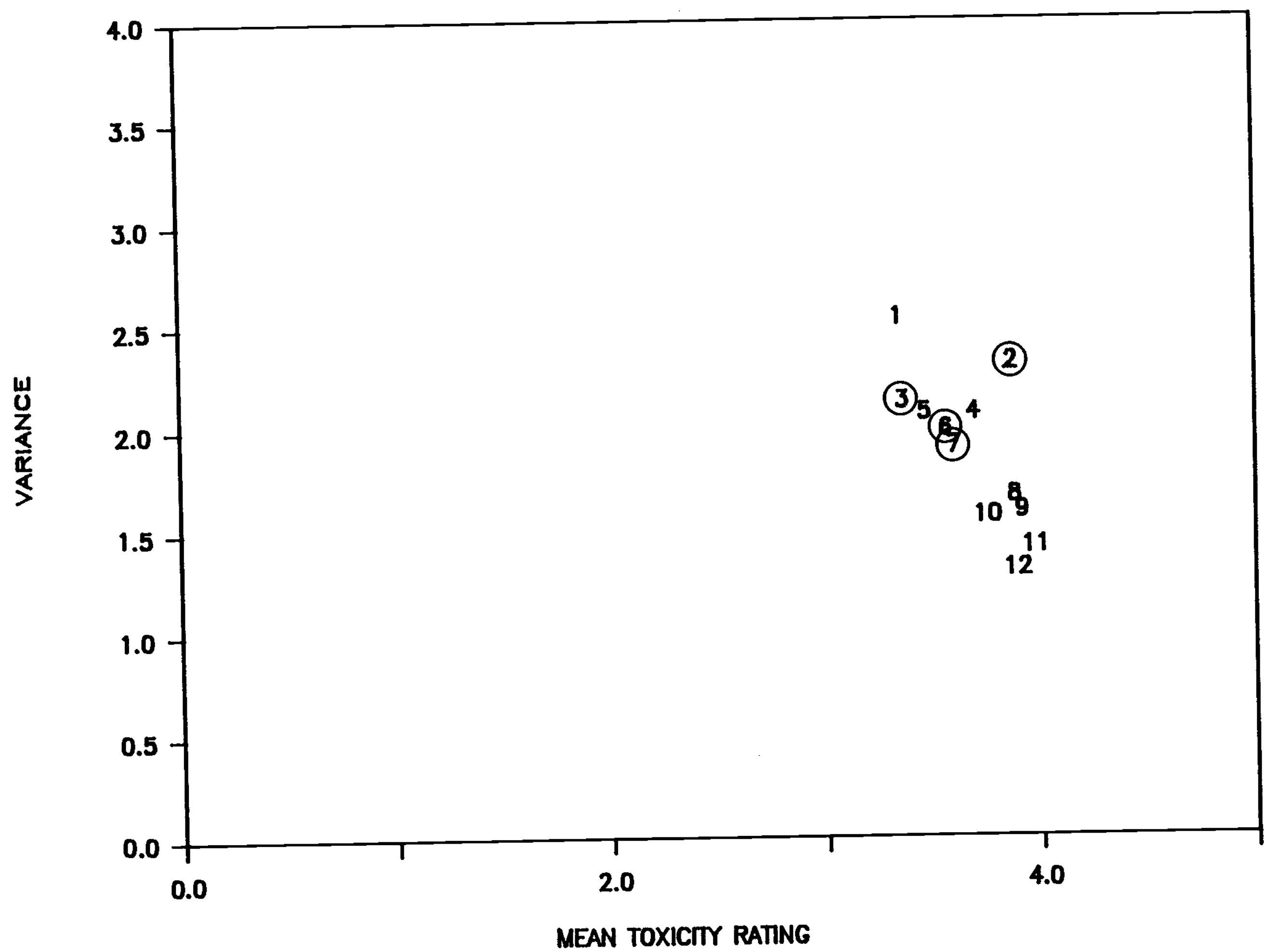


Figure 17. Mean insecticide toxicity ratings versus variance for 12 families of parasitoids in the SELCTV database.

Figure 18. Mean insecticide toxicity ratings versus variance for 28 families of predators in the SELCTV database.

KEY to families: {No. on figure = Family (No. of Obs.)}

* 1 = Clubionidae (17)	* 15 = Veliidae (33)
* 2 = Dytiscidae (15)	16 = Anthocoridae (373)
* 3 = Hydrophidlidae (11)	17 = Coccinellidae (1959)
* 4 = Pentatomidae (37)	18 = Syrphidae (326)
5 = Anystidae (60)	19 = Nabidae (217)
* 6 = Reduviidae (16)	* 20 = Thripidae (19)
* 7 = Berytidae (27)	21 = Phytoseiidae (1345)
8 = Lycosidae (110)	22 = Stigmaeidae (79)
9 = Miridae (569)	* 23 = Micryphantidae (36)
10 = Chrysopidae (903)	24 = Lygaeidae (200)
11 = Carabidae (366)	* 25 = Macrochelidae (15)
* 12 = Malachiidae (33)	26 = Cecidomyiidae (65)
13 = Phloeothripidae (91)	* 27 = Salticidae (13)
14 = Hemerobiidae (64)	* 28 = Theridiidae (16)

(* = circled values on figure; fewer than 50 records.)

Regression parameters:

y = -0.8 + 4.6

r = -0.79

mean x = 3.61

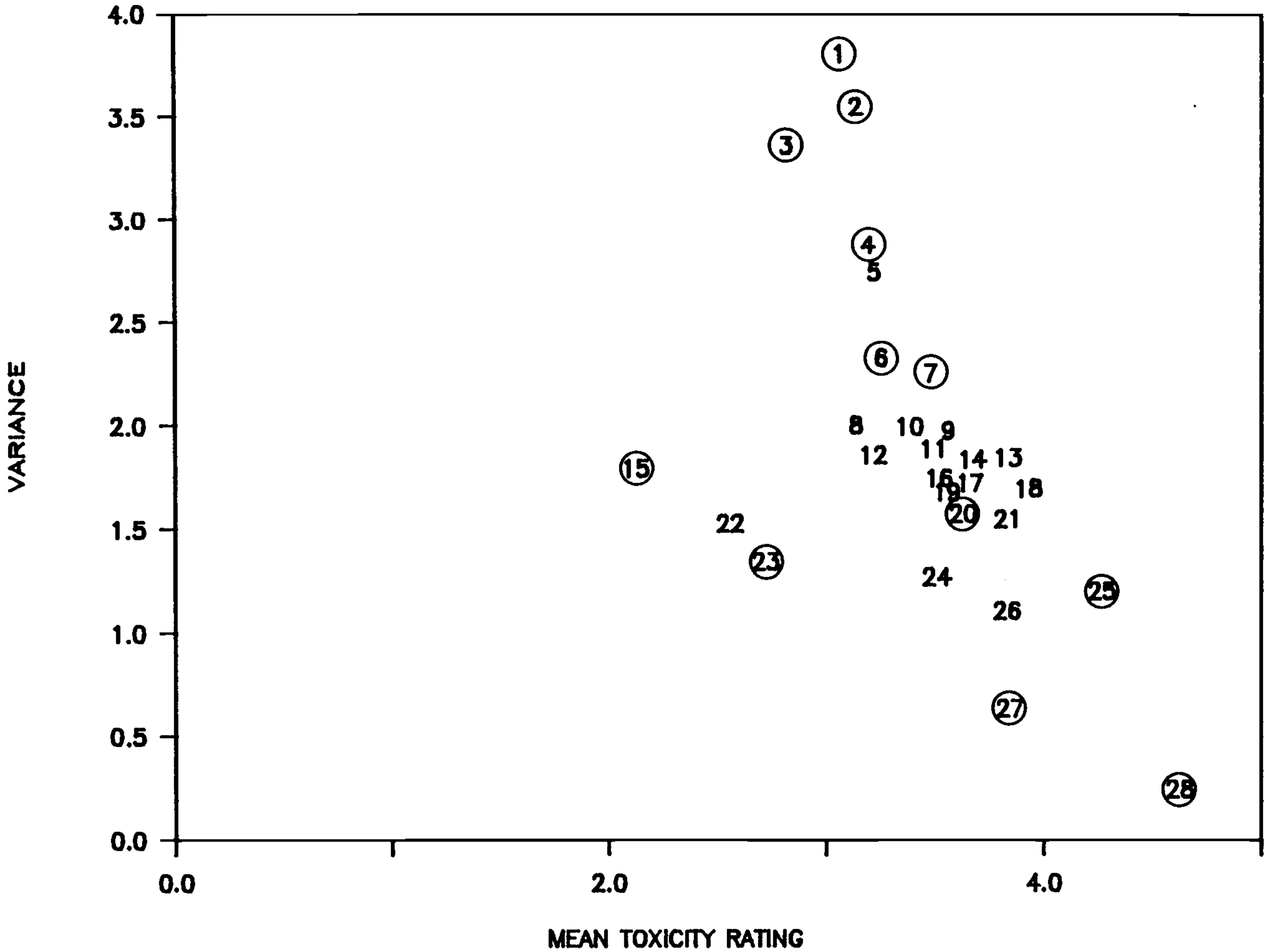


Figure 18. Mean insecticide toxicity versus variance for 28 families of predators in the SELCTV database.

Table 15. Average susceptibility of the 22 most commonly tested natural enemy species to all pesticides from the SELCTV database.

Species	Family	No. of Records	a/ Mean Toxicity
Lycosa pseudoannulata	Lycosidae	85	3.0
Cryptolaemus montrouzieri	Coccinellidae	114	3.0
Chrysopa carnea	Chrysopidae	534	3.1
Hyaliodes harti	Miridae	103	3.2
Encarsia formosa	Aphelinidae	232	3.3
Phytoseiulus persimilis	Phytoseiidae	323	3.4
Typhlodromus pyri	Phytoseiidae	268	3.4
Stethorus punctum	Coccinellidae	150	3.5
Typhlodromus occidentalis	Phytoseiidae	205	3.5
Phygadeuon trichops	Ichneumonidae	124	3.5
Chrysopa oculata	Chrysopidae	137	3.5
Amblysieus fallacis	Phytoseiidae	574	3.5
Leptomastix dactylopii	Encyrtidae	139	3.5
Hippodamia convergens	Coccinellidae	375	3.5
Anthocoris nemorum	Anthocoridae	85	3.6
Coccinella septempunctata	Coccinellidae	440	3.6
Trichogramma evanescens	Trichogrammatidae	86	3.6
Trichogramma cacoeciae	Trichogrammatidae	158	3.6
Coleomegilla maculata	Coccinellidae	102	3.7
Amblyseius hibisci	Phytoseiidae	90	3.7
Metasyrphus corollae	Syrphidae	105	4.1
Opius concolor	Braconidae	85	4.3

a/ Susceptibility is used in reference to a natural enemy, while toxicity generally refers the potency of a chemical.

Typhlodromus pyri, T. occidentalis, Stethorus punctum, Amblyseius fallacis and A. hibisci, most were of intermediate susceptibility. A. fallacis, T. occidentalis, T. pyri and P. persimilis means included response data for resistant strains, which lowered their apparent values (e.g., Lienk et al. 1978, Cranham and Solomon 1981, Overmeer and van Zon 1983, van de Baan et al. 1985). At the species level, parasitoids were well dispersed among natural enemies in terms of susceptibility. Encarsia formosa showed notable tolerancefor a parasitoid. This may due to widespread testing of parasitoids pupating within the host's caste skin or adults emerging from treated pupae (e.g., Hatalane and Budai 1982, Helyer 1982, Delorme and Angot 1983). These studies demonstrated how natural enemies might be conserved through timing of sprays. The high susceptibility of syrphids to pesticides was exemplified again by Metasyrphus corollae (e.g., Grapel 1982, Hellpap 1982, Nasseh 1982).

Natural enemy susceptibility to pesticides varied with life stage (STAGE) as indicated by mean toxicity ratings (Table 16). Eggs and pupae were most tolerant to pesticides, while larvae and adults were most susceptible. Because of their greater susceptibility, larval and adult life stages should receive priority in testing. This is critical for adults which must survive, feed and reproduce. When further differentiated by natural enemy type, the same trend applied to predator lifestages. However, eggs and adults were the most susceptible parasitoid life stages, while larvae and pupae were more tolerant. These trends in susceptibility have been noted by other reviewers (e.g., Bartlett 1964, Croft and Brown 1975, Croft 1977, Hull and Beers 1985) and confirmed in many studies of individual

Table 16. Average susceptibility and variance for all arthropod natural enemies, predators and parasitoids grouped by life stage from SELCTV database records

Life Stage	Predator		Parasitoid		All	
Egg	a/ 3.00	(238)	3.79	(14)	3.04	(252)
Larva	3.52	(1288)	3.22	(345)	3.46	(1622)
Pupa	3.18	(62)	3.26	(178)	3.24	(240)
Adult	3.47	(3761)	3.72	(2117)	3.56	(5884)

a/ (#) = No. of Records

Table 17. Average toxicity ratings and variance for test methods used to assess pesticide impact on natural enemies from the SELCTV database.

Test Method	No. of Records	Mean Toxicity	Variance
Microbial	99	2.84	1.91
Oral	325	3.20	2.08
Field	3842	3.39	1.94
Spray	904	3.46	1.96
Residue	835	3.51	1.74
Topical	790	3.53	1.79
Dips	937	3.54	1.58
Contact	3628	3.55	1.92
Variable	300	3.79	1.50

species responses (e.g., Babrikova 1980, Babrikova 1982, Warner and Croft 1982).

By Test Attributes

Mean toxicity ratings were compared by test method (TST:METHD) for all compounds and natural enemies (Table 17). Of the most common tests, mean toxicity values for contact, dip, residue, spray and topical tests were similar, ca. 3.50. Field tests were slightly lower at 3.39, followed by oral tests at 3.20. The lowest average toxicity by test type was associated with tests in which a microbial insecticide was mediated through a host to its parasitoid. Flexner et al. (1986) reported similarly low toxicities to all natural enemies for most microbial insecticides administered in this manner. Because of the many variables involved in these calculations, variances did not provide meaningful information.

By Pesticide Attributes

Average toxicity by chemical group (CHEM:GROUP) for all natural enemies was depicted for each of the major pesticide classes (Figs. 19-22). Chemical groups and the number of records in the computed average were indicated along the X axis in order of decreasing toxicity. Although 95% confidence intervals were included, they largely reflected size (n) of the data set.

Of insecticide chemical groups (Fig. 19), synthetic pyrethroids, organophosphates, carbamates, DDT derivatives and organochlorines were highly toxic, with averages ranging from 4.00 down to 3.54. Intermediate in impact were juvenile hormone mimics, inorganics, botanicals and chitin inhibitors. Microbial insecticides were very selective to natural enemies.

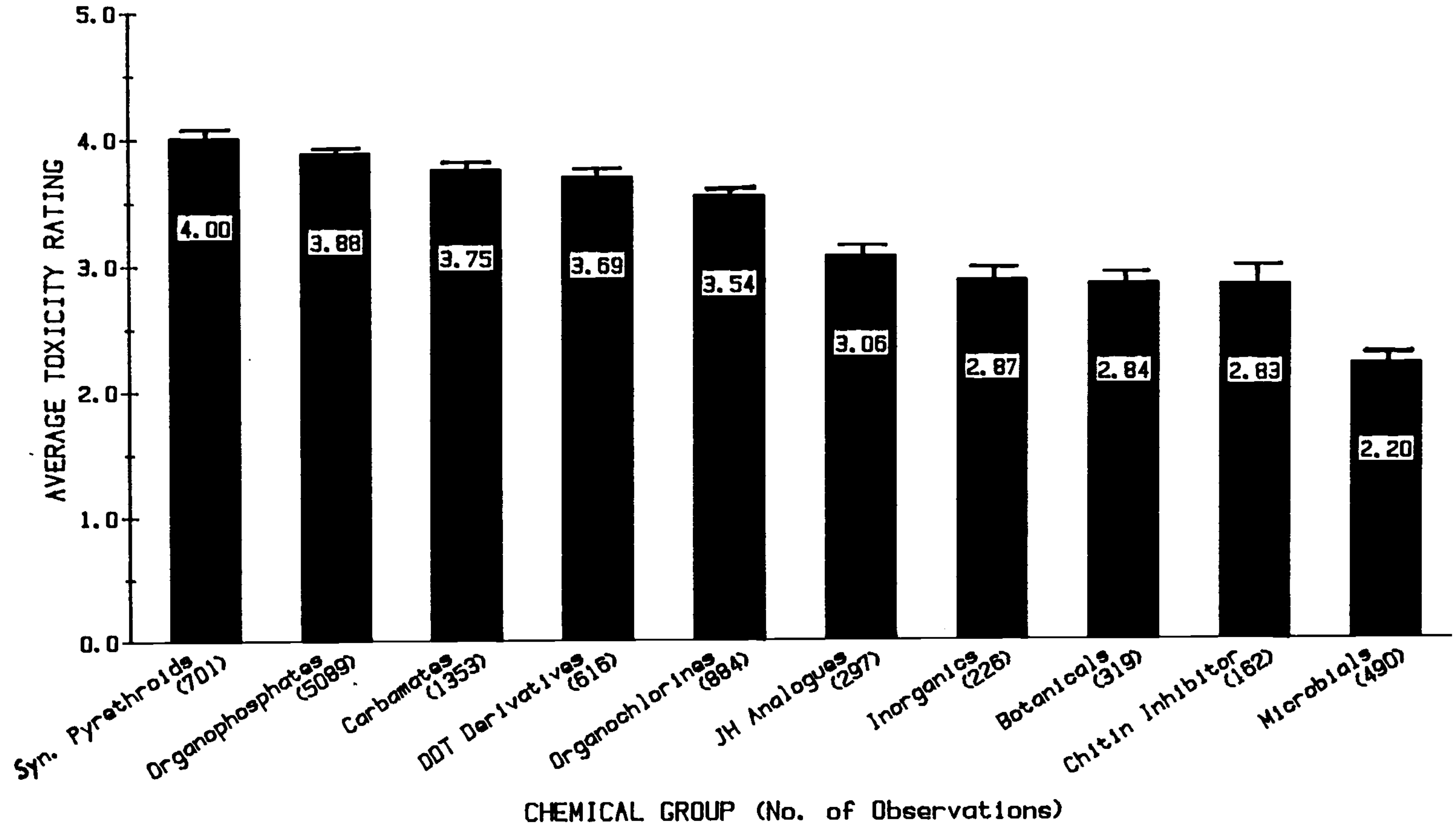


Figure 19. Average toxicity ratings and 95% confidence intervals for insecticide chemical groups tested for side effects on arthropod natural enemies from the SELCTV database.

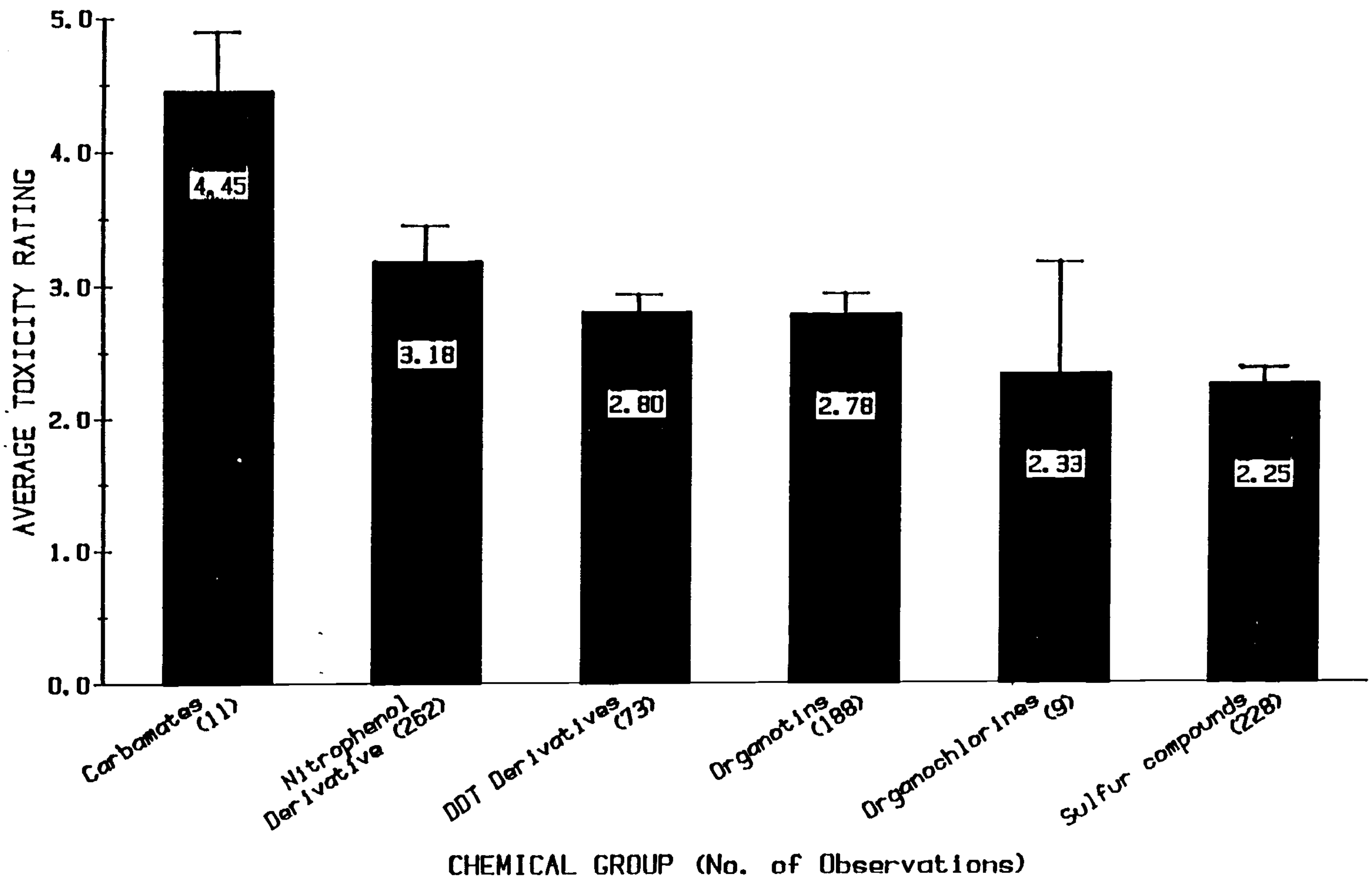


Figure 20. Average toxicity ratings and 95% confidence intervals for acaricide chemical groups tested for side effects on arthropod natural enemies from the SELCTV database.

Mean toxicities for acaricide chemical groups (Fig. 20) showed that organophosphate and carbamate acaricides were most toxic to natural enemies. Nitrophenol derivatives, DDT derivatives and organotins were intermediate in toxicity, while the organochlorine and sulfur containing acaricides were fairly selective to natural enemies. A broader range of confidence intervals was notable here compared to insecticides, but again was a function of data set size (n).

Fungicides comprised the least toxic pesticide class (Fig. 21) as compared to related figures (19,20,22). Nitrophenol derivatives were most toxic to natural enemies at 3.29. However, this toxicity value was intermediate for other pesticide classes. Carbamates and inorganics were of moderate toxicity, while the miscellaneous organics were fairly selective.

Toxicity decreased fairly evenly across herbicide chemical groups (Fig. 22), with less distinct separation into low, intermediate or high classes. Average toxicities for chemical groups ranged from 4.00 for nitrophenol derivatives (e.g., dinoseb) to 2.00 for the phenoxy herbicides (e.g., 2,4-D). Nitrogen heterocyclics and urea derivatives were moderately toxic to natural enemies. The organometallics and phenoxy herbicides had little impact on natural enemies based on test results contained in SELCTV. A low degree of confidence was associated with herbicide toxicity values relative to most other pesticide classes, again reflecting the paucity of impact data for these compounds.

The distribution of insecticide toxicity ratings within each chemical group was arranged to illustrate changes in insecticide selectivity to natural enemies over time (Fig. 23). Chemical groups were ordered chronologically by development along the X axis.

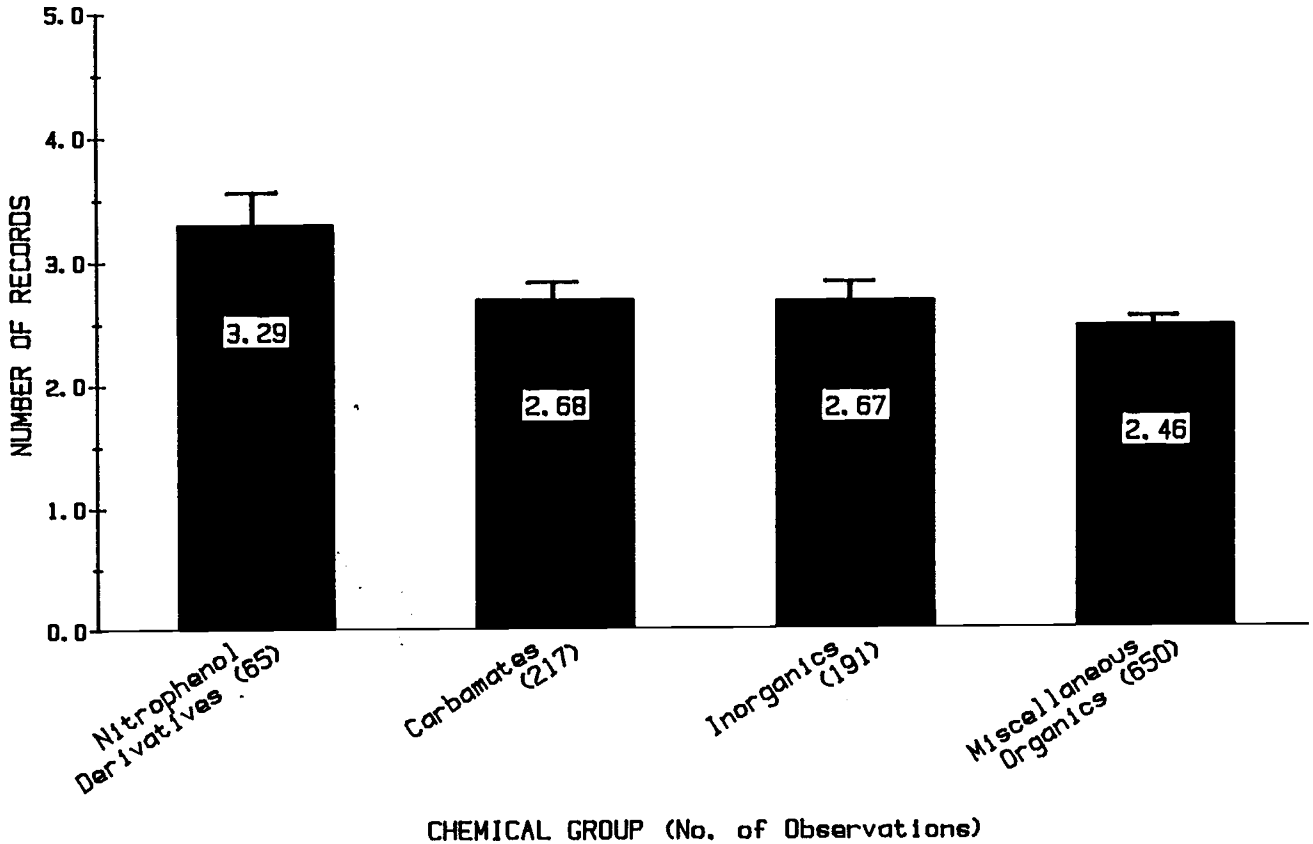


Figure 21. Average toxicity ratings and 95% confidence intervals for fungicide chemical groups tested for side effects on arthropod natural enemies from the SELCTV database.

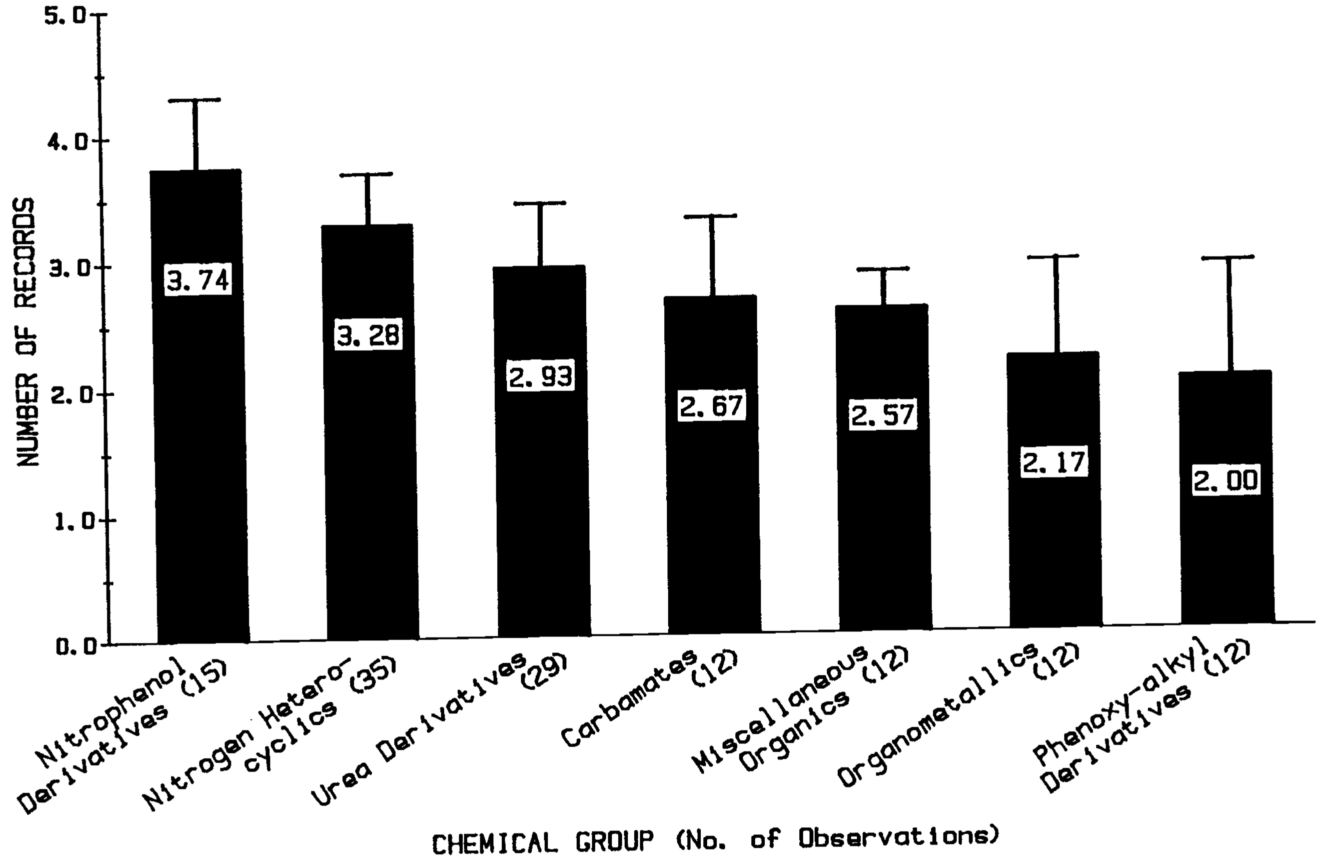


Figure 22. Average toxicity ratings and 95% confidence intervals for herbicide chemical groups tested for side effects on arthropod natural enemies from the SELCTV database.

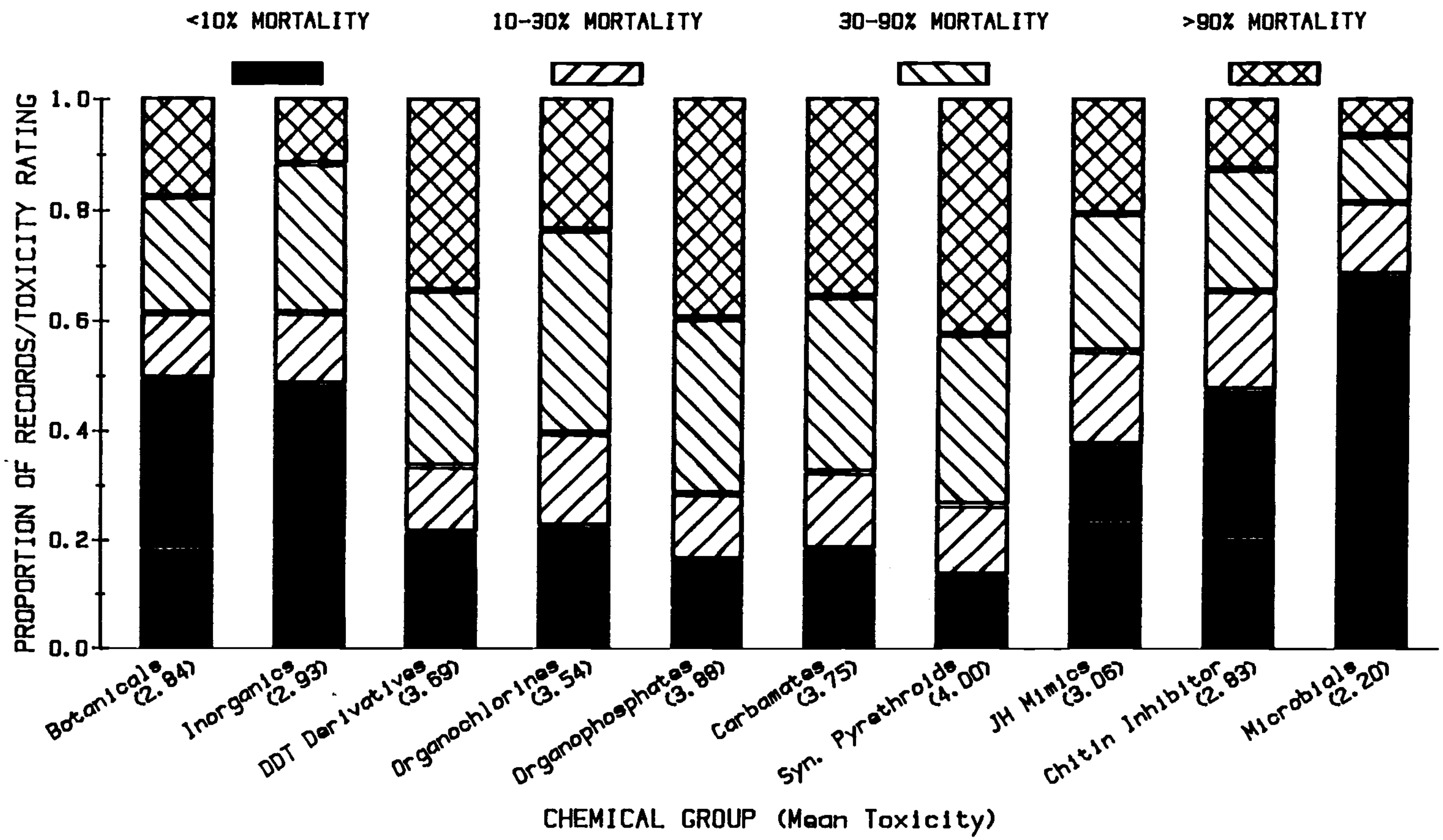


Figure 23. Distribution of toxicity ratings among insecticide chemical groups assessed for side effects on arthropod natural enemies from the SELCTV database.

Examination of the 0% and <10% mortality sections (solid area) for each chemical group provided a relative measure of selectivity. Inorganic and botanical insecticides were moderately selective to natural enemies. Increasing toxicity to non-target arthropods has prevailed since the development of DDT, and has persisted through the synthetic pyrethroids. More recent biorational insecticides show increasing selectivity to beneficial arthropods.

Microbial or biological insecticides were further partitioned on the basis of taxonomic classification or origin (by-products, for example) in Figure 24. Natural enemies were most susceptible to microbial by-products and nematode preparations, with average toxicity ratings of 3.59 and 3.23 respectively. The remaining groups constituted the true microbials: protozoa, viruses, bacteria and fungi. All were relatively innocuous to natural enemies, ranging in toxicity from 2.35 to 1.45 in respective order.

Many of the CHEM:GROUP (chemical group) designations in SELCTV spanned several pesticide classes. For example, carbamates were found in each of the major pesticide classes (CHEM:CLASS). Hence, compounds developed for different target organisms but sharing similar chemical structure could be compared. The distribution of toxicity ratings and average toxicity values for carbamate pesticides were compiled (Fig. 25). Neither carbamate fungicides nor herbicides possessed the high toxicity to natural enemies seen with insecticides and acaricides. These findings concurred with corresponding pesticide class averages.

Average toxicity was computed for each compound (CPD:NAME) in SELCTV, both by natural enemy type and for all natural enemies. Means were computed on a minimum of 10 data points. Hence, compounds with equal or more

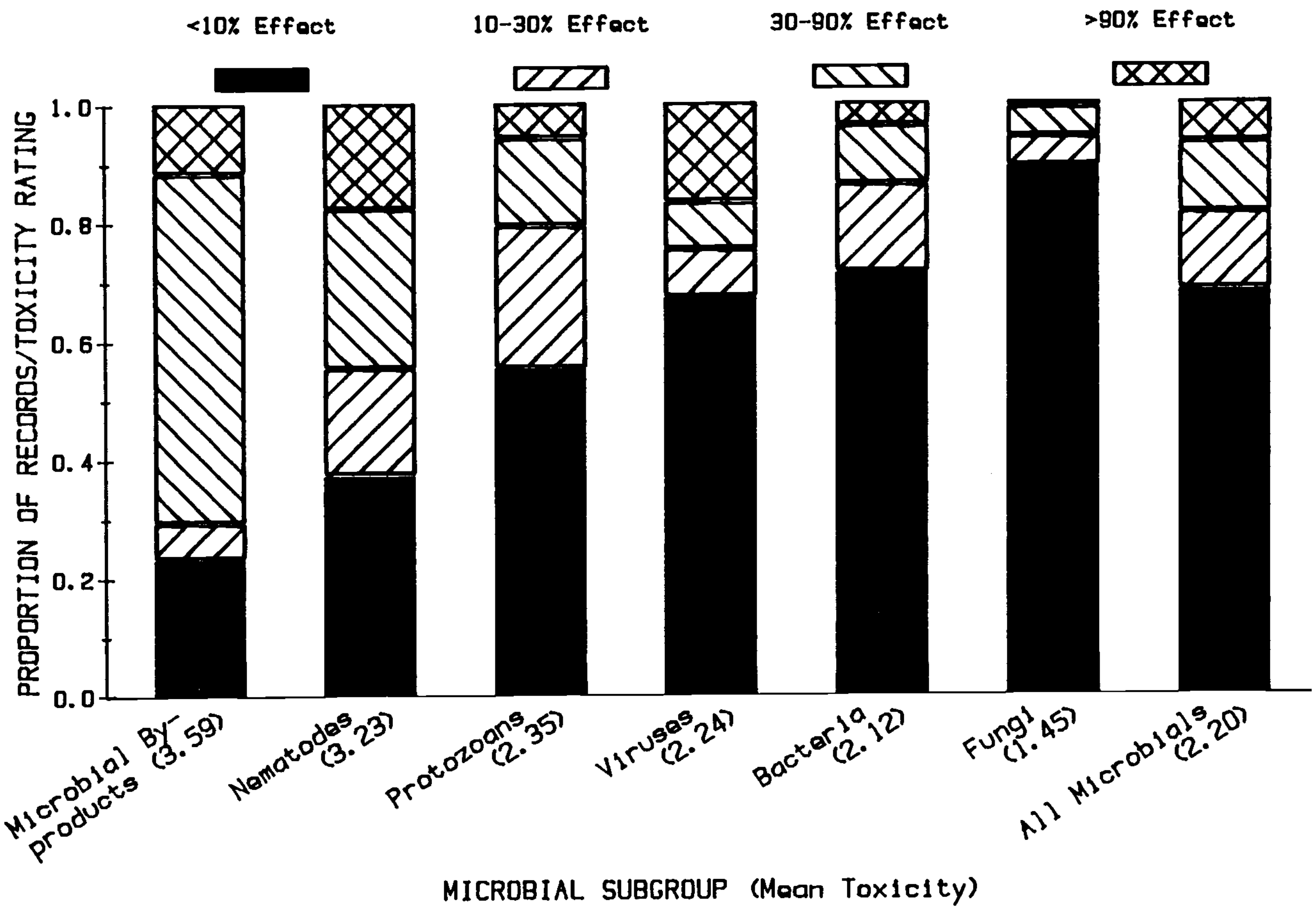


Figure 24. Distribution of toxicity ratings among microbial/biotic insecticides assessed for side effects on arthropod natural enemies from the SELCTV database.

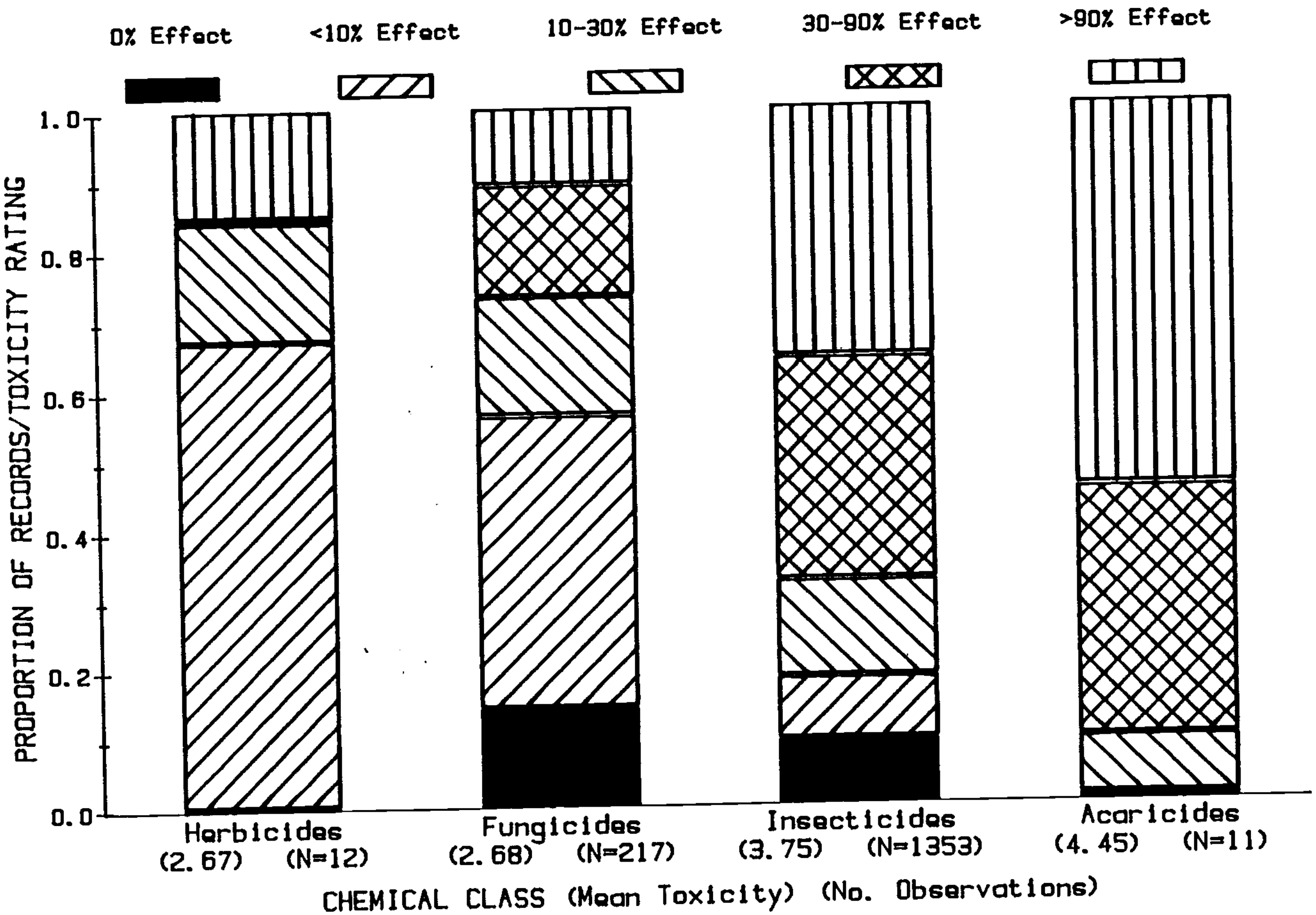


Figure 25. Distribution of toxicity ratings among carbamate pesticides assessed for side effects on arthropod natural enemies from the SELCTV database.

extreme values may exist, but were excluded from analysis because data were insufficient. Similarly, herbicide impact on natural enemies was not sufficiently documented to warrant inclusion in most SELCTV analysis.

Impact of commonly used pesticides was examined for all natural enemies and by predator or parasitoid (Table 18). The first three compounds are fungicides, of which benomyl was most toxic. Again, fungicides were not as toxic to natural enemies as the insecticides or acaricides. The center group of compounds in Table 18 areinsecticides. Pirimicarb, *Bacillus thuringiensis*, hydroprene and diflubenzuron were most selective to both predators and parasitoids, while methomyl, malathion and permethrin were most harmful to these species. The last three compounds are acaricides. All three exhibited moderate selectivity to natural enemies.

In most cases, predators were more pesticide tolerant than parasitoids (Table 18). Compounds whose impact on predators and parasitoids differed substantially included lead arsenate, endosulfan, carbaryl, phosalone, azinphosmethyl, chlordimeform and permethrin. These compounds were much more toxic to parasitoids than predators. The reverse was true for benomyl and cypermethrin.

Pesticides most toxic to natural enemies were arranged by pesticide class (Table 19). These compounds were primarily insecticides belonging to carbamate, organophosphate or synthetic pyrethroid chemical groups (CHEM:GROUP). These pesticides not only possessed high intrinsic toxicity to arthropod natural enemies, but were toxic when mediated through the biotic and abiotic environment, i.e. were neither physiologically or ecologically selective to natural enemies.

Compounds (CPD:NAME) with the lowest average toxicity ratings were assembled by CHEM:CLASS (pesticide class) to

Table 18. Frequency and average toxicity ratings of common pesticides tested for side effects on arthropod predators and parasitoids from the SELCTV database.

Compound Name	Predator No. of Records	Predator Mean Toxicity		Parasitoid No. of Records	Parasitoid Mean Toxicity
Captan	91	1.98	a/	22	2.05
Bordeaux Mixture	30	2.03	*	10	1.90
Benomyl	60	3.02	*	20	2.70
Lead Arsenate	70	2.40		16	3.25
Endosulfan	143	3.37		66	3.82
DDT	342	3.66		130	3.92
Pirimicarb	166	2.98		34	3.03
Carbaryl	324	3.83		165	4.16
Methomyl	122	4.28		53	4.36
Phosalone	94	3.32		31	3.94
Trichlorfon	136	3.42		88	3.47
Azinphosmethyl	296	3.58		69	3.96
Malathion	311	4.23	*	124	4.10
B.T.	100	2.06	*	103	2.04
Hydroprene	17	2.65		31	3.03
Diflubenzuron	75	2.79	*	68	2.74
Chlordimeform	55	3.02		20	3.35
Fenvalerate	155	3.86	*	29	3.79
Permethrin	178	4.03		58	4.38
Cypermethrin	54	4.24	*	19	3.63
Tetradifon	69	2.13		13	2.54
Cyhexatin	96	2.79		16	3.19
Dicofol	126	2.90		29	2.97

a/ These compounds were more toxic to predators than to parasitoids on the average.

Table 19. Average toxicity ratings and pesticide classification for the most toxic pesticides to arthropod natural enemies from susceptibility assessments in the SELCTV database.

Pesticide Class	Pesticide Name	No. of Records	Chemical Group	Mean Toxicity
a/ F	Pyrazophos	26	or	4.19
H	Paraquat	13	nh	4.33
H	Monolinuron	13	ur	4.15
I	Terbufos	12	op	4.75
I	Formothion	45	op	4.69
I	Omethoate	6	op	4.67
I	Dioxathion	18	op	4.59
I	Pirimiphos-methyl	27	op	4.56
I	Quinalphos	17	op	4.47
I	EPN	23	op	4.43
I	Chlorthion	151	op	4.40
I	Deltamethin	21	sp	4.38
I	Profenofos	22	op	4.36
I	Methamidophos	17	op	4.35
I	Parathion	418	op	4.34
I	Methomyl	175	ca	4.30
I	Pyrethrins	14	bt	4.29
I	Mevinphos	101	op	4.28
I	Malathion	435	op	4.20
I	Aldoxycarb	11	ca	4.18
I	Dicrotophos	26	op	4.15
I	Methyl Parathion	203	op	4.13
I	Permethrin	234	sp	4.12
I	Methidation	89	op	4.12
I	Fenitrothion	154	op	4.10
I	Dialifor	12	op	4.08
I	Cypermethrin	73	sp	4.08
I	Decamethrin	52	sp	4.08
I	Heptenophos	15	op	4.07
I	BHC	43	oc	4.07
I	Dimethoate	389	op	4.06
I	Oxydemeton-methyl	204	op	4.04
I	Mephosfolan	7	op	4.00
I	Naled	20	op	4.00
A	Formetanate	11	ca	4.45
A	Chloropropylate	14	dd	4.21

a/ F=Fungicide, H=Herbicide, I=Insecticide, A=Acaricide demonstrate selectivity (Tables 20-22). The most selective insecticides were two microbial preparations (Table 20).The other insecticides varied widely in terms of intrinsic toxicity and spanned many chemical groups (CHEM:GROUP). Both ecological and physiological means of selectivity were represented by these insecticides. With the exception of Beauvaria bassiana and chlordimeform, all compounds were more toxic to parasitoids than predators, some (eg. schradan, ryania, nicotine sulfate, lead arsenate, tepp and perthane) to a large degree. Sulfur containing acaricides, organotins and DDT derivatives were among the most selective acaricides (Table 21). With the exception of fenbutatin oxide and chlorobenzilate, predators were less susceptible to these compounds than parasitoids. Tetradifon and cyhexatin were much less selective to parasitoids than predators.

Selective fungicides included the miscellaneous organics, a few carbamates and bordeaux mixture (Table 22). Mean toxicity values for fungicides were very low for all natural enemies, both predators and parasitoids. Captafol and bupirimate were substantially less selective to predators than to parasitoids. Most other fungicides were equally or less toxic to predators than to parasitoids.

Analysis on Other Fields

Averages calculated on RR:RATIO (Resistance ratio) were disproportionately influenced by some of the higher outliers. Therefore resistance ratios were transformed to a log scale (RR:INDEX). Mean log transformed ratios indicated that the highest level of resistance by family was associated with the phytoseiid mites (Table 23). This value (1.36) corresponded to a normal linear mean of 23-fold resistance on the average (across all compounds for

Table 20. Frequency and average toxicity ratings for the least toxic insecticides to arthropod natural enemies in the SELCTV database.

Compound Name	Chemical Group	Mean Toxicity[a/] All		Predators		Parasitoids	
Beauveria bassiana	mpf	1.52	(21)	1.72	(11)	1.30	(10)
B.T.	mpb	2.05	(203)	2.06	(100)	2.04	(103
Schradan	op	2.23	(35)	2.10	(30)	3.00	(5)
Ryania	bt	2.28	(80)	2.24	(66)	3.50	(14)
Tralomethrin	sp	2.33	(3)	----		----	
Chlorfenvinphos	op	2.42	(38)	2.31	(26)	2.67	(12)
Nicotine Sulfate	bt	2.45	(80)	2.30	(63)	3.00	(17)
Lead Arsenate	io	2.56	(86)	2.40	(70)	3.25	(16)
Fluvalinate	sp	2.60	(5)	2.25	(4)	----	
Diflubenzuron	ici	2.76	(143)	2.79	(75)	2.74	(68)
Menazon	op	2.88	(51)	2.77	(48)	4.67	(3)
Hydroprene	jhm	2.90	(48)	2.65	(17)	3.03	(31)
Pirimicarb	ca	2.99	(200)	2.98	(166)	3.03	(34)
Vamidothion	op	3.19	(32)	3.16	(25)	3.29	(7)
Aldicarb	ca	3.28	(65)	3.23	(59)	3.67	(6)
Tepp	op	3.30	(33)	3.00	(21)	3.83	(12)
Disulfoton	op	3.31	(48)	3.25	(38)	3.60	(10)
Perthane	dd	3.39	(44)	3.31	(39)	4.00	(5)
Chlordimeform	o	3.43	(108)	3.45	(88)	3.35	(20)
Trichlorfon	op	3.44	(224)	3.42	(136)	3.47	(88)

a/ (#) = No. of Records

Table 21. Frequency and average toxicity ratings for the least toxic acaricides to arthropod natural enemies in the SELCTV database.

Compound Name	Chemical Group	Mean Toxicity[a/] All	Predators	Parasitoids
Chlorfenson	sul	1.96 (47)	1.95 (42)	2.00 (5)
Fenbutatin oxide	ot	2.13 (47)	2.21 (33)	1.93 (14)
Tetradifon	sul	2.20 (82)	2.13 (69)	2.54 (13)
Bromopropylate	dd	2.27 (22)	2.19 (21)	----
Benzomate	o	2.30 (23)	2.25 (16)	2.43 (7)
Chlorobenzilate	dd	2.43 (69)	2.46 (50)	2.37 (19)
Propargite	sul	2.61 (54)	2.63 (52)	----
Cyhexatin	ot	2.83 (112)	2.79 (96)	3.19 (16)
Dicofol	dd	2.91 (155)	2.90 (126)	3.00 (29)

a/ (#) = No. of Records

Table 22. Frequency and average toxicity ratings for the least toxic fungicides to arthropod natural enemies in the SELCTV database.

Compound Name	Chemical Group	Mean Toxicity[a/] All	Predators	Parasitoids
Captan	or	1.99 (113)	1.98 (91)	2.05 (22)
Bordeaux Mixture	io	2.00 (40)	2.03 (30)	1.90 (10)
Captafol	or	2.04 (25)	2.33 (12)	1.77 (13)
Bupirimate	or	2.11 (27)	2.38 (16)	1.73 (11)
Dodine	or	2.13 (32)	2.10 (30)	----
Vinclozolin	or	2.14 (22)	2.11 (9)	2.15 (13)
Glyodin	or	2.18 (40)	2.25 (28)	2.00 (12)
Triadimefon	or	2.22 (23)	2.27 (15)	2.13 (8)
Zineb	ca	2.32 (66)	2.30 (46)	2.35 (20)
Ferbam	ca	2.33 (54)	2.41 (37)	2.18 (17)

a/ (#) = No. of Records

which resistance in phytoseiids has been documented). Remaining families in Table 22 averaged less than a 10-fold level of resistance.

By CHEM:GROUP (chemical group), synthetic pyrethroids and organophosphates had the highest average RR:INDEX values, corresponding to resistance levels of 23-fold and 21-fold respectively over susceptible strains (Table 24). Carbamates followed with an average RR:INDEX of 1.18, equivalent to 15-fold resistance. Finally, early work on selection of DDT resistance in the braconid parasitoid, Aphytis melinus, by Pielou and Glasser (1952) accounted for the DDT derivative records. A stable or manageable level of DDT resistance was not attained in natural enemies before DDT was banned in the United States.

By compound, highest average RR:INDEX values were associated with organophosphates, specifically diazinon, phosmet, azinphosmethyl, parathion and methyl parathion (Table 24). Carbaryl, permethrin and DDT were the only non-OP compounds for which sufficient resistance documentation existed to allow computation of averages on 3 or more data points.

SLECTRATIO (Selectivity ratio) analysis was performed on corresponding log-transformed SR:INDEX values. SR:INDEX averages were calculated both for various data groupings. Selectivity ratio estimates from SELCTV tended to give a somewhat distorted perspective of comparative toxicity between pests and natural enemies. The mean value of all SR:INDEX values was 4.61, where 5.00 or less indicated selectivity to natural enemies. Many SLECTRATIO values implied that pesticides were less harmful to natural enemies than to pests. In part, this is because published data favored compounds which selectively allowed natural enemy survival (499 of 870 records). Data showing a lack of selectivity were less frequently reported because they have generally been presumed to be the norm.

Table 23. Average pesticide resistance ratios for arthropod natural enemies from the SELCTV database grouped by family.

No. Records	Family	Mean RR:Index	Linear scale Resistance
115	Phytoseiidae	1.36	22.9
3	Cecidomyiidae	1.03	10.7
9	Coccinellidae	0.91	8.1
12	Braconidae	0.73	5.4
2	Lygaeidae	0.70	5.0
3	Aphelinidae	0.43	2.7

Table 24. Average pesticide resistance ratios for arthropod natural enemies from the SELCTV database by pesticide chemical group and compound.

No. Records	Chemical Group	Mean RR:Index	Linear scale Resistance
22	Syn. Pyrethroids	1.36	22.9
83	Organophosphates	1.33	21.4
23	Carbamates	1.18	15.1
14	DDT Derivatives	0.91	8.1

No. Records	Compound Name	Mean RR:Index	Linear scale Resistance
4	Diazinon	1.72	52.5
4	Phosmet	1.71	51.3
24	Azinphosmethyl	1.69	49.0
14	Parathion	1.47	29.5
11	Permethrin	1.44	27.5
5	Methyl Parathion	1.22	16.6
15	Carbaryl	1.08	12.0
13	DDT	0.88	7.6
7	Dimethoate	0.87	7.4
5	Malathion	0.64	4.4

By natural enemy type, pesticides appeared to be slightly selective to predators (SR:INDEX = 4.45). Parasitoids, on the average, were more susceptible than their hosts (SR:INDEX = 5.19). The relative magnitude of these values in relation to each other are probably more informative than the values on the SR:INDEX scale (see Table 12).

Mean SR:INDEX values by order showed that the Thysanoptera were about 200 times more tolerant of the pesticides tested upon them than their prey, based on a limited number of records (Table 25). The Diptera, Coleoptera, Neuroptera, Hemiptera and Acari were less susceptible to pesticides than their hosts or prey according to ratios reported in the literature. The Dermaptera were equally as susceptible as their prey, while the Hymenoptera tend to be more susceptible than their hosts or prey.

Average SR:INDEX values computed for predominant families with comparative natural enemy-host/prey data in SELCTV (Table 26) formed 4 classes of ratios: 1) Carabids appeared to have a 20-fold advantage over their prey following a pesticide application. 2) The Micryphantidae, Nabidae, Coccinellidae, Chrysopidae and Lycosidae were approximately 20 times more tolerant of pesticides than their prey. 3) The Braconidae, Miridae, Lygaeidae, Aphelinidae and Phytoseiidae were about equally susceptible as their hosts or prey. 4) The Ichneumonidae were nearly 20 times more susceptible to pesticides relative to their hosts. This figure does not conflict with previously mentioned tolerance for this family. It simply reflects that most comparative tests for this group have been run using organosynthetic pesticides rather than more selective compounds.

SR:INDEX was further analyzed by pesticide attributes (Table 27). By pesticide class, acaricides were most selective to predators compared to their prey, and less

Table 25. Average selectivity ratios by natural enemy order for arthropod pests and natural enemies from comparative assessments of pesticide susceptibility in the SELCTV database.

Order	No. Records	Mean SR:Index
Thysanoptera	6	2.67
Diptera	20	4.15
Coleoptera	256	4.25
Neuroptera	69	4.33
Araneae	101	4.52
Hemiptera	64	4.56
Acari	173	4.80
Dermaptera	2	5.00
Hymenoptera	171	5.23

Table 26. Average selectivity ratios by natural enemy family for arthropod pests and natural enemies from comparative assessments of pesticide susceptibility in the SELCTV database.

Family	No. Records	Mean SR:Index
Carabidae	10	3.70
Micryphantidae	19	4.16
Nabidae	23	4.22
Coccinellidae	239	4.27
Chrysopidae	72	4.32
Lycosidae	53	4.36
Braconidae	74	4.80
Miridae	11	4.82
Lygaeidae	12	4.83
Aphelinidae	26	4.96
Phytoseiidae	134	5.00
Ichneumonidae	33	6.21

Table 27. Average selectivity ratios by natural enemy and pesticide groupings for arthropod pests and natural enemies for comparative assessments of pesticide susceptibility in the SELCTV database.

Basis of Comparison	No. Records	Mean SR:Index
All Insecticides	799	4.66
(Predators)	621	4.50
(Parastoids)	177	5.22
All Acaricides	52	3.77
(Predators)	48	3.71
(Parastoids)	4	4.50
All Fungicides	7	4.57
(Predators)	5	4.80
(Parastoids)	2	4.00
All Herbicides	7	4.86
(Predators)	0	----
(Parastoids)	7	4.86
Insecticide Chemical Groups:		
Botanicals	12	4.00
Carbamates	150	4.35
DDT Derivatives	36	4.39
Organophosphates	404	4.68
Syn. Pyrethroids	142	4.77
Organochlorines	49	4.92

selective to parasitoids compared to their hosts. Most selectivity ratios reported in the literature related natural enemy and pest susceptibility to insecticides. Predators were favored slightly over their prey, but hosts had an advantage over parasitoids. This susceptibility trend (pest < predator < parasitoid) has been reported by other authors (Croft and Morse 1979). By CHEM:GROUP, botanicals were most selective with an average SR:INDEX of 4.00. Organochlorines were least selective at 4.92, although this figure still reflects selectivity to natural enemies (i.e. < 5.00). The remaining major insecticide chemical groups fell between these extremes in terms of selectivity.

By compound (CPD:NAME), pirimicarb was most selective, favoring the natural enemy by approximately 200:1 over the host or prey (Table 28). Cyhexatin and dicofol, two acaricides, follow with similar values which are equivalent to about a 20-fold selectivity to natural enemies. Most compounds cluster about the median, neutral SR:INDEX value of 5.00. Few of the compounds for which selectivity ratios are reported in the literature actually favor the pest over the natural enemy, on the average.

Computations were performed on sublethal effects data spanning all pesticides (Table 29). Toxicity or severity of impact values should be interpretted on the same scale as TOX:RATING (see Fig. 15). Locomotion was the most severely affected biological attribute reported in the literature when natural enemies were exposed to a sublethal pesticide dose. Lowered fertility and morphological deformation effects were least severe. By order, Lepidoptera were most severely affected by sublethal pesticide doses (based on very few records and compounds). Hemipteran predators were least impacted by sublethal doses on the average. Order means were influenced by the component sublethal effects studied.

Table 28. Average selectivity ratios by compound for arthropod pests and natural enemies from comparative assessments of susceptibility in the SELCTV database.

Compound Name	No. Records	Mean SR:Index
Pirimicarb	26	2.77
Dicofol	11	3.64
Cyhexatin	8	3.88
Thiometon	20	4.30
Demeton	27	4.33
Chlorpyrifos	13	4.38
Aldicarb	11	4.55
Dimethoate	20	4.60
Diazinon	23	4.65
Trichlorfon	9	4.67
Permethrin	44	4.75
Fenvalerate	27	4.78
Parathion	27	4.78
Azinphosmethyl	13	4.80
Carbaryl	25	4.80
Carbofuran	17	4.82
Malathion	37	4.84
Methomyl	17	4.94
Acephate	13	5.00
DDT	17	5.06
Methyl Parathion	26	5.12
Lindane	14	5.14
Cypermethrin	22	5.22
Fenitrothion	17	5.47

Table 29. Average magnitude of sublethal pesticide side effects individually and by natural enemy order from the SELCTV database.

Sublethal Effect (Effect Means)	Order[a/]								
	L	C	A	N	Y	D	S	O	H
Locomotion (4.0)	---	4.0	3.8	---	4.0	---	---	---	---
Reproduction (3.4)	---	3.0	3.8	---	2.1	---	---	---	---
Oviposition (3.3)	---	3.3	3.7	---	3.1	---	---	---	1.8
Repellency (3.1)	---	1.0	3.8	---	3.0	1.5	---	---	---
Consumption (3.1)	---	3.0	3.3	3.2	---	4.7	2.7	2.0	1.7
Developmental Time (3.0)	---	4.0	3.4	3.4	2.9	2.3	---	---	2.4
Parasitism (2.9)	---	3.8	---	---	2.8	2.6	---	---	---
Fecundity (2.9)	---	3.2	2.9	3.5	3.2	4.0	---	---	2.0
Longevity (2.9)	4.0	3.2	2.2	---	3.0	1.0	---	---	1.3
Fertility (2.2)	---	4.5	3.1	3.3	2.8	---	---	---	1.3
Deformation (2.0)	---	3.0	---	2.3	1.8	---	---	---	2.3
Order Totals	4.0	3.4	3.2	3.2	2.9	2.8	2.7	2.0	1.7

a/ L = Lepidoptera, C = Coleoptera, A = Acari, N = Neuroptera, Y = Hymenoptera, D = Diptera, S = Araneae, O = Orthoptera, H = Hemiptera

All means depended on the compound studied and its propensity to produce measureable sublethal effects.

Case Studies

Four types of case study analysis were conducted to demonstrate SELCTV utility. 1) In the first, average toxicity of insecticide chemical groups (CHEM:GROUP) was compared for four crops. These crops were selected to represent agricultural environments that have received different pesticide loads and sustain different levels of species diversity. 2) A selectivity table was compiled for 8 key natural enemy genera on cotton. Their mean responses to 9 commonly applied insecticides in this cropping system were tabulated to allow identification of the least disruptive compounds. 3) In the third case study, the toxicity of synthetic pyrethroids was examined. Toxicity comparisons were drawn at the chemical group (CHEM:GROUP) and compound (CPD:NAME) levels of resolution. Cotton and apple natural enemy responses were compared to responses of all natural enemies for selected insecticides. 4) Finally, test averages from SELCTV were compared with those of a massive review of natural enemy susceptibility to pesticides. This review was conducted by an IOBC/WPRS working group concerned specifically with developing standardized test methods (see Hassan et al. 1983).

Average Toxicity of Chemical Groups for Selected Crops

Mean toxicity values were compared for insecticide chemical groups (CHEM:GROUP) across the apple, cotton, alfalfa and forest production systems. It was anticipated that a range of toxicity means by crop would be obtained, and that this range would be determined by pesticide pressure and the susceptibility of natural enemy genera by crop (see Table 6). Case study analysis showed that interpretation was not as simple as originally anticipated. More factors required consideration to account for results (Table 30).

Crops in Table 30 were arranged horizontally in order of decreasing pesticide pressure, while chemical groups run vertically in order of decreasing harmfulness. Average toxicity ratings (TOX:RATING) were listed by each chemical group and crop. Composite crop average toxicity ratings were also listed in Table 30.

Several generalizations were drawn from these data. Average natural enemy responses by crop were nearly identical when all chemical groups were combined. By individual chemical group, similar natural enemy responses were elicited across all four crops for carbamates, bacterial insecticides and organophosphates. In contrast, divergent responses were evident among crops for botanicals, juvenile hormones and organochlorines. In part, this divergence reflected variation in the susceptibility of (crop associated) natural enemy groups to various insecticides.

Species composition of natural enemies tested for pesticide susceptibility differed by crop. Therefore, crop averages were influenced by the innate susceptibility of the predominant species. It was expected that forest ecosystems, dominated by parasitoid species, would have the highest toxicity rating (e.g. contain the most susceptible natural enemies). Apple, with dominant natural enemies including one parasitoid species and two predatory mites, would probably follow. These species are of a more moderate level of susceptibility (although, in some cases predatory mites have developed resistance to pesticides). Predominant natural enemies on cotton and alfalfa were generalist predators, many of which have been

Table 30. Average susceptibility of natural enemies from four cropping systems to insecticide groups from SELCTV database records.

Chemical Group	Average Toxicity			
	Apple	Cotton	Alfalfa	Forest
Synthetic pyrethroid	4.2 a/ (7.5)	3.8 (15.5)	--- (---)	4.8 (4.5)
Organo- phosphate	3.8 (51.0)	3.7 (46.8)	3.7 (58.0)	3.8 (26.0)
Carbamate	4.0 (11.0)	3.5 (11.3)	3.7 (11.6)	3.4 (19.0)
DDT Derivative	3.7 (10.0)	3.5 (4.7)	3.3 (9.2)	4.3 (4.0)
Organo- chlorine	3.0 (4.0)	3.5 (11.4)	3.2 (16.1)	4.3 (5.4)
JH Mimic	2.1 (0.5)	3.4 (2.6)	3.1 (3.1)	2.6 (9.1)
Miscel- laneous	3.3 (2.6)	2.6 (2.1)	--- (---)	--- (---)
Inorganic	2.9 (4.5)	3.2 (0.7)	--- (---)	--- (---)
Botanicals	2.4 (6.5)	--- (---)	1.5 (1.0)	3.0 (1.0)
Chitin Inhibitor	2.4 (0.2)	2.4 (2.0)	--- (---)	3.2 (9.0)
Bacterial Insecticide	2.2 (2.7)	2.1 (2.9)	2.2 (1.0)	2.1 (22.0)
Crop Means:	3.6 (100%)	3.6 (100%)	3.5 (100%)	3.6 (100%)
No. of Records	2039	1223	612	222

a/ Crop data distribution by chemical group as a percent of crop totals.

shown to exhibit some degree of tolerance to pesticides (e.g., Mohamad 1974, Sukhoruchenko et al. 1977, Stam et al. 1978, Crowder 1980, Brettell 1982, Bashir and Crowder 1983).

Pesticide potency and the intensity of pesticide selection pressure were additional variables which influenced crop-associated average toxicity values. Historically, cotton and apple production have relied on heavy use of potent pesticides (Metcalf and Luckmann 1982). On a high to low level continuum of pesticide load and potency, cotton would precede apple, followed by alfalfa and then forests. However, natural enemies on crops which were extensively treated were also under selective pressure to adapt to pesticides. Over time pesticide adapted or resistant populations developed. This phenomena was best represented among natural enemies by cases of organophosphate, synthetic pyrethroid and carbamate resistance in predatory mite species (e.g., Lienk et al. 1978, Cranham and Solomon 1981, Overmeer and van Zon 1983, Hoy 1985, van de Baan et al. 1985).

Integration of previously mentioned factors partially accounted for similar crop values. The combination of inconsistent pesticide pressure and the higher innate susceptibility of natural enemies in forest ecosystems might lead one to expect highest susceptibility in this system, followed by alfalfa. Cotton and apple natural enemies have undergone more consistent selection, although apple natural enemies are probably more innately susceptible to pesticides. As this pattern was not exhibited by crop means, the relative proportion of records from each chemical group in crop-associated averages was examined.

Carbamates, synthetic pyrethroids and organophosphates were very toxic to natural enemies compared to the more innocuous microbials and insect growth regulators. The heavily-treated cotton has primarily received carbamate, organophosphate, synthetic pyrethroid and organochlorine insecticides (Table 30). In contrast, forests were treated with organophosphates to a lesser extent. Proportionately, more selective insecticides (microbials, juvenile hormone mimics and chitin inhibitors) were used in forests. This may be due to the selectivity and efficacy of many microbial and growth regulating insecticides against lepidopterous larvae, commonly the cause of cyclic pest outbreaks in forest ecosystems. Equivalent mean toxicities (susceptibilities) for forest and cotton natural enemies, accounting for differences in pesticide potency and load, indicated that natural enemies of cotton were less susceptible and/or more pesticide adapted than forest natural enemies.

Natural enemy susceptiblility was found be affected by many more factors than originally anticipated, and probably more than were identified here. This case study made apparent the importance of user familiarity with factors which influence natural enemy susceptibility. It also highlighted the need to exercise caution in interpreting results. With a data set as large and varied as SELCTV, data can be masked or obscured by interacting factors.

Cotton Selectivity Table

A selectivity table was compiled for 8 important natural enemy genera and the most common insecticides used on cotton (Table 31). Efficacy data for pest species is not available in SELCTV for many of these pest-compound combinations. Although not included in this case study, efficacy against pests is the primary determinant in choosing an insecticide. Ideally, both of these objectives should be balanced in the selection process.

Table 31. Average toxicity of insecticides to natural enemy genera associated with cotton in the United States from SELCTV database records.

Natural Enemy Genus	Major Host or Prey	Insecticide	Mean Toxicity
Apanteles	Heliothis zea	Azinphosmethyl	3.25
	H. virescens	Fenvalerate	2.00
		Methyl Parathion	3.50
		Monocrotophos	2.25
		Trichlorfon	2.50
Campoletis	Heliothis zea	Aldicarb	4.50
	H. virescens	Carbaryl	4.00
		Azinphosmethyl	3.27
		Demeton	4.00
		Methyl Parathion	2.67
		Monocrotophos	3.67
		Trichlorfon	2.73
		Toxaphene	3.00
Chrysopa	Aphis gossypii	Aldicarb	2.29
	Heliothis zea	Carbaryl	3.00
	H. virescens	Demeton	2.00
		Methyl Parathion	4.00
		Monocrotophos	2.00
		Trichlorfon	2.33
		Toxaphene	2.00
		Diflubenzuron	3.13
		Fenvalerate	3.00
Coleomegilla	Aphis gossypii	Carbaryl	4.71
	Heliothis zea	Azinphosmethyl	5.00
	H. virescens	Demeton	1.50
		Methyl Parathion	4.38
		Monocrotophos	4.50
		Toxaphene	2.29
		Diflubenzuron	2.50
Hippodamia	Aphis gossypii	Aldicarb	1.00
	Heliothis zea	Carbaryl	4.50
	H. virescens	Demeton	3.33
		Methyl Parathion	5.00
		Trichlorfon	3.25
		Toxaphene	3.60
		Diflubenzuron	1.00
		Fenvalerate	4.00

Table 31 Continued

Geocoris	Heliothis spp.	Aldicarb	3.00
	Tetranychus spp.	Carbaryl	2.89
		Azinphosmethyl	4.00
		Demeton	3.00
		Methyl Parathion	4.33
		Monocrotophos	4.83
		Trichlorfon	3.00
		Toxaphene	3.20
		Diflubenzuron	2.00
		Fenvalerate	3.50
Nabis	Heliothis spp.	Aldicarb	4.20
		Carbaryl	1.50
		Azinphosmethyl	2.50
		Demeton	3.33
		Methyl Parathion	4.57
		Monocrotophos	4.50
		Trichlorfon	4.00
		Toxaphene	3.25
		Diflubenzuron	4.00
Orius	Heliothis zea	Aldicarb	3.00
	H. virescens	Azinphosmethyl	4.00
		Demeton	3.67
		Methyl Parathion	5.00
		Monocrotophos	4.33
		Trichlorfon	3.75
		Toxaphene	3.50
		Diflubenzuron	1.67
		Fenvalerate	4.00

Based on natural enemies which predominated at a given location, a table such as this could be used to choose an insecticide with the least harmful effect on biocontrol agents. Selectivity tables can be used at several levels of specificity. Across the entire range of genera listed for cotton, methyl parathion was highly toxic to most natural enemies. Diflubenzuron was largely selective. These observations would be useful when considering natural enemies at large. In many cases, specific natural enemies have been identified as importantbiocontrol agents on a crop. Conservation of these species might be attained by a selective insecticide or application strategy. Demeton would be a good choice to conserve *Coleomegilla* (1.5), but would be harmful to *Campoletis* (4.0). Selectivity tables such as this should be made available to pest managers.

Synthetic Pyrethroid Toxicity to Cotton and Apple Natural Enemies

A case study on synthetic pyrethroids was undertaken because of the increasing use of these insecticides and their high toxicity to natural enemies. Synthetic pyrethroids have been widely employed as one of the few effective insecticide groups on cotton pests. On apples, synthetic pyrethroids threaten phytophagous mite management programs because of high toxicity to predatory mites.

The susceptibility of cotton and apple natural enemies was compared by insecticide chemical group (Fig. 26). Natural enemies from these two cropping systems showed different responses to most of the insecticide chemical groups. Carbamate, DDT derivative, synthetic pyrethroid and miscellaneous (other) insecticides were more toxic to apple natural enemies, while cotton natural enemies were more adversely affected by inorganics,

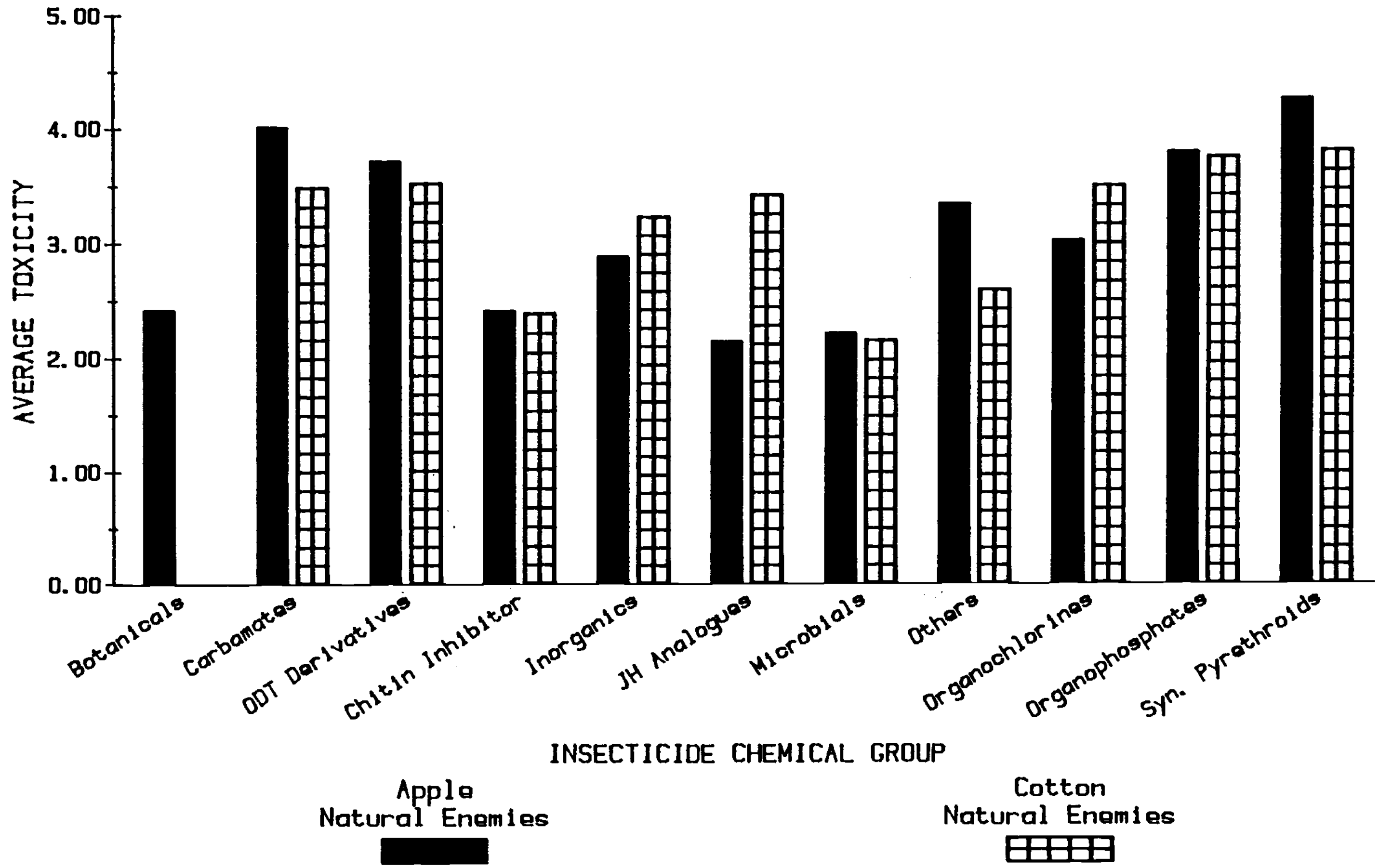


Figure 26. Average toxicity ratings for insecticide chemical groups to arthropod natural enemies of apple and cotton from the SELCTV database.

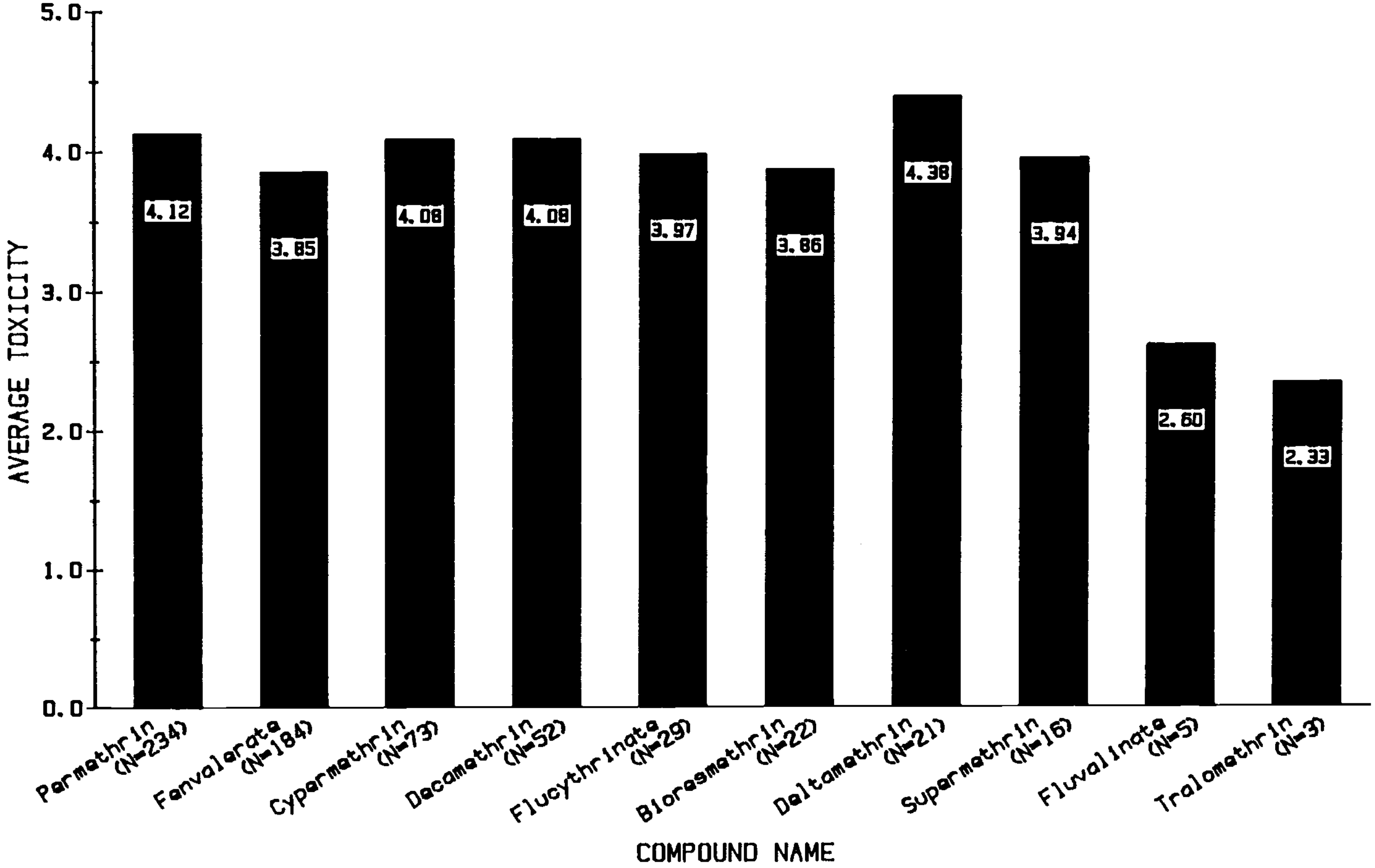


Figure 27. Average toxicity ratings for synthetic pyrethroids across all natural enemy species and crops in the SELCTV database.

juvenile hormone mimics and organochlorines. Overall, the synthetic pyrethroids, organophosphates, carbamates and DDT derivatives were most toxic to natural enemies.

Having established that synthetic pyrethroids are among the most toxic insecticides, individual compounds were examined for hazard to natural enemies. Average toxicity ratings were computed for 10 common synthetic pyrethroids to all natural enemies (Fig. 27). Most of these compounds were very toxic, with averages near or above 4.00. Fluvalinate and tralomethrin appeared to be selective synthetic pyrethroids, with averages of 2.60 and 2.33, respectively. The latter two averages were based on were based on very few database records, but were included to demonstrate the potential for selectivity in synthetic pyrethroids.

The toxicity of 5 commonly tested synthetic pyrethroids was examined for apple and cotton natural enemies (Fig. 28). The three most widely tested synthetic pyrethroids were much more hazardous to apple natural enemies. Deltamethrin and flucythrinate were more toxic to cotton natural enemies. Cotton natural enemies showed limited tolerance to permethrin, fenvalerate and cypermethrin, being somewhat below the average response for all species to these compounds (see Figs. 27-28). The reverse was true for deltamethrin and flucythrinate.

Overall, synthetic pyrethroids were highly toxic to most arthropod natural enemies. Cotton natural enemies generally exhibited greater tolerance to synthetic pyrethroids than those from apple. This difference was accentuated by the high susceptibility of predatory mites from apple to these compounds.

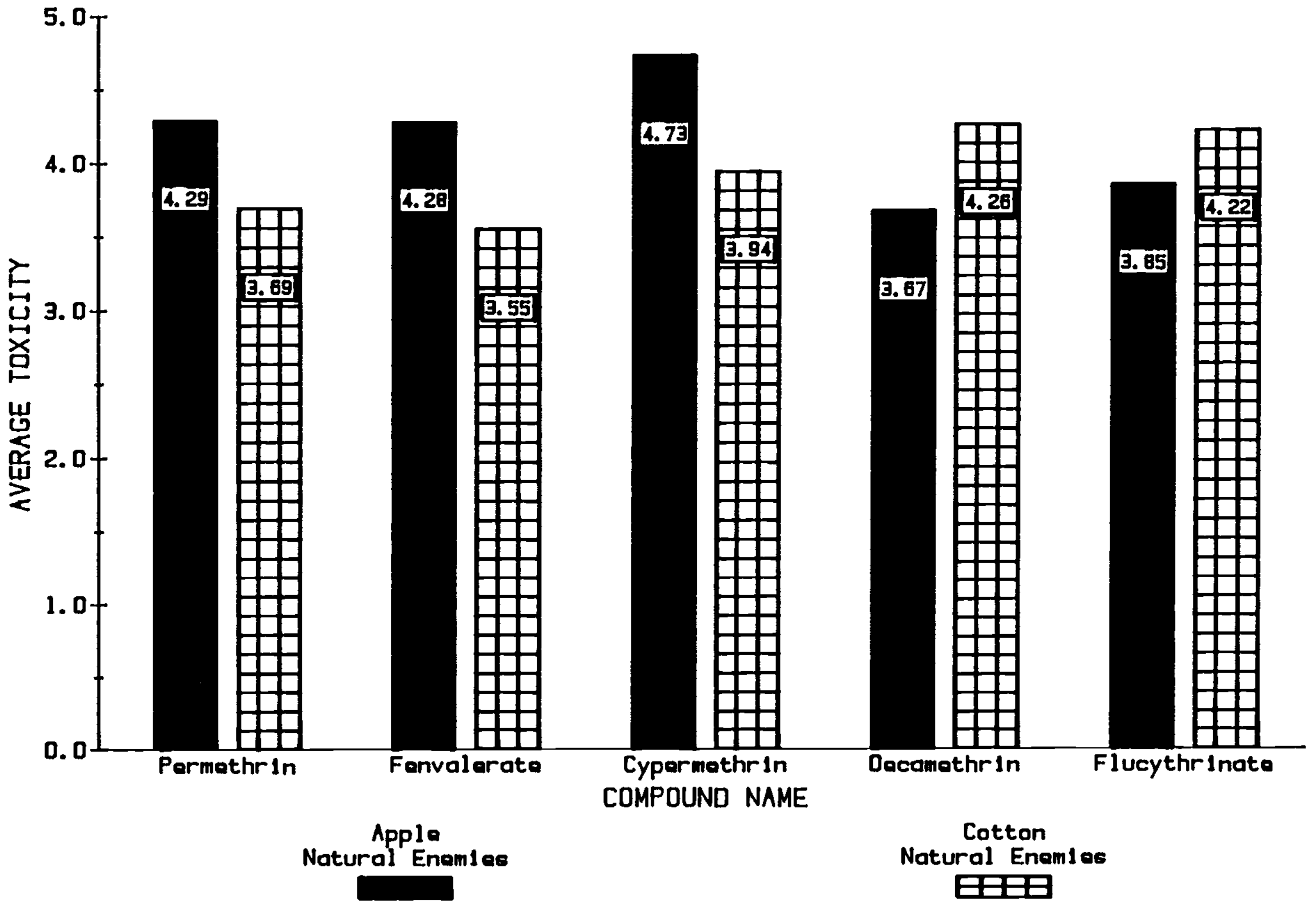


Figure 28. Average toxicity ratings for synthetic pyrethroids to arthropod natural enemies of apple and cotton from the SELCTV database.

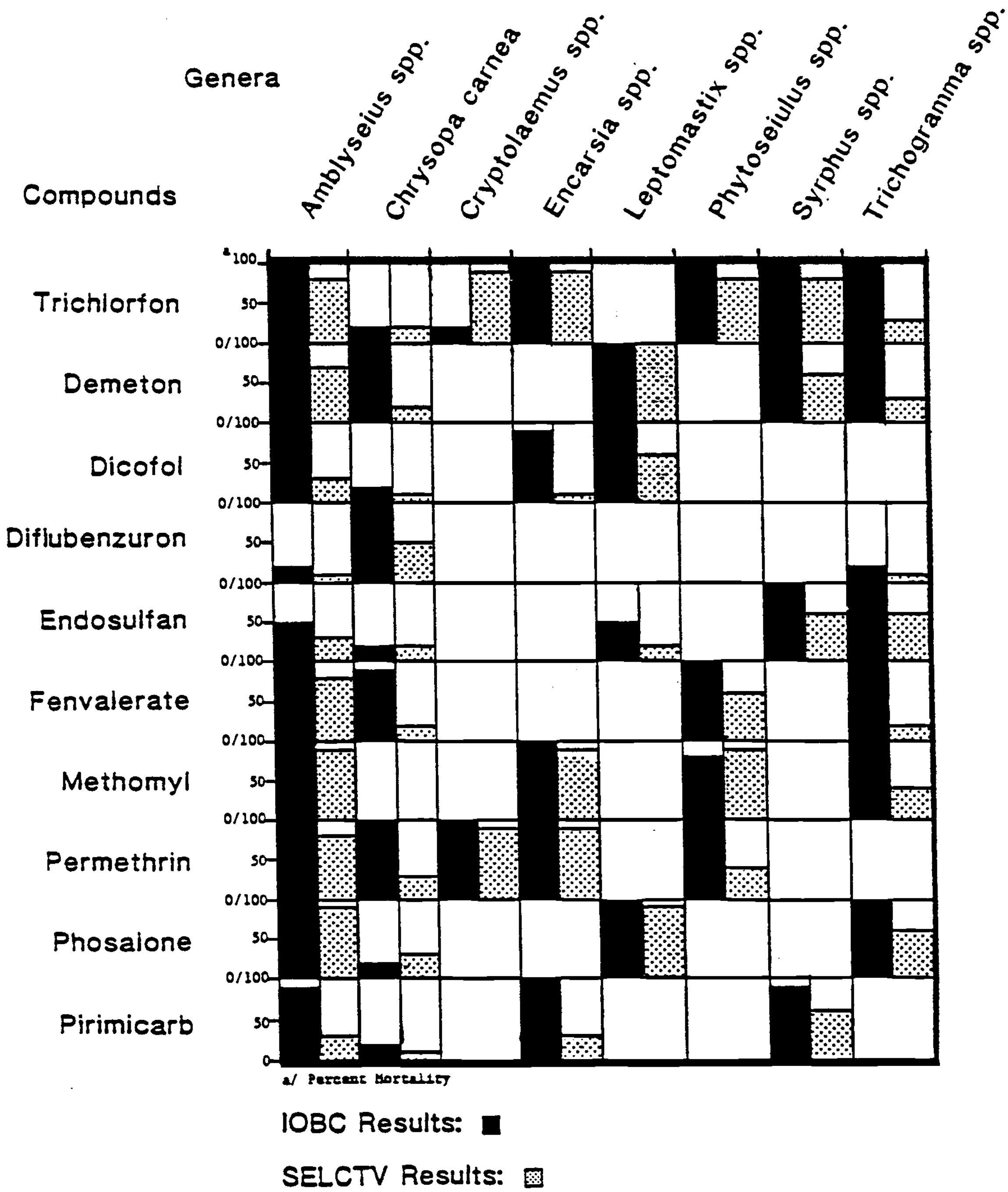
Comparison of Susceptibility Assessments: IOBC and SELCTV

Test results of the Pesticides and Beneficial Arthropods Working Group of the IOBC/WPRS (see Hassan et al. 1983) and average toxicity values from SELCTV were compared in a 2 by 2 table of histograms (Table 32). SELCTV means were computed from a minimum of 3 or more data points for compounds and natural enemy genera found in the IOBC study. Different rating scales were used in the two studies, making translation to a common mortality scale necessary. Common intervals of difference between IOBC and SELCTV mortality estimates were artifacts of the translation process, specifically due to using midpoints of mortality ranges for graphs. Blanks indicated a paucity or absence of data for comparison by one or both sources.

First considering the natural enemy, IOBC and SELCTV ratings diverged with respect to *Trichogramma* spp. susceptibility. *Amblyseius* spp. and *Syrphus* spp. ratings concurred fairly well for all compounds. By compound, phosalone and methomyl were similarly rated in toxicity by both sources. Trichlorfon results were comparatively inconsistent for *Cryptolaemus* and *Trichogramma*. While other dissimilar values are evident, most comparisons show fair to very good agreement.

Overall, less severe impact was suggested from SELCTV averages compared to the IOBC data. SELCTV averages were computed from data encompassing all test types and doses reported in the literature, while IOBC data were derived specifically from standardized contact tests using doses which approximate field rate. Hence, average toxicity ratings from SELCTV were lower and more variable than those from the IOBC study. However, as relative indicators of pesticide susceptibility, standardized

Table 32. A comparison of susceptibility assessments from WPRS/IOBC standardized testing and SELCTV database records for common natural enemy genera-insecticide combinations.



contact tests and literature compilation results were in agreement.

DISCUSSION

The use of a computerized database approach to examine the information base of pesticide impact on arthropod natural enemies is new. Its merits and drawbacks are still being realized. The scope and sources of scientific literature are expanding, as are analysis techniques and applications. These aspects of data management are discussed below. Trends and analyses from SELCTV are incorporated with the literature to support conclusions regarding natural enemy susceptibility and the research conducted in this area.

Literature Documenting Natural Enemy Susceptibility to Pesticides

The body of literature documenting pesticide side effects on arthropod natural enemies has grown tremendously over the past 3 decades (Croft and Brown 1975, Croft 1977; Figs. 1-2). SELCTV gives no indication that this trend has changed as of the early 1980's, based on trends in record generation or publication. While the total data base has grown, documentation of specific aspects of research have fluctuated. These patterns are historically instructive and help provide perspective by which future research can be directed.

Early growth of the literature correlates well with a burgeoning awareness of the disruptive nature of pesticides to natural enemy populations and some early stirrings of IPM (Pickett 1959, Bartlett 1953, Ripper 1956). Many of these studies were conducted to implicate pesticides as the cause of declining biological control or balance (e.g., Lord 1949). Since then, studies elucidating components and mechanisms involved in the ecology and physiology of natural enemy-pesticide interactions has become more diversified (e.g., see reviews by Newsom et al. 1976, Croft 1977, van den Bosch and Flint 1981, Hull and Beers 1985, Mullin and Croft 1985).

As a result, both the number of studies and their specificity has increased. Half of the records in SELCTV document pesticide side effects over the last 10 years alone. The literature has been roughly doubling every decade since 1940. More recent research has focused specifically on aspects of sublethal pesticide effects (e.g., Overmeer and van Zon 1981, Grapel 1982, Hassan 1982, Perera 1982, Moosbeckhofer 1983, Tanigoshi and Congdon 1983, Hoy and Dahlsten 1984, Yokoyama and Pritchard 1984), standardization of test methods (e.g., Bogenschutz 1979, Franz et al. 1980, Overmeer and van Zon 1982, Hassan et al. 1983, von Naton 1983), resistance to pesticides (e.g., Croft and Brown 1975, Head et al. 1977, Croft and Strickler 1983, Overmeer and van Zon 1983, Hoy 1984) and genetic improvement of pesticide resistance strains (e.g., Hoy and Knop 1981, Roush and Hoy 1981, Strickler and Croft 1982, Grafton-Cardwell and Hoy 1986).

SELCTV is believed to be a comprehensive natural enemy/pesticide literature compilation, estimated to be 80-90% complete through 1982. A collection update is currently underway for 1983-present. Thorough searches of abstracting journals and publication bibliographies, scientific and technical citations are obtained at a global level to the extent that these sources draw from world literature.

Limitations in the scope of literature currently exist. North American, western European, Australian and middle eastern literature is fairly complete. However, eastern European, Russian and far eastern literature is least well represented. For some foreign journals, only abstracts from reviews were obtained. Language was an occasional barrier since many, but not all, foreign papers have English summaries. Lower confidence associated with the abstract or summary level of reporting is recorded in the DAT:RATING field (data rating).

SELCTV contains available published literature. Substantial unpublished data exist on the impact of pesticides on natural enemies that are not included in SELCTV. The published literature does not represent a random or objective survey of all natural enemy-pesticide interactions. The agro-ecosystem is represented to the extent that SELCTV data concur with the importance or abundance of natural enemies as biological control agents, pesticide use or crop acreage. Data interpretation is influenced by priorities of researchers, institutions or corporations in choosing natural enemy species, crops, pesticides and methods for testing. Political, economic and geographic forces are operative in determining what research is funded, subsequently published and distributed.

Database Management as a Means of Census and Analysis

Several important limitations to the use of database technology for analysis of a literature base should be stressed. As mentioned previously, an element of subjectivity can be introduced as data are extracted from the literature and appended into database format. Strict, consistent guidelines for data entry must be maintained. Problems associated with variance calculations and their meaningfulness were outlined previously (see Materials and Methods).

Because the distribution of information types and sources usually remains unknown for data subsets retrieved from SELCTV, conclusions should be drawn with caution. The literature was not randomly sampled, but rather was comprehensively collected. Data for a particular species/compound/test type could be the results of several to many researchers working with different objectives and levels of precision and objectives.

Data from abstracts, laboratory assays and field tests are aggregated during the processing of data. Subtle factors which affect data trends can be obscured when surveying at a broad level in SELCTV. The different pictures presented for ichneumonid susceptibility at the family level when examining average toxicity values versus selectivity data is a good example (Tables 14, 27). Different pesticides, formulations, doses, natural enemy species or test protocols can be pooled as assessments become more global in SELCTV. Minor or opposing trends may balance out at this level. In light of these cautions, SELCTV analyses may provide insight into historical aspects of the information base or hypotheses for further experimental verification.

The scope of one's query of SELCTV determines the appropriate level of interpretation. As the specificity of a search increases, results are more directly applicable to real situations. Broader searches are indicative of general trends, but harbor more exceptions. The optimal approach to analysis of pesticide impact on natural enemies using SELCTV is a compliment of specific and general techniques.

The computerized database approach to census and analysis of large data sets has many advantages and applications. The current magnitude of available information makes empirical analysis difficult to perform with accuracy and efficiency. A database is designed for rapid retrieval of information from any field or fields in combination. Within SELCTV, specific compound/natural enemy/host searches can be conducted to test hypotheses or to elucidate the most widely used or consistent assessment techniques. Selectivity indices or charts can be compiled by crop or location. SELCTV can be linked to other pesticide databases to provide a broader complement of data. The most powerful use of SELCTV may come in information processing such as is required for IPM (e.g., Flexner et al. 1986) or regulatory risk assessment (e.g., Messing et al. 1987).

In spite of some limitations, the database approach to large data sets has obvious utility. Regardless of one's field or discipline, expansion of scientific information is difficult to integrate and use creatively. Providing an awareness of trends and characteristics of the information base is the most powerful advantage of database technology. A new breadth of perspective can be achieved. While staggering quantities of data are being generated, less attention has been given to the integration of this information for problem solving. Database technology may allow for better access and more efficient summarization of information for use in decision-making.

Trends and New Research Questions

Natural Enemy-Pest Representation

The distribution of natural enemy taxa in the published literature and in SELCTV is neither random nor normal. This appears to be a function both of research priorities and of the biological importance and abundance of natural enemy species across the Arthropoda.

Natural enemy diversity and specialization are demonstrated for some groups by the composition of various taxonomic levels within SELCTV. For example, the highly specialized Hymenoptera are represented by 21 families in SELCTV, 18 of which contain parasitoid species. Many of these host-parasitoid relationships are genus or species specific (Clausen 1962, DeBach 1964). Diversity, exemplified by the Coleoptera in general, is demonstrated by the 14 coleopteran families in SELCTV (Clausen 1962).

These range from Staphylinidae, which contains both predaceous and parasitic species, to the Coccinellidae which includes herbivorous (pest) as well as predaceous species. Coleopteran natural enemies colonize many different habitats, ranging from leaf and crop litter to ground cover, foliage and forest overstory to aquatic systems. In contrast, natural enemies of some orders are generalists, and have not undergone the sort of speciation seen with more specialized taxa (Clausen 1962, Huffaker and Messenger 1976). Their distribution in SELCTV reflects this: the Neuroptera (2 families in SELCTV) are associated with leaf canopy while the Odonata (2 families) are found in or near aquatic habitats. Both are generalist predators.

Taxonomically, the literature does not represent a random sampling of natural enemies as they occur in the field. The more important biological control agents predominate, particularly those from high value, extensively sprayed systems where pest resistance and pest outbreaks have occurred (Croft and Brown 1975, Croft and Whalon 1982). Crops such as cotton, cereal grains, apple, citrus and greenhouse commodities receive priority funding that provides for much of the selectivity research conducted with natural enemies. Risk assessment for common pesticides is sometimes conducted for natural enemies managed or monitored in pest management programs. For example, resistant strains of phytoseiid mite species have been selected in the field and laboratory (e.g., Hoy et al. 1979, Hoy and Knop 1981, Roush and Hoy 1981, Strickler and Croft 1982, Hoy 1985). Their consequent utilization in phytophagous mite management programs has led to extensive testing of these species (e.g., Lienk et al. 1978, Penman and Chapman 1980, Cranham and Solomon 1981, Helyer 1982).

Ease of culturing, handling and testing natural enemies is another factor influencing the amount of research conducted on natural enemy species. For example, rearing methods for aphelinid scale parasitoids, *Trichogramma* spp., *Chrysopa* spp. and phytoseiid mites are well established (DeBach 1964, McMurtry and Scriven 1964, Xie et al. 1985), as reflected by the number of records in SELCTV for these species. The practicality of supplying host or prey provisions to natural enemies, and the availability of artificial rearing methods will also influence future pesticide susceptibility assessment (Thompson 1986). Generally, predators have been easier to collect and culture than parasitoids for laboratory testing. Published research reflects this fact in that 70% SELCTV records document pesticide side effects on predators.

SELCTV was designed to feature natural enemies. However, host or prey identity and susceptibility status are crucial for determining the selectivity of a pesticide. Achieving selectivity to natural enemies is the general goal of most natural enemy/pesticide research (Bartlett 1964). Most hosts or prey in SELCTV are indirect or pesticide-induced pests such as aphids, mites, scales and whiteflies. In most cases, direct or key pests are not sufficiently regulated by natural enemies to remain below stringent economic thresholds (Hoyt and Simpson 1979, Hoyt and Tanigoshi 1983). However, where some indirect crop damage is sustainable, natural enemies may be the primary regulator of secondary or indirect pest populations. Under these circumstances, pests may be amenable to biological control, provided natural enemies are conserved through judicious pesticide practices.

Most pesticide impact studies have been conducted on natural enemies alone, apart from similar assessments on their hosts or prey. Pesticide efficacy and rate testing is usually carried out on pests well before natural enemies are evaluated. It is generally assumed that pest susceptibility data are available and representative of field populations. More accurate estimates of pesticide selectivity would be obtained by testing natural enemies and pests at similar times and measuring their responses on the same scale of units. Currently, host or prey toxicity data were presented in some fashion in only 30% of SELCTV records. Studies directly comparing pest and natural enemy susceptibility comprised but 7% of records. The development of improved techniques for integrating or fostering biological control would benefit from a greater proportion of these comparative studies.

Pesticide Representation

Among fields in SELCTV which define pesticides or their formulations (CPD:NAME, FORMULATN, CHEM:GROUP), most contain data on insecticide side effects. Arthropod natural enemies belong taxonomically to the target class of organisms for insecticides. It is therefore not surprising that a disproportionate amount of research has been conducted with them relative to pesticide use patterns. The most commonly tested compounds, chemical groups and formulations in SELCTV show that insecticides chosen for side effects research on natural enemies reflect probable field exposure.

Less side effects testing has been conducted on compounds from other pesticide classes. Although SELCTV results show that insecticides are most toxic to natural enemies, all classes contain compounds which can cause deleterious effects (Table 13). Relatively few studies feature side effects testing of fungicides or herbicides, although this is slowly changing (e.g., Eijsackers 1978, Kashio and Tanaka 1981, Huckaba et al. 1983, Teague et al. 1983, Sewall and Croft 1987). Even non-pesticidal agricultural chemicals such as plant growth regulators (Hislop et al. 1978, Gruys 1980, Cranham and Solomon 1981), nutrient sprays (Hislop et al. 1978) and the inert components of formulations (Wilkinson et al. 1978, Haverty 1982) can adversely affect predators and parasitoids. The divergent effects of herbicides on parasitoids and predators indicates that more screening should be conducted for this class. The need to prioritize chemicals and natural enemies for this type of screening is evident.

Pesticide Toxicity and Selectivity

Patterns in pesticide toxicity have shown that insecticides are most toxic to natural enemy species on the average. The toxicity of certain herbicides, particularly to parasitoids, justifies further studies with these compounds as compared to fungicides. The discrepancy between herbicide use and side effects testing on natural enemies becomes even more acute considering their toxicity. While fungicides and acaricides cause less severe side effects on the average, exceptions do exist as shown in SELCTV analysis (Table 19).

Trends in insecticide toxicity in SELCTV are initially encouraging. Movement is indicated toward greater selectivity with insect growth regulators (benzoyl phenyl ureas and JH analogues and antagonists) or IGR's and microbial preparations (Fig. 23). However, these data are for research only. Field use patterns are less encouraging (Pimentel 1982). Major insecticide groups have evolved from the inorganics to DDT and the organochlorines to organophosphates and carbamates. And finally, synthetic pyrethroids appear to be the next dominant group of insecticides (Croft and Whalon 1982). These are highly potent insecticides, identified by SELCTV as the most toxic to date. Additionally, trends in research (SELCTV) are not necessarily predictive. Problems with some of the newer, more selective products, including some microbials, have generated skepticism as to the probability of their widespread introduction and acceptance (e.g., Senuta 1987).

Selectivity ratios are perhaps the most practical values in SELCTV in terms of their value to IPM. Ideally, an insecticide is applied at a rate which suppresses pest populations while allowing at least partial natural enemy survival. Other biological factors permitting, a critical rate exists at which natural enemy survival may be sufficient to allow for biological control of pests below an economically damaging level. Selectivity ratios can implicate candidate compounds for rate manipulation studies. However, few selective compounds have been developed and even fewer utilized sucessfully in the field (Newsom et al. 1976, Metcalf 1980, Hull and Beers 1985, Mullin and Croft 1985). Most documented cases of selectivity from the literature have been ecological, achieved by selective timing or placement of potent pesticides. While physiologically selective pesticides are comparatively rare, they account for the greatest levels of selectivity (Table 28).

While broad spectrum toxicity to pests is a desirable pesticide feature which has been pursued and largely realized, broad spectrum selectivity to non-target predators and parasitoids has not. Physiological selectivity has been achieved primarily for specific natural enemy groups such as aphid predators (pirimicarb) or predatory mites (dicofol, cyhexatin). Some IGR's exhibit a broader spectrum of selecivity, such as diflubenzuron (Wilkinson et al. 1979, Anderson and Elliott 1982, Zungoli et al. 1983, Broadbent and Pree 1984), but registration of these compounds is still fairly limited (Crop Protection Chemicals Reference 1985). Industrial and regulatory constraints threaten the future of these types of pesticides. For example, pirimicarb, the most selective compound identified by SELCTV analysis, is not registered in the United States (Federal Register 1981).

Patterns in Pesticide Susceptibility

Pesticide susceptibility trends among arthropods have been noted in the literature and are evident in SELCTV analyses. These include the greater susceptibility of parasitoids compared to predators and, similarly, that of natural enemies as a group compared to their hosts or prey (Croft and Brown 1975, Plapp 1981, Mullin and Croft 1985). Many factors influence pesticide susceptibility, several of which have been experimentally evaluated. Differences in detoxification potential, population dynamics and the development of pesticide resistance are among factors commonly identified (Croft and Brown 1975, Mullin and Croft 1984, Mullin and Croft 1985, Rosenheim and Hoy 1986).

Numerical differences between predator and parasitoid responses across all SELCTV records and by pesticide class were fairly small (Table 13). However, the size of these data groupings and the breadth of species, test types and pesticides were considerable. Even at this level of generality where many factors influence trends, this pattern was discernible. Scatterplots of predator or parasitoid families (Fig. 17-18) illustrated lower susceptibility as well as higher variablility for predators.

More specific data groupings by taxonomic or chemical criteria also demonstrated lower susceptibility for predators in many cases (Tables 13-15, 18, 20-22). Computations limited to data of the highest precision class (LC_{50} and LD_{50} data) showed a greater difference, comparing 3.53 for predators (1890 records) with 3.78 for parasitoids (648 records). These data come from highly controlled laboratory assays which measured innate susceptibility, and span many individual compounds.

Selectivity ratios (SLECTRATIO) demonstrate lower susceptibility for predators versus their prey compared to parasitoid-host pairings. The average selectivity ratio for predators was 17.5 compared to 83.4 for parasitoids. Therefore predators, on the average, exhibited 5-fold greater pesticide tolerance relative to their prey than parasitoids relative to their hosts. More specific selectivity data for predators and parasitoids by family, species or pesticides followed this trend (see Fig. 25-27).

Parasitoids may be committed to a more biologically complex life history through co-evolution with their hosts (Huffaker 1971). A parasitoid must successfully overcome behavioral or physiological host defenses for development. Perhaps parasitoids have lost resiliency to respond to their external environment as they have gained in temporal and spatial synchrony with their hosts and other specialized behavior (Huffaker and Messenger 1976). Thus, parasitoids may be less fit for survival as free living organisms in a chemically hostile environment. Higher parasitoid susceptibility may be due to lower detoxification enzyme levels, sequestration capacity or some combination of these and other factors (Croft and Morse 1979, Mullin and Croft 1984, Mullin and Croft 1985).

From an evolutionary perspective, proximity to phytophagy may confer to predators an enhanced ability to detoxify or otherwise cope with xenobiotics, including pesticides (Mullin and Croft 1985). Many predatory families contain both entomophagous and herbivorous species, e.g. Coccinellidae, Miridae, Pentatomidae, Lygaeidae, Cecidomyiidae. Most of these families contain pesticide tolerant predatory species (Table 15). While some parasitoids consume pollen or nectar as an alternative food source, they are not strictly phytophagous in that an arthropod host is required for reproduction and nutrition. Parasitoidism and phytophagy rarely occur within the same family. Not surprisingly, the presence of high detoxification enzyme levels among parasitoids has rarely been demonstrated (Mullin and Croft 1985, Duffy et al. 1986).

Over time, predators appear to be better able to adapt to pesticide pressure than parasitoids (Croft and Strickler 1983). High and stable levels of pesticide resistance have been documented almost exclusively among predators. Within SELCTV, over 90% of resistance ratio data are for predators. Average RR:INDEX values show predators 1.31 (20-fold resistance) and parasitoids at only 0.67 (5-fold resistance). Arguments have been presented to support artificial selection of pesticide resistance (Roush 1979, Rosenheim and Hoy 1986). Elevated LD_{50} values have been observed in field collected and laboratory selected parasitoid colonies to a limited extent (Pielou and Glasser 1952, Abdelrahman 1972, Schoones and Giliomee 1982, Rosenheim and Hoy 1986). However, resistance levels comparable to predators have never been maintained.

This raises questions regarding the genetic plasticity of parasitoids in light of resistance development (Huffaker 1971, Croft 1972, Graur 1985, Rosenheim and Hoy 1986). Lower resistance to pesticides could be related to parasitoids lower variablility in response to xenobiotids. These and other factors may be retarding resistance in parasitoids. Pesticide resistance in predators was not documented for several decades after that of pests. Perhaps resistance in parastioids is forthcoming. Hypotheses accounting for differential resistance development in natural enemies and pests have been proposed (Croft and Brown 1975, Tabashnik and Croft 1985, Rosenheim and Hoy 1986), but little work has been conducted to evaluate potentials for resistance in predators and parasitoids.

While research comparing the responses of natural enemies and their hosts or prey to pesticides is slowly increasing, comparative predator-parasitoid study is still minimal. More research on both short and long term effects of xenobiotics on predators and parasitoids is needed to further elucidate the nature of their divergent responses.

Testing and Research: Patterns and Considerations

Natural enemy research is becoming more extensive and detailed, as indicated by SELCTV analysis and recent literature. Recognition of unique aspects of natural enemy biology compared to pests has led to greater focus on natural enemies and the diverse effects of pesticides upon them. Extrapolation from pest responses to natural enemies is no longer acceptable. Consequences of a pesticide application may be very different for these two groups of arthropods. For example, treatment causing marked reduction in both populations may be more deleterious to a natural enemy, as the density of its food supply becomes minimal. However, a pest can still rely on the crop plant in virtually unlimited supply (Croft and Brown 1975). Strategies for management and possible exploitation of selective pesticides is made possible by first having a thorough understanding of the responses of natural enemies as well as pests.

There appears to be a general trend toward more precise susceptibility assessments for natural enemies. This was well supported in SELCTV analysis by an examination of field assays compared to median lethal assays (Fig. 12). Median lethal assays indicate intrinsic susceptibility, unmitigated by the biotic or abiotic environment. A substantial shift in research appears to have occurred over the past 3 decades, from empirical description of pesticide impact at the population level to more analytical studies, some of which quantify pesticide effects at a biochemical level (Bashir and Crowder 1983, Croft and Mullin 1984, Martin and Brown 1984, Bellows et al. 1985). This dissection of the toxic episode for study has provided information for improving field management of pest and natural enemy populations.

Efforts to standardize natural enemy susceptibility testing are currently underway (Bogenschutz 1979, Franz et al. 1980, Hassan et al. 1983). Advantages of standardization include: 1) Extrapolation of results from representative natural enemies to similar species, saving time and resources, and 2) establishment of standard methods or protocols, allowing comparisons of results form different researchers with greater confidence. SELCTV analysis indicated a marked preference among researchers for the contact method of testing, conducted in 48 hours or less (Figs. 9-10, 12-13). Reliance on simple standards is probably adequate for assessment of the relative hazard of a pesticide.

Research in this area has generated discussion of important modes of uptake and probable exposure relative to the development of standard protocols. While field tests may best approximate conditions that natural enemies encounter in the agro-ecosystem, they are generally of lower precision than laboratory tests. The latter are assessments of intrinsic pesticide toxicity, in estimates that tend to be more precise and conservative (severe) compared to field tests. This trend is supported by SELCTV analysis, which shows laboratory tests to be more toxic on the average (mean = 3.51) compared to field tests (mean = 3.39). Although intrinsic toxicity is important to assess, it is unlikely that laboratory assays would reveal ecological features of selectivity which might be evident in field studies.

Standardization is not without drawbacks. The selection of representative species among diverse natural enemies may be difficult. Some side effects may go undetected when using practical protocols which give reproducible results. Individual cases are likely to arise where standard methods are inadequate. For example, seperate protocols are being developed for the microbial pesticides (Flexner et al. 1986). Nonetheless the utility of standardizing must be weighed against the hazards of generalizing.

Measurement of pesticide impact on natural enemies is more complicated than efficacy trials that assay pest mortality. The goal of natural enemy-pesticide research is to document any harmful effects which could interfere with biological control (Brown 1977, Croft and McGroarty 1977). More detailed research on natural enemies has revealed the breadth of their responses to pesticides, ranging from mortality to lower reproductive rate to aberrant development or behavior. In addition, responses can be cryptic. Sublethal or latent pesticide side effects may not be apparent until ecdysis, metamorphosis, sexual maturity or the subsequent generation (Brown 1977, Croft 1977).

Elucidation of the frequency and importance of sublethal effects on natural enemies continues (Fig. 16). Since the early 1950's, documentation of sublethal effects has increased. By the 1980's over 13% of records contained sublethal effects data. While most of the synthetic organic pesticides cause acute mortality to natural enemies at field rate, sublethal effects become important as residues diminish and habitat re-entry begins. Side effects of the microbial insecticides and

IGR's are more commonly sublethal and chronic (Beckage 1985, Flexner et al. 1986). Greater reliance on biological control and widespread use of selective pesticides may be achieved by continuing study of the differential effects of these pesticides on pests, predators and parasitoids in agricultural systems.

CONCLUSIONS

In reporting and discussing results of extensive analyses of the literature documenting pesticide impact on arthropod natural enemies, many points have been raised throughout this thesis. Some of the most relevant and widely supported points are reiterated in the following list of conclusions:

1) The literature documenting pesticide impact on arthropod natural enemies is increasing both in publication rate and in specificity. Studies focusing on specialized aspects of natural enemy susceptibility such as sublethal effects, modes of uptake, standardization of test methods and physiological or ecological selectivity are on the rise.

2) Pesticide impact has been studied more commonly on predators (71%) than parasitoids (29%).

3) Most pesticide impact research on arthropod natural enemies has been conducted on high value crops or crops in which natural enemies afford substantial biological control of some pest component.

4) Pesticide impact has been studied primarily for natural enemies of secondary or induced pests such as scales, aphids, mites and whiteflies, especially where natural enemies are managed or monitored in pest management programs. In some cases, natural enemies of secondary pests are

screened for side effects with compounds used to suppress populations of key or direct pests.

5) Most studies of pesticide impact on arthropod natural enemies have featured insecticides, while fungicides, acaricides and herbicides have been far less commonly examined. Half of the insecticide data are for organophosphates.

6) The most common test method was the laboratory contact test, in which a natural enemy was placed on a fresh, dry pesticide deposit for a given amount of time and evaluated at a later time. Field tests were second most common in total counts, although laboratory testing appeared to have recently succeeded field tests as the most commonly used test when frequency was measured over 5 year intervals across SELCTV.

7) The data which exist on pesticide resistance in arthropod natural enemies are scarce and principally documents resistance in phytoseiid mites, although the incidence of natural enemy resistance is generally on the increase.

8) Comparative studies of pest and natural enemy susceptibility were most commonly conducted when pesticide selectivity favoring natural enemies was suspected.

9) Predators were more variable and less susceptible in response to pesticides than parasitoids, a difference estimated to be about 5:1.

10) Insecticides were most toxic to natural enemies, followed by herbicides, acaricides and fungicides respectively. While herbicides and acaricides varied as to the toxicity of individual compounds, fungicides were more uniformly non-toxic.

11) Insecticide selectivity to natural enemies has decreased gradually over time since the early inorganics and botanically derived compounds. Organochlorines and DDT derivatives were less selective, but the organophosphates and carbamates were worse yet. Synthetic pyrethroids as a group are most harmful to natural enemies of all types of insecticides which have been developed. Insect growth regulators and microbials show substantial promise, although their registration and use is meager in comparison to conventional organo-synthetic pesticides.

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APPENDIX

APPENDIX A

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