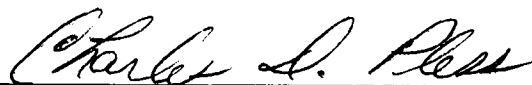


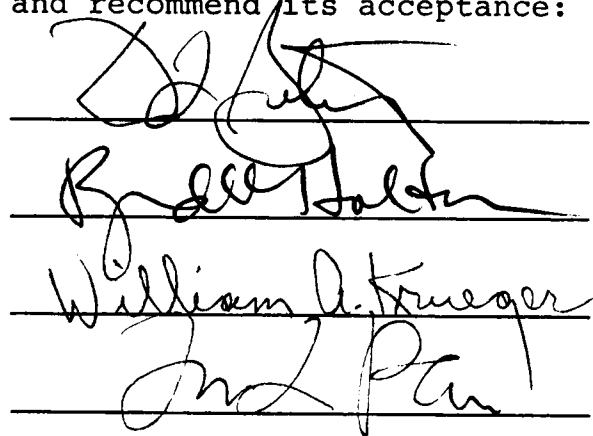
To the Graduate Council:

I am submitting herewith a dissertation written by Ginger Lee Gist entitled "Effects of Synthetic Pyrethroids on Fall Armyworm, Spodoptera frugiperda (J. E. Smith)." I have examined the final copy of this dissertation for form and content and recommend that it be accepted in partial fulfillment of the requirements for the degree of Doctor of Philosophy, with a major in Ecology.



Charles D. Pless
Major Professor

We have read this dissertation
and recommend its acceptance:



Four handwritten signatures are present, each on a horizontal line. The signatures are: 1. A stylized signature starting with 'D'. 2. A signature that appears to be 'R. D. H. H. H.'. 3. A signature that appears to be 'William A. Krueger'. 4. A signature that appears to be 'J. L. P. H.'.

Accepted for the Council:



The Graduate School

EFFECTS OF SYNTHETIC PYRETHROIDS ON FALL ARMYWORM,
SPODOPTERA FRUGIPERDA (J. E. SMITH)

A Dissertation
Presented for the
Doctor of Philosophy
Degree
The University of Tennessee, Knoxville

Ginger Lee Gist

August 1983

This dissertation is dedicated to my mother,
Wanda Dycus,
with love

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ACKNOWLEDGMENTS

I wish to express my heartfelt gratitude and thanks to Dr. Charles D. Pless, my major professor, for his guidance, unlimited patience, encouragement, and, most of all, his friendship during the course of this study. I also wish to thank my committee, Dr. Dewey Bunting, Dr. Raymond Holton, Dr. William Krueger, and Dr. M. L. Pan, for their advice and help concerning the preparation of this manuscript.

My love and appreciation go to my parents and grandparents for their support and encouragement which made my continued education possible.

Thanks are also extended to: Merck Chemical Division, Rohm and Haas Company, the Department of Entomology and Plant Pathology, and the Department of Microbiology for providing me with graduate research assistantships; ICI Americas, Inc., FMC Agricultural Chemical Group, Shell Development Co., Zoecon Corp., and American Cyanamid Co., for providing the chemicals for this study; and the Southern Grain Insects Laboratory, Tifton, Georgia, for providing fall armyworm pupae.

Special thanks go to the faculty, staff, and students of the Department of Entomology and Plant Pathology for their boundless friendship and support.

ABSTRACT

Nine synthetic pyrethroids were tested in the laboratory for acute and chronic effects to the fall armyworm, Spodoptera frugiperda (J. E. Smith). In ovicidal tests LC_{50} values ranged from 0.320 ppm (Pay-Off®) to 12.230 ppm (Pydrin®). All 9 pyrethroids were more toxic to eggs than diazinon, a standard.

All 9 pyrethroids were ovipositional repellents at the concentrations tested. At their respective ovicidal concentrations cypermethrin (FMC) was least repellent. At one-tenth their respective ovicidal concentrations Ammo® and cypermethrin (FMC) were least repellent.

In no-choice feeding deterrent tests all 9 pyrethroids were effective at 50 ppm. At 5 ppm all but Pounce® were significant deterrents.

LD_{50} values for 3rd instar ranged from 0.0041 $\mu\text{g}/\text{insect}$ [permethrin (FMC)] to 0.1558 $\mu\text{g}/\text{insect}$ (Ammo®). All pyrethroids were more toxic than diazinon, a standard, to 3rd instar. LD_{50} values for 6th instar ranged from 0.213 $\mu\text{g}/\text{insect}$ [permethrin (FMC)] to 5.841 $\mu\text{g}/\text{insect}$ (Ammo®). Ammo® was the only pyrethroid less toxic than diazinon to 6th instar.

The pyrethroids were not readily synergized by piperonyl butoxide (1:8, pyrethroid:PB). The cypermethrins

(FMC and ICI) were the only pyrethroids to synergize ovicidal activity (SR = 3.531 and 6.328, respectively). Cypermethrin (FMC) (SR = 3.0700) and Ammo® (SR = 9.1111) were the only pyrethroids to have synergized activity to 3rd instar. Ammo® (SR = 8.641) was the only pyrethroid to have synergized activity to 6th instar.

In growth and development tests all 9 pyrethroids significantly increased the time to maximum larval weight. Pounce®, permethrin (ICI), permethrin (FMC), and cypermethrin (FMC) had significantly lower maximum larval weights than the control. All 9 pyrethroids significantly reduced the relative growth rates of FAW. Pupation and emergence of adults were normal for pyrethroid-treated insects; however, many subsequent adults were unable to inflate their wings. Number of eggs/female was reduced in all pyrethroid-treated populations except those treated with Pydrin® in which there was a 2 fold increase. Eggs laid by females of treated populations had 6× (Ammo®) to 20× [permethrin (FMC)] less survival than control eggs.

In final evaluation, pyrethroid rankings (in descending order) were: permethrin (FMC), cypermethrin (ICI), cypermethrin (FMC), Pay-Off®, permethrin (ICI), Pounce®, Mavrik®, Pydrin®, and Ammo®.

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CHAPTER I

INTRODUCTION

For approximately 185 years the fall armyworm (FAW), Spodoptera frugiperda (J. E. Smith), has been recognized as a pest of major economic importance in the southeastern United States (Chittenden 1900, Fuxa 1982, Hinds and Dew 1915, Luginbill 1928, Vickery 1929). Today average annual losses in the United States attributed to FAW exceed \$300 million, with losses during particularly severe outbreak years, such as those in 1975, 1976, and 1977, exceeding \$500 million annually (Mitchell 1979).

Approximately 80 species of plants, including 30 which are economically important, are attacked by FAW larvae (Ashley 1979, Luginbill 1928, Metcalf et al. 1962, Vickery 1929) with corn being the primary host plant (Luginbill 1928, Wiseman and Davis 1979). During early population development, infestations are concentrated in succulent grass crops (corn, bermudagrass, various weed grasses). Damage may also occur in alfalfa, fescue, peanuts, and cotton during years with greater than 15% of late corn acreage harboring FAW larvae (Hunt 1980). Populations of FAW larvae that develop in the southeastern region by late summer are generally so high that important forage crops cannot be grown profitably at that time of the year.

The polyphagous lifestyle of this insect makes development of successful management programs difficult. Expenditure for insecticide applications to control this pest in the South and Southeast is on the order of \$15 million per year (Knipling 1980). In addition, field studies of FAW have demonstrated a resistance to trichlorfon, diazinon, methyl parathion, ethyl parathion (Bass 1978), and carbaryl and tolerance to methomyl (Burton 1969). Consequently, FAW is considered the major obstacle to a double cropping system in much of the Southeast (Knipling 1980).

A "new era" in control of insects began when the synthetic pyrethroids became available (Anonymous 1977). Pyrethroids are becoming increasingly important as insect control agents because they possess a unique combination of desirable properties, including exceptionally good insecticidal activity, low mammalian toxicity, and rapid biodegradation. These features, combined with their broad spectrum of insecticidal activities, have made them commercially successful as well as environmentally safe (Inoue et al. 1977).

Discovery of pyrethroids which are photostable (Elliott et al. 1973a,b), potent insecticidally (Elliott et al. 1974), and structurally new (Ohno et al. 1974) has greatly increased the potential usefulness of these compounds. Although photostable pyrethroids initially will be more

expensive on a weight to weight basis than most other insecticides because synthesis is more complex, their much greater activity makes possible substantially lower rates of application and, consequently, less contamination of the environment by the toxicant (Elliott et al. 1978). With their combination of favorable properties, as well as activity from 4-40 times that of other classes of insecticides (Croft and Hoyt 1978), synthetic pyrethroids may have importance comparable to organochlorines, organophosphates, and carbamates as practical insecticides used on a large scale (Elliott 1976). Synthetic pyrethroids may indeed be "the insecticide group of the future" (Croft and Hoyt 1978).

CHAPTER II

LITERATURE REVIEW

Fall Armyworm

General Biology

Life cycle. The life cycle of the fall armyworm (FAW), Spodoptera frugiperda (J. E. Smith), has been extensively studied (Burkhardt 1952, Hinds and Dew 1915, Lincoln and Isley 1945, Luginbill 1928, Luginbill, Jr. 1950, Sparks 1979, Vickery 1929, and Walton and Luginbill 1917) and will be generally covered in this review.

Adult FAW are mainly nocturnal, preferring to remain concealed under foliage or debris during the day. Activity begins at dusk and reaches its peak prior to midnight. Activity will vary with weather conditions. Hot, sultry evenings are more favorable than cool, damp evenings.

Generally the feeding period extends for approximately two hours after dusk. Moths feed on nectar of various plants (Luginbill 1928). After feeding, virgin females initiate calling. Usually several males respond to each female. Females will mate only once each night, with polygamy being evident on successive nights.

Oviposition occurs shortly after mating. Egg masses, characteristically layered, are covered with scales of the female, which apparently afford protection against biotic

and abiotic environmental factors (Gross et al. 1981). The undersides of leaves of older, larger plants of the grass family are preferred over other ovipositional sites (Pitre et al. 1983). The number of eggs per mass may vary from a few to several hundred with the average being near 200. Eggs hatch in 2 to 4 days when mean temperatures are 21-27°C.

Immediately after hatching, larvae devour the egg shells and initiate feeding on the host plant. Larvae are most active in early morning and late evening and are positively phototrophic. Young larvae (first-third instars) skeletonize leaves and, when molested, will drop to the ground by spinning silk threads. Older larvae (fourth-sixth instars) often completely destroy small plants and strip larger ones (Luginbill 1928). FAW typically have six instars with the larval period lasting from 11 to 25 days, depending upon such variables as temperature and type and amount of food available.

FAW larvae are polyphagous; however, they prefer plants belonging to the grass family, Poaceae, such as corn, sorghum, bermudagrass, and crabgrass (Luginbill 1928). Level of consumption, developmental rate, survival, pupal weights (Pencoe and Martin 1981) and susceptibility to chemical treatment (Wood et al. 1981) vary with the host plant of the larvae. Different food plants are also known to affect subsequent egg production.

Pupation takes place 1-3 inches below the soil line, depending upon such variables as soil type and texture, moisture and temperature. Length of the pupal period may vary from 7-37 days when soil temperatures range from 15-29°C (Vickery 1929). The FAW has no diapause mechanism and must overwinter in tropical regions.

Emergence of adults from pupal cases occurs from 2-3 hours after sunset until midnight. Newly emerged adults cling to plants and inflate their wings. Adults probably feed the first night of their lives (Sparks 1979) although they do not mate during that time.

In warm weather throughout the southern range of FAW the life cycle typically takes 4 weeks. During colder periods and at the northern limits of the range a generation may take from 80-90 days (Vickery 1929).

Origin and distribution. Because it has no diapause mechanism, Luginbill (1928) speculated that the FAW is probably tropical in origin. This insect overwinters in Florida and southern Texas in the U.S. as well as Mexico and the Caribbean. Moths disperse from these areas each growing season. It may survive mild winters along the Gulf Coast and in Arizona (Hinds and Dew 1915, Snow and Copeland 1969). At the conclusion of the growing season the FAW may be found all the way into southern Canada in the north and Montana and California in the west (Snow and Copeland 1969). The

greatest economic impact, however, is in the southeastern U.S.

Other regions of the world may be infested, including such diverse areas as Israel and Brazil. Wiltshire (1977) pointed out that morphological races of FAW may exist, but differences in these populations may not include pheromone responses (Mitchell and Sparks 1978, Snow et al. 1968).

The FAW was first recognized as a pest of grasses and grain crops in 1797 by Smith and Abbott (Luginbill 1928) who called it a "formidable depredator." The insect drifted back into obscurity until 1845 when it was reported to have done extensive damage to grass, corn, sugarcane, and rice in Florida. From 1856-1928 there were numerous local outbreaks recorded (Luginbill 1928) with the first general outbreak recorded in 1899. The next major outbreak occurred in 1912. During that year practically the whole United States east of the Rockies was invaded. The period from 1928 to 1975 had no well documented cases of outbreaks (Sparks 1979); however, 1975, 1976, and 1977 have been recorded as years of heavy infestation.

Luginbill (1928) summarized the causes conducive to an outbreak as cool weather with an abundance of rainfall. These conditions favor luxurious growth of grasses, check multiplication of natural enemies, and create conditions favorable for a thriving FAW population (Sparks 1979). By the time populations of natural enemies have built up, FAW

populations have increased greatly and migrated northward (Luginbill 1928, Vickery 1929, Walton and Luginbill 1917). The rate has been estimated to be as great as 300 miles per generation in some years. A current hypothesis concerning this migration is that dispersal is carried out by means of weather fronts. Several researchers (Greenbank 1957, Joyce 1973, 1975; Rainey 1973, Schaefer 1973, 1976) have shown that concentrated masses of airborne organisms, including insects, have been known to be moved by weather fronts and deposited great distances from their origin in numbers sufficient to cause serious losses to crops.

Control

The FAW represents a "life style" where polyphagy and mobility seem extremely important to population survival (Barfield and Stimac 1980). Erratic occurrence of FAW "outbreak years" (Sparks 1979) and irregular distribution of heavy infestations indicate that non-crop host plant availability, timing of crop host availability, and natural mortality play dominant roles in the FAWs survival strategy (Barfield et al. 1980). Thus control measures for FAW are usually necessary, even though economic injury thresholds, based on the number of larvae per foot of row, have not been established. Measures for FAW control include mechanical control, cultural control, plant resistance, predators, parasites, pathogens, irradiation, and chemical control.

Mechanical measures were among the first used.

Luginbill (1928) mentioned barriers, such as furrows in which larvae become trapped and ultimately crushed, shallow holes filled with kerosene, and thin lines of liquid coal tar. Crushing larvae with steel lawn rollers, raking larvae with steel rakes, and shaking larvae from plants into receptacles containing small quantities of kerosene were also listed as mechanical measures. All of the above, for the most part, have fallen into disuse.

According to Lynch et al. (1980) possible cultural manipulations for control of FAW include: (1) fertilize and/or harvest frequently to stimulate crop growth before damaging FAW populations can occur; (2) harvest when FAW larval populations reach economic injury level rather than control the insects with an insecticide; (3) delay harvest before peak FAW moth flight so that the crop is not attractive for oviposition; and (4) harvest the crop following peak moth flight to destroy heavy infestations of first or second instar larvae, if the crop is in an attractive stage of regrowth during moth flight.

Luginbill (1969) stated that "the most effective and ideal method of combating insects that attack plants is to grow insect resistant varieties." Plant resistance has been defined as the relative amount of heritable qualities possessed by the plant which influence the ultimate degree of damage by the insect (Painter 1951). In order to be

useful, resistance must be inherited. Painter (1951) also classified plant resistance as nonpreference (resulting when a plant or variety does not possess normal attractive substances or qualities for oviposition, food, and/or shelter), antibiosis (denoting those adverse effects on the insect when the pest uses the resistant variety or plant for food), and tolerance (plants that are able to produce well despite infestations that seriously damage susceptible plants).

Wiseman and Davis (1979) and Davis (1980) reviewed the state of plant resistance to FAW in cereals and grasses, which are preferred hosts of FAW. Ditman and Cory (1936) were the first to report that some U.S. corn strains showed resistance. In 1956 Bertels found that, in Brazil, corn varieties with the "Amargo" character were resistant (Wiseman and Davis 1979). "Guerrero 169," "Guerrero 115," "Cuba 30," and "Yucatán 15" in Mexico (Anonymous 1959) were also reported resistant to FAW. Dicke (1977) reported that northern corn strains were more susceptible to attack than southern strains. Brett and Bastida (1963) stated that resistance of sweet corn varieties tested was largely due to tolerance and that larvae preferred succulent plant tissue in good physical condition.

The first report of pearl millet resistant to FAW was by Leuck et al. in 1968(b). Nonpreference was present in some lines that were more thoroughly investigated and one

inbred had antibiosis. Another important forage crop in the Southeast, bermudagrass, was reported by Leuck et al.

(1968a) and Leuck and Skinner (1970) to have resistant strains. Peanuts (Leuck and Skinner 1971) and sorghum (McMillian and Starks 1967) also have resistant strains.

Plant nutrition also has an effect on the ability of a plant to resist FAW (Leuck et al. 1974, Wiseman et al. 1973a,b). These authors have shown that by manipulating host crop nutrition, resistance levels could be either raised or lowered. Actual behavior and biology of an insect can be altered by host plant nutrition. Leuck and Hammons (1974a,b) have shown that manipulation of host crop nutrients can induce some detrimental effects of plant resistance to FAW among a number of crop cultivars.

Although FAW is attacked by an abundance of natural enemies, it remains a major pest of many annual row crops (Lewis and Nordlund 1980). The ability of entomophages to suppress FAW populations is limited by rapidly expanding area of available host-plant surface during the early and mid-growing seasons. Knipling and McGuire (1968) and Need and Burbuts (1979) assert that this surging increase in habitable space requires entomophages to continuously redistribute and greatly exaggerates the typical lag phase in host-parasitoid and predator-prey relationships.

Fifty-three species (43 genera and 10 families) have been recorded as FAW parasites according to Ashley (1979).

Braconids, ichneumonids, and tachinids accounted for 16, 19, and 47% of the genera and 15, 17, and 53% of the species, respectively. Apantheles marginiventris (Cresson) and Chelonus texanus (Cresson) were the parasites most frequently recovered from FAW larvae. There are also numerous predators known to attack FAW though no summary dealing with them is available. Luginbill (1928) mentions wasps, dragonflies, ants, mites and spiders as possible predators. Predaceous vertebrate enemies of FAW include skunks, lizards, tree frogs, toads, domestic fowl, and native wild birds (Luginbill 1928).

The FAW is susceptible to at least 16 species of entomogenous pathogens including viruses, fungi, protozoa, nematodes, and 2 strains of the bacterium Bacillus thuringiensis Berliner (Gardner and Fuxa 1980). Of the naturally occurring regulatory agents the following have been important: S. frugiperda nuclear polyhedrosis virus (Allen 1921, Chapman and Glaser 1915, Harned 1920/21, Kuno 1979, Luginbill 1928, Steinhaus and Marsh 1962), S. frugiperda granulosis virus (Steinhaus 1957), fungi (Charles 1941, Hamm 1980, Luginbill 1928, Wolcott 1955), a nematode, and a protozoan (Weiser 1959). Attempts to suppress FAW populations with entomogenous pathogens thus far have been restricted to use of microbial insecticides (Gardner and Fuxa 1980).

Initiation and development of epizootics are governed by a complex of factors such as host population density, host behavior, pathogen inoculum quantity, and environmental conditions (Gardner and Fuxa 1980). Effect of pathogens in the enzootic stage is less obvious, but they may cause mortality, interference with development and reproduction, or lowered resistance to insecticides or other mortality factors (Falcon 1971).

Since the FAW lacks a diapause mechanism, forcing it to overwinter in mild regions, use of a sterile male technique has been suggested (Snow et al. 1972). Knippling (1980) discussed the use of irradiated FAW moths and suggested that partially sterile moths carrying an inherited sterility feature could be a major component of FAW management on an area-wide or ecosystem basis. Carpenter et al. (1983) provided the proof that deleterious effects are indeed inherited in the F_1 , F_2 , and F_3 progeny of FAW males that had received substerilizing dosages of gamma radiation. Low dosage radiation gave better control than release of 100% sterile males.

Insecticidal control of FAW is often necessary (Bass 1978, Luginbill 1928, Straub and Hogan 1974, Young 1979). Crops are most susceptible to damage when they are either in seedling stage or in regrowth stage; thus, height and density of the canopy become limiting factors for efficient

insecticidal control because it is difficult to obtain canopy penetration with spray materials (Young 1979).

Generally, control of FAW larvae in seedling corn, millet, sorghum, and southern peas is achieved by using a systemic insecticide at planting time (Kuhn et al. 1975). Control in later stages of growth may be obtained with ground or aerial applications or metering into irrigation systems.

Chemicals approved by the Environmental Protection Agency for FAW control on corn, sorghum, and pasturage include carbaryl, trichlorfon, methyl and ethyl parathion, diazinon, and methomyl (Young 1979). Other insecticides currently being screened include chlorpyrifos, Larvin (=thiocarb), monocrotophos, synthetic pyrethroids (Harrell et al. 1977), Bolstar, ethoprop (Mocap), Oftanol, and acephate (Orthene) (Bass 1978).

Use of these chemicals to control FAW populations depend, at least in part, upon the population itself. Some infestations in the U.S. are brought in by weather fronts (Franceschini 1954, Rose et al. 1975) and therefore have characteristic responses to insecticides based on the parent population.

Synthetic Pyrethroids

General Review

Pyrethroid insecticides have evolved in a classical sequence: activity observed in a natural extract, compounds responsible isolated and identified, increasingly active analogues synthesized (Elliott and Janes 1978). The newer pyrethroids are among the most potent insecticides known and could possibly replace the more suspect organophosphate, carbamate, and organochlorine insecticides.

The parent compound, pyrethrum, is from the powder of dried pyrethrum flowers, Chrysanthemum cinerariaefolium. Pyrethrum powder was first used as an insecticide in the Transcaucasus region of Asia about 1800 (Ware 1978) and was used in Europe during the 19th century as a form of louse control during the Napoleonic wars.

The first synthetic pyrethroids in which characteristically high activity against insects and low mammalian toxicity were combined with greatly increased stability were described in 1973 (Elliott et al. 1973a,b). In addition to being more photostable under appropriate conditions, several of these compounds were also more insecticidally active by at least one order of magnitude. For example, only 25 to 30 g AI/ha provided adequate pest control in most cases compared with 250 to 500 g of traditional organophosphorous and carbamate insecticides per ha (Talekar et al. 1983).

With structural requirements for photostable pyrethroids established, many new compounds were synthesized, including a new class of substituted 2-phenyl alkanoates that are unique in lacking the cyclopropane ring (Ohno et al. 1976), that retained the chemical and stereochemical features of the parent molecules, and hence their biological activity (Elliott et al. 1978).

Properties, Metabolism, Toxicology, and Mutagenicity

Biological activities of pyrethroids are intimately related to their chemical structure and depend on optical and geometrical configurations of their acidic and alcoholic components (Elliott et al. 1978). Synthetic pyrethroids are continually reviewed (Barthel 1961, Breese 1977, Breese and Searle 1977, Elliott 1971, 1977; Elliott et al. 1978, Matsui and Yamamoto 1971, Narahashi 1971b, Ruscoe 1977) and will be briefly summarized here.

Physical properties of pyrethroids probably determine their rapid action in insects (Briggs et al. 1974) and also minimize translaminar action in leaves and systemic movement in plants (Elliott et al. 1978). All pyrethroids are lipophilic compounds and are almost insoluble in water. Rain fastness (Ruscoe 1977), associated with their lipophilicity, favors retention by leaf cuticles. Most pyrethroids are relatively high-boiling, viscous liquids

with low vapor pressures, thus they are unlikely to be dispersed through the environment by air movements.

Mobility of pyrethroids in soil is small. Vapor diffusion in soil airspace is not significant because their vapor pressures are low (Elliott et al. 1978). Their highly lipophilic character with octanol-water coefficients (P) greater than 10^5 (Briggs et al. 1974) suggests that pyrethroids would be strongly adsorbed in most soils and thus not leached readily from the point of application or deposition.

Photostability of newer pyrethroids has been obtained by replacing photolabile centers with alternative structural units. These compounds, however, still retain the favorable characteristics of the earlier pyrethroids. All identified products of photodecomposition have been shown to have reduced biological activity. This, in addition to low application rates, makes it improbable that toxic residues will accumulate to contaminate the environment (Elliott et al. 1978).

The parent pyrethroid is the neuroactive agent and its metabolism is a detoxification process relative to the poisoning of insects and mammals (Casida and Ruza 1980). All known active pyrethroids are esters; therefore, ester cleavage is one route by which they may be deactivated. Most pyrethroid structures also have numerous sites

susceptible to attack by mixed-function oxidase systems (Elliott et al. 1978). Indeed, ester cleavage may in part involve oxidative processes as cleavage is faster when microsome preparations are fortified with reduced nicotinamide-adenine dinucleotide phosphate (Casida and Ruzo 1980). The preferred site of pyrethroid hydroxylation varies with the source of the insect or mammalian microsomal oxidases (Shono et al. 1979). According to Elliott (1976) this susceptibility to metabolic attack is independent of other properties so that compounds have been discovered that persist in abiotic environments yet are rapidly decomposed in metabolizing systems. Possible exceptions of acutely or chronically toxic metabolites include cyanide, released from cyano-pyrethroids, and the (S)-acid, (R)-alcohol isomer of fenvalerate which is biologically racemised to the (S)-alcohol compound (esfenvalerate), a product of greatly increased insecticidal activity (Casida and Ruzo 1980). Metabolism and toxicity of pyrethroids in animals, soils, and plants can be summarized as follows according to Elliott et al. (1978) and Casida and Ruzo (1980).

Mammalian toxicities of pyrethroids are generally lower than those of other classes of insecticides. After external or oral administration to mammals they are eliminated, intact or modified by metabolism, before reaching sensitive regions. Intravenous toxicities, however, are typically

high. Detailed investigations of mammalian metabolism and toxicology of an increasing number of synthetic pyrethroids have been undertaken by various investigators (Casida et al. 1975/76, Crawford et al. 1981, Elliott et al. 1972, Elliott et al. 1976, Gaughan et al. 1977a,b; Gaughan et al. 1978, Hunt and Gilbert 1977, Hutson et al. 1981, Ivie and Hunt 1980, Miyamoto 1976, Miyamoto et al. 1971, Shono et al. 1979).

In insects pyrethroid metabolism is mainly by hydrolysis and oxidation (Bigley and Plapp 1978, Chang and Jordan 1982, Holden 1979, Miyamoto and Suzuki 1973, Shono et al. 1978, Soderlund 1979, Yamamoto et al. 1969). The ability to metabolize pyrethroids varies not only with the compound and insect species but also with the instar of the insect (Yu 1983) due mainly to the variation in detoxifying enzymes with age. This can be further complicated in resistant strains by interaction between the various factors of resistance (Sawicki 1975). Indeed, the number of detailed investigations in insects is limited due to greater experimental difficulties and to the fact that such information is not necessary to establish the safety of an insecticide.

Schimmel et al. (1983) state that synthetic pyrethroids, when used in areas adjacent to estuarine systems, represent a substantial threat in their acute toxicities,

both to fish (Mulla et al. 1978) and to the aquatic invertebrates (Muirhead-Thompson 1978), their tendency to bioconcentrate in estuarine biota, and their tendency to persist in estuarine sediments. The lipophilicity of pyrethroids indicates that they will be absorbed strongly by the gills of fish, even from very low concentrations in water.

Pillmore (1973), Mauck et al. (1976), and Miyamoto et al. (1971) have shown that relative toxicity varies with species and that to any one species the toxicities generally parallel insecticidal activities. Synthetic pyrethroids do not readily disappear from natural waters unless exposed to ambient light (Schimmel et al. 1983); however, rapid adsorption onto river banks, pond sediments, and organic matter in general greatly diminishes concentrations in the water. Microbial activity is responsible for degradation in the sediment (Hill 1981, Schimmel et al. 1983). It has been argued, however, that under practical conditions pyrethroids show little significant effect on nontarget organisms (Breese 1977, Muira and Takahashi 1976, Mulla et al. 1975, 1978, Quélennec 1972, Ruscoe 1977) excluding insects.

From all evidence published to date, toxicities of natural pyrethrins (Pillmore 1973) and synthetic pyrethroids to birds are very low (Shell Development Co. 1976, WHO 1975). According to Gaughan et al. (1978b) the ease of permethrin hydrolysis and oxidation in hens suggests that

rapid detoxification may contribute to the relative unsensitivity of hens and other avian species to pyrethroid poisoning (Casida 1973, FMC Corporation 1977).

Despite the long history of use, essentially nothing was known about degradation or persistence of pyrethroids in soils until recently. Kaufman et al. (1977) showed that permethrin was rapidly degraded in soil and that soil microorganisms played a significant role in decomposition. The principal degradation mechanism involves hydrolysis and/or oxidation with further metabolism to CO_2 (Casida and Ruzo 1980, Kaufman et al. 1981). Similar results have been described by other investigators with cypermethrin (Roberts and Standen 1977, 1981), fenpropathrin (Roberts and Standen 1977), fenvalerate (Ohkawa et al. 1977), and permethrin (Doyle et al. 1981). It has been shown that cultivated soils retain greater quantities of pyrethroids than fallow soils without affecting ammonification, nitrification, cation exchange capacity, or soil microbial populations (Talekar et al. 1983). According to Elliott et al. (1978) the most important conclusions from these and other studies are that pyrethroids are fully degraded in various soil types in 2-4 weeks, in contrast to organochlorine insecticides, which may persist for months or years. At recommended rates, pyrethroids are probably metabolized sufficiently rapidly to minimize adverse effects on soil microflora and fauna.

The lipophilic character of pyrethroids indicates that they will be adsorbed readily onto waxy layers on plant surfaces and penetrate to aqueous inner phases predominantly as more polar metabolites, such as the plant metabolites of permethrin (Gaughan and Casida 1978, Huff 1980). Ohkawa et al. (1977) found that permethrin on bean leaves underwent various reactions including ester cleavage, hydroxylation of the acid and alcohol moieties before or after ester cleavage, and conjugation of the various hydroxy and carboxylic acid derivatives (Gaughan and Casida 1978). Quistad et al. (1982) found that fluvalinate on plants underwent hydrolysis to principally form anilino acid. Neither fluvalinate nor its metabolites were translocated within the plants. Furthermore, photoisomerization at the cyclopropane ring, i.e., interconversions of the trans- and cis- isomers, is also a significant reaction on plants (Gaughan et al. 1977a, Ohkawa et al. 1977) and under other environmental conditions (Holmstead et al. 1977, 1978). It has been established that metabolic products of this type have very low toxicity to mammals (Gaughan et al. 1977a) which is important as Leahey and Carpenter (1980) have shown that residues of permethrin are taken up by sugar beets, wheat, lettuce, and cotton. The half-life of pyrethroids on plant surfaces will vary with temperature, growth dilution, and weather conditions (Hill et al. 1982). The average half-life of pyrethroids as a whole is 3 to 5 weeks.

Pyrethroids in general show no direct mutagenic activity in a variety of assays (Miyamoto 1976, Ruzo and Casida 1977). Allethrin, however, is reported to have mutagenic activity in two in vitro screens, i.e., the Salmonella assay and the chromosomal aberration test in Chinese hamster cells when treated with liver S9 mix for activation (Matsuoka et al. 1979). Kimmel et al. (1982) found allethrin and terallethrin photodecomposition products to be potent mutagenic derivatives, but other pyrethroids examined yielded photoproduct mixtures in sunlight with no more than 10% of the mutagenic activity of the photoproducts of allethrin and terallethrin.

Insecticidal Properties and Mode of Action

From the pioneering work of Staudinger and Ruzicka and R. Yamamoto (Elliott 1971) it is clear that almost all active pyrethroids are esters with constituent acids and alcohols, and simple derivations of them, being practically inactive. Elliott et al. (1980) point out that the stereochemical form of pyrethroids strongly influences the level of their insecticidal activity (in the case of permethrin, cypermethrin, and fenvalerate stereochemical mixtures are the marketed product). Greatest potency depends on at least two centers having appropriate chirality, with two centers of unsaturation at the extremities of the molecule, and a gem-dimethyl group on its steric equivalent β to the ester

group (Elliott and Janes 1978). These are features of all potent pyrethroids thus far described.

Many new pyrethroids with high insecticidal properties have been synthesized by adding substituents to the alcohol and/or acid moieties of these compounds (Ackerman et al. 1980, Bentley et al. 1980, Bull et al. 1980, Greuter et al. 1980, Henrik et al. 1980, Matsuo et al. 1980). The delicate balance between structure and activity in pyrethroids is demonstrated by the fact that the 3-phenoxybenzyl ester, related to the knockdown agent Kadethrin, almost completely lacks knockdown activity (Elliott 1977).

Some understanding of the mode of action of pyrethroids has been achieved only recently. It is known that there are common features in the mode(s) of action of pyrethroids in mammals and insects. Several reviews (Aldridge 1980, Beeman 1982, Gammon 1980a, Narahashi 1971b, 1976, 1979, 1980, Narashashi et al. 1977) have covered the subject extensively.

The synthetic pyrethroids are directly toxic to nerves. The major sites of pyrethroid action are the sodium gates on the nerve axon (Vijverberg et al. 1982). The pyrethroid molecules wedge into the conducting Na^+ channels, such that Na^+ conductance is unimpeded, but the channels cannot return to their nonconducting, "closed-gate" configuration (Holan 1971) thus opposing membrane repolarization. A second mode

of action involves certain Ca-dependent ATPases which have been found to be inhibited by pyrethroids (Clark and Matsumura 1982). Such an effect in vivo might lead to calcium pump dysfunction or to a decalcification of the external surface of the axon, which in turn might disrupt the normal regulation of the conductance gating of monovalent cations (Beeman 1982). High concentrations of external Ca^{2+} are well known to antagonize pyrethroid-induced excitation of the nerve (Gammon 1980a, Gordon and Welsh 1948).

Synthetic pyrethroids have a greater effect on peripheral nerves than on the central nervous system (Gammon 1980b) particularly the sensory cell bodies (Clements and May 1977) and motor nerve terminals. There is evidence for some CNS activity, however. Adams and Miller (1980) found that pyrethroids uncouple the house fly flight motor by a central action. Burt and Goodchild (1974) found rapid knockdown to be related to CNS action. Clements and May (1977), however, observed that in most cases knockdown by the pyrethroids was accompanied by hyperexcitation of sensory nerves. The pyrethroids acting most rapidly in the mammalian brain are those with the highest knockdown activity for insects (Lawrence and Casida 1982).

The differences between pyrethroid neurophysiological effects depend on the presence or absence of an α -cyano

group (Gammon and Holden 1979, Narahashi 1980). Indeed, these separations can be made on the basis of biochemical, electrophysiological, and symptomological responses. Thus the pyrethroids can be identified as either Type I or Type II compounds based mainly on the work by Gammon et al. (1981).

Type I compounds lack an α -cyano group and can be represented by permethrin. In insects, poisoning by these compounds causes repetitive firing in the sensory nerves (Gammon et al. 1981). Symptoms of poisoning include restlessness, incoordination, hyperactivity, prostration, and paralysis. For a more detailed description of symptoms see Gammon (1978a,b). Rats poisoned with these compounds display tremors and convulsions of the so-called T-syndrome which is also associated with the peripheral nervous system (Lawrence and Casida 1982).

Type II compounds have an α -cyano group and are represented by compounds such as cypermethrin and fenvalerate. Insects poisoned with these compounds show no repetitive firing but rather bursts of spikes from motor nerves. The symptomology also varies somewhat in that a pronounced convulsive phase, sometimes accompanied by salivation, is evident. Similar symptoms are seen in rats and mice poisoned by these compounds. The symptomology is labeled the CS-syndrome and includes choreoathetosis (a

writhing type of toxicity), convulsions, and salivation (Lawrence and Casida 1982). In rats and mice, however, the target site is believed to be the CNS.

A novel symptom of pyrethroid-poisoning in insects was reported by Bodnaryk (1982) for moths of the bertha army-worm, Mamestra configurata Wlk. He found that moths treated with either class of pyrethroids often had grossly bloated abdomens several hours after treatment. The bloating, seen more frequently in females than in males, was attributed to gas in a greatly expanded abdominal air sac. This gas, apparently air with the oxygen content partially depleted by respiration, was hypothesized to have accumulated from a disordering of the ventilation system enhanced by thoracic pumping caused by pyrethroid-induced movements.

Another aspect of pyrethroid poisoning is the negative temperature coefficient displayed by these compounds. This increased toxicity and irritancy with decreasing temperatures was documented by Blum and Kearns (1956), DeVries and Georghiou (1979), Fullbrook and Holden (1980), Gammon (1978a,b), Harris and Kinoshita (1979), Harris et al. (1978), Hirano (1979), Miller et al. (1979), Narahashi (1971a), Scott and Matsumura (1983), Sparks et al. (1982, 1983), Tan (1982), and Wang et al. (1972).

Synergism and Resistance

When combined action of two compounds administered at the same time is adjuvantive the effect is known as synergism. The term synergism as applied to pyrethroids has a slightly different connotation as it applies to potentiating effect obtained from a mixture of pyrethroids with supposedly relatively nontoxic substances.

The mode of action of synergists is not yet adequately understood but may involve suppression of oxidases and esterases in pyrethroid detoxification. Synergism by means of enzyme inhibition has been shown by marked increases in toxicity of pyrethroids when these enzymes are inhibited with organophosphate compounds, alkylcarbamates, and methylenedioxyphenyl derivatives (Abernathy et al. 1973, Casida 1973, Jao and Casida 1974a,b, Miyamoto 1976, Ruzo et al. 1979). Other mechanisms have also been suggested for synergists such as the possibility that the small residual factor of synergism shown by even the most potent pyrethroids may be explained by physical effects of the large dose of lipophilic synergist on penetration rather than by suppressing detoxification (Burt et al. 1977).

According to Elliott and Janes (1978) most commercial formulations of natural pyrethrins include a synergist (usually piperonyl butoxide in the ratio of 8:1 or 10:1, synergist:insecticide). Potency is thereby increased up to

10 fold, despite inactivity of the additive alone. In such preparations, natural compounds, though expensive, compete with less well synergized synthetic alternatives. While it is tempting to add esterase and oxidase inhibitors to pyrethroids to increase their insecticidal potency and cost efficiency, concomitant alterations in mammalian toxicity may shift compounds otherwise considered safe into a hazardous category (Casida and Ruzo 1980).

Resistance and tolerance to synthetic pyrethroids has been demonstrated for several arthropod species. Among these are Wiseana cervinata larvae (Chang and Jordan, 1982), Culex quinquefasciatus (Priester and Georghiou 1980), Spodoptera littoralis (Holden 1979), Heliothis virescens and H. zea (Bigley and Plapp 1978), Chrysopa carnea Stephens (Ishaaya and Casida 1981), Tribolium castaneum (Herbst) (Lloyd and Ruczkowski 1980), Amblyseius fallacis Garman (Strickler and Croft 1982), Metaseiulus occidentalis (Nesbitt) (Hoy et al. 1980), Musca domestica L. (Harris et al. 1982), Myzus persicae (Devonshire and Moores 1982), and Boophilus microplus (Can.) (Schnitzerling et al. 1983). As recently as 1976 (Georghiou 1976) only 6 of 364 arthropod species, in which resistance of any sort had been reported, were resistant to pyrethroids. The upsurge in resistance since that time is probably due to the widespread increase in both use and commercial development of these compounds.

Resistance to pyrethroids has appeared mainly in areas where natural and synthetic pyrethroids have been used intensively, especially to control insects resistant to most commonly used insecticides (Farnham 1971, 1973, Farnham and Sawicki 1976, Keiding 1976, Priester and Georghiou 1980).

In response to this, cross-resistance between organochlorine, carbamate, organophosphorous, and pyrethroid-like insecticides has definitely been established (Harris et al. 1982, Lloyd and Ruczkowski 1980, MacDonald et al. 1983, Schnitzerling et al. 1983, Scott et al. 1983).

Tolerance and resistance could be due to one or more of the following mechanisms: high esterase(s) activity; high mixed-function oxidase (MFO) activity; low cuticular penetration; excretion; and low nerve target sensitivity (DeVries and Georghiou 1981a,b, Gammon 1980b, Ishaaya and Casida 1981). Of these, metabolic activity (Bashir and Crowder 1983, Bigley and Plapp 1978, Chang and Jordon 1982, Devonshire and Moores 1982, Ishaaya and Casida 1981, Lloyd and Ruczkowski 1980, Riskallah 1983, Schnitzerling et al. 1983) and nervous mechanisms, such as knockdown resistance (kdr) (Farnham 1977, Priester and Georghiou 1980, Scott et al. 1983), appear to be the major mechanisms. In view of this, Brown (1981), Georghiou (1980), and MacDonald et al. (1983) suggest three practices to reduce selective pressure in order to postpone the development of resistance:

alternate insecticides; use mixtures of insecticides; and use synergists.

CHAPTER III

OVICIDAL ACTIVITY

Introduction

Traditionally insecticides have been selected for their effects upon the larvae and adults of target species. It is only within the last 20 years that progress of any significance has been made in the study of ovicidal activity of the various classes of insecticides.

The earliest known ovicides were the petroleum oils and dinitrophenol compounds (Barber 1944, Smith and Salkeld 1966). Since that time literature reviews and research (Chalfant et al. 1973, Dittrich 1967, Hartman 1973, Mitri and Kamel 1970, Mohammed and Roohi 1970, Phillips 1971, Swenson et al. 1969) indicated that many larvicides and adulticides are also ovicidal. Synthetic pyrethroids have been reported to show promise as ovicidal compounds (Chalfant et al. 1979, Pitts and Pieters 1980, Tysowsky and Gallo 1977).

The purpose of this study was to evaluate ovicidal activity of 9 synthetic pyrethroids to a laboratory strain of fall armyworm (FAW), Spodoptera frugiperda (J. E. Smith).

Materials and Methods

Egg masses collected from laboratory reared adults were clipped from paper toweling on which they were deposited.

All egg masses were surface sterilized with sodium hypochlorite.

Towel sections containing egg masses were dipped in acetone solutions of the insecticides for 5 sec, then allowed to air dry. Acetone treated eggs served as a control. After dipping, eggs were placed onto water moistened filter paper in 5 cm dia Petri dishes to maintain humidity at 100%. The eggs were maintained in environmental chambers at 30°C ($\pm 2^\circ\text{C}$) and 14 h/24 h photoperiod.

Eggs which hatched were counted daily for 7 days, well beyond the normal hatch period. Living larvae were removed daily. Larvae that were dead (no response to probing) were counted as not hatched. After establishing a toxic range, 5 concentrations of each insecticide were evaluated using three replicates of 75-100 eggs each. After correcting with Abbott's (1925) formula (see Appendix), LC_{50} , LC_{90} , confidence limits, and slope of each dosage-mortality line were calculated according to Finney (1964) (see Appendix). A toxicity index (Sun 1950) (see Appendix) was used to compare the relative toxicities of the pyrethroids to diazinon, an organophosphate.

The pyrethroids used were permethrin and cypermethrin (ICI Americas, Inc.), permethrin, cypermethrin, Pounce®, and Ammo® (FMC Agricultural Chemical Group), Pydrin® (Shell Development Co.), Mavrik® (Zoecon Corp.), and Pay-Off®

(American Cyanamid Co.) (Table 1; Figures 1-5). The permethrins and cypermethrins tested varied in their isomeric ratios.

Results and Discussion

There was considerable variation in the response of the eggs to the compounds (Table 2). The LC_{50} value of Pay-Off®, the most toxic pyrethroid, was 38 times less than that of Pydrin®, the least toxic. All the pyrethroids were 3 to 94 times more toxic than diazinon.

Eggs treated with pyrethroids often reached the "blackhead" stage; however, larvae frequently died during or shortly after hatching. This characteristic response to pyrethroids was noted in the cabbage looper by Chalfant et al. (1979) and in the Colorado potato beetle by Ruscoe (1977). Smith and Salkeld (1966) suggested that embryos under chemical stress often reach maturity and die before eclosion. In addition, some toxins are absorbed by the epembryonic membranes and released to exert their toxic effect upon the embryo when the membranes are broken down prior to eclosion. A toxic dose, therefore, was probably acquired either by contact or ingestion during or immediately preceding eclosion.

The female FAW usually lays her eggs in globose masses on the undersides of foliage. In addition, the masses are

Table 1. Names, manufacturers, toxicity classifications, and chemical structures of pyrethroids used.

Compound used	Manufacturer	Common name	Trade name	Chemical name	Type ¹	Structure
cypermethrin (ICI)	ICI Americas, Inc.			(±)-cyano-3-phenoxy- benzyl (±) cis, trans-3- (2,2-dichlorovinyl)-	II	Fig. 1
cypermethrin (FMC)	FMC Agricultural Chemical Group	cypermethrin		2,2-dimethyl cyclo- propane carboxylate		
Ammo®	FMC Agricultural Chemical Group		Ammo®			
Pydrin®	Shell Development Co.	fenvalerate	Pydrin®	(±)-cyano(3-phenoxy- phenyl)methyl 4-chloro- α-(1-methylethyl) benzeneacetate	II	Fig. 2
Mavrik®	Zoecon Corp.	fluvalinate	Mavrik®	N-[2-chloro-4-(trifluoro- methyl)phenyl]-D-valine(±)- α-cyano-(3-phenoxyphenyl) methyl ester	II	Fig. 3
Pay-Off®	American Cyanamid Co.	flucythrinate	Pay-Off®	(±)-cyano(3-phenoxyphenyl) methyl (+)-4-(difluoromethoxy)- α-(1-methylethyl) benzeneacetate	II	Fig. 4
permethrin (ICI)	ICI Americas, Inc.			3-(phenoxyphenyl)methyl		
permethrin (FMC)	FMC Agricultural Chemical Group	permethrin		(±)-cis, trans-3-(2,2- dichloroethenyl)-2,2- dimethyl cyclopropane carboxylate	I	Fig. 5
Pounce®	FMC Agricultural Chemical Group		Pounce®			

¹Type I = pyrethroids lacking a cyano group (cause repetitive firing in insect sensory nerves)Type II = pyrethroids containing a cyano group (cause bursts of spikes from insect motor nerves)
(Gammon et al. 1981)

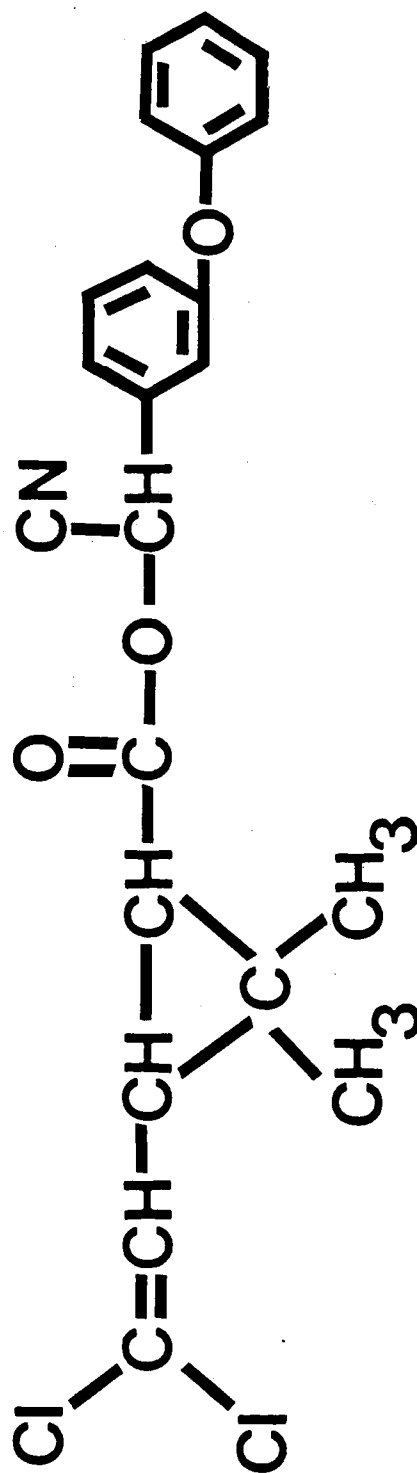


Figure 1. Chemical structure of cypermethrin.

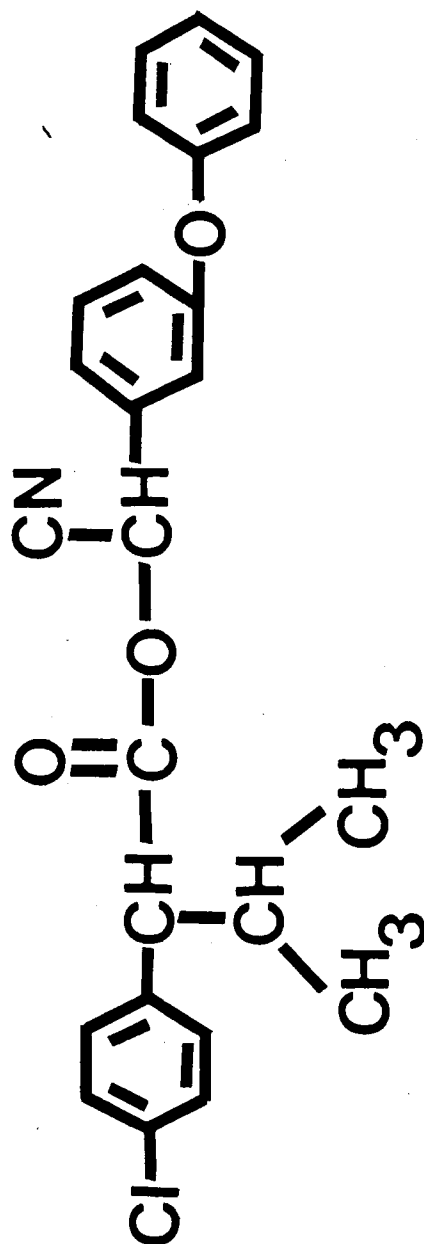


Figure 2. Chemical structure of fenvalerate.

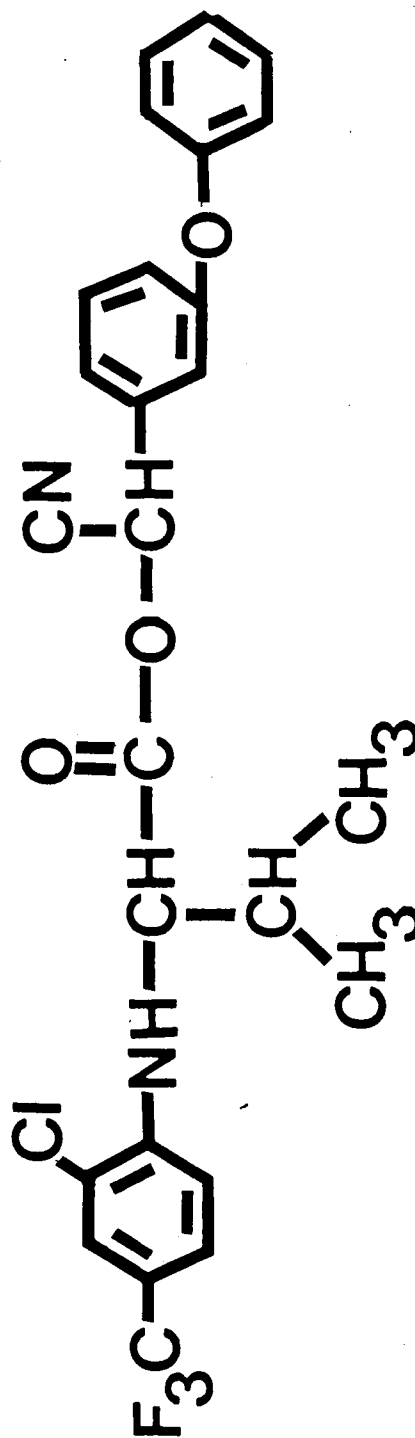


Figure 3. Chemical structure of fluvalinate.

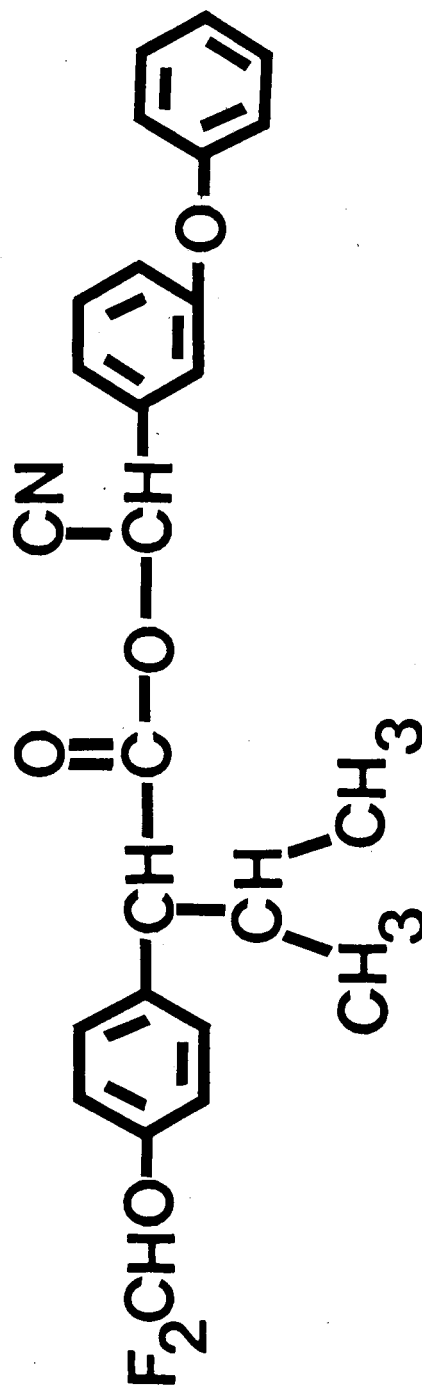


Figure 4. Chemical structure of flucythrinate.

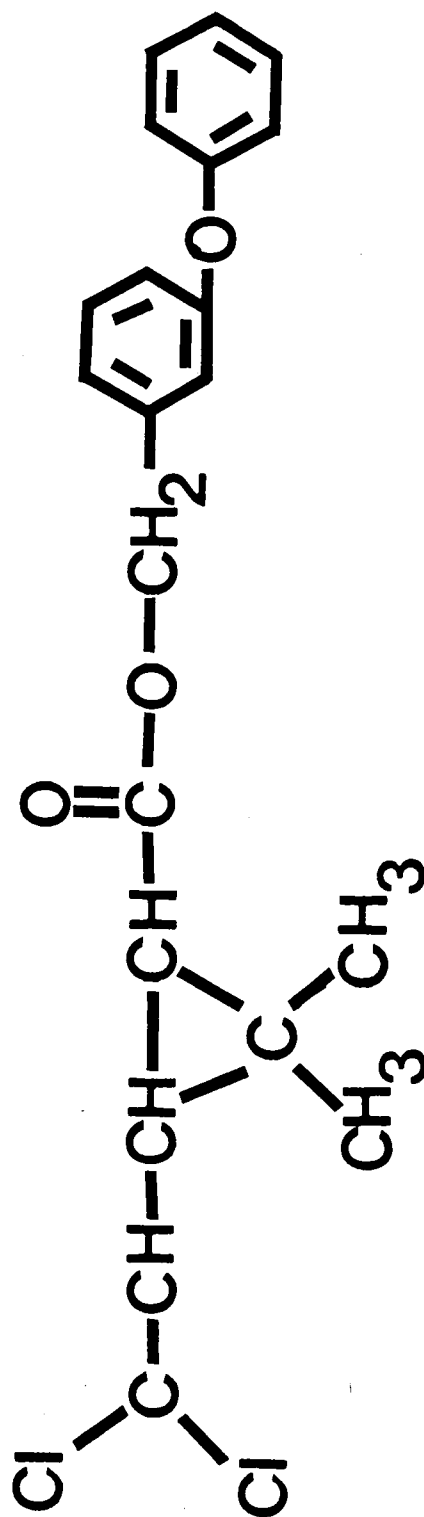


Figure 5. Chemical structure of permethrin.

Table 2. Effect of nine synthetic pyrethroids and diazinon as ovicides to Spodoptera frugiperda seven days after treatment.

Chemical	LC ₅₀ ¹	LC ₅₀ 95% conf. limits ¹	LC ₉₀ ¹	Slope ²	Toxicity Index
Pay-Off®	0.320	0.270- 1.622	1.937	1.39	9412
Mavrik®	1.164	1.116- 2.090	6.719	0.86	2588
permethrin (FMC)	1.378	0.938- 1.410	3.808	1.22	2186
permethrin (ICI)	1.527	1.522- 1.531	3.931	1.22	1972
cypermethrin (FMC)	1.557	0.791- 2.997	4.511	1.13	1934
cypermethrin (ICI)	2.006	2.004- 2.010	4.067	1.29	1501
Pounce®	4.000	2.866- 5.033	39.470	1.05	752
Ammo®	7.375	6.752- 9.823	23.019	2.56	408
Pydrin®	12.230	6.251-17.870	43.075	1.11	246
diazinon	30.118	21.038-44.078	124.235	0.78	100

¹ppm

²Regressions significant at $P \leq 0.05$.

usually densely covered with wing scales from the female. Effective ovicidal treatment with the pyrethroids could consist of a directed up-and-under spray application of ultra-low dosages. Since the fall armyworm migrates northward each year from overwintering sites in the tropical regions, knowledge of annual arrival date combined with diligent monitoring should allow accurate timing of applications to be made.

CHAPTER IV

OVIPOSITIONAL REPELLENT PROPERTIES

Introduction

Synthetic pyrethroids are effective larvicides and ovicides of the fall armyworm (FAW), Spodoptera frugiperda (J. E. Smith) (Hall 1979, Plapp 1981, Rajakulendran and Plapp 1982, Tysowsky and Gallo 1977). Repellency is another potentially valuable characteristic of the pyrethroids, as noted by many investigators (Barlow et al. 1977, Blackman and Hodson 1977, Burden 1975, Carter and Chadwick 1978, Ebert 1976, Elliott et al. 1978, Matter et al. 1976, Schmidt et al. 1976 Shemanchuk 1981). Ruscoe (1977) found that the Egyptian cotton leafworm, Spodoptera littoralis Boisd., preferred to oviposit on untreated rather than permethrin-treated foliage. He suggested that a repellent effect can complement a lethal effect by inhibition of oviposition.

The purpose of this study was to evaluate the ovipositional repellency of 9 synthetic pyrethroids using a laboratory strain of FAW.

Materials and Methods

Single pairs of laboratory reared pupae were placed in 450 ml waxed cups where they emerged 10-14 days later.

Pupae and adults were maintained in environmental chambers at 30°C ($\pm 2^\circ\text{C}$) 14 h/24 h photoperiod, and 60-70% RH. A piece of cotton saturated with an ascorbic acid-beer (1.5 g/828 ml) solution was placed into each cup for adult diet. Graduated pipetts were used to apply 2 ml quantities of specified concentrations of acetone-insecticide solutions to Schleicher and Schuell analytical filter paper discs no. 597, 15 cm dia. Each disc was allowed to air dry and was cut into halves. Ovipositional substrate discs were made by taping one acetone-treated (control) half to one insecticide-treated half. Those discs were placed over the open ends of the waxed cups and held in place with the cup lids. Five replicates of each treatment were used.

Number of eggs deposited on each half of the discs was counted. New discs, treated at the same time as the original, were supplied to each cup on alternate days for 7 days. Because males frequently died soon after mating, dead males were replaced with live males from the stock culture to encourage multiple matings.

Insecticides used included permethrin (ICI Americas, Inc. and FMC Agricultural Chemical Group), cypermethrin (ICI Americas, Inc. and FMC Agricultural Chemical Group), Pounce® and Ammo® (FMC Agricultural Chemical Group), Mavrik® (Zoecon Corp.), Pay-Off® (American Cyanamid Co.), and Pydrin® (Shell Development Co.) (Table 1, page 35) in pesticide

grade acetone. Solutions used were ovicidal and one-tenth ovicidal concentrations, determined by previous work (Gist and Pless 1983a). Control percentages were calculated by Abbott's (1925) formula (see Appendix). Significant difference among means was determined by the Student-Newman-Keuls (SNK) test (see Appendix) at the 5% probability level.

Results and Discussion

All compounds were significantly repellent at ovicidal concentrations (Table 3). Cypermethrin (FMC) was the least effective repellent.

All of the pyrethroids at one-tenth ovicidal concentration were repellent (Table 4). Ammo® and cypermethrin (FMC) were less repellent than all the other compounds.

According to Ruscoe (1977) inhibition of oviposition by synthetic pyrethroids does not appear to be a significant factor with lepidopterans in the field, except at high rates of application. Rates that were larvicidal to Heliothis zea Boddie did not inhibit its oviposition. Moore (1980) found in both field and laboratory tests that oviposition by the boll weevil, Anthonomus grandis grandis Boheman, decreased on cotton and artificial diet treated with 0.01-1.0 ppm of NRDC-161 (cypermethrin).

Table 3. Effect of nine synthetic pyrethroids at ovicidal concentrations as repellents of oviposition by Spodoptera frugiperda seven days after treatment.

Compound	ppm	Mean No. eggs ($\pm$ SE) ¹		% control ^{2,3}
		treated	untreated	
Pounce®	20.0	19.17 ($\pm$ 4.07)	506.83 ($\pm$ 23.98)	96.22 a
Pay-Off®	1.0	13.21 ($\pm$ 3.06)	151.51 ($\pm$ 15.97)	91.28 ab
permethrin (ICI)	2.0	28.33 ($\pm$ 6.34)	276.83 ($\pm$ 31.25)	89.77 ab
permethrin (FMC)	2.0	55.67 ($\pm$ 12.45)	389.00 ($\pm$ 33.70)	85.69 ab
Ammo®	20.0	129.83 ($\pm$ 14.79)	811.67 ($\pm$ 43.79)	84.00 ab
cypermethrin (ICI)	3.0	110.00 ($\pm$ 21.27)	659.00 ($\pm$ 39.47)	83.31 ab
Mavrik®	5.0	134.00 ($\pm$ 12.28)	771.67 ($\pm$ 73.73)	82.60 ab
Pydrin®	30.0	185.67 ($\pm$ 6.09)	790.50 ($\pm$ 45.85)	76.51 b
cypermethrin (FMC)	20.0	144.50 ($\pm$ 21.82)	287.33 ($\pm$ 23.98)	49.71 c

¹Numbers are the means of 5 replicates.

²Control percentages were calculated by Abbott's formula.

³Numbers followed by same letters are not significantly different using SNK test (P = 0.05) of arcsine transformations.

Table 4. Effect of nine synthetic pyrethroids at one-tenth ovicidal concentrations as repellents of oviposition by Spodoptera frugiperda seven days after treatment.

Compound	ppm	Mean No. eggs ($\pm$ SE) ¹		% control ^{2,3}
		treated	untreated	
Pounce®	2.0	17.33 ($\pm$ 2.80)	172.00 ($\pm$ 16.86)	89.92 a
permethrin (ICI)	0.2	50.50 ($\pm$ 9.39)	377.50 ($\pm$ 32.36)	86.62 a
permethrin (FMC)	0.2	45.17 ($\pm$ 5.64)	272.00 ($\pm$ 26.70)	83.39 a
cypermethrin (ICI)	0.3	94.83 ($\pm$ 19.10)	478.83 ($\pm$ 30.09)	80.20 a
Pay-Off®	0.1	229.32 ($\pm$ 9.50)	1050.33 ($\pm$ 26.24)	78.17 a
Mavrik®	0.5	200.50 ($\pm$ 39.50)	916.00 ($\pm$ 32.38)	78.11 a
Pydrin®	3.0	121.00 ($\pm$ 31.00)	485.40 ($\pm$ 35.94)	75.07 a
Ammo®	2.0	141.67 ($\pm$ 17.53)	255.00 ($\pm$ 17.88)	44.44 b
cypermethrin (FMC)	2.0	127.50 ($\pm$ 19.60)	185.67 ($\pm$ 9.16)	31.94 b

¹Numbers are the means of 5 replicates.

²Control percentages were calculated by Abbott's formula.

³Numbers followed by same letters are not significantly different using SNK test (P = 0.05) of arcsine transformations.

Oviposition of FAW in the laboratory was significantly decreased at concentrations that were not only ovicidal but also as low as 0.5% of the ovicidal dosage. Differences in results of field and laboratory tests can partially be explained by the fact that in the laboratory many of the factors that affect oviposition, such as nutrition, mating, and female longevity, are controlled.

In field corn FAW eggs are deposited primarily on the undersides of foliage. Control might be possible by directing spray applications of synthetic pyrethroids onto those ovipositional sites at concentrations in the range of 15-20 ppm. It is possible this would not only help deter oviposition but also destroy eggs already present.

CHAPTER V

FEEDING DETERRENT PROPERTIES

Introduction

An insect feeding deterrent is a chemical which, after initial gustatory contact, prevents further biting by the insect (Chapman 1974). Chemical feeding deterrents which reduce feeding damage to individual plants without necessarily reducing absolute pest numbers, may have potential as an unconventional approach to pest control (Munakata 1970, Pedigo 1975).

The synthetic pyrethroids have shown distinctive insect repellent effects. Tan (1981) reported that permethrin and cypermethrin were feeding deterrents for Pieris brassicae larvae, and they exhibited an irritant response with repeated regurgitation. Ruscoe (1977) found permethrin to be a feeding deterrent for Plutella xylostella (Linnaeus) larvae; at sublethal doses they actively avoided treated surfaces. Hall (1979) observed behavioral changes, most notably reduced feeding and avoidance reactions, in Conotrachelus nenuphar (Herbst) and Tetranychus urticae Koch in response to pyrethroid treatment. Ruscoe (1977) noted that crop damage attributed to Trichoplusia ni (Hubner) and Anthonomus grandis grandis Boheman in pyrethroid-treated fields was lower than

could be accounted for by the LD₅₀ value. He hypothesized the reduction to be due to the feeding repellent properties of the pyrethroids.

The purpose of this study was to evaluate in the laboratory the effects of 9 synthetic pyrethroids on the feeding behavior of larvae of the fall armyworm (FAW), Spodoptera frugiperda (J. E. Smith).

Materials and Methods

No-Choice Tests

These feeding behavior tests were modified from Wada and Munakata (1968). One cm² leaf "bits" were clipped from corn leaves (Zea maise) ca 8-10 weeks old. One-tenth ml of an acetone solution of each insecticide was applied to each leaf bit and allowed to air dry. Acetone was used as a control.

Five treated leaf bits were placed at random in 15 cm diam petri dishes with 5 laboratory-reared 3rd instar larvae that had been deprived of food (corn leaves) for the 2 previous hours. Dishes containing larvae and leaf bits were placed in darkened environmental chambers at 27°C (±2°C) and 60-70% RH. After 2h leaf area consumed was measured according to Dethier's (1947) method. The concentrations tested were 50 ppm and 5 ppm, with 5 replications at each concentration.

Two-Choice Tests

These differential feeding behavior tests were modified from Young and McMillan (1979). Petri dishes, 15 cm diam, were divided into quadrants which were labeled alphabetically clockwise. Two leaf bits each, treated in the manner described above, were placed in quadrants A and C. Two acetone-treated leaf bits each were placed in quadrants B and D. One laboratory-reared 3rd instar larva was placed in the center of the dish. Dishes containing the leaf bits and larvae were placed in darkened environmental chambers under the conditions described above. After 24h leaf area consumed was measured according to Dethier's (1947) method. The concentrations tested were 50 ppm and 5 ppm, with five replications at each concentration. Significant difference among means (in both experiments) was determined by the SNK test (see Appendix) at the 5% probability level.

Insecticides used in both experiments were permethrin and cypermethrin (ICI Americas, Inc.), permethrin, cypermethrin, Pounce®, and Ammo® (FMC Agricultural Chemical Group), Mavrik® (Zoecon Corp.), Pydrin® (Shell Development Co.), and Pay-Off® (American Cyanamid Co.) (Table 1, page 35).

Results

No-Choice Test

At 50 ppm all pyrethroids were effective feeding deterrents (Table 5). Reduction of leaf area consumed ranged from 92.5% (Pydrin®) to 55% (Pounce®).

At 5 ppm (Table 6), the feeding ratios increased 2 to 6 fold over those at 50 ppm, indicating a reduction in the protection by the pyrethroids when used at lower concentrations. Reduction of leaf area consumed ranged from 82.5% [permethrin (FMC)] to 7.2% (Pounce®). Pounce® was not an effective feeding deterrent at this concentration.

Two-Choice Tests

At 50 ppm all of the pyrethroids were effective feeding deterrents (Table 7). Reduction of leaf area consumed ranged from 97.7% [cypermethrin (ICI)] to 83.9% (Ammo®).

At 5 ppm (Table 8), the feeding ratios again were higher than at 50 ppm although the differences (averaging ca 2 fold) were not as great as those in the no-choice tests. Reduction of leaf area consumed ranged from 93.9% [cypermethrin (FMC)] to 55.0% (Pounce®).

Discussion

Chapman (1974) stated that effective feeding deterrents should have 3 main properties: (1) they should be persistent,

Table 5. Feeding deterrence of nine synthetic pyrethroids at 50 ppm in no-choice tests on 3rd instar Spodoptera frugiperda.

Compound	Area consumed ¹ (+SE)	Feeding Ratio ^{2, 3}
Pydrin®	4.0 (±1.6)	0.075 a
cypermethrin (ICI)	4.3 (±0.5)	0.081 a
Mavrik®	4.5 (±1.1)	0.084 a
permethrin (FMC)	8.2 (±1.7)	0.153 a
cypermethrin (FMC)	8.8 (±1.9)	0.166 a
permethrin (ICI)	10.0 (±0.7)	0.188 a
Pay-Off®	11.3 (±1.6)	0.213 a
Ammo®	14.7 (±1.9)	0.275 a
Pounce®	24.0 (±7.6)	0.450 b
control	53.3 (±2.5)	1.000 c

¹Means of 5 replicates expressed as mm².

²Treated area consumed (mm²)/control area consumed (mm²).

³Numbers followed by a common letter are not significantly different according to the SNK test (P = 0.05).

Table 6. Feeding deterrence of nine synthetic pyrethroids at 5 ppm in no-choice tests on 3rd instar Spodoptera frugiperda.

Compound	Area consumed ¹ ($\pm$ SE)	Feeding Ratio ^{2,3}
permethrin (FMC)	9.3 ($\pm$ 2.5)	0.175 a
cypermethrin (ICI)	10.5 ($\pm$ 0.4)	0.197 a
Pay-Off®	13.0 ($\pm$ 1.5)	0.244 ab
Pydrin®	14.3 ($\pm$ 2.4)	0.269 ab
Ammo®	16.3 ($\pm$ 2.5)	0.306 ab
permethrin (ICI)	20.8 ($\pm$ 1.0)	0.391 bc
cypermethrin (FMC)	21.8 ($\pm$ 1.4)	0.410 c
Mavrik®	27.7 ($\pm$ 2.2)	0.519 c
Pounce®	49.5 ($\pm$ 8.6)	0.928 d
control	53.3 ($\pm$ 2.5)	1.000 d

¹Means of 5 replicates expressed as mm².

²Treated area consumed (mm²)/control area consumed (mm²).

³Numbers followed by a common letter are not significantly different according to the SNK test (P = 0.05).

Table 7. Feeding deterrence of nine synthetic pyrethroids at 50 ppm in 2-choice tests on 3rd instar Spodoptera frugiperda.

Compound	Area consumed ¹ ($\pm$ SE)		Feeding Ratio ^{2,3}
	treated	control	
cypermethrin (ICI)	1.0 ($\pm$ 0.5)	42.9 ($\pm$ 5.9)	0.023 a
Pydrin®	0.6 ($\pm$ 0.3)	25.5 ($\pm$ 6.4)	0.024 a
cypermethrin (FMC)	1.0 ($\pm$ 0.4)	38.2 ($\pm$ 3.0)	0.026 a
permethrin (FMC)	0.7 ($\pm$ 0.2)	19.7 ($\pm$ 6.3)	0.035 a
Pay-Off®	4.7 ($\pm$ 2.8)	77.8 ($\pm$ 21.7)	0.060 a
Mavrik®	1.7 ($\pm$ 0.4)	22.2 ($\pm$ 7.3)	0.077 a
Pounce®	4.6 ($\pm$ 2.1)	58.6 ($\pm$ 20.2)	0.078 a
permethrin (ICI)	1.1 ($\pm$ 0.2)	9.3 ($\pm$ 4.1)	0.118 a
Ammo®	5.6 ($\pm$ 3.2)	34.8 ($\pm$ 10.5)	0.161 a
control	—	74.5 ($\pm$ 17.5)	1.000 b

¹Means of 5 replicates expressed as mm².

²Treated area consumed (mm²)/control area consumed (mm²).

³Numbers followed by a common letter are not significantly different according to the SNK test (P = 0.05).

Table 8. Feeding deterrence of nine synthetic pyrethroids at 5 ppm in 2-choice tests on 3rd instar Spodoptera frugiperda.

Compound	Area consumed ¹ ($\pm$ SE)		Feeding Ratio ^{2,3}
	treated	control	
cypermethrin (FMC)	1.7 ($\pm$ 1.3)	27.7 ($\pm$ 10.9)	0.061 a
cypermethrin (ICI)	1.9 ($\pm$ 1.4)	25.1 ($\pm$ 3.4)	0.076 a
Ammo®	12.2 ($\pm$ 7.8)	142.0 ($\pm$ 16.5)	0.086 a
Pay-Off®	8.5 ($\pm$ 3.2)	93.6 ($\pm$ 15.2)	0.091 a
Mavrik®	10.6 ($\pm$ 5.3)	75.3 ($\pm$ 30.0)	0.141 a
permethrin (ICI)	6.6 ($\pm$ 1.8)	46.3 ($\pm$ 22.2)	0.143 a
permethrin (FMC)	22.1 ($\pm$ 3.7)	130.4 ($\pm$ 29.6)	0.169 a
Pydrin®	4.3 ($\pm$ 1.4)	21.9 ($\pm$ 1.3)	0.196 a
Pounce®	44.4 ($\pm$ 15.9)	96.8 ($\pm$ 29.0)	0.450 b
control	—	74.5 ($\pm$ 17.5)	1.000 c

¹Means of 5 replicates expressed as mm².

²Treated area consumed (mm²)/control area consumed (mm²).

³Numbers followed by a common letter are not significantly different according to the SNK test (P = 0.05).

(2) they should have no harmful effects on nontarget organisms, and (3) they should be translocated to untreated parts of the plant. The greater photostability of the synthetic pyrethroids relative to the more commonly used classes of insecticides is well documented (Breese 1977, Burt et al. 1977, Elliott et al. 1978). The pyrethroids have also been shown to have low toxicity to many parasites and predators (Coats et al. 1979, Rajakulendran and Plapp 1982, Wilkinson et al. 1979). Due to their low polarity the pyrethroids are not plant systemics; however, because the pyrethroids are toxicants as well as feeding deterrents the need for systemic activity of the deterrent is reduced.

Feeding deterrents may provide indirect benefits. Irritant responses to pyrethroid exposure, probably due to the excitorepellent effect of the chemical on insect tarsi (Metcalf and Metcalf 1975), often caused the insect to drop from the plant, wander off the plant in a search for food, or starve (Lange 1962, Wright 1967). This may explain the variation in amount of control leaf area consumed in the 2-choice tests since a strong irritant response to crawling over the pyrethroids would result in a disturbance of feeding.

In this study the synthetic pyrethroids were effective feeding deterrents for FAW at rates comparable to their LD₅₀ values (Chapter VI). Feeding deterrent concentrations were also ovicidal (Gist and Pless 1983a) as well as effective

ovipositional repellents (Gist and Pless 1983b). This combination of toxic and repellent effects, along with greater field stability, reduced toxicities to predators and parasites, and lower environmental health hazards makes the pyrethroids possible insecticide choices for many pest management programs.

CHAPTER VI

COMPARATIVE TOXICITIES

Introduction

The synthetic pyrethroids have been cited for their potential as agricultural pest control agents (Breese 1977, Elliott et al. 1978, Hall 1979, Harris and Svec 1976, Schmidt et al. 1976). High toxicity levels for pyrethroids have been reported for the tobacco budworm and boll weevil (Davis et al. 1975, 1977, Harding et al. 1977, Plapp 1981, Wolfenbarger et al. 1977), the Colorado potato beetle (McDonald 1976), the Egyptian cotton leafworm (Ford et al. 1977), common field cricket nymphs, onion maggot adults, darksided-cutworms, and northern corn rootworm adults (Harris and Turnbull 1978), plum cucurlio, codling moth, and redbanded leaf roller (Hall 1979), army cutworm (McDonald 1979), and others.

The fall armyworm (FAW), Spodoptera frugiperda (J. E. Smith) is one of the most important insect pests in the United States, based on recent damage estimates (Fuxa 1982, Mitchell 1979). Reported degree of control of FAW with the synthetic pyrethroids has varied. Bass (1978) reported poor control in peanuts with Ambush® and Pydrin® and unacceptable control on grain sorghum from Pounce®,

Pydrin®, and FMC 45498. Wood et al. (1981) found permethrin to be more toxic than methyl parathion, trichlorfon, or carbaryl to FAW larvae reared on various diets.

The purpose of this study was to evaluate contact toxicities of 9 synthetic pyrethroids to a laboratory strain of FAW.

Materials and Methods

Larvae used in contact toxicity tests were from a laboratory-reared colony established in February 1982 with pupae obtained from the Southern Grain Insects Research Laboratory in Tifton, GA. The insects were reared on artificial diet (Bio-Serv Corn Earworm Rearing Media, Bio-Mix #9394) according to a procedure modified from Perkins (1979).

Insecticide application was made by applying 1 μ l of insecticide-acetone (wt/vol) solutions to the dorsal thoracic region of 3rd or 6th instars with a syringe microburet. Larvae were placed into individual 5 cm diam petri dishes and allowed to feed freely on artificial diet. Larvae were maintained in environmental chambers at 27°C ($\pm 2^\circ$ C), 14:10 L:D, and 60-70% RH. Mortality, determined by failure to respond to probing, was recorded at 24h.

Preliminary dosages of insecticides were used to establish mortality ranges. Dosage-mortality regression

lines, obtained by probit analysis (Finney 1964) (see Appendix), provided LD_{50} values, confidence intervals, LD_{90} values, and slopes for each insecticide for 5-10 dose levels using a minimum of 30 larvae/dose. A toxicity index (Sun 1950) (see Appendix) was used to compare the toxicity of the synthetic pyrethroids with that of diazinon, an organophosphate, used as a standard.

Synthetic pyrethroids used in this study were technical formulations of permethrin and cypermethrin (ICI Americas, Inc.), permethrin, cypermethrin, Pounce®, and Ammo® (FMC Agricultural Chemical Group), Pydrin® (Shell Development Co.), Mavrik® (Zoecon Corp.) and Pay-Off® (American Cyanamid Co.) (Table 1, page 35).

Results and Discussion

The pyrethroids were 3 to 120 times more toxic than diazinon to 3rd instars (Table 9). The regressions for Pounce®, Pay-Off®, and Pydrin® were significant at $P = 0.20$; all others were significant at $P = 0.05$. LD_{50} values ranged from 0.1558 $\mu\text{g/insect}$ (Ammo®) to 0.0041 $\mu\text{g/insect}$ [permethrin (FMC)], representing a 38-fold decrease in concentration. Relatively flat regression lines for Pydrin®, cypermethrin (ICI), and Ammo® suggest heterogenous responses (Hoskins and Gordon 1956), indicating a possible tolerance to those insecticides by portions of the population.

Table 9. Comparative toxicities of nine synthetic pyrethroids to laboratory-reared 3rd instar Spodoptera frugiperda.

Compound	LD ₅₀		LD ₉₀		Slope ¹	Toxicity Index
	µg/insect	95% conf. lmts.	µg/insect			
permethrin (FMC)	0.0041	0.0036-0.0045	0.0102	3.82 *		11,968
permethrin (ICI)	0.0067	0.0062-0.0071	0.0110	5.67 *		7,324
Pounce®	0.0271	0.0178-0.0354	0.0590	3.10 **		1,811
cypermethrin (FMC)	0.0307	0.0104-0.0407	0.1053	2.73 *		1,598
Pay-Off®	0.0407	0.0275-0.0696	0.1215	2.70 **		1,207
Mavrik®	0.0487	0.0409-0.0507	0.0776	4.74 *		1,008
Pydrin®	0.1277	0.0712-0.1701	0.5808	1.95 **		384
cypermethrin (ICI)	0.1327	0.1301-0.2104	0.9445	1.69 *		370
Ammo®	0.1558	0.1390-0.2291	0.9339	1.71 *		315
diazinon	0.4907	0.4883-0.5158	1.0321	2.87 *		100

¹ *Regression significant at $P \leq 0.05$.

**Regression significant at $P \leq 0.20$.

The synthetic pyrethroids, with the exception of Ammo® were also effective contact insecticides to 6th instar FAW (Table 10). The regressions for cypermethrin (FMC), Pydrin®, and Mavrik® were significant at $P = 0.20$; all others were significant at $P = 0.05$. LD_{50} values ranged from 5.84 $\mu\text{g/insect}$ (Ammo®) to 0.213 $\mu\text{g/insect}$ [permethrin (FMC)], a 27-fold decrease in concentration. The pyrethroids, except Pounce® and Ammo® were from 2 1/2 to 18 times more toxic than diazinon to 6th instars. Pounce® had approximately the same toxicity as diazinon, and Ammo® was approximately 2/3 as toxic as diazinon. All pyrethroids had relatively steep regression lines indicating a homogenous response. This is a characteristic for insect populations that have not been exposed to any significant chemical selection pressure which allows a buildup of tolerance to the toxicant (Hoskins 1960).

Third instars were more susceptible to the pyrethroids than were 6th instars. Differences in susceptibility ranged from 5 $\times$ [cypermethrin (ICI)] to 128 $\times$ (Pounce®). Diazinon was ca. 8 $\times$ more toxic to 3rd instar than 6th instar.

Within 10 min after treatment with pyrethroids at any concentration larvae displayed classic symptoms of pyrethroid poisoning (Ford et al. 1977), including initial hyperactivity, fluid loss due to regurgitation and eversion of the rectum, loss of coordination, knockdown leading to paralysis, and

Table 10. Comparative toxicities of nine synthetic pyrethroids to laboratory-reared 6th instar Spodoptera frugiperda.

Compound	LD ₅₀		LD ₉₀		Toxicity Index
	µg/insect	95% conf. lmts.	µg/insect	Slope ¹	
permethrin (FMC)	0.213	0.200-0.372	0.561	2.49 *	1820
cypermethrin (FMC)	0.205	0.187-0.687	0.788	2.87 **	1550
Pay-Off®	0.306	0.190-0.385	0.978	2.78 *	1267
permethrin (ICI)	0.662	0.649-0.706	1.122	5.23 *	585
cypermethrin (ICI)	0.684	0.501-0.882	1.289	5.50 *	567
Pydrin®	0.813	0.524-1.214	1.574	5.26 **	477
Mavrik®	1.456	0.340-1.657	7.435	2.83 **	266
Pounce®	3.471	2.044-4.202	7.100	4.20 *	112
Ammo®	5.841	5.204-6.582	11.847	3.91 *	66
diazinon	3.876	3.477-4.000	10.980	4.63 *	100

¹ *Regression significant at $P \leq 0.05$.

**Regression significant at $P \leq 0.20$.

death. These reactions to poisoning may provide additional protection to plants by dislodging surviving insects and/or exposing them to increased predation. Water loss may also contribute to mortality, especially in hot summer weather.

McDonald (1979) found pyrethroids in general to be more toxic than organophosphates to the army cutworm. In this study the pyrethroids were found to be more toxic than diazinon to FAW larvae even though the modes of action of the two insecticide classes are thought to be similar. Synthetic pyrethroids are better contact poisons than oral poisons (McDonald 1976), possibly because of their feeding deterrent properties (Chapter V) which cause the insect to avoid ingesting the toxin.

The difference in toxicities of the pyrethroids in the laboratory vs the field can be partially explained by the absence of selective pressure in the laboratory population, demonstrated by the relatively steep dosage-mortality lines. Variation in toxicities to FAW may be explained on the basis of insect resistance (Farnham and Sawicki 1976), tolerance, cross resistance (Crowder et al. 1979, Twine and Reynolds 1980), and differences in the host crop (Wood et al. 1981). Because susceptibility of FAW to insecticides varies with the crop upon which they are feeding (Wood et al. 1981), additional field evaluations are needed to correlate efficacy in the field with that in the laboratory.

CHAPTER VII

SYNERGISTIC ACTIVITY

Introduction

Synergism can be defined as increased activity of an insecticide resulting from the effect of one chemical on another. The first synergist was introduced in 1940 to increase the effectiveness of the botanical insecticide, pyrethrum. Since that time it has been well established that synergists increase the effectiveness of pyrethroids by reducing their rate of metabolism in insects (Casida 1970, Jao and Casida 1974a,b, Yamamoto 1973).

Esterases and oxidases are the major pyrethroid detoxifying mechanisms in insects (Casida and Ruzo 1980, Ishaaya and Casida 1981) thus addition of esterase and/or oxidase inhibitors to pyrethroids could increase their insecticidal potency while decreasing the cost of the relatively expensive pyrethroids. Examples of esterase inhibitors that have been investigated include phenyl saligenin phosphotriethioate (DEF) (Georghiou and Pasteur 1978, Jao and Casida 1974a, Priester and Georghiou 1980, Riskallah 1983, Scott et al. 1983), organophosphates (Holden 1979, Jao and Casida 1974a, Schnitzerling et al. 1983), 1-naphthyl N-propylcarbamate (NPC) (Jao and Casida 1974a), and carbamates (Abdel-Aal and Soderlund 1980, DeVries and

Georghiou 1981b, Gaughan et al. 1980, Ishaaya and Casida 1980). Oxidase inhibitors investigated include piperonyl butoxide (PB) (Casida 1970, Chang and Jordan 1982, 1983, Jao and Casida 1974a, Lloyd and Ruczkowski 1980, MacDonald et al. 1983, Priester and Georghiou 1980, Yu 1983), 1-dodecylimidazole (Chang and Jordan 1983, Wilkinson et al. 1974), DEF (Attia et al. 1980), and O-(2-methylpropyl) O-(2-propynyl)phenylphosphonate (MPP) (Jao and Casida 1974a). General permethrin-hydrolyzing enzyme inhibitors include carbaryl (Chang and Jordan 1982, 1983), pirimiphos-methyl and tetrabromophenolphthalein (Chang and Jordan 1983). Other synergists include isomers of the pyrethroids themselves (Davis et al. 1977, Wickham 1976, Wolfenbarger et al. 1977), formamidines (Plapp 1979), methyl parathion and methomyl (All et al. 1977, Wolfenbarger et al. 1977), and chlorpyrifos (Wolfenbarger et al. 1977).

The optimal synergist varies with the insect species and pyrethroid (Jao and Casida 1974a) as well as the stage of the insect's development. It is well known that an insect's defense mechanisms vary considerably during growth and development, with certain stages being more susceptible than others. Yu (1983) pointed out that activities of various detoxifying enzymes such as microsomal oxidases (Krieger and Wilkinson 1969, Yu and Terriere 1971), glutathione S-transferase (Gould and Hodgson 1980), esterases (Yu

and Terriere 1975), and epoxide hydrase (Yu and Terriere 1978) have been found to fluctuate during the life stages of insects. Since these enzymes play important roles in detoxification, low activity of these enzymes would indicate a susceptible period and vice versa.

The purpose of this study was to evaluate the synergistic activity of piperonyl butoxide with 9 synthetic pyrethroids to a laboratory strain of fall armyworm (FAW), Spodoptera frugiperda (J. E. Smith).

Materials and Methods

Procedures for treating egg masses and larvae have been discussed in detail in earlier chapters (Chapters III and VI, respectively). Insecticide-acetone(wt/vol): synergist-acetone(wt/vol) (1:8) solutions were tested. Preliminary dosages of insecticide:synergist solutions were used to establish mortality ranges. Dosage-mortality regression lines, obtained by probit analysis (Finney 1964) (see Appendix) provided LD_{50} values for each insecticide:synergist solution for 5-10 dose levels using a minimum of 30 larvae/dose. Synergistic ratios (LD_{50} of pyrethroid alone/ LD_{50} of pyrethroid + synergist) (see Appendix) were established with LD_{50} values from Chapter VI. The Mann-Whitney U Test (see Appendix) was used to determine significance of synergised vs. nonsynergised comparisons.

Synthetic pyrethroids used in this study were technical formulations of permethrin and cypermethrin (ICI Americas, Inc.), permethrin, cypermethrin, Pounce®, and Ammo® (FMC Agricultural Chemical Group), Pydrin® (Shell Development Co.), Mavrik® (Zoecon Corp.), and Pay-Off® (American Cyanamide Co.) (Table 1, page 35). The synergist used was Prentox® PBO 8TM (91.3% technical piperonyl butoxide) (Prentiss Drug and Chemical Co., Inc.).

Results and Discussion

The pyrethroids were not readily synergised by PB when applied to FAW (Table 11). The only pyrethroids to have synergistic activity on eggs were cypermethrin (FMC) (SR $\approx$ 3.5) and cypermethrin (ICI) (SR $\approx$ 6.3). Cypermethrin (FMC) (SR $\approx$ 3.1) and Ammo® (SR $\approx$ 9.1) had synergistic activity on 3rd instar. Ammo® (SR $\approx$ 8.6) was the only pyrethroid to have synergistic activity on 6th instar. All of the above synergistic ratios are in the low to slightly moderate range of synergism.

For metabolic research, synergism is usually investigated by applying a synergist followed by an application of the active insecticide (Elliott and Janes 1978). This method would not be practical in field situations therefore it was not used in this study.

The cypermethrins (ICI, FMC, and Ammo®) tested were the only pyrethroids to show synergistic activity on FAW. In

Table 11. Toxicity of nine synthetic pyrethroids alone (A) and with piperonyl butoxide (1:8) (B) to eggs (seven days posttreatment), third, and sixth instar (24 h posttreatment) of Spodoptera frugiperda.

Compound	Eggs (LC ₅₀ ¹)			3rd instar (LD ₅₀ ²)			6th instar (LD ₅₀ ²)		
	(A)	(B)	SR ³	(A)	(B)	SR ³	(A)	(B)	SR ³
Pay-Off®	0.320	0.360	0.890 NS	0.0407	0.0153	2.6601 NS	0.306	0.524	0.584 NS
Mavrik®	1.164	0.866	1.344 NS	0.0487	0.0189	2.5767 NS	1.456	1.121	1.299 NS
permethrin (FMC)	1.378	2.198	0.627 NS	0.0041	0.0019	2.1579 NS	0.213	0.330	0.646 NS
permethrin (ICI)	1.572	0.813	1.934 NS	0.0067	0.0042	1.5952 NS	0.662	0.781	0.848 NS
cypermethrin (FMC)	1.557	0.441	3.531 *	0.0307	0.0100	3.0700 *	0.250	0.341	0.748 NS
cypermethrin (ICI)	2.006	0.317	6.328 *	0.1327	0.1155	1.1489 NS	0.684	0.431	1.587 NS
Pounce®	4.000	3.754	1.066 NS	0.0271	0.0093	2.9140 NS	3.471	4.246	0.817 NS
Anmo®	7.375	3.875	1.903 NS	0.1558	0.0171	9.1111 *	5.841	0.676	8.641 *
Pydrin®	12.230	15.405	0.794 NS	0.1277	0.1085	1.1770 NS	0.813	0.591	1.376 NS

¹LC₅₀ = Concentration to kill 50% of individuals tested (ppm).

²LD₅₀ = Dosage to kill 50% of individuals tested (µg/insect).

³SR = Synergistic ratio = (A)/(B).

*Significantly greater than 1.0 at $p \leq 0.05$; NS, not significantly greater than 1.0.

each case, synergism decreased with increased age of the insects. Chang and Jordan (1982) showed that permethrin penetrated into Wiseana cervinata larvae faster than cypermethrin. Casida (1970) pointed out that most well-known synergists, including PB, are fat-soluble and therefore favor penetration through the insect cuticle. Pepper and Hastings (1943) and Gast (1961) found that, during larval development, the insect cuticle varied in its composition. For example, lipid content causes changes in insecticide susceptibility. It is thus possible that the small residual factor of synergism shown by cypermethrin may be explained by physical effects of the large dose of lipophilic synergist on penetration as well as the increased penetration of the pyrethroid itself. The decrease in insecticide susceptibility with increased larval age of FAW could also be due to an increase in insecticide metabolizing enzymes in older larvae (Yu 1983).

Yu (1982) indicated that an increase in detoxifying enzymes due to host plant induction results in a protective effect against various insecticides, including pyrethroids, in FAW. This is supported by Wood et al. (1981) who showed that FAW susceptibility to insecticides, including permethrin, varied with the host plant. In view of this, addition of a synergist to pyrethroids to increase their insecticidal potency and cost efficiency is tempting;

however, concomitant alterations in mammalian toxicity may shift compounds otherwise considered safe into a hazardous category (Casida and Ruze 1980). For these reasons, unless more effective synergists for pyrethroid use on FAW are discovered, more extensive use of these adjuvants seems unlikely.

CHAPTER VIII

GROWTH AND DEVELOPMENT

Introduction

In recent studies the photostable synthetic pyrethroids have been found to have many beneficial chronic effects on fall armyworm (FAW), Spodoptera frugiperda (J. E. Smith), such as feeding deterrency (Chapter V) and ovipositional deterrency (Gist and Pless 1983b) in addition to their high acute toxicities (Gist and Pless 1983a, Chapter VI). These chronic effects are evident at much lower concentrations than those necessary to cause mortality. These strategies are aimed at preventing damage to the plant rather than killing the insect which might have advantages in reduced risks of pest resistance and side effects on beneficials (Ross and Brown 1982).

Reese and Beck (1976) hypothesized that chronic effects, such as lower developmental rate, could increase mortality through longer exposure of target species to parasites, predators, pathogens, and adverse physical factors, even though the chemical may not be immediately lethal to the insect. Until recently, effects of sublethal dietary concentrations of pyrethroids on insects had not been investigated. Tan (1981) found that cypermethrin and permethrin induced a significant extension of the larval

period of Pieris brassicae larvae, with a reduction in the maximal larval and pupal weights. Resulting fecundity was also reduced, possibly due to the reduction of pupal weights. Ross and Brown (1982) found that sublethal concentrations of fenvalerate and permethrin inhibited larval growth (decreased overall larval weight) of Spodoptera frugiperda larvae. NRDC-161 in the diet of Anthonomus grandis grandis reduced the fecundity of the females (Moore 1980).

The quantitative nutritional approach to studying insect growth and development consists of measuring the amount of food consumed, digested and assimilated, excreted, metabolized, and converted into biomass (Waldbauer 1968). Analysis of these measurements reveals how organisms respond to different foods and which food components (or additives) exert the greatest effects on growth (Scriber and Slansky 1981). Information on the effects of sublethal dietary concentrations of pyrethroids on feeding indices has not been published.

The purpose of this study was to evaluate the effects of sublethal dietary concentrations of 9 synthetic pyrethroids on the growth, development, and subsequent fecundity of a laboratory strain of FAW.

Materials and Methods

Insecticide-acetone (wt/vol) solutions used in this study were mixed with dry diet components (Bio-Serv Corn Earworm Rearing Media, Bio-Mix #9394, packet A) in a blender for 10 min. The acetone was allowed to evaporate overnight. Diet was then prepared according to directions and stored in a refrigerator (12°C) until needed. Final concentrations of pyrethroid in the diet was 1 ppm. Acetone alone was added to control diet. Synthetic pyrethroids used in this study were technical formulations of permethrin and cypermethrin (ICI Americas, Inc.), permethrin, cypermethrin, Pounce®, and Ammo® (FMC Agricultural Chemical Group), Pydrin® (Shell Development Co.), Mavrik® (Zoecon Corp.), and Pay-Off® (American Cyanamide Co.) (Table 1, page 35).

Thirty 3rd instars from the stock culture were weighed and placed individually onto weighed squares of treated or control diet in 15 mm dia petri dishes. All measurements were made with 4th-6th instars because young FAW (1st-3rd instars) consume <2% of the total dietary intake (Luginbill 1928). "Loss of appetite" upon initial exposure to a new food, as discussed by Wiklund (1973) and Jermy et al. (1968), was avoided by allowing the 3rd instar to acclimate. Fresh diet was provided as needed to allow the larvae to feed freely. All larvae were kept within environmental chambers at 27°C ($\pm 2^\circ\text{C}$), 14:10 photoperiod, and 60-70% RH.

Frass was carefully separated from uneaten diet, dried and weighed. Uneaten diet was also dried and weighed. Daily measurements of larval weight, and instar duration were taken. Thirty aliquots of each experimental diet and control diet were weighed, dried, and reweighed for calculation of initial percentage dry matter.

As adults emerged they were placed in 1 gal cylindrical wire cages lined with paper toweling for an ovipositional substrate. Cotton saturated with an ascorbic acid-beer (1.5 g/828 ml) solution was placed into each cage for adult diet. Number of egg masses and number of eggs for each treatment were recorded. Egg masses were clipped from the paper toweling, surface sterilized with sodium hypochlorite, and placed on control diet within environmental chambers ($27^{\circ}\text{C} \pm 2^{\circ}\text{C}$, 14:10 photoperiod, 60-70% RH). Number of eggs that had not hatched after 7 days was recorded.

Nutritional indices (Scribner and Slansky 1981, Waldbauer 1968) calculated were relative growth rate (RGR), relative consumption rate (RCR), assimilation efficiency or approximate digestibility (AD), net growth efficiency, metabolic efficiency, or efficiency of conversion of digested food (ECD), and gross growth efficiency, growth efficiency, or efficiency of conversion of ingested food (ECI). Statistical analyses were performed where needed and significant differences between each mean and the control

mean were analyzed by Dunnett's test (see Appendix) at a 5% significance level.

Results and Discussion

All synthetic pyrethroids tested significantly increased the time to maximum weight of the larvae (Table 12). Increases ranged from 2X [permethrin (ICI)] to 3X [cypermethrin (FMC)]. Although the duration of stadia 4-6 was increased, the duration of the prepupal (pharate pupa) and pupal (pupa and pharate adult) stadia remained approximately the same as for the control. This suggests that pyrethroids exert a detrimental effect on the actively feeding stages, even at 1 ppm.

All pyrethroids tested caused significantly lower maximum larval weights when compared with the control (Table 12). Scriber (1977) pointed out that larval growth can be reduced by lack of water. Water loss is a symptom of acute pyrethroid poisoning in insects. Although the test diets contained sufficient water (ca. 81%) for maximal growth the larvae possibly lost water in response to the toxic effect of the pyrethroids. Loss of weight was not readily apparent until the 6th instar for all treated larvae (Figures 6-10). The most extreme reductions in pupal weights were with permethrin (FMC) (38% less than control) and cypermethrin (FMC) (44% less than control).

Table 12. Effects of nine synthetic pyrethroids on nutritional indices,¹ survival, time to maximum larval weight (T), maximum larval weight, and pupal weight of *Spodoptera frugiperda* (4th-6th instars).

Compound	AD ¹	ECD ¹	ECI ¹	RCR ¹	RGR ¹	% Mortality	T ²	Maximum larval weight ³	Pupal weight ³
Control	67.5	15.8	10.5	3.38	0.35	0.0	6.0(±0.0)	436.1(±14.3)	258.6(±26.2)
permethrin (FMC)	55.3 NS	8.9 NS	4.8 NS	2.08 *	0.10 *	53.3	18.3(±1.3) *	272.3(122.5) *	159.4(±24.4) *
Amro®	48.8 NS	14.1 NS	6.0 NS	2.87 *	0.16 *	3.3	12.7(±1.3) *	375.6(±30.6) *	229.4(±34.8) NS
Mavrik®	47.0 NS	15.5 NS	7.3 NS	2.03 *	0.15 *	0.0	13.7(±0.5) *	408.0(±20.9) *	261.6(±34.5) NS
Pounce®	46.4 NS	14.4 NS	6.6 NS	1.83 *	0.12 *	3.0	14.3(±0.5) *	331.5(±30.5) *	220.4(±45.7) NS
cypermethrin (ICI)	46.0 NS	14.1 NS	5.9 NS	2.08 *	0.13 *	13.3	16.3(±2.1) *	370.3(±18.0) *	208.2(±41.8) *
cypermethrin (FMC)	42.3 NS	9.3 NS	3.9 NS	2.94 *	0.12 *	60.0	20.3(±0.5) *	272.8(±87.7) *	145.5(±26.5) *
permethrin (ICI)	42.2 NS	16.3 NS	6.8 NS	2.43 *	0.17 *	16.7	12.3(±0.9) *	317.1(±30.4) *	204.3(±47.1) *
Pydrin®	42.2 NS	17.6 NS	7.0 NS	1.88 *	0.13 *	10.0	13.7(±0.5) *	393.6(±15.6) *	230.4(±33.9) NS
Pay-Off®	36.0 NS	16.9 NS	6.0 NS	2.11 *	0.13 *	0.0	15.3(±1.7) *	360.1(±38.5) *	206.7(±35.4) *

¹ AD = Approximate digestibility = (I-F)/I

ECD = Efficiency of conversion of digested food = B/(I-F)

ECI = Efficiency of conversion of ingested food = AD × ECD

RCR = Relative consumption rate = I/T/B

RGR = Relative growth rate = RCR × ECI; where B = biomass gained, I = ingested food, F = feces egested undigested food + excretory products,

I-F = assimilated food, B = mean weight during time period T, and T = time (in days) to maximum weight.

²Mean in days (±SE).

³Mean in mg (±SE).

* = Significantly different from control ($p \leq 0.05$), NS = not significantly different from control according to Dunnett's test.

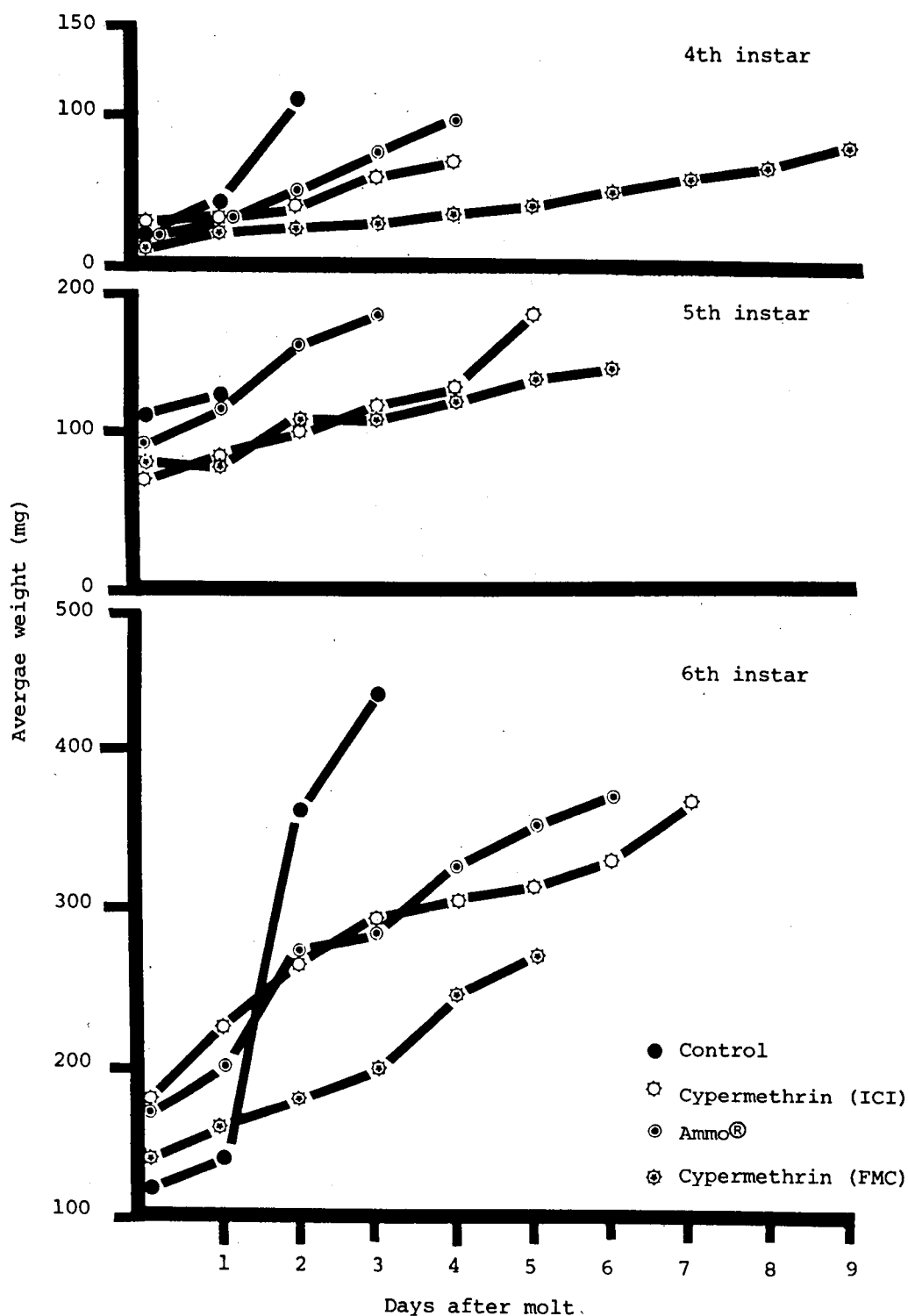


Figure 6. Effect of cypermethrin (1 ppm) impregnated diet on average daily weight and instar duration of *Spodoptera frugiperda* (4th-6th instars). (The small SE of each point is not plotted for sake of clarity.)

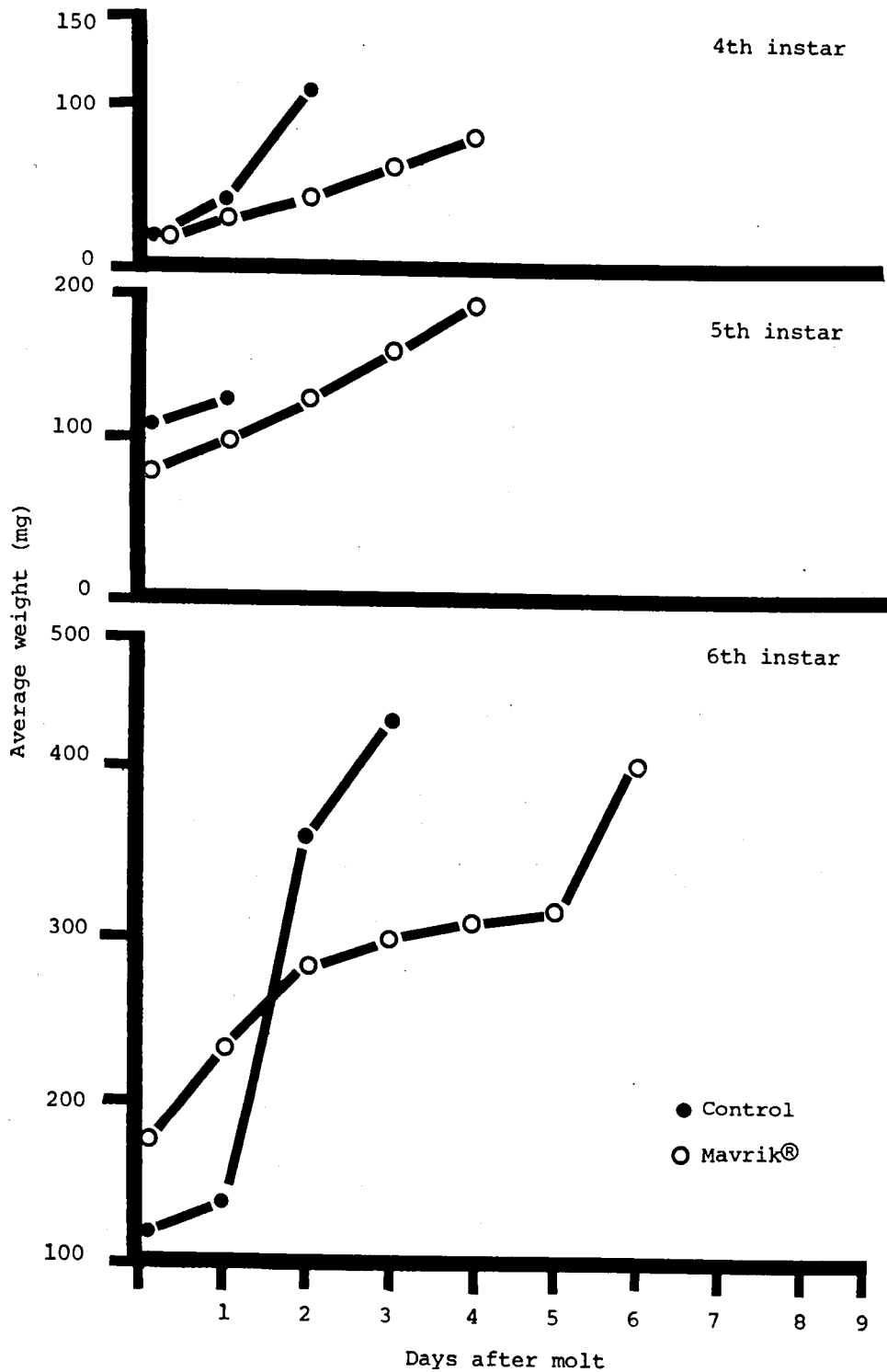


Figure 7. Effect of Mavrik® (1 ppm) impregnated diet on average daily weight and instar duration of *Spodoptera frugiperda* (4th-6th instars). (The small SE of each point is not plotted for the sake of clarity.)

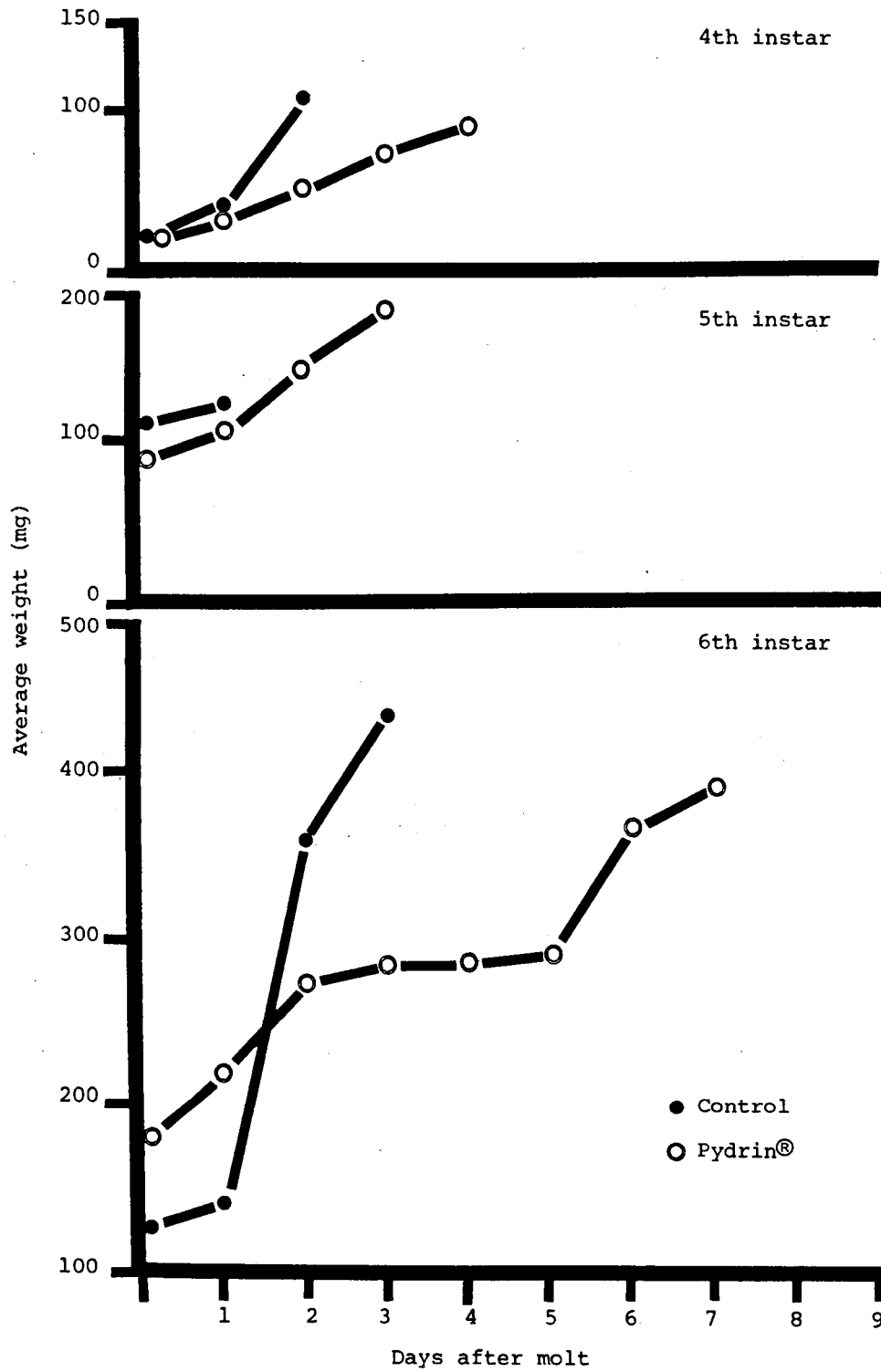


Figure 8. Effect of Pydrin® (1 ppm) impregnated diet on average daily weight and instar duration of *Spodoptera frugiperda* (4th-6th instars). (The small SE of each point is not plotted for sake of clarity.)

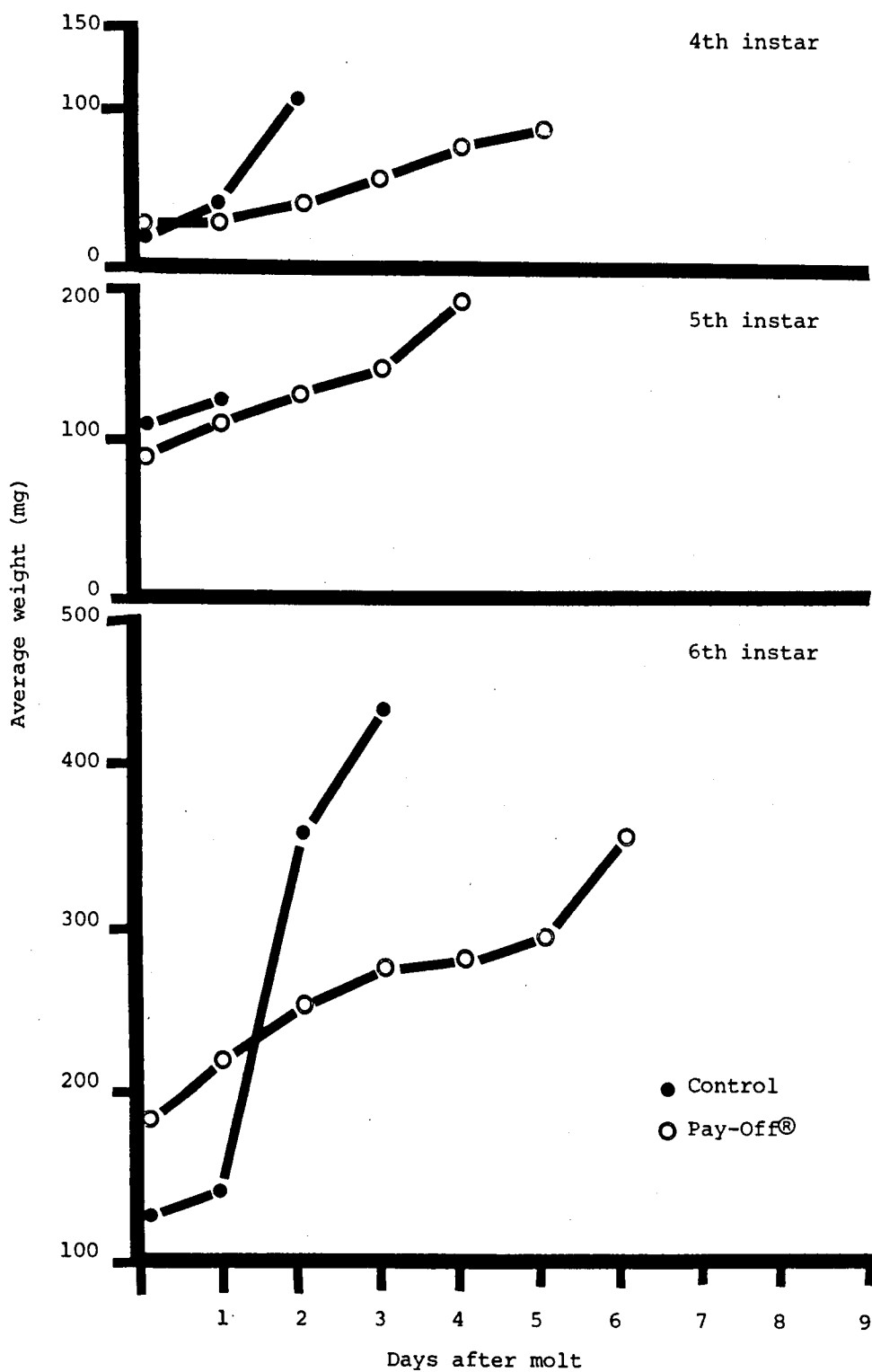


Figure 9. Effect of Pay-Off® (1 ppm) impregnated diet on average daily weight and instar duration of *Spodoptera frugiperda* (4th-6th instars). (The small SE of each point is not plotted for sake of clarity.)

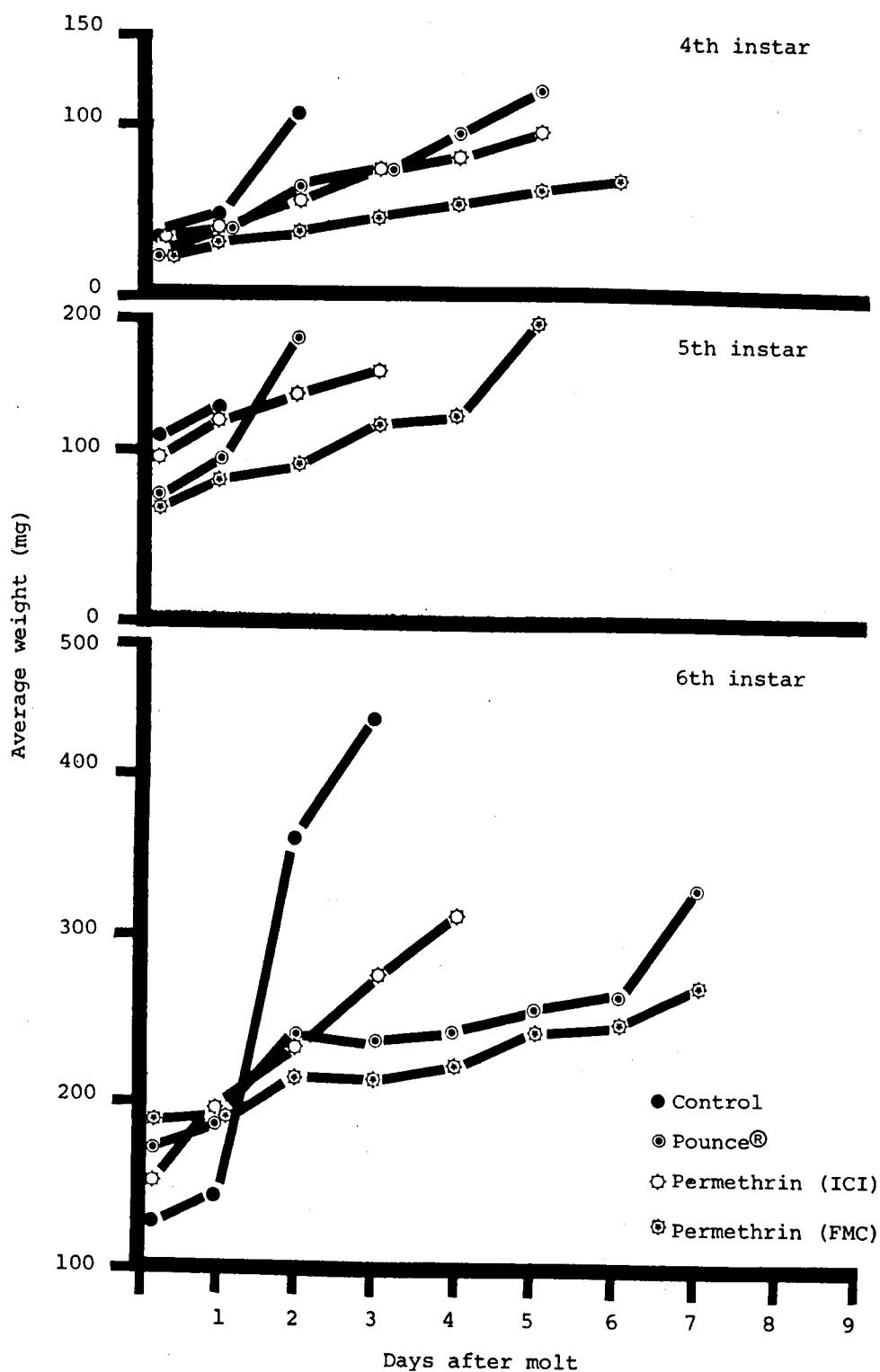


Figure 10. Effect of permethrin (1 ppm) impregnated diet on average daily weight and instar duration of *Spodoptera frugiperda* (4th-6th instars). (The small SE of each point is not plotted for sake of clarity.)

All of the pyrethroids tested significantly reduced the RGRs (Table 12). Assimilation and digestion of the food ingested (AD) was not significantly reduced for any of the pyrethroids. In no case was the ECD reduced by the pyrethroids, indicating that although these compounds do affect mortality when incorporated into the diet at 1 ppm, there is no metabolic "cost" incurred to detoxify them (Scriber and Slansky 1981). Additives in the food that reduce feeding usually impose a reduced RCR (Scriber and Slansky 1981). All the pyrethroids tested showed a significant reduction in RCR indicating that these compounds deter feeding. This has been further substantiated by the experiments in Chapter V in which these pyrethroids were found to deter feeding by 3rd instar FAW at 50 ppm and 5 ppm, both in 2-choice and no-choice tests. An imposed reduction in RCR should result in lengthy extension of the larval stadium with final body weight reduced below normal (Mathavan and Muthukrishnan 1976, McGinnis and Kasting 1959, Mukerji and Guppy 1970, Rojas-Rousse and Kalmes 1978). We concluded that reduction in RCR was induced by the pyrethroids because they deter feeding (at higher concentrations), increase time in the larval stage, and decrease final body weights.

Larvae reared on the treated diets pupated normally. Percent emergence of the adults was comparable to control

adults (Table 13); however, many of the subsequent adults were unable to inflate their wings upon emergence. Percentages of insects with uninflated wings ranged from 0% (Pounce®) and 8.0% [cypermethrin (ICI)] on the lower end to 21.4% (Ammo®) and 43.3% (Mavrik®). This characteristic might add to population control since adults would be unable to fly when disturbed, thus making them more susceptible to natural mortality factors. FAW adults hide in debris during the day and emerge at dusk to feed and mate (Luginbill 1928). These activities would obviously be inhibited by their inability to fly.

With treatment, number of eggs/female typically was reduced by ca. 50%; however, there was a 2-fold increase with Pydrin®-treated insects. Hormologosis, a phenomenon in which subharmful quantities of many stress agents are stimulating (Luckey 1968), is a possible explanation for the increase seen with Pydrin®. Eggs laid by treated females had 6X (Ammo) to 20X [permethrin (FMC)] greater mortality than eggs laid by control females.

In conclusion, the synthetic pyrethroids can be effective insecticides for FAW control at sublethal concentrations because they inhibit growth of the larvae (by increasing time spent in the larval period and by reducing maximum weight of the larvae), reduce amount of feeding by larvae, reduce mobility of the adults, and reduce fecundity

Table 13. Adult emergence, fecundity, and % egg hatch of Spodoptera frugiperda reared on artificial diet impregnated with nine synthetic pyrethroids.

Compound	% failure to emerge	% uninflated wings	egg masses/	eggs/	% eggs not hatching
Control	10.0	0.0	9.8	1011.4	0.7
Pydrin®	14.8	13.0	19.8	1982.0	10.7
Pounce®	10.3	0.0	8.2	575.6	10.2
cypermethrin (FMC)	8.3	9.1	8.5	353.6	11.3
permethrin (ICI)	8.0	17.4	5.7	465.7	6.7
permethrin (FMC)	7.1	15.4	4.9	355.7	14.3
cypermethrin (ICI)	3.9	8.0	7.5	454.5	10.0
Ammo®	3.5	21.4	6.2	497.9	4.2
Pay-Off®	3.3	10.3	7.0	571.9	4.5
Mavrik®	0.0	43.3	6.3	407.0	7.4

of the adults. These characteristics might help prevent the formation of large FAW populations in the field thus reducing overall economic damage.

CHAPTER IX
FINAL EVALUATIONS OF THE PYRETHROIDS
AND CONCLUSIONS

The synthetic pyrethroids were highly toxic to eggs and larvae of FAW. In addition, the pyrethroids, used at sublethal concentrations, were found to have characteristics that could aid in plant protection. These protectant characteristics include ovipositional repellency, feeding deterrence, and reduced growth, development, and fecundity. The pyrethroids were not readily synergised by piperonyl butoxide, a commonly used synergist.

A rating scale for the pyrethroids was made by assigning a rank to each pyrethroid related to its performance in each test. Compiling these rankings resulted in an overall performance assessment (Table 14). The final rankings (in decreasing order) were: permethrin (FMC), cypermethrin (ICI), cypermethrin (FMC), Pay-Off®, permethrin (ICI), Pounce®, Mavrik®, Pydrin®, and Ammo®. The permethrins [technical (ICI) and (FMC) and Pounce®] and the cypermethrins [technical (ICI) and (FMC) and Ammo®] differed in their isomeric ratios, which accounts for the difference in rankings. In FAW control, however, as in any pest control situation, an evaluation of the benefits and risks of a control method, or combination of methods, is necessary.

T

Synergism		Time to Max. Larval Weight	Maximum Larval Weight	RCR	RGR	Eggs/♀	Total	Final Rank	
3rd Instar	6th Instar								
A	1	1	8	7	8	8	6	107.0	9
c	2	7	1	2	9	2.5	1	71.5	3
c	8	2	3	6	4.5	5	4	69.5	2
M	5	4	6.5	9	3	7	3	92.5	7
P	4	9	4	5	6	5	7	82.0	4
p	6	8	2	1	4.5	1	2	61.5	1
p	7	5	9	3	7	9	5	89.0	5
P	3	6	5	4	1	2.5	8	89.5	6
P	9	3	6.5	8	2	5	9	102.5	8

Ideally the best protectant would be a compound that kept the pest away from the host plant. Since FAW has no diapause mechanism, each growing season local populations begin with migrating moths (page 6). Ovipositional repellency would therefore be the first step in crop protection. The pyrethroids were effective ovipositional repellents (Tables 3 and 4, pages 46 and 47), with the possible exception of cypermethrin (FMC). The permethrins [technical (FMC) and (ICI) and Pounce®], which contain cyclopropane rings, were more repellent than the compounds containing a cyano group. Feeding deterrence is another aspect of repellency, one that applies to the insect population after it becomes established. The pyrethroids containing a cyano group deter feeding better than the permethrins (Tables 5-8, pages 53-56), which lack the cyano group. Further, a combination of the cyano group with a cyclopropane ring (i.e., cypermethrin) gives the best protection against larval feeding. Thus, for repellency, compounds with cyclopropane rings (permethrin and cypermethrin) are the best pyrethroids to use.

Once eggs have been deposited on the host plant, control of hatch becomes the next measure to consider. The pyrethroids containing fluorine (Pay-Off® and Mavrik®) were the best ovicides (Table 2, page 41), closely followed by the permethrins. Control of early larval instars (i.e., 3rd instar) was best achieved with the three permethrins

(Table 9, page 62), while control of later instars (i.e., 6th instar) was best achieved with compounds containing cyclopropane rings (the technical permethrins and cypermethrins) (Table 10, page 64). Therefore, for ovicidal and larvicidal purposes, the compounds containing cyclopropane rings, especially the permethrins, are best.

Extended protection is a favorable characteristic for an insecticide. Over a period of time the pyrethroids begin to break down (page 22) leaving decreasing concentrations of active ingredient available. Compounds, such as the pyrethroids, that can inhibit growth of FAW at low concentrations (Chapter VIII) are ideal. Of the pyrethroids tested, permethrin (FMC), cypermethrin (FMC), and Pounce® had the greatest effects on growth (Table 12, page 78). All of these compounds have cyclopropane rings. Pydrin® would be a poor choice for control of this type since it stimulates egg production in female FAW (Table 13, page 86).

With all these control factors in mind, a true assessment of the pyrethroids can be made. According to rankings, pyrethroids containing a cyclopropane ring are best for control. This assessment also holds true for individual control measures (repellency, kill, growth reduction). The presence of a cyano group is mainly important for feeding deterency. This is understandable

since cyanide is a known feeding deterrent (Jones 1972). thus it is concluded that the cyclopropane ring-containing pyrethroids are best for FAW control, the permethrins (no cyano group) more so than the cypermethrins (containing cyano groups). Of the other pyrethroids, that is those without cyclopropane rings, Pay-Off® and Mavrik®, both of which contain fluorine, gave acceptable control. Pydrin® should not be used for FAW control since it stimulates egg production. Pydrin®, also lacking a cyclopropane ring, does not contain fluorine.

Synthetic pyrethroids are unusual in that there have been reports that these compounds are sometimes more toxic to pests than to the predators and parasites of the pests (Bashir and Crowder 1983, Hull and Starner 1983, Ishaaya and Casida 1981, Rajakulendran and Plapp 1982). Sublethal concentrations could possibly allow for selection of pyrethroid-resistant strains of beneficial species (Croft and Whalon 1983, Strickler and Croft 1982). Another unusual characteristic of some pyrethroids is that they show less synergism against parasites than against pest (Plapp 1979) which would also allow reduced concentrations of pyrethroids to be used effectively without endangering beneficial populations.

Further comprehensive research with the pyrethroids could result in more beneficial information about these

versatile insecticides. For example, Wood et al. (1981) found that various food plants affect the toxicity of insecticides to FAW. In the same manner, this test could be applied to the various pyrethroids to help establish the most useful pyrethroid structural type as a contact insecticide for FAW control. The test should be expanded, however, to corn varieties with emphasis on the resistant strains. The final goal of this test would be to find a corn variety that would allow maximum protection from minimum pyrethroid applications. In addition, these tests should be expanded to include feeding deterrent and growth and development effects of the pyrethroids to FAW reared on various host plants, again to include different varieties of corn. This would allow additive effects of allelochemicals with pyrethroid activity to be observed.

Since resistance to pyrethroids is being more frequently observed, tests to determine resistance of FAW to pyrethroids should be included in any comprehensive research program. There are several ways to approach this. One method would involve rearing continuous generations of FAW on pyrethroid-impregnated diet (as outlined in Chapter VIII). Each generation would be tested for an increase in contact LD_{50} concentrations. Another method would be to treat each generation with sublethal topical applications of the pyrethroids. Subsequent generations would be tested for

an increase in contact LD₅₀ concentrations. A combination of these two methods, however, would be best since that would more closely approximate the natural situation.

Predators and parasites are important in any pest control program. To date no research has been reported for predators and parasites of FAW (pages 11-13) with respect to pyrethroids. This area should be thoroughly investigated before any long-term applications of the synthetic pyrethroids is started.

In conclusion, the synthetic pyrethroids are potentially useful compounds for FAW control programs. Crop protection aspects of the pyrethroids that had not been previously reported were discovered in this study. These include ovipositional repellency and certain aspects of growth and development such as reduced growth rates, based on nutritional indices, and inability of treated adults to inflate their wings upon emergence. In addition, ovicidal activity, comparative toxicities, feeding deterrence, and synergistic activity of the pyrethroids to FAW has been established by this study. Control considerations should turn more to using lower concentrations which could possibly result in chronic effects to the pest population without concomitant acute toxicity to beneficial populations. Field tests, based on the results of this study, are now needed to

relate laboratory studies to natural conditions in order that definitive statements concerning agricultural use of these compounds can be made.

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APPENDIX

ABBOTT'S FORMULA

According to Finney (1964) if in a toxicity test a proportion C of test subjects would die even without any poison, the total death rate expected from a dose sufficient to kill a proportion P of those which would otherwise survive is

$$P' = C + P(1 - C) ,$$

providing that the two types of mortality operate independently. From this equation it follows that, if the total proportion dead is P', the proportion killed by the poison alone is

$$P = (P' - C) / (1 - C) .$$

This is commonly known as "Abbott's formula," on account of its use in a paper by W. S. Abbott (1925) on the adjustment of the results of insecticidal tests; in fact, it had been used earlier, for the same purpose, by Tattersfield and Morris (1924), and is an application of the well-known rule for the combination of independent probabilities. In this paper it is used in Chapters III, IV, and VI.

PROBIT TRANSFORMATION

A typical test used in the evaluation of an insecticide is one in which successive batches of insects are exposed to

different concentrations of the poison for a constant time and scored for the numbers dead and alive. The form of analysis of this data is generally based upon the probit transformation of the experimental results as explained by Finney (1964). It is used in Chapters III and VI.

Bliss (1934) first proposed the name "probit" for his modification of Gaddum's normal equivalent deviate, which he increased by 5 so as to simplify the arithmetical procedure by avoiding negative values. The probit of the proportion P is defined as the abscissa which corresponds to a probability P in a normal distribution with mean 5 and variance 1; in symbols, the probit of P is Y , where

$$P = \frac{1}{\sqrt{2(\pi)}} \int_{-\infty}^{Y-5} e^{-1/2 u^2} du .$$

The normal sigmoid curve of percentages is thusly transformed to a straight line (obtained when percentage ordinates are replotted on a linear scale of probits). The transformation may be considered as a stretching during which the sigmoid curve becomes straightened.

The distribution of tolerances on the x scale of dosages is represented by

$$dP = \frac{1}{\sigma \sqrt{2\pi}} e^{-1/2\sigma^2(x - \mu)^2} dx ,$$

where μ is the center of the distribution and σ^2 is the variance, therefore the expected proportion of insects killed by a dosage x_0 is

$$P = \frac{1}{\sigma \sqrt{2\pi}} \int_{-\infty}^{x_0} e^{-1/2\sigma^2(x - \mu)^2} dx ,$$

Comparison of the two formulae for P then shows that the probit of the expected proportion killed is related to the dosage by the linear equation.

$$Y = 5 + 1/\sigma (x - \mu) .$$

By means of the probit transformation, experimental results may be used to give an estimate of this equation, and the parameters of the tolerance distribution may then be estimated; in particular, the median effective dosage is estimated as that value of x which gives $Y = 5$.

The binomial distribution of probabilities shows that if a batch of n insects is exposed to a concentration which, on an average, will kill a proportion P , the probabilities of $n, (n - 1), \dots, 2, 1$ being killed are the successive terms in the expansion of $(P + Q)^n$, provided that the n insects react independently to the poison. By a well-known result of elementary statistical theory, it follows that the standard deviation of the number of affected insects in samples of size n is $\pm\sqrt{nPQ}$, and that the standard

deviation of the observed proportion p , about its mean value of P , is $\pm\sqrt{(PQ/n)}$. The square of a standard deviation is known as the variance; here the variance of the proportion killed is PQ/n , which is inversely proportional to the number in the batch. The reciprocal of the variance, sometimes called the invariance or quantity of information, is proportional to n , and represents the weight to be attached to the observation on the batch in respect of the information it provides on P .

After weighting, regressions were calculated as outlined in Chapter 14 of Sokal and Rohlf (1969). The significance of the regression coefficient was tested as

$$t_s = \frac{(b - 0)}{S_b}$$

where b is the regression coefficient and S_b is the standard error of the regression coefficient.

TOXICITY INDEX

Since its development by Sun (1950) the toxicity index (Chapters III and IV) has become a standard method of expressing the relative toxicity of insecticides. It is defined as the ratio between the LD_{50} of a standard insecticide and that of the test sample, multiplied by 100. The toxicity index of a standard insecticide is always taken as 100. An insecticide which is more toxic than the

standard should have an index greater than 100 and vice versa. Unlike % mortality or the LD_{50} , the toxicity index of an insecticide should remain reasonably constant with respect to the standard. The following formula is used to calculate the toxicity index.

$$\text{Toxicity index} = \frac{LD_{50} \text{ of the standard}}{LD_{50} \text{ of a test sample}} \times 100$$

STUDENT-NEWMAN-KEULS TEST

The Student-Newman-Keuls test (SNK) (Newman 1939, Keuls 1952) is one of the most commonly used multiple range tests. It is used in Chapters IV and V. According to Zar (1974) the multiple comparison procedure exemplified by the SNK test considers the null hypothesis $H_0: \mu_B = \mu_A$ versus $H_A: \mu_B \neq \mu_A$, where the subscripts denote any possible pair of groups. For k groups, $k(k - 1)/2$ different pairwise comparisons can be made. Since ANOV rejects $H_0: \mu_1 = \mu_2 = \dots \mu_k$, a multiple range test is called for to determine between which population means differences exist. The first step in the analysis is to arrange and number all sample means in order of increasing magnitude. Then pairwise differences, $\bar{X}_B - \bar{X}_A$, are tabulated. In this test, values known as "Studentized ranges," abbreviated q , which are dependent upon v , the error DF for the analysis and p , the number of means in the range of means being tested, are

utilized. To compare ranked means μ_5 and μ_1 , for example, $p = 5$, to test mean 5 vs. mean 2, $p = 4$, etc. A q value in the SNK test is calculated by dividing a difference between means by

$$SE = \sqrt{\frac{s^2}{n}}$$

where s^2 is the error mean square from the analysis of variance and n is the number of data in each of groups A and B (in these tests, n was equal for all groups). If this calculated q value,

$$q = \frac{\bar{X}_B - \bar{X}_A}{SE} ,$$

is equal to or greater than the critical value, $q_{\alpha, v, p}$, then $H_0: \mu_B = \mu_A$ is rejected. The significance level, α , is the probability of encountering at least one Type I error during the course of comparing all the pairs of means, it is not the probability of committing a Type I error for a single comparison.

The conclusions reached by multiple range testing are dependent upon the order in which the pairwise comparison are considered. The proper procedure is to first compare the largest mean against the smallest, then the largest against the next smallest, and so on, until the largest has

been compared with the second largest. Then one compares the second largest with the smallest, the second largest with the next smallest, and so on. For example, after ranking five means in ascending order, the sequence of comparisons is as follows: means 5 vs. 1, 5 vs. 2, 5 vs. 3, 5 vs. 4, 4 vs. 1, 4 vs. 2, 4 vs. 3, 3 vs. 1, 3 vs. 2, 2 vs. 1. Another important procedural rule is that if no difference is found between two means, then it is concluded that no difference exists between any means enclosed by these two, and such differences are not tested for.

ARCSINE TRANSFORMATION

Zar (1974) states that it is known from statistical theory that percentages or proportions form a binomial, rather than a normal distribution, the deviation from normality being great for small or large percentages (0 to 30% and 70 to 100%). But if the square root of each proportion is transformed to its arcsine (i.e., the angle whose sine is $\sqrt{X}$), then the resultant data will have an underlying distribution that is nearly normal. This transformation is calculated

$$X' = \arcsin \sqrt{X} \quad .$$

For proportions of 0 to 1.00 (i.e., percentages of 0 to 100%), the transformed values will range between 0 and 90

degrees. This transformation was used in Chapter IV to correct data for the SNK test.

SYNERGISTIC RATIO

The synergistic ratio (SR) is the most widely used and most precise measure of the ease of detoxification of an insecticide (Metcalf 1967). Other investigators have used SRs under such terms as degree or factor of synergism, synergistic activity, cotoxicity coefficient, and synergistic effect. SRs are calculated by dividing the LD₅₀ of the insecticide alone by the LD₅₀ of the insecticide + the synergist as seen in the following formula

$$SR = \frac{LD_{50} \text{ of insecticide}}{LD_{50} \text{ of insecticide} + \text{synergist}} \quad .$$

This formula was used in Chapter VII.

MANN-WHITNEY U TEST

The Mann-Whitney U Test is a nonparametric analogue to the two-sample t-test (Zar 1974). It was originally proposed by Wilcoxon (1945) and later enlarged upon by Mann and Whitney (1947). Actual measurements are not employed in the Mann-Whitney test. Instead the ranges of the measurements (from the highest to the lowest or from lowest to highest values) are used. The Mann-Whitney is calculated,

$$U' = n_1 n_2 + \frac{n_1(n_1 + 1)}{2} - R_1 ,$$

where n_1 and n_2 are the number of observations in samples 1 and 2, respectively, and R_1 is the sum of the ranks of the observations in sample 1. For two-tailed hypotheses the calculated U is compared with the two-tailed value of $U_{\alpha(2), n_1, n_2}$. The Mann-Whitney statistic can also be calculated as

$$U' = n_1 n_2 + \frac{n_2(n_2 + 1)}{2} - R_2 ,$$

because the labeling of the two samples as 1 and 2 is purely arbitrary. Since the values of U and U' will generally not be equal, both values must be known so that the larger of the two may be compared with the critical value. This test was used in Chapter VII.

DUNNETT'S TEST

According to Zar (1974) when the objective of multisample experiments with k samples, or groups, is to determine whether the mean of one group, designated as a "control," differs significantly from each of the means of the $k - 1$ other groups, Dunnett's (1955) test is used. This test differs from the multiple comparison approach in that the investigator is not interested in all possible comparisons of group means, but only in those $k - 1$ comparisons

involving the "control" group. Knowing k , the total number of groups in the experiment, and v , the error degrees of freedom from the analysis of variance for $H_0: \mu_1 = \mu_2 = \dots = \mu_k$, one obtains critical values from tables, depending on whether the hypotheses are to be one-tailed or two-tailed. These tabled values are referred to as $q'_{\alpha, v, p}$, for they are used in a manner similar to that of the $q_{\alpha, v, p}$ values employed in the SNK test. As in the SNK procedure, the error rate, α , denotes the probability of committing a Type I error somewhere among all of the pairwise comparisons made. The standard error for Dunnett's test is

$$SE = \sqrt{\frac{2s^2}{n}}$$

where group sizes are equal. For a two-tailed test, if $|q'| \geq q'_{\alpha(2), v, p}$, then $H_0: \mu_{\text{control}} = \mu_A$ is rejected. In a one-tailed test $H_0: \mu_{\text{control}} \leq \mu_A$ would be rejected if $|q'| \geq q'_{\alpha(1), v, p}$ and $\bar{X}_{\text{control}} > \bar{X}_A$; and $H_0: \mu_{\text{control}} \geq \mu_A$ would be rejected if $|q'| \geq q'_{\alpha(1), v, p}$ and $\bar{X}_{\text{control}} < \bar{X}_A$.

Subjected to a one-way ANOV, a nonparametric analysis may be performed to test for either one-tailed or two-tailed significant differences between one group (designated as the "control") and each of the other groups of data. This is done in a manner paralleling that mentioned above, but using group rank sums instead of group means. The standard error is calculated

$$SE = \sqrt{\frac{n(np)(np + 1)}{6}},$$

and one uses critical values of either $q'_{\alpha(1),v,p}$ or $q'_{\alpha(2),v,p}$ for one-tailed or two-tailed hypotheses, respectively.

VITA

Ginger Lee Gist was born in Detroit, Michigan, on August 28, 1954. Her family moved to Jonesboro, Arkansas, in 1961. She attended elementary, junior high, and high school in that city, graduating with honors in June 1972. The following September she entered Arkansas State University, and in June 1976 she received a Bachelor of Science in Education degree in Biology. In June 1976 she began graduate study at Arkansas State University and was awarded a Master of Science in Education degree in Biology in May 1979. She was employed as a science teacher for the Bay-Brown School System during the 1976-77 and 1977-78 school years and as a biology teacher for Manila School System during the 1978-79 school year.

Miss Gist accepted a graduate assistantship at The University of Tennessee, Knoxville, and began study for a Doctor of Philosophy degree in Ecology in the fall of 1979. She received her degree in August 1983.

The author is a member of Alpha Lambda Delta, Gamma Beta Phi, Phi Kappa Phi, and Gamma Sigma Delta honor societies. She is a member of the American Association for the Advancement of Science, American Chemical Society, American Institute of Biological Sciences, Association of Applied Insect Ecologists, Association of Southeastern

Biologists, Entomological Society of America, Florida Entomological Society, Sigma Delta Epsilon--Graduate Women in Science, Inc., Southeastern Biological Control Working Group, and the Tennessee Entomological Society. She has received various honors including being named an Outstanding Young Woman of America and has been included in Who's Who Among Students in American Colleges and Universities.