PESTICIDE RESISTANCE IN FLORIDA INSECTS LIMITS MANAGEMENT OPTIONS

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ABSTRACT

Pesticide resistance in Florida was characterized through a survey and literature review. The survey was conducted in 1994 among public-sector entomologists to determine the current and future status, extent, context, pattern, and instances of pesticide (insecticide and acaricide) resistance in Florida. Results attested to the impact of pesticide resistance on the management of numerous arthropods in Florida. Twenty-five examples of insecticide and acaricide resistance were cited by survey respondents in agricultural, ornamental and landscape, medical and veterinary, or household and structural pests. It remains possible to manage most arthropods by using chemical pesticides, but the current and anticipated lack of efficacious materials threatens current practices in some areas. Trends in extent, context, or patterns of resistance were noted as follows: high value crops, frequently treated arthropods, smaller arthropods, and pyrethroids were all considered factors associated with resistance. Insecticide resistance and its management were reviewed in depth for the leafminer *Liriomyza trifolii* and the diamondback moth, *Plutella xylostella*, two major insect pests in Florida for which management options have become severely limited because of insecticide resistance. Both cultural practices (continuous cropping, isolation, transport of infested seedlings) and pesticide use patterns (frequent application of broad spectrum pesticides) contributed to *L. trifolii* and *P. xylostella* resistance development. The history of pesticide resistance in these two insects is probably typical of pest resistance in Florida and may portend similar future problems unless dependency on pesticides for pest suppression is reduced through adoption of IPM philosophy and practices.

Key Words: Insecticide resistance, *Liriomyza trifolii*, *Plutella xylostella*.

RESUMEN

La resistencia a los pesticidas en la Florida fue caracterizada a través de una encuesta y una revisión de la literatura. La encuesta fue conducida en 1994 entre los entomólogos del sector público para determinar el estado presente y futuro, extensión, contexto, patrón e instancias de la resistencia a pesticidas (insecticidas y acaricidas) en la Florida. Veinte y cinco ejemplos de resistencia a insecticidas y acaricidas fueron citados por los que respondieron la encuesta sobre plagas agrícolas, de ornamentales y de jardines, de importancia médica y veterinaria, o domésticas y de otras estructuras. Parece posible manejar la mayoría de los artrópodos usando pesticidas químicos, pero la falta actual y anticipada de materiales amenaza las prácticas presentes en algunas áreas. La tendencia en la extensión, contexto, o patrones de resistencia fue como sigue: cultivos de alto valor, artrópodos frecuentemente tratados, pequeños artrópodos, y piretroides fueron todos considerados como factores asociados con la resistencia.

La resistenca a los insecticidas y su manejo fueron revisados en profundidad para el minador de las hojas *Liriomyza trifolii* y para la polilla de la col, *Plutella xylostella*, los insectos plagas principales en la Florida para los cuales las opciones de manejo se han tornado severamente limitadas debido a la resisitencia a los insecticidas. Tanto las prácticas culturales (cosecha continua, aislamiento, transporte de plántulas infestadas) como los patrones de uso de pesticidas (aplicación frecuente de insecticidas de amplio espectro) contribuyeron al desarrollo de la resistencia de *L. trifolii* y *P. xylostella*. La historia de la resistencia a los pesticidas en estos dos insectos es probablemente típica para la resistencia de las plagas en la Florida, y podría significar problemas futuros similares a menos que la dependencia de los pesticidas para la supresión de las plagas sea reducida a través de la adopción de filosofía y prácticas de MIP.

Insecticide resistance has had an impact on the management of insect pests in Florida since the mid-1940s following the widespread adoption of synthetic insecticides, especially the organochlorines, organophosphates, and pyrethroids. Numerous anecdotal reports exist, wherein consistently effective insecticides have become ineffective and remained so for several seasons. Such reports have been considered ample evidence of resistance development (Hoskins & Gordon 1956). In fact, Genung (1957) provided strong evidence based on anecdotal reports and data from field efficacy trials for resistance development in the cabbage looper, *Trichoplusia ni* Hubner, imported cabbageworm, *Artogeia rapae* (L.), a *Liriomyza* sp., and leafhoppers, *Empoasca* sp., at a session of the Florida State Horticultural Society Meeting in 1957 entitled "Symposium-Vegetable Insect Resistance to Insecticides in Florida" (Brogdon 1957). Resistance episodes in Florida have also been documented in a number of species with laboratory studies in which concentration-mortality response has been used to compare resistant and susceptible strains. Much of this work has been conducted within the last 10 years and involves species such as cabbage looper (Shelton & Soderlund 1983), diamondback moth, *Plutella xylostella* (L.), (Leibee & Savage 1992a, Shelton et al. 1993, Yu & Nguyen 1992), silverleaf whitefly, *Bemisia argentifolii* Bellows & Perring, (G. L. L. unpublished data), house fly, *Musca domestica* L., (Bailey et al. 1970, Bloomcamp et al. 1987), German cockroach, *Blatella germanica* (L.), (Milio et al. 1987, Koehler 1991, Hostetler & Brenner 1994), *Liriomyza trifolii* Burgess (Keil & Parella 1990, G. L. L. unpublished data), fall armyworm, *Spodoptera frugiperda* (J. E. Smith), (Pitre 1988, Yu 1992), cat flea, *Ctenocephalides felis* (Bouche), (El-Gazzar et al. 1986), and citrus rust mite, *Phyllocoptruta oleivora* (Ashmead), (Omoto et al. 1994).

In hopes of providing a better understanding of current pesticide resistance and its consequences in Florida, we report here the results of a recent survey of public-sector entomologists conducted to assess the extent of pesticide resistance in Florida, and its current and potential impacts. In addition, we provide an in-depth account of two important insect pests of vegetables in Florida, the dipterous leafminer *L. trifolii* and the diamondback moth, for which management options have become extremely limited because of insecticide resistance.

Resistance Survey

During the spring of 1994, 16 public-sector entomologists were sent survey forms to measure their opinion about the extent of pesticide (defined as insecticide and acaricide) resistance in Florida, and its current and potential impact. We polled University and USDA entomologists from various backgrounds, representing the fields of agricultural, ornamental and landscape, medical and veterinary, or household and structural pest management. Entomologists with considerable field experience, and a close relationship with producers or pest control professionals, were favored. We received responses from 14 of those surveyed, and 12 respondents provided useful information. Additional information was sought from other knowledgeable individuals to round out the survey. The questions and responses were as follows:

The Current and Future Status of Pesticide Resistance

Respondents were asked to indicate if resistance was: not a problem, a minor problem, a significant problem, or a critical problem. Only a single response was requested. The time frame for future problems was specified as 10 years in the future.

The respondents differed in their assessment of the severity of the resistance problem depending on the crop or environment being considered. Resistance was viewed to be a critical problem in greenhouses (foliage plants, flowering plants, and some woody ornamentals), floriculture (both greenhouse and field-grown flowers), and animal production (penned and free-ranging). Ornamental plants have long been considered to be extremely sensitive to damage, hence they are treated frequently and prone to insecticide resistance problems. Resistance in animal production is a more recent phenomenon, however, apparently resulting from widespread use of insecticide impregnated ear tags.

Resistance was considered to be a significant, but not critical, problem in vegetable crops, some field crops, and households. This might be viewed as surprising, because many vegetable crops, some field crops, and households in Florida receive insecticide treatments at frequencies similar to the aforementioned situations where pesticide resistance was judged to be critical. It is likely that the severity of the problem is due as much to corporate marketing strategies as to pesticide use patterns. Specifically, the pesticide market is smaller for greenhouse, floriculture and animal uses, so pesticide companies support fewer registrations. Therefore, when pesticide failures occur, there are few options, or in some cases none. This, of course, results in a critical situation.

For medical pests, which in Florida is principally mosquitoes, the significance of the resistance problem apparently is related to location. Resistance was reported to be a significant problem in coastal locations, but only a minor problem in other areas. Coastal regions not only are extremely favorable for mosquito breeding, but a high proportion of the state's population (79%) dwells along the coast, so there is frequent need for chemical suppression.

Landscape plants seem to be relatively free of resistance problems. Woody ornamentals are not usually planted in large single-species stands, which may help them to avoid development of high pest populations. Such landscape plants often tolerate considerable defoliation or pest density without obvious symptoms, so chemical treatment is not a regular feature of landscape maintenance. Also, in recent years there has been a concerted effort to introduce native, hardy, pest-resistant plants into the landscape, reducing the need for insecticide treatment. Among landscape plants, perhaps only turfgrass is treated regularly, and the southern chinch bug, *Blissus insularis* Barber, exhibits some degree of resistance, particularly in southern Florida. Nursery production of landscape ornamentals is also an exception, and mites can present resistance problems in this environment.

Although the number of pests displaying resistance to pesticides has increased markedly in the last two decades, respondents generally did not see the resistance problem worsening greatly in the next 10 years. The only exception was the area of household pest management, where the situation is anticipated to become critical. This generally optimistic attitude likely reflects faith in the agrichemical industry, which has continued to introduce novel pesticide chemistry or biorational materials that allow producers to continue with traditional agriculture and pest control practices despite increasing numbers of pests that have become somewhat resistant to one or more pesticides. The scientific community has also responded quickly and effectively to the onset of resistance by identifying alternative pest control chemicals and by helping to integrate other types of pest suppression into traditional production systems.

The Extent of Resistance

Respondents were asked to indicate whether resistance applied to: a few compounds, numerous compounds, a few pests, or numerous pests. Up to two responses were possible. Respondents were also asked to designate how many pests or compounds were affected and to indicate either a specific number or range.

The extent of the resistance problem was reported to be variable, depending on whether the focus was the number of pests or pesticides. Resistance was generally reported to be limited to few pests in each commodity or environment. The number of resistant species was generally reported to be 3-5 per respondent, with a range given as 1-10 per respondent. Although the number of species was small, the number of chemical compounds to which the pests were reported resistant was considerably larger. Respondents generally indicated that pests exhibiting resistance were resistant to 5-10 compounds. The range in the number of compounds was given as from 1 product to all those on the market.

The Context of Pesticide Resistance

Respondents were asked to indicate if particular pests, crops, or environments existed in which resistance occurred more frequently.

Respondents most frequently indicated that high value, damage-sensitive crops were prone to have pesticide resistance problems. They cited greenhouse, floricultural, and vegetable crops as examples.

The environments next most frequently cited as having resistance problems were those in which frequent or routine pesticide applications were made. Of course this corresponds to the aforementioned high value crops, but there are also situations in which value and damage sensitivity are not a major issue; examples are households, livestock, and certain field crops.

Only infrequently were the biological characteristics of the pests cited as favoring frequent occurrence of resistance. Pests with short generation times and high intrinsic rates of increase were suggested to be more prone to display resistance.

The Pattern of Pesticide Resistance

Respondents were asked if there were any patterns evident wherein entire classes of pesticide compounds or groups of arthropods displayed a tendency toward increased frequency of resistance, or whether resistance applied only to specific materials or pests.

Patterns of pesticide resistance related to chemical or biological taxon were not especially evident to our respondents. Many said that pesticide resistance was species-specific, that biological taxon was not a very good predictor of resistance problems. A few, however, suggested that whiteflies, thrips, and especially mites were resistance prone. Similarly, although cross resistance within chemical classes was acknowledged, respondents indicated that they generally considered each pesticide to have unique chemical properties, so that development of resistance was difficult to predict based on chemical taxon. The exception to this generalization seems to be the pyrethroids, where there is general acknowledgment that resistance is likely to develop.

Instances of Pesticide Resistance

Respondents were asked to name specific instances of pesticide resistance, including the pesticide, pest, and approximate date, and also to indicate whether the information on resistance was "documented" or anecdotal.

Instances of pesticide resistance in Florida provided by respondents are shown in Table 1. Surely this is not a complete list, either of pests or problem pesticides, but serves to demonstrate adequately the diversity of arthropod taxa affected. Also, arthropods found in numerous environments or crop systems are affected, and some historical trends are evident. Respondents acknowledged that only about one-half of the purported cases of resistance are "documented," with the remainder based on anecdotal information. However, we carefully selected experienced entomologists and asked them to respond only in their area of expertise. Thus, we are confident that instances of misapplication and other potential sources of erroneous reports of resistance are not included. Because some of the "documented" resistance is from industry sources and not accessible to us, we have not included this specific information. Note also that this table does not include information on the leafminer *L. trifolii* and the diamondback moth, two insects with well-documented histories of insecticide resistance in Florida. A review of insecticide resistance in these two troublesome insects follows.

INSECTICIDE RESISTANCE IN *L. TRIFOLII*

Past and Present Situation

Prior to 1945, leafminer problems on celery and other vegetables in Florida were apparently almost nonexistent. Control consisted mainly of clean-up measures and application of nicotine sulphate (Wolfenbarger 1947). Wolfenbarger (1947) recommended chlordane for control of leafminer on potatoes in south Florida. Harris (1962) reported that dimethoate, which was not labeled for celery, and diazinon and naled which were labeled, could control leafminer on celery in 1962. Genung et al. (1979) reported that with the use of diazinon, naled, and azinphos-methyl, the mortality of vegetable seedlings and yield reductions declined and leafminer populations remained low until 1974, when they began to heavily infest celery and tomato. Genung et al. (1979) reported that in 1974 growers could not control leafminers on celery with diazinon, naled, or azinphos-methyl and that dimethoate, which was approved for use on celery the same year, also did not give the desired level of control. Poe & Strandberg (1979) reported that oxamyl, which was approved for use on celery in 1975, was effective for about two years. They also reported that in 1976 and 1977 leafminer on celery was uncontrollable in Florida by any insecticide labeled for use. Florida growers acquired the use of methamidophos in 1977 and permethrin in 1978 for the control of leafminer on celery. Permethrin became ineffective for leafminer control on celery in less than two years. Methamidophos was then considered the only insecticide that gave any amount of control in celery in Florida, and it was considered marginally effective. The possibility of effective chemical control did not come until the spring of

TABLE 1. EXAMPLES OF INSECTICIDE AND ACARICIDE RESISTANCE IN FLORIDA CITED BY RESPONDENTS IN A 1994 SURVEY OF PUBLIC SECTOR ENTOMOLOGISTS.

Arthropod	Date (decade)	Pesticide
House fly	1940	DDT
Musca domestica (L.)	1950	chlordane, dieldrin, lindane, malathion
	1970	dimethoate, ronnel, tetrachlorvinphos
	1980	cyromazine, methomyl, various pyrethroids
German cockroach	1950	chlordane, dieldrin, lindane
Blatella germanica (L.)	1960	allethrin, diazinon, malathion
	1970	carbaryl, propoxur
	1980	cyfluthrin, cypermethrin
Cat flea	1950-70	diazinon, malathion
Ctenocephalides felis	1970-80	bendiocarb, carbaryl, propoxur
(Bouché)	1980-90	cyfluthrin, fenvalerate, permethrin
Horn fly *Haematobia irritans* (L.)	1980	fenthion, fenvalerate, flucythrinate, permethrin, stirophos
Salt marsh mosquito	1950	DDT
Culex nigripalpus	1960	malathion
Theobald	1990	methoprene
Soybean looper *Pseudoplusia includens* (Walker)	1970	acephate, methomyl, various pyrethroids
Fall armyworm *Spodoptera frugiperda* (J. E. Smith)	1970-80	malathion, carbaryl, methyl parathion, diazinon, trichlorfon, fluvalinate, bifenthrin, tralomethrin
Southern green stinkbug	1970	carbaryl, methomyl
Nezara viridula (L.)	1980	endosulfan
Tobacco budworm *Heliothis virescens* (Fabricius)	1970	ethyl parathion
Corn earworm	1950-60	malathion, diazinon,
Helicoverpa zea (L.)	1960-70	ethyl parathion, carbaryl
Pepper weevil *Anthonomus eugenii* Cano	1990	fenvalerate, permethrin, oxamyl
Beet armyworm *Spodoptera exigua* (Hübner)	1980	chlorpyrifos, methomyl
Tomato pinworm	1970	carbaryl
Keiferia	1980	methomyl, fenvalerate
lycopersicella (Walsingham)	1990	oxamyl
Western flower thrips *Frankliniella occidentalis* (Pergande)	1980	pyrethroids
Mole crickets *Scapteriscus* spp.	1970	chlordane

TABLE 1. (CONT.) EXAMPLES OF INSECTICIDE AND ACARICIDE RESISTANCE IN FLORIDA CITED BY RESPONDENTS IN A 1994 SURVEY OF PUBLIC SECTOR ENTOMOLOGISTS.

Arthropod	Date (decade)	Pesticide
Green peach aphid *Myzus persicae* (Sulzer)	1970-80	malathion, diazinon, oxydemeton-methyl, dimethoate
Cabbage looper	1950-60	DDT, toxaphene, parathion
Trichoplusia ni	1960-70	endrin, mevinphos, naled
(Hübner)	1970-80	methomyl
Cowpea curculio *Chalcodermus aeneus* Boheman	1980	endosulfan
Citrus rust mite *Phyllocoptruta oleivora* (Ashmead)	1990	dicofol
Yellow pecan aphids *Monellia caryella* (Fitch), *Monelliopis pecanis* Bissell	1980	various pyrethroids
Silverleaf whitefly *Bemisia argentifolii* Bellows & Perring	1990	bifenthrin, fenvalerate, permethrin, endosulfan
Two-spotted spider mite	1980	fenbutatin-oxide
Tetranychus urticae Koch	1990	avermectin
Melon aphid *Aphis gossypii* Glover	1990	acephate

1982 when the celery industry secured the use of cyromazine. With the use of cyromazine, leafminer problems were considered under control until late 1989 when an unusual lack of efficacy occurred in the Everglades area.

Laboratory studies confirmed the presence of a high level of cyromazine resistance in a suspect strain of *L. trifolii* (G. L. L., unpublished data). Larval mortality in the resistant strain at 300 ppm of cyromazine, the highest label concentration used in the field, was low enough to explain the loss of efficacy. The cyromazine resistance was expressed as an incompletely recessive trait and not sex-linked. Backcrossing suggested that the resistance was conferred by a major gene. The resistance was considered unstable since sensitivity returned in the resistant strain (from an LC_{50} of about 440 ppm to an LC_{50} of about 85 ppm) within 5 generations of laboratory rearing without selection. This was consistent with a survey of leafminer populations that indicated susceptibility to cyromazine had returned during the summer of 1990 (J. S. Ferguson, unpublished data). This reversion was probably due to the immigration of susceptible individuals during what is traditionally a period of little or no celery production and very little use of cyromazine.

The cyromazine-resistant strain was not resistant to abamectin (G. L. L., unpublished data), the only logical alternative insecticide available for control of leafminer in celery. This information contributed to the granting of a crisis exemption (Section 18, FIFRA) in early 1990 for the use of abamectin in celery to control leafminer. Further efforts of the Florida Fruit and Vegetable Association, celery growers, CIBA, Merck Research Laboratories, and the University of Florida resulted in the subsequent granting by the EPA (Section 18, FIFRA) in October 1990 of a specific exemption for the use of abamectin in celery. Since then, abamectin has been used in celery under specific exemptions. These specific exemptions are unique in that, in order to discourage the onset of resistance to abamectin, only two consecutive applications are allowed, forcing rotation with another insecticide. However, no other effective insecticide was available for rotation except for cyromazine which, due to reversion, had become efficacious again. Since cyromazine and abamectin have different modes of action and no cross resistance was indicated, cyromazine was included in the leafminer control program under well-defined resistance management guidelines.

Management of Cyromazine Resistance in *L. trifolii*

A program for managing cyromazine resistance in *L. trifolii* was presented to celery growers. The goal of this program was to control L. trifolii while increasing and preserving susceptibility to cyromazine and minimizing the possibility of selecting for resistance to abamectin. Cyromazine use patterns and celery culture were suggested that would reduce selection of resistant phenotypes and encourage the immigration of feral, hopefully susceptible, leafminers into resistant populations.

Recommendations included: using noninfested transplants; initiating the spray program based on a threshold to reduce the number of insecticide applications; starting with abamectin to maximize early control; rotating two sprays of abamectin with two sprays of cyromazine to avoid excessive use of one insecticide; finishing a planting with two applications of abamectin to reduce the number of adults emerging from the soil and the trash after harvest; disking in trash as soon as possible to remove this source of leafminers; and not using pyrethroids, such as permethrin and esfenvalerate, to minimize adverse effects on parasites and predators.

In addition, since acreage is very low in the production fields as harvesting ends (June) and the transplanting begins (September), it was recommended to not use cyromazine during the summer (June through September) to prevent the continued selection of isolated populations and to encourage the immigration of susceptible individuals when celery acreage is at its lowest. Except for seedling production, July and August are otherwise free of celery. Not using cyromazine at all in seedling beds was recommended, since transplanting from infested seedling beds is considered an important mechanism for transferring resistant leafminers to the production fields. Lastly, seedlings were recommended to be grown distant from the field production areas to reduce the chances of infestation by resistant leafminers.

Insecticide Resistance in the Diamondback Moth

Past and Present Situation

Historically, the diamondback moth was considered a minor pest, usually included in a complex of cabbage caterpillars along with the cabbage looper and the imported cabbageworm, *Artogeia rapae* (L.), but of much less importance. Control recommendations for the diamondback moth generally have been the same as for the other cabbage caterpillars (Sanderson 1921, Metcalf & Flint 1939, Watson & Tissot 1942, Metcalf et al. 1951, 1962). Prior to the mid-1940s, insecticides used for cabbage caterpillar control included nicotine, arsenicals, pyrethrum, rotenone, kerosene, and hot water (150°F), and from the mid-1940s through the 1970s included DDT, toxaphene, parathion, methoxychlor, mevinphos, endosulfan, naled, methomyl, and methamidophos. *Bacillus thuringiensis* was also available, but was not used extensively due to expense and the perception of less than desirable control. In the early 1980s growers switched to the newly available and extremely effective pyrethroids, permethrin and fenvalerate for control of the cabbage looper and diamondback moth, both of which had become difficult to control with the other insecticides.

Insecticide resistance had long been suspected as the cause of the poor cabbage looper control (Genung 1957, Workman & Greene 1970), and Shelton & Soderlund (1983) showed that a population from Florida was one of the most resistant to methomyl in the eastern U.S. The poor control of diamondback moth has been attributed to the destruction of parasites by excessive use of insecticides, such as methomyl, which were applied for cabbage looper suppression, but which were relatively ineffective on diamondback moth. However, the poor control of diamondback moth may have actually been the earliest indications of resistance problems.

Permethrin and fenvalerate proved to be very effective for control of all cabbage insects until the mid-1980s when growers observed that these insecticides were no longer providing effective control of the diamondback moth. University trials reflected the same lack of control with fenvalerate (Leibee 1986) and from the winter of 1986-87 to the present, pyrethroid insecticides provided poor control of diamondback moth at Sanford, FL (G. L. L., unpublished data). Magaro & Edelson (1990) noted that failures to control diamondback moth in south Texas were first reported by cabbage producers in the spring of 1987. Leibee & Savage (1992b) reported a high level of resistance to fenvalerate in a laboratory strain of diamondback moth collected in central Florida in 1987.

Loss of efficacy with pyrethroids for control of diamondback moth caused growers to switch to intensive use of several organophosphates, endosulfan, and *B. thuringiensis* subspecies *kurstaki* (Btk), all of which did not provide the level of control provided by pyrethroids prior to resistance. At present, many diamondback moth populations have become very difficult to control with any of the registered synthetic insecticides and Btk.

The presence of Btk resistance in Florida was immediately suspected because Btk resistance in diamondback moth had been reported in Hawaii (Tabashnik et al. 1990), Japan (Tanaka & Kimura 1991), and Malaysia (Syed 1992); it was eventually confirmed for Florida (Leibee & Savage 1992a, Shelton et al. 1993). With the presence of Btk-resistance, there were essentially no effective insecticides available for control of many diamondback moth populations in Florida until the recent introduction of *B. thuringiensis* subspecies *aizawai* (Bta)-based insecticides. Bta-based insecticides (those possessing the Cry1C toxin) are being successfully used in areas where Btk-based insecticides have failed. Lack of resistance to Bta in diamondback moth resistant to Btk has been documented in Japan (Hama et al. 1992), Malaysia (Syed 1992), and Florida (Leibee & Savage 1992a, Shelton et al. 1993).

Diamondback moth abundance has been considered low for several seasons in central Florida (G. L. L., personal observation). This is due in part to the return of substantial amounts of natural control from parasites, which in turn is attributed to reduced pyrethroid use. Growers are not spraying as frequently for diamondback moth and are able to use Btk-based insecticides, suggesting a return of susceptibility to Btk.

Management of Resistance in the Diamondback Moth

Crop culture and control recommendations were made that would reduce the selection of resistant phenotypes of diamondback moth and encourage the immigration of feral, hopefully susceptible, individuals into resistant populations. These recommendations were based on the following knowledge. Susceptibility to Btk had been greatly reduced in some populations. *Bacillus thuringiensis* resistance in diamondback moth in Hawaii was shown to be inherited as a recessive trait (Tabashnik et al. 1992) and observations from field and laboratory studies in Florida suggested the same (G. L. L., unpublished data). *Bacillus thuringiensis* subspecies *aizawai*-based products (those possessing the Cry1C toxin) appeared to be effective in populations where Btk susceptibility was reduced. Tank-mixing Bt with mevinphos was shown to be quite effective at reducing infestations in early season (G. L. L. unpublished data); however, the use of mevinphos was to be discontinued in 1995, eliminating the most effective insecticide other than Bt for diamondback moth control on cabbage in Florida. Use of pyrethroids and carbamates can select for resistance that might further reduce the efficacy of organophosphate insecticides and endosulfan, and also destroy the parasites and predators providing natural control of the diamondback moth.

Crop culture recommendations included: not growing cabbage in the warmest months (May through September in central Florida) when insect pressure is the highest and Bt-based insecticides are the least efficacious; immediately disposing of crop residues to prevent migration from heavily selected populations into new plantings and seedling production areas; and using noninfested transplants, which not only contributes to control but also reduces spread of diamondback moths to new locations. Diamondback moths that infest purchased transplants may be highly resistant due to heavy usage of insecticides on the transplants or in fields near transplant production areas. Producers growing their own transplants are at an advantage because they have more control over infestation levels and have specific knowledge about the resistance problems in their production areas.

Control recommendations included: inspecting crops frequently (about twice per wk) to determine the presence of the pest of concern or unexpected pests; beginning inspections at the seedling stage because reducing infestations in early season appears to be critical to managing diamondback moth; minimizing insecticide applications whenever possible by using action thresholds developed through research or by intuition; and using pheromone traps to monitor the presence or absence of diamondback moth before and during the growing season, and also for monitoring peaks of adult activity (Baker et al. 1982) for timing insecticide applications.

Specific insecticide recommendations included: using Btk and Bta as the principle insecticides for control of diamondback moth; if the population was known to be susceptible to Btk, alternating a Bta-based product with a Btk-based product to avoid repetitive applications of the same insecticide to reduce the selection of resistance to any one product; using only Bta to insure maximum control if Btk resistance was known to be present or the status of Btk susceptibility was unknown; applying Bt twice weekly and tank-mixing with mevinphos weekly, starting with the tank-mix to maximize the control that is critical early in crop; including endosulfan, chlorpyrifos, and methamidophos as alternatives or substitutes for mevinphos in the tank-mixes with Bt, especially endosulfan, since it belongs to a different chemical class than mevinphos; avoiding the use of carbamates; and, not using pyrethroids.

Observations on Insecticide Resistance in *L. trifolii* and Diamondback Moth

Probably the greatest factor contributing to the development of insecticide resistance in *L. trifolii* and diamondback moth was long term and frequent use of single insecticides or classes of insecticides. However, celery and cabbage cultural practices in Florida probably contribute to the rapidity and degree with which insecticide resistance develops in these two insects. Both crops are grown in relatively small and isolated areas, or pockets, of agricultural activity. In addition, both crops are grown in some form year round. This isolation and the lack of a substantial crop-free period result in the containment and “cycling” of resistant populations. This results in the same population being exposed to insecticides continually. In addition, the constant use of insecticides removes susceptible individuals that may be immigrating into the population, thus preventing the opportunity for reversion.

These factors are believed to be especially evident with the development of high levels of resistance in the diamondback moth in the 1980s. Several changes in the production of cabbage in the 1980s contributed greatly to the "cycling" of resistant populations in the production areas and the movement of resistant populations between production areas within and outside Florida. Among these changes was the lengthening of the crucifer production period by harvesting later in the spring and transplanting earlier in the summer. Prior to this situation, much of the summer (June-September) in central Florida was basically a crucifer production-free period and diamondback moth populations were very low. Crucifer production was thrust into the warmer, drier parts of the year when diamondback moth became more of a problem, resulting in increased use of insecticides and subsequent exposure of additional generations to more selection pressure. With development of the container grown transplant industry and the ability to grow transplants in the summer, a situation was eventually created in which crucifers were continually produced throughout the year in the same localities, either as transplants or field crops, or both. Insecticide resistant diamondback moth could move from the fields to transplants in the summer, and be redistributed back to the fields in late summer and early fall. Therefore, heavy populations of resistant diamondback moth were being perpetuated locally throughout the year and continually exposed to insecticides. Opportunities for the return of susceptibility by the immigration of individuals with susceptible phenotypes was essentially eliminated.

Transplants probably were a major factor in the development of resistance problems in diamondback moth on a national level during the 1980s; container-grown transplants were popular and a healthy containerized transplant industry developed in the south. Much of the transplant production in the south in the winter and spring supplied more northern growers with transplants to establish stands in the spring when environmental conditions were not conducive to direct seeding. Transplants were also produced during summer months in the north to facilitate establishment of stands in the south when soil temperatures are too high for germination.

Transplant growers likely were oblivious to the fact that they were shipping resistant diamondback moth. They were probably controlling the later larval stages that cause obvious damage and shipping what appeared to be uninfested plants. Adults flying into the open-sided greenhouses from the field could maintain a supply of eggs and early mining instars before shipment. In addition, larvae have been observed to be deep inside the bud of the transplant, out of reach of the insecticide and the eye of the grower. It is possible that avoidance of the insecticide deposits drives diamondback moth larvae emerging from the leafmine into the bud.

Another aspect of the transplant industry that could have contributed to the development of resistance was that only a few large growers in areas of high levels of resistance produced most of the transplants used in Florida and the rest of the U.S. This greatly increased the probability of many growers receiving transplants from areas with resistant diamondback moth populations.

Conclusion

The results of the survey attest to the impact of insecticide resistance on past and present pest management in Florida. The review of resistance problems with *L. trifolii* and diamondback moth illustrates how insecticide resistance can complicate the management of pestiferous arthropods. Insecticide resistance seems to be pervasive in Florida, suggesting that we are not adequately considering the consequences of the way we use pesticides. Resistance management strategies should be integrated with nonchemical control whenever possible. In the case of the aforementioned *L. trifolii* and diamondback moth problems, crop management (isolation and continuous cropping) were key factors in development of resistance.

In most cases, pesticides are the most efficient, easiest, and cheapest methods of controlling pestiferous insects and mites. The number of pesticides available is dwindling rapidly, however, due to cancellation of registrations and lack of re-registration. As a result, the conservation of arthropod susceptibility to the remaining pesticides, and to newly developed pesticides, is becoming extremely important. Unfortunately, we have not made adequate effort to conserve susceptibility of arthropods to pesticides. The minimum effort should include development of baseline data that would allow the investigation of potential resistance episodes in a timely manner. Conserving pesticide susceptibility takes the development of knowledge and a commitment from those responsible for producing, using, and conducting research on pesticides. Thus, educational efforts should be enhanced.

Something everyone can do to help manage resistance to any pesticide is to refine its use. Application of the correct amount and type of insecticide in a timely and efficient manner would help forestall the onset of resistance, particularly if nonchemical techniques could be used to reduce the numbers and frequency of application. This is best accomplished following research on, and implementation of, IPM strategies. Increasingly, pesticide resistance management must be considered an important component of IPM.

ACKNOWLEDGMENTS

We gratefully acknowledge the assistance of the following individuals who gave generously of their time to make the survey component of this paper possible: Joe Funderburk, Jerry Hogsette, Freddie Johnson, Joe Knapp, Phil Koehler, Russ Mizell, Charlie Morris, Lance Osborne, Jim Price, Dakshina Seal, Dave Schuster, Phil Stansly, and Simon Yu. We are also grateful to Brett Highland for his critical review of the manuscript. Florida Agricultural Experiment Stations Journal Series No. R-04551.

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