MULTITACTIC RESISTANCE MANAGEMENT: AN APPROACH THAT IS LONG OVERDUE?

MARJORIE A. HOY
Department of Entomology and Nematology
University of Florida, Gainesville, FL 32611-0620

ABSTRACT

"Resistance management" tactics have been much discussed, but such tactics have provided surprisingly limited practical results for pest management programs to date. We have learned a great deal about pesticide resistance mechanisms, the mode of inheritance of resistances, the molecular basis of resistance and cross resistance mechanisms, and how to evaluate the impact of resistance on fitness. However, it remains difficult to "manage" resistance once resistant individuals make up more than 5 to 10% of the population. Generally, the best that can be achieved is to *delay* the development of high levels of resistance for a few years, most often by using the product less often.

A more effective resistance management strategy will combine a variety of effective pest management tactics along with a reduction in numbers and rates of pesticides applied. Effective pest management tactics include monitoring, evaluating economic injury levels so that pesticides are applied only when needed, biological control, host plant resistance, cultural controls, biorational pest controls, and genetic control methods. As a part of this multi-tactic strategy, it is crucial to evaluate the impact of pesticides on natural enemies. Sometimes, pesticide-resistant natural enemies can be effective components of a program to delay the development of resistance in pest arthropods.

Key Words: Pesticide resistance, integrated pest management, biological control, pesticide selectivity, resistance management.

RESUMEN

Las tácticas de manejo de la resistencia han sido muy discutidas pero sorprendentemente, hasta la fecha, tales tácticas han dado resultados prácticos limitados en programas de manejo de plagas. Hemos aprendido mucho sobre los mecanismos de resistencia, el modo de heredarse, sus bases moleculares y los mecanismos de resistencia cruzada, así como a evaluar el impacto de la resistencia en el ajuste genético. Sin embargo, es aún difícil manejar la resistencia cuando los individuos resistentes integran más del 5-10% de la población. Generalmente, lo mejor que se ha logrado ha sido retrasar en varios años el desarrollo de altos niveles de resistencia en la población, más a menudo usando menos f recuentemente el producto que la provoca. Una estrategia más efectiva de manejo de la resisitencia combinaría una variedad de tácticas eficaces de manejo de plagas con la de reducir el número y dosis de los pesticidas aplicados. Las tácticas efectivas de manejo inculyen el monitoreo, la evaluación del daño económico de modo que los pesticidas sean aplicados solamente cuando es necesario, el control biológico, la resistencia de las plantas hospedantes, el control cultural, el control biorracional de plagas, y los métodos de control genético. Como parte de esta estrategia multitáctica, es crucial evaluar el impacto de los pesticidas en los enemigos naturales. A veces, los enemigos naturales resistentes pueden ser conponentes efectivos de un programa para retrasar el desarrollo de la resistencia en los artrópodos plagas.

This commentary will make the following argument: "integrated pest management" (IPM) and "management of pesticide resistance in pest arthropods" (MPR), which are usually perceived to be distinct topics for research, should be considered to have equivalent goals and methods. When we accept that the goals and tactics are similar, we will develop effective resistance management programs for arthropods. Effective management of resistance and effective IPM programs require an holistic and multitactic strategy. A key component of this holistic and multitactic approach includes enhancing the *compatibility* of pesticides and biological control agents (Hoy 1992).

Resistance to pesticides is an extremely significant problem internationally, nationally (Georghiou 1986, Roush & Tabashnik 1990), and within Florida (Leibee & Capinera, this volume). At least 440 arthropod species have become resistant to insecticides and acaricides, with many species having become resistant to all the major classes of such products (Georghiou & Saito 1983, Georghiou 1986, Roush & Tabashnik 1990). Resistance to pesticides in weeds, plant pathogens, and nematodes also is increasing, although somewhat more slowly (National Academy of Sciences 1986, Denholm et al. 1992). While my commentary focuses on resistance to insecticides and acaricides, it will probably be applicable to fungicides, herbicides, and nematicides.

Developing and registering a new pesticide is an elaborate, and increasingly expensive, business in the USA (Georghiou 1986) with costs estimated to be more than

$60 million per successful compound. Thus, pesticide producers should be increasingly interested in extending the economic life of their products in order to maximize a return on their investment.

Likewise, most pest management specialists want to preserve registered pesticides. This is especially true for products that are effective against arthropod pests in minor crops, which are increasingly being ignored by pesticide companies because they are such a small market. These so-called 'minor' crops of fruits and vegetables are a major component of Florida's agriculture. Registration of new pesticides is likely to be more difficult and expensive in the future, which could leave some pest management specialists with extremely limited options for managing certain recalcitrant pests.

A few environmentalists have argued that we do not need pesticides, that they will soon be outlawed, and that pesticide resistance will no longer be an important issue. However, it is unrealistic to eliminate all pesticides from agriculture; there are significant arthropod pests for which we have no other effective control tactic. Pesticides are the most effective tools for fighting outbreaks and emergency arthropod pest problems, and they are often required to control plant pathogens, weeds, or nematodes that cannot be controlled by alternative methods.

RESEARCH APPROACHES TO RESISTANCE MANAGEMENT

Scientists have approached the problem of pesticide resistance in a variety of ways. Fundamental research over the past 40 years has produced insights into resistance mechanisms (Corbett et al. 1984, Scott 1990, Soderlund & Bloomquist 1990) and the mode of inheritance of resistance in arthropods (Georghiou & Saito 1983, Scott 1990, Soderlund & Bloomquist 1990). Simulation models have been developed to evaluate different options for managing resistance (for a recent review, see Tabashnik 1990), but the debate over whether to recommend (1) alternation of different pesticides or (2) mixtures of different pesticides for slowing the development of resistance remains controversial and field-tested experimental data available are not strong enough to support either model (Roush & Daly 1990, Tabashnik et al. 1992). The hypothesis that reduced fitness, which is often associated with resistance alleles, could be used in management programs continues to be controversial and may have limited application (Tabashnik 1990). Not all resistance alleles confer lowered fitness (for example, Hoy & Conley 1989, Hoy 1990) and natural selection can select for modifying genes that restore fitness to individuals carrying resistance alleles. Various monitoring techniques have been developed to identify resistant individuals and detect their establishment and spread (ffrench-Constant & Roush 1990). These methods are particularly useful for documenting that resistance has occurred. However, monitoring methods that would allow us to detect rare resistant individuals in populations in sufficient time that operational programs could be altered remain difficult and expensive to execute (Brent 1986).

Resistance management research programs and IPM research programs have had fairly distinct identities to date (Denholm et al. 1992, Croft 1990b, Hoy 1992). Because they have been distinct, an effective paradigm for resistance management has not been adopted in US agriculture. The current scenario usually goes something like this: A pesticide is registered and used, resistant individuals are detected in populations, people begin to discuss developing and implementing a resistance management program. With this short-sighted approach, it is exceedingly difficult to develop and execute a program in sufficient time to have the desired results.

Developing a resistance management program can take several years; studies typically are conducted to develop an appropriate monitoring method, estimate the frequency of resistant individuals in populations, detect cross resistances, and evaluate mode of inheritance and stability of the resistance (Roush & Daly 1990). Meanwhile, unless pesticide applications are discontinued, selection for resistance continues. Initial detection of resistance usually requires that resistant individuals comprise at least 5% of the population (Brent 1986). Thus, by the time resistant individuals are detected, selection by additional pesticide applications is likely to increase their frequency in the population. This scenario is particularly familiar with multivoltine and highly fecund pests such as aphids, spider mites, whiteflies, and leafminers.

Although we can learn from the experiences of scientists studying pesticide resistance in ubiquitous pests in other geographic regions and thus be alerted to a potential problem, this seems to be an inefficient method for managing resistance in arthropods. Furthermore, this approach may be misleading because geneticists recognize that different species or different geographic populations may develop resistance to a particular toxic chemical by a variety of mechanisms. The mechanisms, their mode of inheritance, and the degree of reduction in fitness associated with them may vary, because the resistance alleles at each site are different. Because it is difficult to sample for rare individuals in natural populations, monitoring programs may not be cost effective if employed other than as a method to document a problem once it has developed. Waiting until the pest becomes resistant before instituting a resistance management program is ineffectual (Hoy 1992).

RESISTANCE AND IPM

A better paradigm for managing resistance in arthropods involves altering pesticide use patterns, and nearly everyone will agree that reducing pesticide use is an effective resistance management tactic (Croft 1990a, Tabashnik 1990, Leeper et al. 1986). What has not been widely acknowledged is that resistance management programs should include: 1) Altering the way pesticides are developed and registered, and 2) Recognizing that resistance management must be a broad-based, multitactic endeavor (Hoy 1992, Fig. 1).

It seems reasonable, conservative, and fiscally-responsible to assume that nearly all major insect and mite pests will eventually become resistant to all classes of pesticides given sufficient selection pressure over sufficient time. There may be some exceptions, but this generalization is reasonable given the documented record of resistance development in arthropod pests during the past 40 years. Resistance to stress is a fundamental and natural response by living organisms (Scott, this volume). On an evolutionary time scale, it is apparent that insects will develop multiple and diverse mechanisms to survive extreme temperatures, allelochemicals, and other environmental stresses. Thus, we should expect most insects to develop resistance to most pesticides, if subjected to appropriate and sustained selection. While new pesticide classes have been proclaimed to be potential ‘silver bullets’, and not amenable to resistance development, these hopes have been misplaced to date. It seems appropriate to assume that the development of resistance is nearly inevitable and the issue is not *whether* resistance will develop, but *when*. With this assumption, resistance management programs have the goal of *delaying* rather than preventing resistance (Hoy 1992).

Growers and pest management experts can not afford to rely on pesticides as their primary management tool, as has been done for the past 30 years. There are increasing social, economic, and ecological pressures to reduce pesticide use and to increase the use of nonchemical control tactics such as host plant resistance, biorational methods, cultural controls, and biological controls (National Research Council 1989, Office of Technology Assessment 1992). There is an increasing priority by research scien-

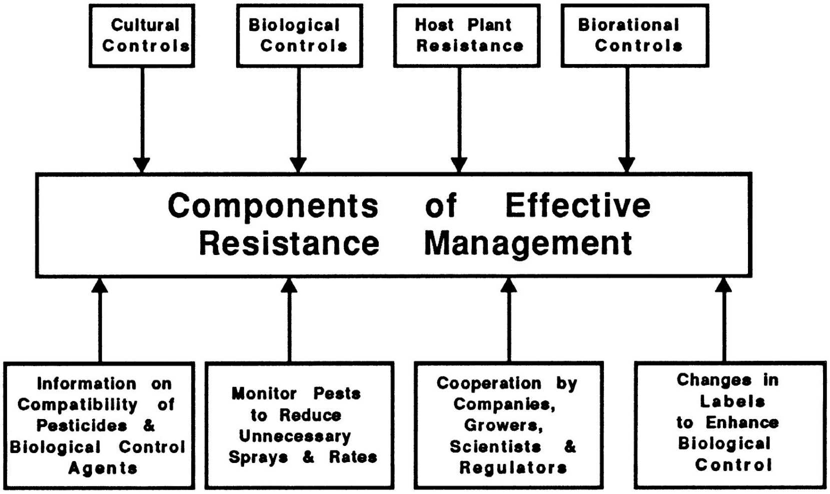

Figure 1. Effective resistance management programs will incorporate multiple tactics as part of a fully integrated IPM program. Pesticides should be used only when needed, at the lowest rates possible, and in a manner to reduce negative impacts on arthropod natural enemies. Pesticide labels should include information about its impact on natural enemies.

tists, regulatory agencies, legislators, and the public on using pesticides that are nontoxic to biological control agents and have minimal impact on the environment. Compatibility of pesticides with natural enemies and other nonchemical tactics is critical for improving pest management and environmental quality, and for managing resistance to pesticides. Enhancing the compatibility of pesticides and biological control agents is complex and sometimes difficult (Croft 1990a, Hoy 1985a, 1990), but can reward us with handsome dividends in improved pest control (Metcalf 1994) and pesticide resistance management (Tabashnik & Croft 1985).

The way pesticides are registered should be changed as part of an effective resistance management strategy (Hoy 1992). These changes also are essential in achieving improved integrated pest management. For example, some pesticides are relatively nontoxic to important natural enemies in cropping systems at *low rates*, but the recommended application rates are too high (Hoy 1985b). These high rates disrupt effective biological control, leading to additional pesticide applications, which exert unnecessary selection for resistance in the pest. Under these circumstances, it may be appropriate for the label to contain two different directions for use; one rate could be recommended for the traditional strategy of relying on pesticides to provide control (although this is becoming a less and less viable option). A lower rate could be recommended for use in an IPM program that employs effective natural enemies. This approach to labeling could reduce the number of pesticide applications and reduce rates, resulting in reduced selection for resistance in both target and nontarget pests.

Another innovation in pesticide registration would require that the toxicity of the pesticide to a selected list of biological control agents be determined for each cropping system. This information should be provided, either on the label or in readily-available computerized data bases, perhaps via the internet. Without such information, use of these pesticides could disrupt benefits derived from effective biological control agents.

This often results in unnecessary use of pesticides, leading to more rapid evolution of pesticide resistance. Enhancing biological control not only leads to improved pest management, but is also an essential tool in managing pesticide resistance.

How could information about the toxicity of pesticides to biological control agents be made available to the end user most effectively? How should bioassays be conducted to evaluate pesticide selectivity? There are no simple answers to these questions. Theiling & Croft (1988) and Croft (1990b) compiled an extensive set of data on the impact of pesticides on natural enemies, but additional data are also buried in many publications or reports that are difficult to find. Unfortunately, even if the data can be found, it is not always easy to interpret bioassay data obtained by different scientists using different methods. Thus, different conclusions about the toxicity of pesticides to natural enemies can be drawn. Also, it is often difficult to predict the impact of pesticides under field conditions based on laboratory assays (Hoy 1990, Hassan et al. 1991, Robertson & Preisler 1992). Consequently, the recommendation that labels or data bases be developed with information on the impact of pesticides on natural enemies requires considerable discussion and additional research. Should pesticide companies conduct the research using standard bioassay methods? Should a consortium of pest management scientists conduct the assays? Who should pay for the research? What species of natural enemies should be tested? These questions are not new, and in Europe standardized bioassays already are being conducted on selected natural enemy species by a scientific working group (Hassan et al. 1991). Whether this concept can be imported to the USA and Florida should be explored. Increased international consultation and cooperation between scientists, regulatory agencies, and pesticide companies could resolve many of the questions raised above.

Evolution of pesticide resistance has been shown by computer simulations of predator and prey systems to be slowed by reduced pesticide use (Tabashnik & Croft 1985, Tabashnik 1990). There is general agreement that reduced pesticide use is one of the essential elements of any resistance management program (Croft 1990b, Tabashnik 1990, Metcalf 1994). Thus, the compatibility of pesticides and biological control agents is a crucial issue in pesticide resistance management.

Attempts to manage pesticide resistance generally has involved making relatively minor tactical shifts in use patterns. What we need is a major shift in thinking about pesticide development and use, if we are to develop effective resistance management tactics. It is time to recognize that effective resistance management *begins* before the product is even registered (Figure 1). The strategy thus should be to manage the pesticide, even before it is fully developed and registered, with the goal of delaying resistance development. If this farsighted strategy is adopted, decisions on application rates and the numbers of applications per growing season will be made with the understanding that they affect the speed with which resistance will develop. In some cases, new products may not be developed because they are toxic to biological control agents and thus could disrupt effective IPM programs already in place. This would only speed up the development of resistance in specific pests.

Some people suggest that financial incentives may have to be provided to induce pesticide companies to develop and register products that are harmless to biological control agents (= physiological selectivity). Others argue that many pesticides can be applied in a manner that affords substantial selectivity (= ecological selectivity) if the timing, location, rates, and methods of application are altered (Hull & Beers 1985). Relying on ecological selectivity is more likely to be cost effective than developing large numbers of special use products with physiological selectivity. However, a complete financial analysis may indicate that, over the long term, selective pesticides (based both on physiological and ecological selectivity) are among the most cost effective approaches to managing resistance to pesticides.

The Role of Pesticide-Resistant Natural Enemies

Pesticide-resistant natural enemies are a special category of pesticide selectivity. Relatively few natural enemies have developed resistance to pesticides through natural selection, but several have been employed in effective IPM programs (Croft 1990a, Hoy 1990). Artificial selection of phytoseiid predators for pesticide resistance can be a practical and cost effective tactic for the biological control of spider mites (Hoy 1985a, b, 1990). Field tests have been conducted with several laboratory-selected phytoseiid species and some are being used in IPM programs. Laboratory selection of resistant strains of parasitoids and insect predators currently lags behind efforts with predatory mites, but several laboratory-selected insect natural enemies are being evaluated for incorporation into integrated pest management programs (Hoy 1994). The use of mutagenesis and recombinant DNA techniques could improve the efficiency of genetic improvement projects. However, development of pesticide-resistant natural enemies is time consuming and expensive and should not be considered before exploring other, less expensive, options for IPM and pesticide resistance management.

Conclusions

We need to maintain a source of pesticides because they are powerful and effective pest management tools. Pesticides can be highly selective, rapid in their impact, adaptable to many situations, and relatively economical. Thus, preserving pesticides is essential.

Effective paradigms for resistance management are not yet deployed in US and Florida agriculture. This is because resistance management and IPM have been considered separate issues. We need to recognize that effective resistance management is based on the development of effective, fully-integrated, multitactic IPM programs. Such programs will acknowledge the role of biological control, host plant resistance, cultural controls, and biorational controls, such as mating disruption, insect growth regulators, and mass trapping. A key issue should always be whether pesticides can be used in a precise and selective manner without disrupting the impact of natural enemies.

While altering the way in which pesticides are registered and labeled is difficult, the potential benefits are great for both IPM and resistance management programs. The dialogue should begin on how best to change pesticide labeling and develop databases on the selectivity of pesticides to natural enemies.

Acknowledgments

This is University of Florida, Institute of Food and Agricultural Sciences, journal series number R-04510. I thank D. C. Herzog for comments on the manuscript and the Florida Entomological Society for the opportunity to organize the symposium, “Myths of Managing Resistance”. A brief essay containing many of the ideas presented here has been published (Hoy 1992). The references cited provide an entre to the extensive literature on resistance and are not complete.

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