Reprinted from: INTEGRATED PEST MANAGEMENT (1976)
Edited by J. Lawrence Apple and Ray F. Smith
Book available from: Plenum Publishing Corporation
227 West 17th Street, New York, New York 10011



1

# The Origins of Integrated Pest Management Concepts for Agricultural Crops

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Most discussions of the conceptual origins of integrated pest management (IPM) for crop protection center on the overuse and overdependence of chemical pesticides following World War II and their subsequent unfavorable consequences. Included among examples of these unfavorable consequences are the development of chemical-pesticide-resistant insect and plant pathogen populations, rapid resurgence of target pest populations following treatment, outbreaks of unleashed secondary pests, and undesirable environmental effects. Then as the story goes, this series of mishaps was countered by the wisdom of a few omniscient soothsayers in the form of pest management. Another account described it as a mixture of "idealism, evangelism, pursuit of fashion, fund-raising, and even empire-building. The movement has indeed acquired the impetus and character of a religious revival. . . ." (Price Jones, 1970).

There are elements of veracity in both of these versions of the modern origins of IPM, but the fundamental origins are less simplistic and more remote in history. The evolution of the concept and its terminology spans a period of several decades and has been influenced greatly by changing technologies and societal values. Some crop protection specialists continue to discredit the concept as representing only new jargon applied to long-established crop protection

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practices. We acknowledge that IPM is not a disjunct development in crop protection—it is an evolutionary stage in pest control strategy—but it represents a new conceptual approach that sets crop protection in a new context within a crop production system. Many components of the IPM concept were developed in the late nineteenth and early twentieth centuries, but IPM as now conceived is unique because it is based on ecological principles and integrates multidisciplinary methodologies in developing agroecosystem management strategies that are practical, effective, economical, and protective of both public health and the environment. The early efforts of crop protectionists to control pests with ecologically based cultural methods were not satisfactory; consequently, entomologists, plant pathologists, and later weed scientists were preoccupied with the discovery of pesticides that were economical and effective. Unfortunately, chemical methods were often not used to supplement cultural methods but to supplant them. Our state of technology and understanding of host–pest interactions has evolved to the point that an integration of pest control tactics for the control of a given class of pest (e.g., insects, plant pathogens, etc.) and for multiple classes of pests is not only feasible but necessary given the inadequacies of single-method, single-discipline approaches and their potential for undesirable effects on nontarget beneficial and pest species.

The concept of integrated control was first articulated by entomologists (Smith and Allen, 1954; Stern *et al.*, 1959) as an approach that applied ecological principles in utilizing biological and chemical control methods against insect pests. It was subsequently broadened to include all control methods (Smith and Reynolds, 1965). The idea of "managing" insect pests populations was proposed by Geier and Clark (1961), and "pest management" was advocated by Geier (1970) in preference to "integrated control." The concept of pest management has now been broadened to include all classes of pests (pathogens, insects, nematodes, weeds) and in this context is commonly referred to as IPM with the implication of both methodological and disciplinary integration.

Although IPM terminology evolved principally within the ranks of entomology, elements of IPM are deeply rooted in plant pathology. Even prior to the demonstration of the pathogenic nature of plant diseases in the nineteenth century, but principally after that time, methods for "managing" plant diseases were developed.

## Evolution of Pest Control Practices

The history of man is a history of attempts to gain increasing control over the environment. At first this control was subminimal to the degree that poor shelter and unstable food supplies imposed population constraints. The gradual gain of man's capacity to control his environment parallels the gradual rise of civilization. But as man aggregated into villages and as he planted crops in clusters near rivers, he encountered increasingly severe attacks by pests against himself and his crops. For thousands of years, man could do nothing about these pests but appeal to the power of magic and a variety of gods. For the most part, he had to live with and tolerate the ravages of plant diseases and insects, but early man learned how to improve his conditions through "trial and error" experiences.

Prior to the emergence of the crop protection sciences and even before the biology of insects and the causal nature of plant diseases were understood, man evolved many cultural and physical control practices for protection of his crops. Many of these practices were subsequently proven to be scientifically valid even though they were derived mostly through empirical methods. Such methods now include sanitation (destruction or utilization of crop refuse, roguing of diseased plants, etc.), tillage to destroy overwintering insects and inoculum, removal of alternate hosts of pathogens and insects, rotation of crops to discourage buildup of damaging populations of insects and pathogens, timing of planting dates to avoid high-damage prone periods, use of insect- and pathogen-free seed and seedling methods, use of trap crops, selection of planting sites, pruning and defoliation, isolation from other crops, and management of water and fertilizers. Interestingly, laws were passed in Connecticut and Massachusetts to eradicate the barberry (Parris, 1968) as an alternate host for the stem rust of wheat (*Puccinia graminis*) even before this relationship was proven by DeBary in 1865.

The appropriate use of these cultural methods can reduce the damage potential to crops of essentially all pests and can provide economic control of many insect and disease pests. But there were many pests of high damage potential that could not be controlled adequately by early agriculturists by any combination of known cultural control methods. As biological knowledge grew during the eighteenth and nineteenth centuries and as pest problems became more severe resulting from an intensification of agriculture and the introduction of various pests into new areas, man became increasingly preoccupied with the search for more effective pest control measures. For plant diseases, this effort was stimulated especially by the introduction about 1872 of downy mildew (*Plasmopara viticola*) and powdery mildew (*Uncinula necator*) of grape from the United States into France on phylloxera-resistant root stocks. The result was devastating to the French wine industry. The late blight disease (*Phytophthora infestans*) epidemic on potatoes in Western Europe, especially in Ireland, during the 1840s resulted in widespread famine, starvation, and migration of human populations (Large, 1940). The need for effective control measures for diseases was urgent. The discovery during the 1850s that fungi may produce diseases of plants opened the way for the scientific study of agents to control diseases, and the principal search was for chemical compounds (Parris, 1968).

Various chemicals and concoctions were recommended for the control of insects and diseases as early as the eighteenth century (Lodeman, 1903). A liquid suspension of slacked lime and powdered tobacco was recommended during this period for the control of plant lice; various other concoctions of plant materials, animal manures, soot, dry ashes, sea water, urine, soap, turpentine, alcohol, farmyard drainage, and much more were recommended for insect and/or disease control. It appears that the gardeners of that day were of the persuasion that the effectiveness of a chemical or mixture was directly proportional to the offensiveness of its odor or taste.

No important changes took place in the materials used for the destruction of fungi or insects until about 1882 with Millardet's serendipitous discovery of "Bordeaux mixture" (quicklime and copper sulfate) in France. This set the stage for practical chemical control of plant diseases. Probably the destruction of the potato crop (*Solanum tuberosum*) in the United States by the potato beetle (*Leptinotarsa decemlineata*) prompted the discovery of Paris green about 1870, which ushered in the era of chemical insecticides (Lodeman, 1903). Much progress was made in the technique of chemical control of both plant diseases and insects during the last quarter of the nineteenth century—so much in fact that Lodeman (1903) was prompted to state that

> The best is generally the most profitable commodity, and the poorest is the least so; and the grower of today has it in his power to produce the best. It rests entirely with him whether his apples shall be wormy or not, whether his trees shall retain their foliage or lose it from disease. There are few evils that affect his crops which he cannot control, in many cases almost absolutely. Only a few diseases remain which still refuse to submit to treatment, but the number is rapidly decreasing, and the time will come when these also will disclose some vulnerable point which will allow for their destruction. . . . Foremost among the operations by means of which cultivated plants are protected from their enemies is spraying.

There was indeed optimism as early as the turn of the twentieth century that both diseases and insects would ultimately be controlled by chemical pesticides.

Cultural control of plant diseases was stimulated by the work of Sorauer in Germany, who was one of the first to demonstrate the predisposition of a host to infection by environmental conditions. This knowledge of the plant disease process is essential to the development of effective cultural control procedures since these aim chiefly at altering the environment as it affects the crop and pathogen, the interaction of crop and pathogen, and their interactions over time (Stevens, 1960).

Plants resistant to insects and diseases were recognized in the nineteenth century, but the deliberate development of pest-resistant varieties was not possible until after the rediscovery of Mendel's laws of heredity in 1900. Following this breakthrough, the approach was quickly exploited for the control of important plant diseases of cereal and other crops, but was pursued less vigorously for insect control until recent years.

The success with chemical control and host resistance in controlling plant pests distracted from the importance of cultural control in many instances. This situation prompted Stevens (1960) to conclude that the simplicity and general effectiveness of the host resistance and chemical control approaches had drawn attention away from cultural control to the point that it enjoyed less popular understanding and support. The plant pest control literature of the 1900–1965 period demonstrates clearly a preoccupation with the development of better resistant varieties (principally against pathogens) and better chemicals, but comparatively little attention was given to pathogen or insect ecology and cultural controls.

## Early Advocates of an Ecological Approach to Pest Control

As the agricultural experiment stations emerged in the United States in the late nineteenth century, entomologists and plant pathologists began to discover biological explanations for the earlier empirically developed pest control methodology which had been restricted largely to natural and cultural measures, sometimes augmented by minimal use of the earliest insecticides or fungicides. Partly by intuitive insight and partly because there was little choice, leading entomologists advocated an ecological approach to pest control. In the 1880s, Stephen A. Forbes, State Entomologist of Illinois and Professor of Zoology and Entomology at the University of Illinois, adopted the word "ecology" and insisted upon the broad application of ecological studies in dealing with insect problems of agricultural crops (Metcalf, 1930). A number of others concerned with crop protection also advocated this fundamental approach.

In spite of this position by leading entomologists, there was over the next half-century a gradual erosion of the understanding of the importance of ecology in controlling insect pests. There were, of course, exceptions to this, and from time to time a plea was made for the ecological approach. Charles W. Woodworth, Professor of Entomology at the University of California, advocated an ecologically based pest management approach throughout his long career (Smith, 1975). For example, in 1896 (Woodworth, 1896) he stated that everyone should have a clear idea of the controls available and how to apply them:

> But it is equally essential that he should fully understand when to apply and not to apply. . . . Money or time should only be invested in (pest control) when there is

> good prospect of an ample return. It is safe to say that, even in California, where this matter has been agitated for so many years, in only a very small fraction of the cases where injury might be prevented is the proper treatment made. . . . On the other hand, it may also be said that when treatment is made it is often of no effect, and a waste of time and money. Careful observations of the practices in this State in reference to treating insects and fungi makes it appear that fully half of what it now costs to treat our crops is wasted.

Professor Woodworth (1908) also discussed the need for carefully evaluating each mortality factor and investigating the interactions of the separate components in terminology that clearly showed his familiarity with what we now call the "ecosystem concept" and "density-dependent" mortality. He was the first entomologist to point out the important fact that percent parasitism of an insect pest is not a valid criterion for assessing the efficacy of a parasite.

There were other early advocates of an "ecological approach" to insect pest control. In 1926 Charles Townsend, influenced by his experience in Peru, stated that "environmental investigations furnish the only sure basis for work leading to the speedy discovery of proper measures for the control of insects, whether for the suppression of injurious forms or for the extension of beneficial ones." In 1945, before the impact of DDT and the organic pesticides, Michelbacher also stressed the importance of ecology in insect control.

There was apparently no strong parallel concern among plant pathologists about the application of ecological principles to the "management" of plant diseases. After "cause and effect" relationships between pathogens and disease symptoms were established, it was generally recognized that pathogen life cycles should be understood to reveal a "weak link" that might be exploited for control. But probably due to the fact that plant pathologists were trained as botanists, they were not as concerned about the interaction of pathogen populations and their total environment as were some entomologists on behalf of insect populations.

## Early Pest Management for the Cotton Boll Weevil

An analysis of the development of insect control in cotton also reveals the early foundations of IPM. The boll weevil, a native of Mexico, entered the United States in the late 1890s. Gradually the pest spread from its point of entry in South Texas into other states, and by 1922 it was distributed throughout practically the entire Cotton Belt, from Texas to the East Coast (Gaines, 1957). Research designed to control or eradicate the pest was begun in 1891 by an entomologist at the A & M College of Texas (now Texas A & M University) and in 1894 by USDA entomologists (Gaines, 1957). The earlier workers recognized the boll weevil problem as an extremely complex and serious one. Regardless of their initial notions about dealing with the pest, they soon rejected eradication as a realistic goal and commenced to develop what gradually evolved into a highly sophisticated system of pest management. It is difficult to determine whose influence was dominant in developing this system. Howard (1896), incorporating the results of field studies by Schwarz and Townsend, undoubtedly influenced others into looking at multicomponent suppression techniques. He stressed cultural control, especially the early fall destruction of cotton plants, and recommended early planting and clean cultivation. He also encouraged trapping weevils late in the fall and overwintering weevils early in spring and destruction of volunteer plants. Malley (1901), Hunter (1902, 1903) and Hunter and Hinds (1904) and several others (Dunn, 1964) further expanded the multicomponent management approach.

Though the term "pest management" was not mentioned in any reference on boll weevil prior to about a decade ago, the early workers not only preached but also practiced this approach. In 1901, Malley stressed the utilization of cultural controls in fighting the weevil. He stated in his 1901 publication that

> Another difficulty in securing a general acceptance of this method * lies in the fact that there is a small percentage of immature bolls which might yet open, but which the stock eats. Again the scarcity of pickers sometimes results in the planters being far behind with their picking. This is the planter's misfortune and not the fault of the method suggested. Much depends on their *management* (our emphasis) along this line.

Although Hunter (1903) argued that Malley's (1901) suggestion for insecticidal control of boll weevil was futile, Malley nevertheless continued for some time to recommend control with arsenic and arsenate of lead. But Malley (1901) himself obviously was aware of the limitations in using insecticide:

> It must be plain from the discussions in the foregoing page that spraying should not be depended upon solely, but in conjunction with the cultural methods. Neither *system* (our emphasis) used alone will attain the greater efficiency. If neither one is to be depended upon alone, the cultural methods are far more economical and efficient, and are capable of more general application under a greater variety of conditions. There can be no question of the desirability and the advantage of spraying, but it should be secondary, and should be practiced in conjunction with the cultural system.

Hence, by 1901, a system approach to cotton insect management had been advocated, and many components of the weevil's life system and cotton agroecosystem as well were understood. By 1904, Hunter and Hinds had presented a fairly good conceptual model of the pest's life system and recognized many

* The method Malley referred to was the grazing of livestock in cotton fields after harvest. The animals consumed green squares and bolls, thereby not only destroying immature boll weevils inside these forms but also reducing the adult weevil's food supply.

of the interdependent environmental factors causing a seasonal change in population density. A highly complex and sophisticated system had been fully developed as early as 1920, at which time economic thresholds were determined as guidelines for beginning treatments with calcium arsenate.

The classical publication of Hunter and Coad (1923) serves as a testimony to the advanced state of knowledge of boll weevil management in the early 1920s. This publication synthesized much that was known at the time about factors involved in controlling the pest. Although calcium arsenate was advocated as a method of control (Howard, 1919), Hunter and Coad cautioned against unilateral dependence on this material:

> Although the success of poisoning the weevil under certain conditions has been proven beyond doubt, there is danger that farmers may depend too much upon it and neglect the cultural practices which are absolutely essential in any system of weevil control. . . . Poisoning is supplementary and depends for its success upon the other necessary steps. . . . The crop itself must actually be made by other expedients; poisoning is merely a device to protect it when it is made.

In summing up the rules to follow in using calcium arsenate against the weevil, Hunter and Coad wisely recommended:

1. Start poisoning when the weevils have punctured 10 to 15% of the squares.
2. Then stop poisoning until the weevils again become abundant.
3. Do not expect to eradicate the weevils.
4. Always leave an occasional portion of a cut (of cotton) unpoisoned for comparison with the adjoining poisoned tract. This will show how much you have increased your yield by poisoning.

At the same time the concept of pest management was evolving for the boll weevil, basic concepts were being molded for managing other cotton pests too. Whitcomb (1970), in a review of the history of integrated control of cotton insects in the United States, pointed out that "Comstock's (1879) thoroughness in his studies of predators and parasites attacking cotton insect pests would shame many modern workers."

Many of these early management strategies were highly efficient and were adopted by the more progressive cotton farmers of the day.

## Shift to Dependence on Chemicals and to a Lesser Extent on Resistant Varieties

In spite of the occasional warnings about the hazards of unilateral approaches to pest control, crop protection in the United States since 1920 has gradually shifted toward dependence on chemical pesticides and on disease-resistant varieties but to a less extent on insect-resistant varieties. The signals from populations of pests resistant to chemicals (e.g., red scale resistant to

HCN on citrus and codling moth to lead arsenate on apples) were ignored. The pattern of developments with cotton insect control during the period 1920–1945 is a good example of what happened.

It is difficult to pinpoint the causes of the paralysis of applied cotton entomology which began in the 1920s and peaked just a few years ago. Applied entomology as a whole suffered the same fate at about the same point. Perhaps the cause was a social one, and the remedy lay in public policies that were beyond the grasp of the age. On the other hand, the attitudes and mistakes of the entomologists added more than any other single factor.

Ironically, the beginning coincided with the time that a number of cotton entomologists discovered practical methods for applying calcium arsenate. These entomologists dropped their ecologically based work on cultural control, biological control, and resistant varieties and began exhaustive research on dusting schedules, dosages, swath patterns, and nozzle orifices. This shift in research emphasis paid tremendous dividends too, because control with the insecticides was spectacular. The applied entomologist became obsessed by the immense power he commanded over nature with this potent weapon.

The early 1920s to middle 1940s were definitely dominated by applied entomologists who adhered to and practiced this chemical approach. There were a few dissenters (notably, Isely and Baerg, 1924; Baerg *et al.*, 1938), who warned that the inorganic insecticides should be applied only as necessary to supplement other controls. Baerg *et al.* (1938), Gaines (1942), Bishopp (1929), Fletcher (1929), Sherman (1930), and Ewing and Ivy (1943) recognized that application of the inorganics to control the boll weevil accentuated the infestation of cotton aphid, *Aphis gossypii* Glover, and bollworm, *Heliothis zea* Boddie. Nevertheless, the unilateral insecticide approach dominated.

## Initial Impact of Organic Pesticides

The prevailing philosophy adhered to by applied entomologists during the second quarter of this century was given yet even greater opportunities for expression when the post-World War II organic insecticides were introduced in the late 1940s. Entomologists enthusiastically adopted into their control programs DDT and other organochlorines and later organophosphorus (OP) and carbamate materials.

Whitcomb (1970) and Newsom (1970) described the approach that a majority of the cotton entomologists in the post-War period advocated for the new organic materials. In general, entomologists recommended that farmers spray their cotton once weekly from the time it started squaring until near harvest, but there was no method by which the farmer could determine if the spray was actually needed. Certainly, some entomologists had more influence than others in promoting this method of control. Nevertheless, this approach was favorably accepted by most entomologists of the day. Articles by Rainwater (1952), Gaines (1952, 1957), Curl and White (1952), and Ewing (1952) expressed the general philosophy which prevailed during the first 5 to 15 years following introduction of the organochlorines.

Despite this prevailing philosophy, there also were some very sound insect management programs developed during this period. A classical example was the cultural control program developed for pink bollworm, *Pectinophora gossypiella* Saunders, recently reviewed by Adkisson (1972). Also, several entomologists continued to encourage farmers or scouts to check the cotton fields regularly and to apply insecticides only when the pest population reached economic thresholds (G. L. Smith, 1953; R. F. Smith, 1949; Boyer *et al.*, 1962). And Newsom and Smith (1949) and a few of their followers gathered evidence that the new organic insecticides seriously affected the populations of several natural enemies. In general, however, the period from the late 1940s to the early mid-1960s marked a time when most major cotton growing areas troubled with severe insect pests came under a heavy blanket of insecticide.

The rest of the story has been documented recently in publications by Stern (1969), Adkisson (1969, 1971, 1972, 1973*a,b*), Smith and van den Bosch (1967); van den Bosch *et al.* (1971), Smith (1969, 1970, 1971), Doutt and Smith (1971), and Newsom (1970). All of these articles pointed to the problems which eventually arose as a result of overuse of the insecticides introduced after World War II.

## Return to Ecological Approaches in Pest Control

The pest problems of agricultural crops in the United States have been aggravated and intensified by a complex of factors. Some of the factors were related to the limited base of tactics employed (primarily chemicals and host resistance). In many instances these no longer controlled the target pests, interfered with the control of other pests, and released species from existing natural control so that they became pests. In some cases, the chemicals modified the physiology of the crop plants unfavorably, created hazards to man's health, destroyed pollinators and other desirable wildlife, and in other ways produced undesirable effects.

The introduction of new pest species into the U.S. agroecosystems has also placed stress on an already overburdened pest control technology. Furthermore, the pressure on agroecosystems toward greater intensity of production over the years has forced them to evolve very rapidly and has created new environments for the pests. As a result the agroecosystems often have become more vulnerable to pests. Changes in tillage, water management, crop varieties, fertilization, and other agronomic practices greatly influenced pest incidence, very often in favor of the abundance of the pest species. The increased complexity and intensity of agricultural production practices along with reduced genetic diversity in many agricultural crop species combined to produce a new magnitude of crop hazards.

The intensification and increasing complexity of crop protection problems coupled with the associated environmental, financial, and health hazards of heavy chemical usage have combined to stimulate great interest in the importance of crop protection and in the broad ecological approach as a sound approach to acceptable solutions. And also of great importance has been the increased financial support for pest management research, extension and field-implementation programs.

As the problems intensified in crop protection, the debate over the matter also intensified. This finally erupted in the *Silent Spring* episode (Carson, 1962; Westcott, 1962). The President's Science Advisory Committee issued a special report in 1963 entitled *Use of Pesticides* that found fault with a number of crop protection chemicals, especially insecticides. The Southern Corn Leaf Blight epidemic of 1970 (Tatum, 1971) emphasized the problem of the genetic vulnerability of major crop species in the United States to damaging attacks by pests (NAS, 1972). These situations combined with increased awareness of a world food crisis motivated government and institutional actions supportive of the development of IPM systems for major agroecosystems in the United States.

A major step toward development of IPM programs was taken by the Federal Government in 1972. In his Message on Environmental Protection, the President of the United States directed the cognizant agencies of government to take immediate action toward development of pest management programs in order to protect (a) the Nation's food supply against the ravages of pests, (b) the health of the population, (c) and the environment. The President's Directive prompted funding of a national research project involving 19 universities and various federal agencies entitled *The Principles, Strategies, and Tactics of Pest Population Regulation and Control in Major Crop Ecosystems* (known as the "Huffaker IPM Project"). Other programs initiated in 1972 were pilot projects for implementing pest management programs in the various states; curriculum development for training and certification of crop protection specialists by the land-grant universities; and pilot pest management research projects within the Agricultural Research Service in collaboration with state groups. These actions have been followed with an intensification of pest management research within state agricultural experiment stations and federal agencies financed by both state and federal sources.

## The Modern Integrated Pest Management Approach

The great advances made in recent decades to provide more food and other agricultural products serve as testimony to man's ability to develop and manipulate scientific technology to his advantage. However, experience has proven repeatedly that technology often has been developed and manipulated to satisfy only short-term needs. The unfortunate consequences of two of these technological advances have provided much of the underlying rationale for IPM. One of these advances emerged shortly after World War II with the introduction of DDT and other pesticides. The other of these advances was the introduction and world-wide use of the high-yielding but narrow genetically based crop varieties that now serve as the basis of the "green revolution."

It hardly seems appropriate here to discuss in detail the consequences already experienced from these two technological advances or the implications of this technology for the future. The appearance of numerous insecticide-resistant strains of crop pests and the growing evidence of new biotypes or strains of pests that resist and adapt to previously pest-resistant crop varieties adequately portray the consequences and shortcomings of technological advances aimed at satisfying short-term needs. These unfortunate experiences have come about because technology was pursued unilaterally, indifferent to the potential countermanding ecological consequences that have already caught up with us in some instances. A benefit has evolved from these unfavorable consequences, however, in the form of closer attention by all crop protection specialists to those ecological principles that are basic to successful long-term pest control.

Scientific pest control has always required a knowledge of ecological principles, the biological intricacies of each pest, and the natural factors that tend to regulate their numbers. Today, it is more necessary than ever before to take a broad ecological overview concerning these problems, and to consider all possible factors, both natural and artificial, that can be used against crop pests. We cannot afford any longer to disregard the considerable capabilities of pest organisms for countering control efforts. Most of these organisms are extremely fitted to thrive in our agroecosystems and to adapt to changing crop production conditions. It is for this prudent reason that we must understand Nature's methods of regulating populations and maximize their application. This clearly requires a realignment of research objectives and practices. A unified, balanced approach is needed, predicated mainly on widely proven principles of pest control and ways of implementing them, and recognizing the limitations as well as the advantages of any new methods that are evolved.

Hence, the IPM activity is attempting to bring together teams of scientists who are capable of taking a broad ecological overview of the pest problems associated with our major agroecosystems and who are willing to assume leadership in developing unified, ecologically based approaches to pest control. These multidisciplinary teams will have the potential for developing effective, economical, and long-term solutions for agricultural pest problems if they approach cropping systems as ecological units and if they apply the most sophisticated methods of experimentation, synthesis, and analysis.

One of the many pitfalls of unilaterally designed pest control that focuses on only one pest or a closely related group of pests is the result of the countermanding effects of a similarly designed control to remedy the emergence of a different pest or pest complex. An extremely effective unilateral control strategy developed for a given crop insect pest, for example, may be totally negated on the arrival of a new pest inhabitant such as a weed, plant pathogen, spider mite, or other insect. For that matter, the arrival of a new pest in a given cropping district may even negate the effect of highly sophisticated IPM programs. A classic example exists in the desert cotton-producing areas of California and Arizona. Effective integrated control programs had been developed for the cotton insect pests native to these areas and were being successfully adopted by many of the area farmers until arrival of the pink bollworm in the late 1960s. The prophylactic action to control this invader, which consisted principally of wholesale insecticidal applications, totally disrupted and counteracted benefits of the previously adopted integrated control programs. This is one of several examples that demonstrate the need for built-in safeguards to prevent negation of an operational IPM strategy when confronted with an invasion by a new type of pest or the evolution of new biotypes of old pests. This will be no easy task since the arrival of these new situations cannot be readily predicted. However, the emerging IPM strategies offer superior safeguard mechanisms through surveillance systems, but these are conditioned by our limited understanding of highly complex, evolving pests, pest mobility, pest interactions, and shifting germ plasm of agricultural crops. First, the holistic approach has provided much new insight into the complexities of interspecific relationships of pests and potential pests in the agroecosystems. For example, the major natural enemies and other population-regulating factors of key pests, occasional pests, and potential pests of many major cropping systems have been identified. Hence, we have become more aware of the sensitivity of these natural interrelationships and have a much clearer understanding of the disruptive, catastrophic events (such as insecticides, plant varieties, cultural practices, etc.) that may upset this balance. Second, today's IPM programs are bringing together teams comprising specialists in crop protection and other supportive disciplines. This improved interdisciplinary communication and interaction should prevent the emergence of unilateral counteracting control measures as exemplified by the following example. Currently, in the southern United States, a fungicide (benomyl) is being applied to large acreages of soybeans to control a complex of plant pathogens without knowledge of the specific pathogens being controlled or the economic damage actually being caused by them. Unfortunately, this wholesale "tonic treatment" is negating the otherwise highly effective integrated control programs against soybean insects. For, in addition to control of the plant pathogenic fungi, the fungicide has adverse effects on populations of entomopathogenic fungi that are important natural enemies of several lepidopterous insect pests of soybean. More disrupting yet, however, is the inclusion of broad spectrum "insurance" insecticides with the fungicide treatments. Though this problem has yet to be resolved, entomologists working in concert with plant pathologists in the course of developing IPM programs are in a much better position than ever before to develop a satisfactory solution. Third, the IPM strategies under development promise to provide options and pathways to alternate solutions in the event of "crisis" developments such as the emergence of pesticide-resistant strains, biotypes that can overcome host resistance, or arrival of pest invaders in an ecosystem. The optional approaches will be developed, however, only through the continued close collaboration of scientists in many disciplines focusing on holistic systems. But they will be essential to safeguard against disrupting crises that are certain to emerge in pest management programs of the future because dynamic agroecosystems provoke counteracting changes in the dynamic pest subsystems that must be "managed" to preserve our crop production potential.

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