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# INTEGRATED PEST MANAGEMENT: Historical Perspectives and Contemporary Developments

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ABSTRACT

Twenty five years after its first enunciation, IPM is recognized as one of the most robust constructs to arise in the agricultural sciences during the second half of the twentieth century. The history of IPM, however, can be traced back to the late 1800s when ecology was identified as the foundation for scientific plant protection. That history, since the advent of modern organosynthetic pesticides, acquired elements of drama, intrigue, jealousy, and controversy that mark the path of many great scientific or technological achievements. Evolution of IPM followed multiple paths in several countries and reached beyond the confines of entomological sciences. Time and space constraints, however, bias this review toward entomology, among the plant protection sciences, and give it an obvious US slant, despite the global impact of IPM.

## PREAMBLE

After nearly 25 years of usage, the acronym IPM can appear on line one of this review without need for an explanation nor a definition; these will come later. The nature of IPM in the waning years of the twentieth century is such that it has become a household term, generally understood, frequently used, but just as often misused by professionals and laypersons alike, often without much thought given to the subtleties and implications of the expression nor its impact on modern agriculture.

Although this review has an obvious entomological bias, a "pest" in IPM subsumes weeds, pathogens, and nonarthropod animals as well. The entomological



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focus is necessary to limit the scope of this paper despite recognition of the valuable contributions to IPM made by plant pathologists and weed scientists. The review also has a clear US slant that should be corrected by workers in those countries that share the credit with the United States for developing IPM to its current status. While relying heavily on previous historical papers (6, 16, 21, 47, 82, 121, 132, 138, 160, 161), some by early framers of IPM, this review reflects my personal perspectives. It was written with some trepidation, for historical reviews of contemporary events must face the scrutiny of those who have lived through similar experiences but have their own perspectives.

## ORIGINS

Basic tactics of IPM were proposed and used to defend crop plants against the ravages of pests long before that expression was coined (82, 168). Throughout the late nineteenth and early twentieth centuries, in the absence of powerful pesticides, crop protection specialists relied on knowledge of pest biology and cultural practices to produce multitactical control strategies that, in some instances, were precursors of modern IPM systems (50).

During the first half of the twentieth century, economic entomology was the subdiscipline responsible for research on and teaching about economically important insect species (= pests) and the means to control them. "Pest control" was understood as the set of actions taken to avoid, attenuate, or delay the impact of pests on crops or domestic animals. Goals and procedures of pest control were clearly understood. That stance changed in the early 1940s with the advent of organosynthetic insecticides (138) when protection specialists began to focus on testing chemicals, to the detriment of studying pest biology and noninsecticidal methods of control. The period from the late 1940s through the mid-1960s has been called the dark ages of pest control (122). By the late 1950s, however, warnings about the risks of the preponderance of insecticides in pest control began to be heard. Concern arose mainly from traditional centers of excellence in biological control, particularly in California (149), and from workers on cotton in North and South America (35) and deciduous tree fruit in Canada, the United States, and Europe (103), who detected early signs of the catastrophic results from overreliance on insecticides.

### *Integrated Control*

The seed of the idea of integrated control appears in a paper by Hoskins et al (70), as cited in Smith (160): "...biological and chemical control are considered as supplementary to one another or as the two edges of the same sword... nature's own balance provides the major part of the protection that is required for the successful pursuit of agriculture... insecticides should be used so as to interfere with natural control of pests as little as possible... ." Conceivably, "integrated control" was uttered by entomologists long before formally appearing in a publication, as is often the nature of an expression before it is committed to paper by a then-recognized originator. For integrated control, that role is ascribed to Michelbacher & Bacon (112). They described the effect of insecticides, especially DDT, for control of the codling moth, *Cydia pomonella*, on populations of other walnut insect pests, and they stressed "the importance of considering the entire entomological picture in developing a treatment for any particular pest.... All effort was directed towards developing an effective *integrated control* program of the important pests of walnut" (my emphasis) (112:1020). However, it was the series of papers starting with Smith & Allen (163) that established integrated control as a new trend in economic entomology (143, 156, 157, 165, 178, 187). Towards the end of the 1960s, integrated control was well entrenched both in the scientific literature and in the practice of pest control (158–161, 164, 166, 167), although by then "pest management" as a sibling concept was gaining popularity (146).

No doubt recognition of the failings of the new organosynthetic insecticides—resistance, resurgence of primary pests, upsurges of secondary pests, and overall environmental contamination—was the primary factor in the initial formulation and then the growing popularity of the integrated control concept. In addition, the vigor with which the new concept was embraced by biological control researchers, particularly at the Riverside and Berkeley campuses of the University of California system, may have been intensified in reaction to the aggressiveness of pesticide-based program proponents (186) and anti-biocontrol attitudes of entomologists who trusted that newer and more powerful insecticides would always be available to replace those that became useless owing to resistance.

The desire to reconcile the use of insecticides with biological control transcended the US scientific community. For example, "complementary," "coordinated," and "harmonious" (34) were used by Canadian and European entomologists to qualify "control" aimed at maximizing the impact of the combined methods (187). Unquestionably, the impression caused by publication of *Silent Spring* (20) accelerated acceptance of the integrated control concept (58, 188). The book added an element of drama essential for the movement that was characterized by spokespersons of agrochemical industries as just another bandwagon (81).

In its original formulation, the scope of integrated control was broad. Smith & Allen (163) stated that "*integrated control*... will utilize all the resources of ecology and give us the most permanent, satisfactory, and economical insect control that is possible" (my emphasis). However, in subsequent publications, integrated control was more narrowly defined as "applied pest control which combines and integrates biological and chemical control" (178), a definition that stood through much of the late 1950s and the early 1960s (11, 12, 165, 187) but began to change again in the early 1960s as the concept of pest management gained acceptance among crop protection specialists (143, 156, 157).

### *Pest Management*

The concept of “protective population management” (53), later shortened to “pest management” (52), gained considerable exposure at the twelfth International Congress of Entomology, London (190). The Australian ecologists who coined the expression contended that “control,” as in pest control, subsumes the effect of elements that act independently of human interference. Populations are naturally controlled by biotic and abiotic factors, even if at levels intolerable to humans. Management, on the other hand, implies human interference. Although the concept of pest management rapidly captured the attention of the scientific community, in 1966 Geier seemed to minimize the semantic argument that favored “pest management” by stating that the term had no other value than that of a convenient label coined to convey the idea of intelligent manipulation of nature for humans’ lasting benefit, as in “wildlife management” (52).

Two publications, in 1969 (115) and 1970 (146), contributed significantly to the acceptance by American entomologists of the Australian “pest management” in lieu of the American “integrated control.” By the mid-1970s both integrated control and pest management coexisted essentially as synonyms in the English language literature (75, 87, 161), although Stark (174) argued that the two expressions should be considered distinct entities, a view that was initially shared by the Food and Agriculture Organization (FAO) Panel of Experts on Integrated Pest Control (IPC) (40) but later retracted. The subtleties of Stark’s argument, however, seem to have been lost, as the two expressions continue to be used interchangeably.

### *Integrated Control Versus Pest Management*

In 1965 a symposium convened in Rome, Italy, by the United Nations (UN) FAO (38) and attended by leading plant protection specialists from 36 countries became a landmark in the advancement of the integrated control concept in its broadest sense. Participants at the symposium recommended establishment of the FAO Panel of Experts in IPC. The definition of IPC proposed by Smith & Reynolds (169) was adopted with modifications at the first session of the Panel of Experts in 1967 (39). Debate over the terminology of crop protection as well as on its underlying conceptual value, thereafter, mostly centered around the FAO panel. The following is based on personal communication from DF Waterhouse, CSIRO, Australia, a member of the first FAO Panel of Experts.

The Australian school of pest management, developed under the influence of Nicholson’s theories of population dynamics, stressed the role of density-dependent mortality factors, including intraspecific competition, as stabilizing mechanisms acting within a species life system (25, 123). Life system, a conceptual extension of Nicholson's theories by his coworkers (24, 25), is "that part of an ecosystem which determines the abundance and evolution of a particular species population" (24). Against this ecological background evolved the concept of pest management that, while making inroads in the United States and worldwide (146), was resisted by the FAO Panel of Experts, who were still under the influence of the Californians (RF Smith, H Reynolds, V Stern, R Van den Bosch). At its third meeting (40), the Panel reiterated that "[i]ntegrated control is not synonymous with pest management, which is equivalent in most usage to the term pest control." But at the fourth meeting, held in 1972, and thereafter, that view changed to consider IPC and pest management as equivalent expressions. In the end, the argument on the use of "integrated control" seems to have been resolved mainly because "pest management" did not translate into most other languages as easily as "integrated control" or "integrated plant protection," not because of intrinsic conceptual merits of the expressions.

### *Integrated Pest Management*

Although the orismological argument continued well into the 1980s, the solution, a synthesis of the two expressions, had already been available since 1967, when Smith & van den Bosch (170) wrote, "The determination of insect numbers is broadly under the influence of the total agro-ecosystem, and a background knowledge of the role of the principal elements is essential to *integrated pest* population *management*" (my emphasis) (170:311).

Not until 1972, however, were "integrated pest management" and its acronym IPM incorporated into the English literature and accepted by the scientific community. A February 1972 message from President Nixon to the US Congress, transmitting a program for environmental protection, included a paragraph on IPM (124).[1] Later, in November 1972, the report *Integrated Pest Management* prepared by the Council on Environmental Quality was published (28). In creating the synthesis between integrated control and pest management, no obvious attempt was made to advance a new paradigm. Much of the debate had been exhausted during the 1960s and by then there was substantial agreement that 1. "integration" meant the harmonious use of multiple methods to control single pests as well as the impacts of multiple pests; 2. "pests" were any organism detrimental to humans, including invertebrate and vertebrate animals, pathogens, and weeds; 3. IPM was a multidisciplinary endeavor;

[1] I could not confirm the name of the Council on Environmental Quality (CEQ) officer who wrote the background paper used by Nixon. That officer should be credited for the first use of "integrated pest management" in print. HL Mason, archivist with the Nixon Project, National Archives, Washington, DC, found a letter from the President's Office thanking those who assisted in the preparation of the report. Russell E Train, chairman of CEQ at the time, was the recipient of the letter.

4. "management" referred to a set of decision rules based on ecological principles and economic and social considerations. The backbone for the management of pests in an agricultural system was the concept of economic injury level (EIL) (66, 131, 176–178).

Ironically, as the argument came to a closure in the early 1970s and IPM became firmly established as the approach of choice to pest problems, Geier & Clark (54), revisiting the issue, suggested a return to the use of "pest control" when referring to the regulation of pests in production systems. Their argument, however, was lost in the flurry of activity under the IPM banner worldwide.

## DEFINITIONS

The search for a perfect definition of IPM has endured since integrated control was first defined (178). A survey recorded 64 definitions of integrated control, pest management, or integrated pest management (8). The most often cited definition, based on the Science Citation Index, still is Stern et al's (178) for integrated control. A broader definition was adopted by the FAO Panel of Experts (41): "Integrated Pest Control is a pest management system that, in the context of the associated environment and the population dynamics of the pest species, utilizes all suitable techniques and methods in as compatible a manner as possible and maintains the pest population at levels below those causing economic injury." This definition has been cited frequently and has served as a template for others. Unfortunately, most of them perpetuate the perception of an entomological bias in IPM because of the emphasis on pest populations and economic injury levels, of which the former is not always applicable to plant pathogens, and the latter is usually attached to the notion of an action threshold often incompatible with pathogen epidemiology or many weed management systems (but see 7, 113, 197). Furthermore, most definitions stress the use of combinations of multiple control methods, ignoring informed inaction that in some cases can be a better IPM option for arthropod pest management (175). A numerical analysis of the key words included in those 64 definitions suggests that authors attempted to capture the concept's essence in terms of (*a*) the appropriate selection of pest control methods, used singly or in combination; (*b*) the economic benefits to growers and to society; (*c*) the benefits to the environment; (*d*) the decision rules that guide the selection of the control action; and (*e*) the need to consider impacts of multiple pests. Several authors (2, 16, 198) have come close to meeting the criteria for a good definition, but a consensus is yet to be reached.

Consensus on definition is desirable to aid in the choice of performance criteria for IPM implementation targets in regional and national programs (14) and to help to correct distortions and unwarranted claims that a pest control program is IPM even if it ignores essential IPM premises. Based on an analysis of definitions spanning the past 35 years, the following is offered in an attempt to synthesize what seems to be the current thought: "IPM is a decision support system for the selection and use of pest control tactics, singly or harmoniously coordinated into a management strategy, based on cost/benefit analyses that take into account the interests of and impacts on producers, society, and the environment."

## ECOLOGY AND IPM

The need for sound ecological information about pests and their crop environment was considered essential for efficient pest control well before IPM was equated to "applied ecology," an expression apparently first used by Ullyett (182; see also 44, 111, 195). Many authors have written about the ecological foundations of IPM (30, 55, 69, 93, 94, 102, 140, 145, 171, 173), in particular the need to consider the total ecosystem, the first principle of IPM, according to Smith (16, 156, 157).

Yet, contemporary IPM programs, including some of the most successful, have been implemented with little consideration of ecosystem processes. Species and population ecology have been the ecological foundations of those programs because populations are the biological units in which species exist (52). In a critical review of the nature of pest control, Geier & Clark (54) concluded that ecology "has drawn more from pest control than it has given," suggesting that IPM has had considerable success, despite a weak theoretical foundation. Such a view of the impact of ecological theory on IPM, although not shared by most IPM theoreticians (93, 102, 144, 145), served to highlight the fact that despite achievements of the past 30 years, IPM still is in its infancy. At this stage the focus is the crop field, a small ecological unit, in which ecosystem processes are difficult to model and incorporate into decision-making rules.

Understanding the characteristics, processes, and dynamics of natural ecosystems (57), however, is essential for a scientific analysis of agroecosystems (150). The major determinant of the degree of differentiation of agroecosystems from natural ecosystems is the level of human impact and control (65, 127). Thus, the transition from natural ecosystems to agroecosystems may be interpreted as the end result of interactions of two distinct systems: the ecological and the socioeconomic, which produce a third one, the agricultural. Ecological systems increase in complexity and expand spatially from the population to the community, to the ecosystem, to the landscape, to the biome, or to the entire biosphere. By analogy, human social systems increase in complexity and expand spatially from the individual to the household or extended family, to the farm or village, to the county, state, or province, to the country or continent. A

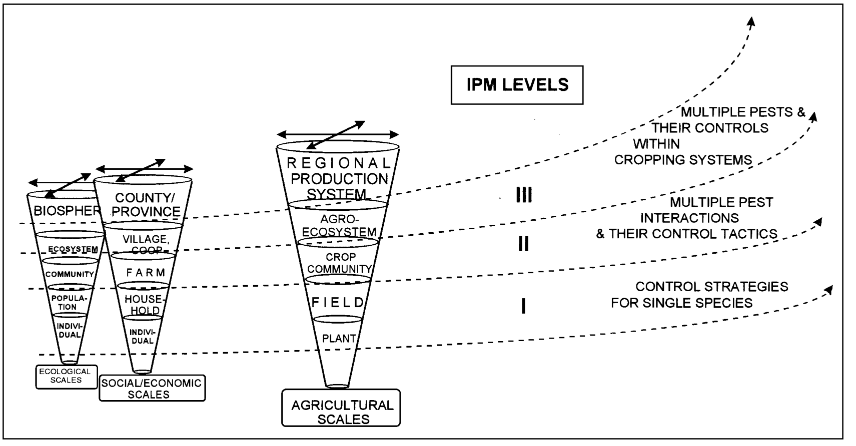


*Figure 1* Graphical representation of the interactions of the ecological and socioeconomic scales that define the regional characteristics of the scales of agricultural systems and levels of IPM integration within the context of the ecological, socioeconomic, and agricultural scales.

parallel hierarchy exists in agropastoral systems, which encompass crop plants or domestic animals, fields or herds, crop communities, agroecosystems, and regional production systems. Agropastoral systems are, therefore, the dynamic end result of the interactions, in ecological time, of the ecological and socioeconomic systems (Figure 1). This model for ecological/socioeconomic interactions in the shaping of agroecosystems provides a platform to consider the levels of IPM integration as a function of the targeted agroecological scale (94, 145). With IPM anchored in an expanding ecological foundation, implementation of IPM gained impetus around the world.

## IPM PROGRESS IN THE UNITED STATES

A series of events in the early 1970s converged to help advance the IPM "cause" in the United States. Klassen (89), of the US Department of Agriculture (USDA) Agricultural Research Service (ARS), identified six events that culminated in the creation in 1972 of the Federal IPM Thrust. 1. The geographical range of the pink bollworm expanded to Arizona and southern California and caused the number of sprays used in cotton, mainly DDT, to increase up to 25; DDT in forages and feed created detectable residues in milk that exceeded federal tolerances. 2. A series of reported poisonings in North Carolina led the USDA to organize an IPM program for tobacco and the North Carolina Department of Agriculture to restrict sales of parathion in mixtures with other pesticides. 3. Venezuelan equine encephalomyelitis rapidly spread along the eastern coast of Mexico into Texas and was halted through massive sprays to control mosquito vectors of the disease agent, and a horse vaccination campaign was carried out by private veterinarians; a similarly competent professional resource was not available for crop protection, should the need have arisen. 4. Cancellation hearings for DDT generated considerable public debate. 5. The epidemic of southern corn leaf blight in 1970 exposed the genetic vulnerability of most crops to insect pests and diseases. 6. Outbreaks of the gypsy moth (*Lymantria dispar*), Douglas fir tussock moth (*Orgyia pseudotsugata*), and southern pine beetle (*Dendroctonus frontalis*) at the time were assumed to have been aggravated by the lack of adequate substitutes for DDT, which had been banned since 1957 for use in forest pest control.

These developments, plus coordinated political activism on the part of several entomologists within land grant universities, may have provided the support in the US Congress for special funding for IPM. On September 3, 1971, a Senate Subcommittee of the Committee on Agriculture and Forestry met to discuss Senate Bill 1794, "To Authorize Pilot Field Research Programs for the Control of Agricultural and Forest Pests by Integrated Biological-Cultural Methods," introduced by Senator Gaylord Nelson of Wisconsin and cosponsored by 26 senators representing virtually every major agricultural state in the United States. Participating in the hearings were leading plant protection specialists from land grant universities, several top USDA scientists and administrators, industry leaders, and representatives of environmental organizations. The bill provided the financial backing for the large IPM programs both at the state and federal levels encompassed under the IPM Thrust (184). These developments culminated with a message on environmental protection from President Nixon to the House of Representatives (124) that referred to integrated pest management as the "...judicious use of selective chemical pesticides in combination with non-chemical agents and methods." The President's directive contained four specific recommendations: (*a*) for the USDA, National Science Foundation (NSF), and EPA to launch a large-scale IPM research and development program through a number of leading universities; (*b*) for the USDA to increase field testing of new pest control and detection methods; (*c*) for the USDA and HEW (Health, Education, and Welfare Department) to develop a training and certification program at appropriate academic institutions to prepare the large number of crop protection specialists needed to support expansion of IPM; and (*d*) for the USDA to expand a crop field scout demonstration program to cover nearly 1.6 million hectares (ha) under agricultural production by the upcoming growing season (21). A most significant outcome of these directives for IPM was the guarantee of substantial financial support for a 5-year program under the combined sponsorship of NSF, EPA, and USDA, known initially as the

US-IBP (International Biological Program) for IPM and later as the "Huffaker Project."

### *The Huffaker Project*

The IBP-IPM program in pest management, "The Principles, Strategies, and Tactics of Pest Population Regulation and Control in Major Crop Ecosystems," would bring together a "breadth of disciplines and expertise among Federal, State and private sector scientists to develop sophisticated methods of experimentation, synthesis and analysis [towards]... a new systematized pattern for research development and decision-making [under]... the philosophy, strategy and tactics... of integrated control" (76). Much emphasis was given to the then-novel and increasingly fashionable applications of systems science to integrated control (76, 77).

Six crops—alfalfa, citrus, cotton, pines (bark beetle), pome and stone fruits, and soybean—were selected following criteria that included current level of insecticide use (very high in cotton and citrus, very low in soybean), potential for successful biological control (alfalfa, citrus, pome and stone fruit), and representation of a nonagricultural system (pines). An anticipated outcome of the program was a "40–50 percent reduction in the use of the more environmentally polluting insecticides within a five-year period, and perhaps by 70–80 percent in 10 years" (76), a harbinger of similar targets set nearly 20 years later by other programs both in the United States and in Europe. The project spanned 1972–1978, and achievements were summarized in a book edited by Huffaker (74). Expanded volumes on each of the six component crops were to follow, but only three were produced: pome and stone fruit (32), pine bark beetle (191), and cotton (48). Huffaker & Smith (77) offered a brief critical review of the project's successes and shortcomings. Modeling of population dynamics and crop phenologies received considerable support from the project, which allowed a serious test of the potential for their practical applications in forecasting and decision making in IPM. A generation of talented mathematical ecologists was driven by this project to contribute to quantitative aspects of IPM (31, 62, 152, 154). Advances were made in many aspects of implementing improved IPM strategies for all systems, but insufficient involvement of extension specialists may have reduced the potential of the program to gain greater IPM adoption. The project retained a strong entomological focus, thus reinforcing the perception in other protection disciplines that IPM was "entomocentric."

### *CIPM—The Sequel*

Capitalizing on the success of the Huffaker Project, a group of scientists under the leadership of PL Adkisson, Texas A&M University, obtained EPA (1979–1981) and USDA-CSRS (Cooperative States Research Stations) (1981–1985) funding for the second large-scale IPM project in the United States, to be known by the acronym CIPM, the Consortium for Integrated Pest Management (46). The origins, organization, objectives, and administrative structure of the CIPM project were summarized by RE Frisbie, the project director, in the symposium celebrating the conclusion of the project (45). Major accomplishments for all four crops—alfalfa, apple, cotton, and soybean—and specific subject areas are part of the symposium volume (46). A projectwide summary of accomplishments (1) claims the average adoption of IPM for the four crops at about 66% over 5.76 million ha. The main indicators of adoption were the use of scouting and economic injury levels for spray decisions, use of selective pesticides, or application of lower dosages of broad spectrum insecticides. A significant achievement of the program was the genuine attempt to integrate weed science and plant pathology and the emphasis on economic assessments of IPM adoption (45). Termination of the CIPM project marked the end of the first era of large-scale IPM projects in the United States.

## *USDA Regional IPM Program*

With the CIPM project conclusion in 1985, the USDA-CSRS redirected some IPM funds to management through the newly formed National IPM Coordinating Committee (NIPMCC), which gave deans and experiment station directors at land grant universities control over the direction of IPM funding. Funding was provided through a competitive grants program administered by each of four regional IPM coordinators, which led to promoting projects that were short term, more narrowly focused, and less interdisciplinary; on the other hand, the program opened up opportunities to states previously excluded from either the Huffaker or CIPM projects (116). Under the auspices of the NIPMCC and CSRS, the first National IPM Symposium/Workshop was organized in 1989 (117). Two following national symposia, in 1994 (36) and 1996 (37), were instrumental in promoting a national agenda for IPM and ushering in the Clinton Administration's National IPM Initiative.

## *The National IPM Initiative*

In September 1993, the Clinton Administration submitted that implementing IPM practices on 75% of the nation's crop acres by the year 2000 was a national goal (172). The IPM Initiative was the outcome of a lengthy process of assessment of needs and constraints for IPM adoption, which culminated with the National IPM Forum, convened in Arlington, Virginia, June 17–19, 1992. The National IPM Initiative was a response to the plea for a national commitment to IPM reflecting a "redirection and combination of old and new resources of USDA and land-grant university programs into a single coordinated and cooperative effort with farmers, private consultants, and industry to address important pest control problems and to achieve the national goal of IPM implementation on 75% of crop acres by the year 2000." A significant conceptual development, linked to the Initiative, was the Areawide IPM Program (26).

## *Areawide IPM Systems*

Knipling (90) was an early proponent of the concept of suppression of insect pests over large areas, instead of the field-by-field approach of contemporary pest control programs. The areawide suppression of key pests in large eradication projects had been interpreted as a competing paradigm with IPM. Perkins (132) called the eradication programs of the 1960s and 1970s TPM, for total pest management. The areawide approach to pest control was not limited to eradication, however (91, 92). The concept of "areawide pest management" was introduced by Knipling and Rohwer in a proposal to the North American Plant Protection Organization. They argued that areawide pest management projects (*a*) must be conducted on large geographic areas; (*b*) should be coordinated by organizations rather than by individual farmers; (*c*) should focus on reducing and maintaining key pest populations at acceptable low densities, although eradication may be involved if practical and advantageous; and (*d*) may involve a mandatory component "to insure full participation in the program." A synthesis of these principles with principles of IPM resulted in a draft document submitted to the Experiment Station Committee on Organization and Policy (ESCOP), Pest Management Strategies Subcommittee (26). That document became a blueprint for the new Areawide IPM Program (96).

A special feature of the plan was pilot testing of promising IPM strategies more likely to succeed if implemented over large areas. One such strategy used mating disruption for the management of the codling moth, *C. pomonella*, a key pest on apples and pears in the western United States. Mating disruption of the codling moth, to be successful, had to operate under an optimal perimeter-to-area ratio to minimize border effects and the risk of re-invasion of treated areas by mated females from untreated neighboring blocks (61, 193). A program based on these principles was developed and became the first pilot test of the areawide IPM concept (95, 96). In 1995, the Yakima Agricultural Research Laboratory of the USDA-ARS received funds to launch the program in California, Oregon, and Washington.

## *Extension IPM Program*

The uniquely American Cooperative Extension Service (CES) played a key role in the diffusion of IPM in the United States. The onset of clearly identified CES IPM programs coincided with the era of the large, federally funded projects for IPM research and pilot testing and was probably motivated by the same public demands (2, 15). The CES IPM programs in the early 1970s were structured mainly as large-scale demonstrations of benefits derived from field scouting as the basis for decisions on pesticide applications using available economic thresholds. Federal funds were used mainly to subsidize scouting and to pay for IPM CES specialists, but the guidelines also provided that, in time, the programs should become grower supported (15). Success of the scouting program may have provided stimulus for expansion of a relatively new profession in agriculture, the private consultant (100), whose numbers increased by 1000% between 1969 and 1985 (2). As IPM programs evolved and expanded to include the entire crop pest complex, there was greater emphasis on multidisciplinary team approaches to IPM, with CES and research cooperating at all phases of program development, implementation, and evaluation. The lack of such interaction, inadequate educational programs, and lack of market incentives were perceived as impediments for more rapid adoption of IPM (59, 60, 192).

### *Teaching IPM*

IPM as a new approach to plant protection has replaced the traditional economic entomology teaching programs at most academic entomology departments in the United States and around the world. In the mid-1970s, revisions of curricula and offerings of new minors and majors in IPM began to be discussed. The new emphasis on systems science applications and the agroecosystems focus of IPM required proficiency in mathematics and levels of ecological understanding not hitherto part of the background of most crop protection specialists. Comprehensive assessments of formal educational needs for IPM were the subject of several workshops and symposia (56, 126). Emphasis was placed on the need to promote interdisciplinary programs in which, for example, entomology majors would have minors in plant pathology and weed science. Model curricula for degree programs included principles of sampling, computer programming, and simulation techniques.

By 1979, 75% of 51 entomology departments in the United States that were surveyed offered a course in IPM (136). To support this intense teaching activity, textbooks were published to cover the basic components of IPM, its ecological foundations, and the description of case histories. Beirne's (13) may have been one of the first commentaries on IPM to appear in a book format. Perhaps one of the earliest to fill the demand for a text for teaching introductory courses in IPM was edited by Metcalf & Luckmann in 1975, now in its third edition (109). Other works soon followed (9), and in 1996 an electronic IPM textbook became available on the Web (147).

### *IPM Research and Implementation*

Strategy in IPM is the optimized multicomponent approach to the management of a pest or pests, including the selection of the appropriate methods and decision rules for their most effective application. Tactics are the methods to solve a given pest problem or the details of how a chosen method should be applied (22). The selection and use of control methods, sampling or monitoring procedures, and economic injury levels are the tactical components of the IPM strategy. Any IPM program includes basic components that are indispensable for its development and implementation, whether explicitly in its organization or not. Description of these components has been the object of numerous general reviews (52, 187), reports (16, 56), and books (72, 109, 130, 137, 155). A valuable source of references to the development and implementation of IPM for 28 major crops is found in 35 papers published in the *Annual Review of Entomology* in the past 30 years. From those reviews comes the conclusion that historically, major departures from the basic research/implementation paradigm have not occurred, though there have been significant technological advances that are drastically changing its information and decision-making components and expanding its tactical options. Most significant changes relate to computer communications (79), reliability of weather-driven computer models and diffusion of the information in near-real time, and applications of geographic information systems (GIS) and precision farming to IPM (27, 151). Changes in control tactics have been substantial as well, and among those most likely to impact IPM are the development of selective pesticides and botanicals (67, 139); applications of genetic engineering to the development and release of pest-resistant crop cultivars and natural enemies of arthropod pests (73, 99, 107, 133); advances in semiochemical identification, formulation, and practical applications (19, 71, 110); and advances in trap cropping and in habitat management to enhance natural enemies (4, 5, 68, 196).

## INTERNATIONAL PERSPECTIVE

The same factors that drove IPM to the forefront of the plant protection sciences in the United States during the second half of the twentieth century also impacted most other countries. In fact, the classical integrated control programs for apple orchard pests in Nova Scotia, Canada (134, 135), and for cotton pests in Peru (10, 35) provided some of the early models for successful implementation of IPM in the field; however, the activity of the UN-FAO, through its Panel of Experts on Integrated Pest Control (see above), provided the necessary coordination, leadership, and resources to promote IPM, particularly among developing countries (39).

### *IPM in the Food and Agriculture Organization (FAO)*

The role of FAO in the diffusion of IPM (or IPC—integrated pest control—in their terminology) has been well documented (17, 23, 153). The concepts and ideas developed by the Panel of Experts between the first meeting, in 1968, through the fifth, in 1974, coalesced into a new program sponsored by FAO and the United Nations Environmental Program (UNEP)—the Cooperative Global Program (41). This program set priorities for crops or cropping systems and regions, for adaptation of IPM strategies, implementation, research, and training and education. A summary of the historical development of the rice project in Southeast Asia, the most succesful of the FAO IPM programs, is provided (42). By the end of 1995, 35,000 trainers and 1.2 million farmers had been exposed to IPM through the program.

Key for the success of the Intercountry IPM-Rice Program was demonstration of the relationship between outbreaks of the brown planthopper, *Nilaparvata lugens*, with overuse of broad-spectrum insecticides. Farmers were induced to overspray as insurance or under instruction of extension service and industry representatives. However, sprays were not only cost-ineffective (84–86), but in the absence of insecticides, planthoppers were usually kept below the economic injury level (EIL) by naturally occurring predators, particularly spiders, in the rice paddy (88). Creative aspects of the IPM-Rice Program were its emphasis on field demonstrations and training through Farmer Field Schools that used innovative approaches to give farmers IPM skills (85, 153). In addition, key to the program's success in Indonesia (85, 194) was the banning of 57 broad-spectrum organophosphate, pyrethroid, and chlorinated hydrocarbon insecticides by presidential decree in 1987, following an outbreak of the brown planthopper (153).

The latest development in the support for IPM at FAO is the establishment of the Global IPM Facility with cosponsorship of FAO, UN Development Program (UNDP), UNEP, and the World Bank. The concept is in response to the UN Conference on Environment and Development (Rio de Janeiro, Brazil, 1992), which assigned a central role for IPM in agriculture as part of its "Agenda 21." The Facility will serve as a coordinating, consulting, advising, and promoting entity for the advancement of IPM worldwide (43).

## *The International Agricultural Research Centers (IARCs)*

In the early 1940s, a joint program of the government of Mexico and the Rockefeller Foundation, which focused on wheat and maize and on training young Mexican scientists to conduct this research, demonstrated that agricultural research on-site was essential to solve problems of food production in developing countries. A parallel development in India, a collaborative program in agricultural extension with the Ford Foundation, showed the limitations of technologies transferred from other environments. These programs convinced foundation leaders, as well as representative governments, that there was a need to establish centers of excellence in agricultural research as close as possible to target regions. The International Rice Research Institute was established in 1960 as a collaborative effort of the two foundations and the government of the Philippines (18). The Centro Internacional de Mejoramiento de Maiz y Trigo (CIMMYT, International Center for Maize and Wheat Improvement) was established in Mexico in 1966. Other centers followed, and by 1996 the family of centers under the Consultative Group on International Agricultural Research (CGIAR) had grown to 16, with several others operating in similar mode but outside the CGIAR.

The IARCs considerably impacted development of IPM worldwide. Emphasis in the early days was on breeding high-yielding varieties, those that led to the "green revolution" of the 1970s and 1980s (33, 80). Varieties of wheat and rice bred to maximize yields lacked resistance to insect pests and to some diseases. The spread of new rice varieties caused insecticide use to spiral up (78). As a result, most IARCs created teams of crop protection specialists and breeders to screen germplasm collections for sources of resistance to the main pests and, when found, to breed them into commercial varieties. The same emphasis on host-plant resistance dominated most crop protection programs at the IARCs through the 1980s. The slow development of new resistant varieties and the need to control pests for which no effective resistance was found propelled IPM into the forefront of the IARCs' crop protection programs. In time the IARCs incorporated biological control (64) and cultural methods into their IPM programs with considerable success.

### *Examples of National IPM Programs*

Concurrently, many national IPM programs developed, in part, through technical cooperation. Brazil is an outstanding example. In the late 1960s and early 1970s, the US Agency for International Development (USAID) sponsored various programs in Brazil, including technical assistance for soybean production and protection. With economic development of the country, started in the late 1970s, the USAID assistance to Brazil was terminated and agricultural research under the Ministry of Agriculture reorganized. A network of agricultural research centers was established under the Empresa Brasileira de Pesquisa Agropecuaria (EMBRAPA—the Brazilian Agricultural Research Corporation). The National Soybean Research Center, in Londrina, Paraná, was established in 1975. From the outset, IPM was a high priority, and the success of the IPM programs for soybean served as a model for similar programs in other commodity centers in Brazil and other Latin American countries (51, 98, 114). Despite considerable support from national and international agencies, adoption of IPM has been slow, and vast areas under agricultural production the world over still face unacceptable losses due to pests or suffer from overuse of pesticides, which led some to suggest that new paradigms were needed.

## VARIATIONS ON THE BASIC THEME

Although success of IPM worldwide over the past 10 years (14, 63, 101, 181) cannot be disputed, legitimate concern exists that (*a*) the rate of adoption of programs has been disappointingly slow; (*b*) many programs still rely primarily on timely applications of pesticides as the principal management tactic; and (*c*) the majority of those programs focus on pests within categories (arthropods, pathogens, or weedy plants) with little consideration of multiple pest interactions (120). Although the concern is legitimate, the result has been criticism of IPM itself, not the implementers of IPM. Critics offered proposals for alternative paradigms.

### *Biologically Intensive IPM*

Because of its entomological roots, the use of EILs and scouting for the assessment of pest populations have been the main criteria of IPM adoption (185). Based on these criteria, programs that rely entirely on pesticidal controls may qualify as IPM, if treatments are made following scouting to determine whether pest populations have reached the EIL. As these programs have been endorsed by the agrochemical industry, the perception exists that IPM has become "agrochemically intensive." Furthermore, despite nearly three decades of IPM educational and implementation programs, use of pesticides has not declined (183). In view of this trend, Frisbie & Smith (49) proposed a switch to "biologically intensive" IPM or "biointensive" IPM. Biointensive IPM would rely on host-plant resistance, biological control, and cultural controls (49), and the industry would develop biorational pesticides more easily integrated into biointensive IPM systems. IPM has historically aimed at building programs based as much as possible on biological and other nonchemical controls. "Biointensive" seems tautological because by its very definition IPM is biointensive pest control.

### *Ecologically Based IPM*

Criticism of IPM reached a new height in a report by a special committee of the National Research Council's Board of Agriculture. The report proposed a new paradigm termed Ecologically Based Pest Management (EBPM) (120). The EBPM report is an excellent review of IPM, if "IPM" replaces "EBPM" throughout the text. The Committee, however, opted to promote a new paradigm to supersede IPM, claiming it to be (*a*) safe for growers, farmworkers, and consumers; (*b*) cost-effective and easy to adopt and integrate with other production practices; (*c*) long-term sustainable ("durable" in the report) and "without adverse environmental, economic, or safety consequences"; and (*d*) with ecosystems as the ecological focus. If some of this sounds familiar, it is because these same goals have been restated by IPM theoreticians and practitioners for the past

25 years. Indeed, even the expression ecologically based was used by Smith almost 20 years ago: "The concept of IPM... [is a] stage in the development of an *ecologically based pest control strategy*" (162) (my emphasis).

With regard to "new solutions for the new century" proposed in the report, other than the emphasis on genetic engineering, most have been in the IPM "tool box" for several decades. However, the main criticisms of IPM offered by the report, "a) the domination of pesticides in IPM, and b) IPM history of implementation primarily for control of arthropods," ignore the enormous inroads that IPM has made in weed and disease management in the past 15 years (125, 148, 180) and the fact that one of the most spectacular achievements of IPM to date, the management of rice pests in Southeast Asia, was based mainly on the restoration of natural controls through the removal of broad-spectrum insecticides (84–86).

A serious concern that IPM practitioners should have with this report is that it attempts to introduce a different acronym at a time when IPM has reached a peak in name recognition and public support. EBPM, furthermore, removes the term integrated from the expression, yet, *integration* probably is the most powerful component of the IPM philosophy. For over 30 years, extension and education professionals have offered IPM to the public as an ecologically sound approach to pest control. Such a report, produced under the prestigious umbrella of the National Academy of Science, could easily undermine the trust that was painstakingly built among the agricultural community, public administrators, and the public at large in the commitment of IPM practitioners to apply the best science available to the solution of pest problems.

### *Sustainable Agriculture*

The term sustainable agriculture first appeared in the literature in 1978 (105) but was formally introduced in 1985 when the US Congress "enacted the Food Security Act that initiated a program in 'Low Input Sustainable Agriculture' to help farmers use resources more efficiently, protect the environment, and preserve rural communities" (105). With a theoretical foundation in agroecology (3, 57), proponents of the sustainability concept for crop production have found great affinity with principles and approaches of IPM. Indeed, IPM provided both a conceptual approach and an implementation paradigm for sustainable agriculture (57, 106, 118, 119, 129). From an IPM perspective, the concept of sustainable agriculture provides a platform for launching IPM to higher levels of integration (94).

### *Levels of IPM Integration and Agroecosystem Sustainability*

IPM is the component of sustainable agriculture with the most robust ecological foundation. IPM not only contributes to the sustainability of agriculture, it also serves as a model for the practical application of ecological theory and provides a paradigm for the development of other agricultural system components. The IPM paradigm provides that pests and their management exist at the interface of three multidimensional universes: ecological, socioeconomic, and agricultural, in hierarchical order, with ascending levels of complexity and expanding spatial scales (see Figure 1). Based on these considerations, IPM can be conceived as interactive systems with multiple levels of integration. Rabb et al (145) suggested these in ascending order: control tactics, pests, crops, farms, agroecosystems, resources, and goals. Kogan (94) proposed that the three basic hierarchical ecological scales—species/populations, communities, and ecosystems—serve as the template for IPM integration (Figure 1). Thus, integration in IPM would have three basic levels: level I, integration of methods for the control of single species or species complexes (species/population level integration); level II, integration of impacts of multiple pest categories (insects, pathogens, and weeds) and the methods for their control (community level integration); level III, integration of multiple pest impacts and the methods for their control within the context of the total cropping system (ecosystem level integration).

Prokopy & Croft (141) added a fourth level: integration of psychological, social, political, and legal constraints to IPM. These, however, impinge, albeit with differing intensities, on any IPM system, regardless of the level of integration. Similarly, management of all other agricultural systems components—soil, water, nutrients—also can be conceived at those three levels of integration. If, at the ecosystems level, decision support systems lead to adequate evaluations of social and environmental consequences of management actions, then the system should tend toward increased sustainability. Most IPM programs to date are at level I integration, although some programs are already advancing to higher levels (142, 179).

## *IPM Implementation at Three Levels of Integration*

Targets set for IPM implementation under national programs (104) require criteria to measure adoption. Criteria have been proposed and used in surveys of IPM (14, 185), and from these the notion of a continuum of adoption emerged. The continuum ranges from no adoption through adoption of transitional systems, or those based primarily on scouting and pesticide applications following EILs; to systems that incorporate crop rotations, resistant varieties, and habitat management to enhance natural controls; and culminates in systems that rely primarily on biological controls with minimal, if any, pesticidal interventions, a level called by Benbrook et al (14) biointensive IPM, following Frisbie & Smith (49). The continuum of IPM adoption coupled with the concept of the three levels of IPM/ecology integration is represented in Figure 2. A band that includes a minimum set of tactical components (IPM threshold) defines which pest control system qualifies as IPM. To be IPM, a

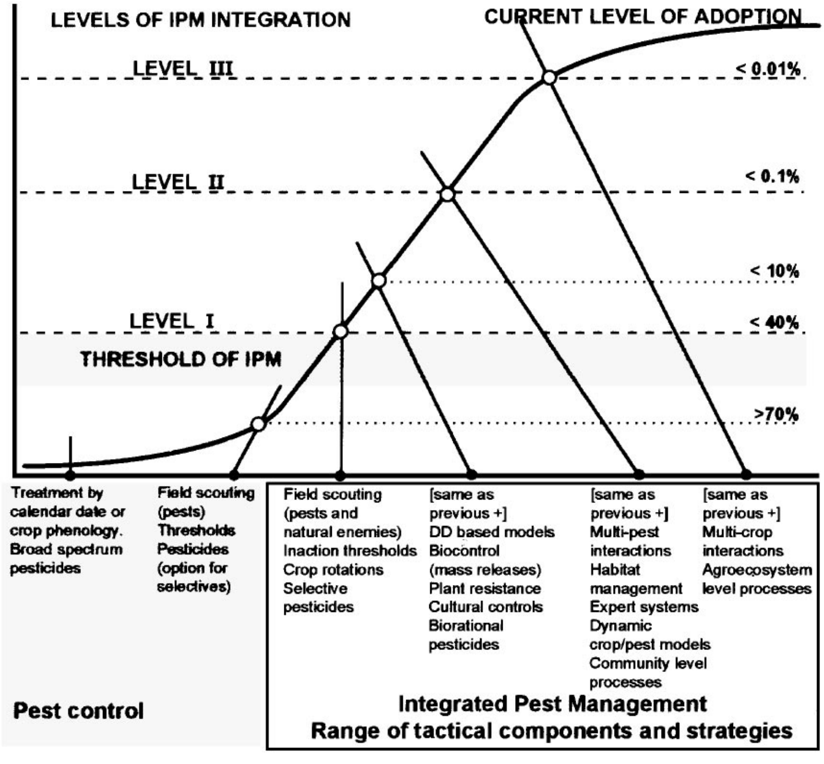


*Figure 2* Example of continuum from conventional pest control to level III IPM, suggesting that there is a minimum set of tactical components combined within a basic strategy that define the "IPM threshold." Hypothetical levels of adoption are assumed for field and vegetable crops in the United States.

pest control program must offer a suite of optional control tactics, with emphasis on those most ecologically benign, and a set of decision rules for their deployment. The basic decision rules are the economic injury level and economic threshold for arthropods (66) or the equivalents for plant pathogens (7, 197) or weeds (113). The suite of control tactics for arthropod management includes, in order of preference, (*a*) preventive tactics (i.e. enhancement of natural controls, cultural methods, plant resistance, behavioral controls) and (*b*) remedial tactics, i.e. augmentative or inundative releases of natural enemies, mechanical or physical methods, microbial pesticides, "biorational" pesticides, selective pesticides, and lowest effective dosages of broad-spectrum pesticides.

Success of IPM programs often has been measured by the overall reduction in the volume of pesticides used to control prevalent pests. Although reduction in pesticide usage is a desirable consequence of IPM, it cannot be the only measure of success. There are special circumstances in which to maintain a viable agricultural production; even under IPM guidelines, it may be necessary to use more, not less, pesticides. The issue is pesticide use within the principles of IPM, i.e. selective use after maximizing effectiveness of natural controls (29).

## THE FUTURE

A historical review is not complete without a glance toward the future, but because futurism is in vogue as the end of the millennium approaches, it is difficult to be original. CAB International assessed IPM and the environment in 2000 (83), and several papers and reports attempt to project IPM towards the next century (97, 108, 120, 128, 189). Most important developments have been anticipated in novel IPM tactics, with both plant and insect (natural enemy) products of genetic engineering heading the list. Exploitation of hitherto underused natural enemies (such as entomopathogenic nematodes), development of novel biorational pesticides, management of resistance to extend the useful life of essential pesticides and of transgenic plants, and clever use of semiochemicals all bode a vastly expanded repertoire of tactical options to enrich extant IPM strategies. The strategic innovations are fewer, but some show much promise. One that provides new opportunities for ecosystem level IPM is the strategic approach of areawide IPM.

The ease and speed of information dissemination through the Internet will certainly impact IPM in the next century (79). The promise of reliable predictive models based on real-time weather data may finally become reality, as programs and weather information are accessible through the Web. Extension information and educational programs via the Web are already available and, when cleverly used, have provided positive results.

The excitement about genetic engineering, however, dominates the futurist literature in IPM. If there is a lesson to learn from the past 35 years, it is that a silver bullet is unlikely to come out of any of the new technologies, and nothing would have been learned from the past if genetic engineering is emphasized over all other technologies that are also blossoming. IPM has proven to be a robust construct. It does not need qualifiers such as biointensive or ecologically based to convey the gamut of opportunities for innovators in the laboratories, the experimental plots, or on the farms. Opportunities to be creative within the confines of the original IPM formulation are limitless. Review of the vast literature on IPM confirms that success has come from a fundamental understanding of the ecology of crop/pest interactions, rarely from a revolutionarily new control tactic. The advance of IPM to higher levels of integration will hinge on the depth of understanding of agroecosystem structure and dynamics. As the agroecosystem is the result of the overlap of the ecological and socioeconomic scales, no technological innovation will be adopted unless it contributes to producers' economic goals and meets the requisites for acceptance by society.

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