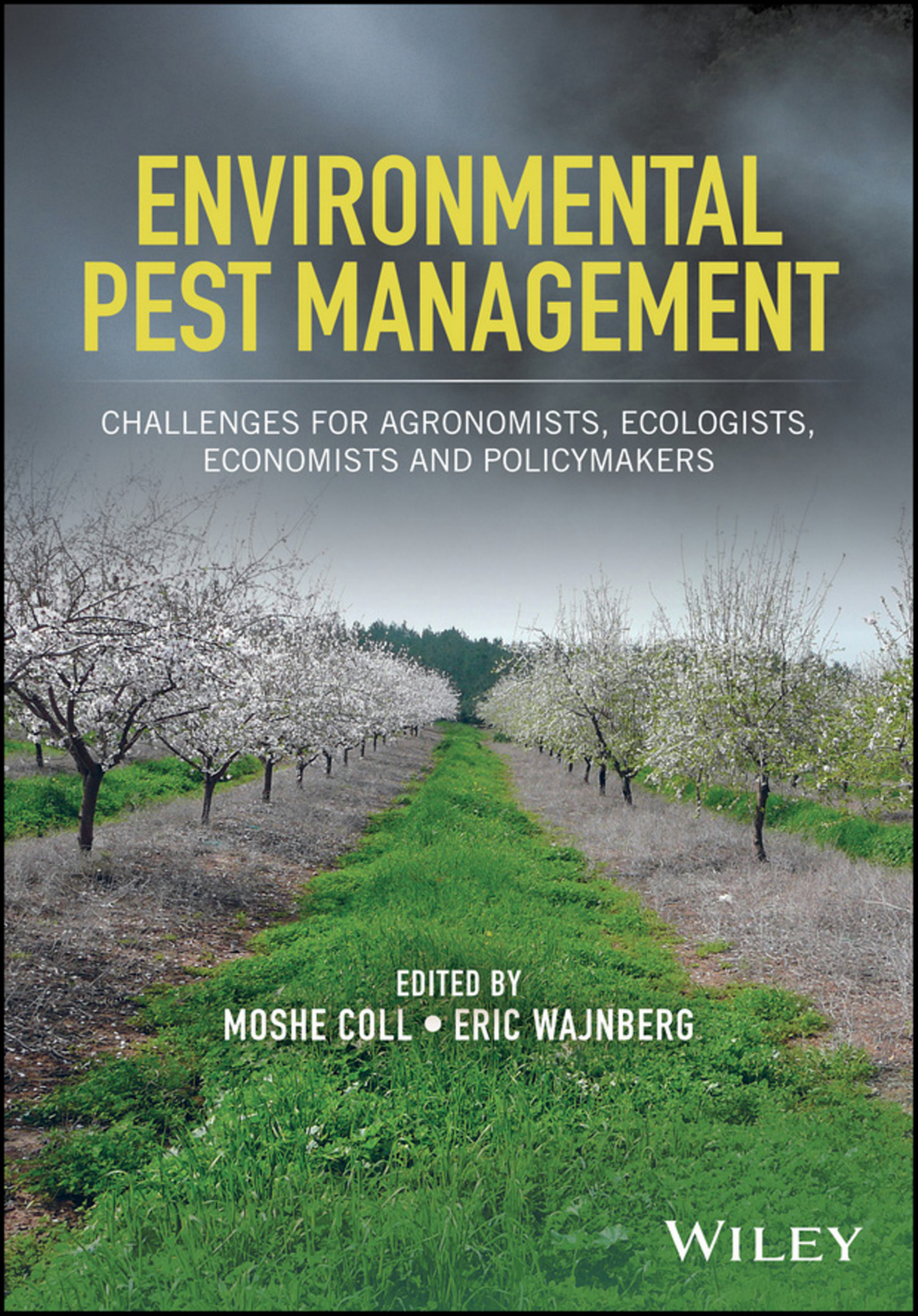
ENVIRONMENTAL PEST MANAGEMENT

CHALLENGES FOR AGRONOMISTS, ECOLOGISTS, ECONOMISTS AND POLICYMAKERS



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Environmental Pest Management

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Challenges for Agronomists, Ecologists, Economists and Policymakers

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Preface

With the rapid growth of awareness and concern regarding adverse effects of pest management activities on human and environmental health, researchers and, to a lesser extent, policymakers have recently begun to appreciate these impacts as well as the influence of environmental factors on our ability to manage pest populations. In this respect, we were surprised to find that no single volume has as yet been devoted to these complex interactions. In addition, economic and societal considerations have been largely neglected while other topics, such as pesticide toxicity, have been the focus of much attention.

This volume is aimed at filling these gaps by addressing these pressing issues. It is designed to help develop and improve environmental pest management policies and agro-environmental schemes so that they encompass all major elements operating between pest management practices and the environment. It provides up-to-date fundamental information as well as recent research findings and current thinking on each topic so that complex issues are made available to readers across disciplines. It overviews major agronomic, ecological and human health aspects of pest management–environment interactions, discusses economic tools and caveats, and assesses shortcomings of various agro-environmental policies. Finally, taken together, it proposes a new framework for the development of effective, sustainable and environmentally compatible pest management programmes.

We believe that this timely treatment of the topic in a single, interdisciplinary volume will be of interest to an unusually wide readership. The book should be valuable for everyone interested in agriculture, ecology, entomology, pest control, public health, environmental economics and ecotoxicology, as well as policymakers worldwide. It will also be useful as a versatile teaching resource. Teachers of undergraduate and graduate courses in related fields will find the book useful as both a reference and background reading ahead of group discussions on controversial issues. Finally, we hope the book will promote interdisciplinary discussion and co-ordination between pest management stakeholders, conservation ecologists and environmentalist groups.

After a short introductory chapter (Chapter 1), the first part of the book provides general background to Integrated Pest Management (Chapter 2) and to pest management economics (Chapter 3). The second part addresses environmental concerns surrounding various pest management tactics, such as pesticide use (Chapter 4), biological control (Chapter 5) and the use of transgenic crops (Chapter 6). The third section discusses positive and negative ecosystem services provided by natural areas to influence pest management (Chapters 7 and 8, respectively). Then, the fourth section addresses effects of global processes such as climate change (Chapter 9) and biological invasions (Chapter 10) on pest suppression. The fifth section covers the influence of pesticide use and the consumption of genetically modified foods on public health (Chapters 11 and 12, respectively). The sixth section then discusses policies related to pesticide use (Chapter 13), importation of biological control agents (Chapter 14), food safety (Chapter 15), externalizing economic drivers (Chapter 16) and agro-environmental schemes (Chapter 17). In the concluding chapter (Chapter 18), we summarize take-home messages and propose a new framework for future research, extension and legislative work.

We thank the following referees for their critical comments on the book's chapters: Nir Becker, Dale G. Bottrell, Ephraim Cohen, Antonio Cusumano, Georges de Sousa, Roy van Driesche, Peter Follett, Fred Gould, Isaac Ishaaya, Hagai Levine, Philippe Nicot, Yvan Rahbé, Helen Roy, Clement Tisdell, Linda Thomson, and Steve Wratten. However, all information, results, views and discussions are the sole responsibility of the respective authors. Finally, we express our sincere thanks to the people at Wiley for their efficient help and support in the production of this book.

November 2016

Moshe Coll
Eric Wajnberg

1

Environmental Pest Management: A Call to Shift from a Pest-Centric to a System-Centric Approach

Moshe Coll and Eric Wajnberg

1.1 Introduction

According to a United Nations Food and Agriculture Organization estimate, about 795 million people suffered from chronic undernourishment in 2015 (FAO, IFAD and WFP 2015), indicating that one in nine people is deficient in calories, protein, iron, iodine or vitamin A, B, C or D, or any combination thereof (Sommer and West 1996). Such high levels of global food insecurity make many human societies vulnerable to health problems, reduced productivity and geopolitical unrest. A crop loss due to pest activity is a major contributor to food insecurity: 30–40% of potential world crop production is destroyed by pests (Natural Resources Institute 1992; Oerke *et al*. 1994). Of all pests, insects cause an estimated 14% of crop losses, plant pathogens 13% and weeds 13% (Pimentel 2007). An additional 30% of the crop is destroyed by postharvest insect pests and diseases, particularly in the developing world (Kumar 1984).

Humans have probably struggled with pestiferous insects, mites, nematodes, plant pathogens, weeds and vertebrates since the dawn of agriculture some 10 000 years ago (Figure 1.1). The earliest approaches employed were probably hand removal of pests and weeds, scaring away seed-consuming birds and trapping of granivorous rodents. Crop rotation, intercropping and selection of pest-resistant cultivars soon followed. The earliest recorded use of chemical pesticides dates back to 2500 BC, when the Sumerians used sulphur compounds as insecticides (see Figure 1.1). The use of botanical compounds, such as nicotine and pyrethrum, was later reported. However, pesticide application became common practice only in the 19th century, with increased agricultural mechanization.

1.2 Modern Developments in Pest Control

In the 20th century, the discovery of synthetic compounds with insecticidal and herbicidal properties, such as DDT and 2,4-D in 1939 and 1940, respectively, quickly made chemical control the predominant method of pest control. In most cropping systems, this has remained the case to this day, in spite of growing awareness of the negative impacts of pesticides on human health and the environment. In fact, many of our current serious pest problems have been brought about by intensification

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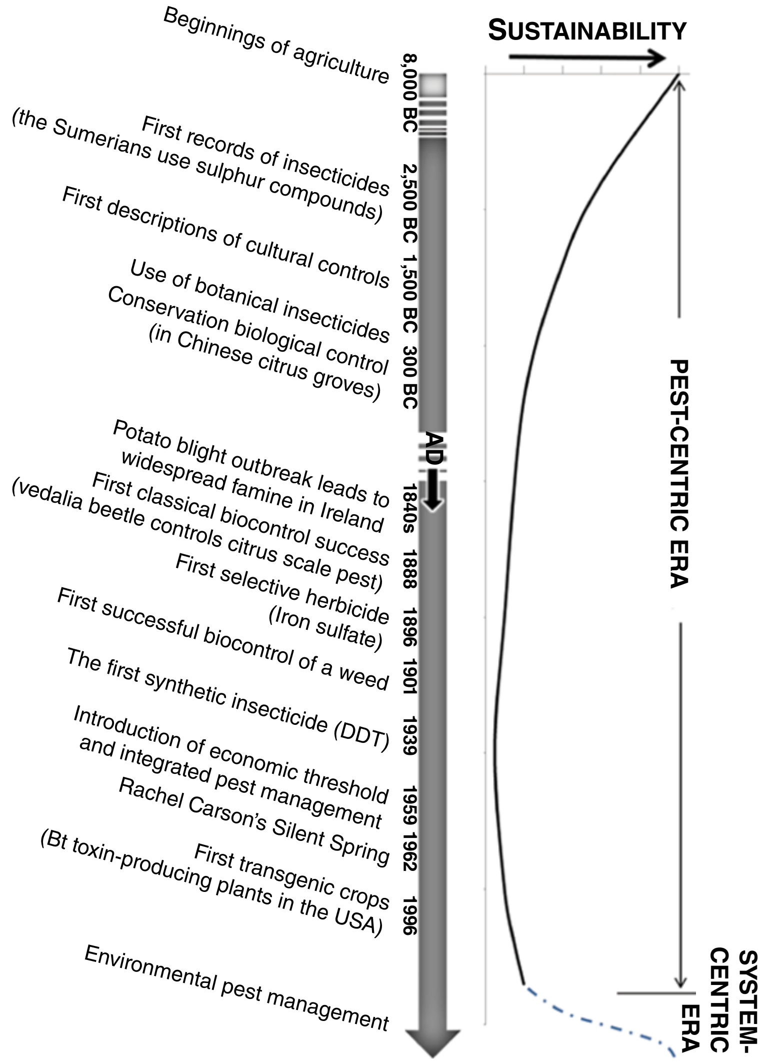

Figure 1.1 The history of pest management and changes in agro-ecosystem sustainability. Historic data are based on Abrol and Shankar (2012) and https://courses.cit.cornell.edu/ipm444/lec-notes/extra/ipm-history.html.

of cropping systems, mechanization, selection for high yielding but pest-susceptible crop genotypes, fertilization and irrigation inputs, and frequent application of pesticides (Thomas 1999; Waage 1993). Therefore, since the middle of the 20th century, most pest control measures have targeted specific pests on particular crops within single fields. Although reliance on a single tactic, usually the application of chemical pesticides, provides only a short-term solution (Thomas 1999), such a bottom-up approach has remained dominant is spite of widespread promotion of Integrated Pest Management (IPM) (Ehler 2006).

Integrated Pest Management has been accepted worldwide as the strategy of choice for pest population management. Since the United Nations Conference on the Environment in 1992 in Rio de Janeiro, Brazil, it has been the global policy in agriculture, natural resource management and trade. As a result, most of the world's population now lives in countries with IPM-guided policies for the production of most of the world's staple foods (Vreysen *et al.* 2007). Nonetheless, the definition of IPM has remained vague and highly inconsistent for more than 55 years (Table 1.1) (Bajwa and Kogan 2002). Van den Bosch and Stern (1962) stated that 'it is the entire ecosystem and its components that are of primary concern and not a particular pest'. Yet only 24% (16 of 67) of IPM definitions surveyed by Bajwa and Kogan (2002) included the term 'system' as the implementable programme or ecological unit. Furthermore, none of the surveyed definitions presented the term 'integrated' (in IPM) to indicate the integration of different measures employed simultaneously against several taxa across pest types (plant pathogens, insects, mites, nematodes, weeds, etc.). Since IPM is not legislatively defined, its definitions seem to reflect the respective interests and points of view of different individuals and organizations. Therefore, IPM is not a distinct, well-defined crop production strategy.

In spite of the original intent, IPM, as practised today, cannot be considered a holistic, system-wide approach. As pointed out by Ehler and Bottrell (2000) in the online periodical of the US National Academy of Sciences, 'despite three decades of research, there is very little "I" in IPM'. Instead, the vast majority of 'IPM' programmes are dominated by single technologies, a few of them by biological control, host plant resistance or biopesticides that are used as replacements for synthetic chemicals. All other programmes rely primarily on pesticides to suppress pest populations. Furthermore, these so-called IPM programmes rarely integrate different technologies. Their compatibility and the potential for interactive effects among control measures are not being explored. Therefore, the vast majority of IPM systems are not currently based upon the truly integrated, ecosystem-based strategy envisioned by, for example, researches and extension officers at the University of California (UC-IPM 2008). Furthermore, surveys completed between 2003 and 2006 (USDA NRCS Conservation Effects Assessment Project 2016) found that multiple IPM tactics are employed in only about 6% of cropland in the Mid-Western United States.

1.3 The Disillusionment with Integrated Pest Management

Much like the situation throughout the history of pest control, IPM programmes have generally focused on single pest species rather than on whole agro-ecosystems (Ehler 2006). Moreover, reduction in pesticide use is not indicated as a goal even in the 'true' ecosystem-based IPM approach (UC-IPM 2008), and pesticide reduction is not mentioned as a defining component of successful IPM (Kogan 1998). Therefore, it is not surprising that 'IPM' has had only a limited impact in reducing overall use of pesticides. Actually, pesticide use increased between 1970 and 2015 (see Chapter 2). It is disturbing that after decades of research, extension and legislation promoting true IPM programmes, the vast majority of current so-called 'IPM programmes' are 'nothing more than a reinvention of the supervised control of 50 [now 55] years ago' (Ehler and Bottrell 2000). The 'supervised control' approach, developed shortly after World War II, merely promoted the idea that decisions concerning insecticide application should be based on

Table 1.1 Selected definitions of Integrated Pest Management proposed or used by prominent authorities, arranged in chronological order (based in part on Bajwa and Kogan 2002).

Year	Definition	Source
1959	Applied pest control which combines and integrates biological and chemical control. Chemical control is used as necessary and in a manner which is least disruptive to biological control. Integrated control may make use of naturally occurring biological control as well as biological control affected by manipulated or induced biotic agents.	Stern *et al.* (1959)
1966	A pest population management system that utilizes all suitable techniques in a compatible manner to reduce pest populations and maintain them at levels below those causing economic injury.	Smith and Reynolds (1966)
1967	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 populations at levels below those causing economic injury.	FAO (1967)
1969	Utilization of all suitable techniques to reduce and maintain pest populations at levels below those causing injury of economic importance to agriculture and forestry, or bringing two or more methods of control into a harmonized system designed to maintain pest levels below those at which they cause harm – a system that must rest on firm ecological principles and approaches.	National Academy of Science (1969)
1972	An approach that employs a combination of techniques to control the wide variety of potential pests that may threaten crops. It involves maximum reliance on natural pest population controls, along with a combination of techniques that may contribute to suppression – cultural methods, pest-specific diseases, resistant crop varieties, sterile insects, attractants, augmentation of parasites or predators, or chemical pesticides as needed.	Council on Environmental Quality (1972)
1978	A multidisciplinary, ecological approach to the management of pest populations, which utilizes a variety of control tactics compatibly in a single co-ordinated pest management system.	Smith (1978)
1979	The selection, integration and implementation of pest control based on predicted economic, ecological and sociological consequences.	Bottrell (1979)
1979	The optimization of pest control in an economically and ecologically sound manner, accomplished by the co-ordinated use of multiple tactics to assure stable crop production and to maintain pest damage below the economic injury level while minimizing hazards to humans, animals, plants and the environment.	Office of Technology Assessment (1979)
1980	An interdisciplinary approach incorporating the judicious application of the most efficient methods of maintaining pest populations at tolerable levels. Recognition of the problems associated with widespread pesticide application has encouraged the development and utilization of alternative pest control techniques. Rather than employing a single control tactic, attention is being directed to the co-ordinated use of multiple tactics, an approach known as integrated pest management.	FAO (1980)

Table 1.1 (Continued)

Year	Definition	Source
1981	An ecologically based pest control strategy that relies heavily on natural mortality factors, such as natural enemies and weather, and seeks out control tactics that disrupt these factors as little as possible. IPM uses pesticides, but only after systematic monitoring of pest populations and natural control factors indicate a need. Ideally, an integrated pest management programme considers all available pest control actions, including no action, and evaluates the potential interaction among various control tactics, cultural practices, weather, other pests, and the crop to be protected.	Flint and van den Bosch (1981)
1982	The use of two or more tactics in a compatible manner to maintain the population of one or more pests at acceptable levels in the production of food and fiber while providing protection against hazards to humans, domestic animals, plants and the environment.	Council for Agricultural Science and Technology (1982)
1984	A strategy for keeping plant damage within bounds by carefully monitoring crops, predicting trouble before it happens, and then selecting the appropriate controls – biological, cultural or chemical control as necessary.	Yepsen (1984)
1987	A pest population management system that anticipates and prevents pests from reaching damaging levels by using all suitable techniques, such as natural enemies, pest-resistant plants, cultural management and judicious use of pesticides.	National Coalition on Integrated Pest Management (1987)
1989	An ecologically based pest control strategy that relies on natural mortality factors such as natural enemies, weather and crop management and seeks control tactics that disrupt these factors as little as possible.	National Academy of Science, Board of Agriculture (1989)
1989	A pest control strategy based on the determination of an economic threshold that indicates when pest population is approaching the level at which control measures are necessary to prevent a decline in net returns. In principle, IPM is an ecologically based strategy that relies on natural mortality factors and seeks control tactics that disrupt these factors as little as possible.	National Research Council, Board of Agriculture (1989)
1989	A comprehensive approach to pest control that uses combined means to reduce the status of pests to tolerable levels while maintaining a quality environment.	Pedigo (1989)
1990	A systematic approach to crop protection that uses increased information and improved decision-making paradigms to reduce purchased inputs and improve economic, social and environmental conditions on the farm and in society. Moreover, the concept emphasizes the integration of pest suppression technologies that include biological, chemical, legal and cultural controls.	Allen and Rajotte (1990)
1991	An approach to pest control that utilizes regular monitoring to determine if and when treatments are needed and employs physical, mechanical, cultural, biological and educational tactics to keep pest numbers low enough to prevent intolerable damage or annoyance. Least-toxic chemical controls are used as a last resort.	Olkowski and Daar (1991)

(*Continued*)

Table 1.1 (Continued)

Year	Definition	Source
1992	The co-ordinated use of pest and environmental information along with available pest control methods, including cultural, biological, genetic and chemical methods, to prevent unacceptable levels of pest damage by the most economical means, and with the least possible hazard to people, property and the environment.	Sorensen (1992)
1992	An ecologically based pest control strategy which is part of the overall crop production system. 'Integrated' because all appropriate methods from multiple scientific disciplines are combined into a systematic approach for optimizing pest control. 'Management' implies acceptance of pests as inevitable components, at some population level of agricultural system.	Zalom *et al.* (1992)
1993	A management approach that encourages natural control of pest populations by anticipating pest problems and preventing pests from reaching economically damaging levels. All appropriate techniques are used such as enhancing natural enemies, planting pest-resistant crops, adapting cultural management and using pesticides judiciously.	United States Department of Agriculture, Agricultural Research Service (1993)
1993	Management activities that are carried out by farmers that result in potential pest populations being maintained below densities at which they become pests, without endangering the productivity and profitability of the farming system as a whole, the health of the family and its livestock, and the quality of the adjacent and downstream environments.	Wightman (1993)
1994	The use of all economically, ecologically and toxicologically justifiable means to keep pests below the economic threshold, with the emphasis on the deliberate use of natural forms of control and preventive measures.	Dehne and Schonbeck (1994)
1994	Integrated Pest Management is the use of a variety of pest control methods designed to protect public health and the environment, and to produce high-quality crops and other commodities with the most judicious use of pesticides.	Co-operative Extension System, University of Connecticut (1994)
1994	An effective and environmentally sensitive approach to pest management that relies on a combination of common-sense practices. IPM programmes use current, comprehensive information on the life cycles of pests and their interactions with the environment. This information, in combination with available pest control methods, is used to manage pest damage by the most economical means, and with the least possible hazard to people, property and the environment. IPM takes advantage of all pest management options possible, including, but not limited to, the judicious use of pesticides.	Leslie (1994)
1994	A control strategy in which a variety of biological, chemical and cultural control practices are combined to give stable long-term pest control.	Ramalho (1994)
1995	A pest management system that, in the socioeconomic context of farming systems, the associated environment and the population dynamics of the pest species, utilizes all suitable techniques in as compatible a manner as possible and maintains the pest population levels below those causing economic injury.	Dent (1995)

Table 1.1 (Continued)

Year	Definition	Source
1996	A sustainable approach to managing pests by combining biological, cultural, physical and chemical tools in a way that minimizes economic, health and environmental risks.	Food Quality Protection Act (1996)
1996	A crop protection system which is based on rational and unbiased information leading to a balance of non-chemical and chemical components moving pesticide use levels away from their present political optimum to a social optimum defined in the context of welfare economics.	Waibel and Zadoks (1996)
1997	An ecosystem-based strategy that focuses on long-term prevention of pests or their damage through a combination of techniques such as biological control, habitat manipulation, modification of cultural practices and use of resistance varieties. Pesticides are used only after monitoring indicates they are needed according to established guidelines, and treatments are made with the goal of removing only target organisms. Pest control materials are selected and applied in a manner that minimizes risks to human health, beneficial and non-target organisms and the environment.	University of California (1997)
1998	A decision support system for the selection and use of pest control tactics, singly or harmoniously co-ordinated into a management strategy, based on cost/benefit analyses that take into account the interests of and impacts on producers, society and the environment.	Kogan (1998)
2000	An approach to the management of pests in public facilities that combines biological, cultural, physical and chemical tools in a way that minimizes economic, health and environmental risks.	Children's Health Act (2000)
2002	A broad ecological approach to pest management utilizing a variety of pest control techniques targeting the entire complex of a crop ecosystem. This approach promises to ensure high-quality agricultural production in a sustainable, environmentally safe and economically sound manner.	Bajwa and Kogan (2002)
2009	The rational application of a combination of biological, biotechnical, chemical, cultural or plant-breeding measures, whereby the use of plant protection products is limited to the strict minimum necessary to maintain the pest population at levels below those causing economically unacceptable damage or loss.	European Union, Directive 91/414/EEC (2009)
2013	A science-based, decision-making process that identifies and reduces risks from pests and pest management-related strategies. IPM co-ordinates the use of pest biology, environmental information and available technology to prevent unacceptable levels of pest damage by the most economical means, while minimizing risk to people, property, resources and the environment. IPM provides an effective strategy for managing pests in all arenas from developed agricultural, residential and public lands to natural and wilderness areas. IPM provides an effective, all-encompassing, low-risk approach to protect resources and people from pests.	USDA national road map for integrated pest management (2013)
2015	A system based on three main principles: (1) the use and integration of measures that discourage the development of populations of harmful organisms (prevention), (2) the careful consideration of all available plant protection methods, and (3) their use to levels that are economically and ecologically justified.	Lefebvre *et al.* (2015)

(*Continued*)

Table 1.1 (Continued)

Year	Definition	Source
2016	A sustainable approach to managing pests by combining biological, cultural, physical and chemical tools in a way that minimizes economic, health and environmental risks. IPM emphasizes the growth of a healthy crop with the least possible disruption to agricultural ecosystems and encourages natural pest control mechanisms.	Department of Agriculture, Environment and Rural Affairs, UK (2016)
2016	Socially acceptable, environmentally responsible and economically practical crop protection.	IPM Centers (2016)
2016	Management of agricultural and horticultural pests that minimizes the use of chemicals and emphasizes natural and low-toxicity methods (as the use of crop rotation and beneficial predatory insects).	Merriam-Webster Dictionary (2016)
2016	An ecosystem approach to crop production and protection that combines different management strategies and practices to grow healthy crops and minimize the use of pesticides.	UN-FAO (2016)
2016	The implementation of diverse methods of pest controls, paired with monitoring to reduce unnecessary pesticide applications.	US Department of Agriculture (2016)
2016	An environmentally friendly, common-sense approach to controlling pests that is focused on pest prevention, the use of pesticides only as needed, the integration of multiple control methods based on site information obtained through inspection, monitoring, and reports.	US Environmental Protection Agency (2016)

routine pest monitoring rather than on calendar-based treatments (Smith and Smith 1949). For the most part, this is the current situation: efforts are largely limited to pesticide management (Ehler 2006), in line with a World Bank (2005) report that concluded that IPM adoption level is low with no indication of change in pesticide use.

1.3.1 Causes for IPM Failure

Why, then, did the IPM approach largely fail to provide growers, and society at large, with effective, safe and sustainable pest management systems? It was clear from the outset that successful IPM is 'knowledge intensive': it requires in-depth ecological understanding of the structure and function of agro-ecosystems, particularly the food webs and species associations and interactions through which energy flows in the system (Barfield and Swisher 1994; Wood 2002). IPM also requires a good grasp of economic, public health and consumer concerns, as well as an appreciation of environmental conservation. These complexities, and the multidisciplinary nature of IPM in the field, are evidently unsuited to the bottom-up manner in which IPM has evolved. Furthermore, the idiosyncratic behaviour of many agro-ecosystems, as well as the site-specific nature of most pest problems, often makes predetermined thresholds operationally intractable (Ehler and Bottrell 2000). Moreover, a field-by-field IPM approach is often insufficient, particularly when pests are mobile. Finally, the cost of generating ecological information needed for development and implementation of functional IPM systems for local situations is prohibitive (Morse and Buhler 1997).

The use of multiple pest control tactics, a fundamental paradigm underlying IPM, presents additional levels of complications, especially when multiple pest types, such as plant pathogens, insects, mites and nematodes, are targeted. This is particularly important because simply combining different management tactics is not sufficient for the implementation of true IPM programmes (Ehler and Bottrell 2000). Control measures often interact in their effects on various organisms in the field. Furthermore, reliance on a single control tactic rarely yields satisfactory results and often causes environmental degradation, food contamination and resistance development in both target and non-target species, seriously impairing agro-ecosystem sustainability (Abrol and Shankar 2012). In general, the use of multiple pest control tactics provides more reliable, efficient and cost-effective solutions. However, mixing control measures employed against one pest without determining their compatibility or effects on other organisms in the system may actually aggravate pest problems or bring about unintended results. Clearly, integrating tactics across different groups of pests – insects, plant pathogens, weeds, etc. – presents even greater challenges than integrating several tactics against a single pest. Combining harmonious – and not antagonistic – tactics to achieve the best long-term control of individual pests or groups of different pests, while ensuring compatibility with the local ecological community, requires considerable research. This integrated study on different pest classes may be discouraged by the organizational structure of research institutions, as departments are often arranged by pest disciplines (Ehler 2006). As a result, perhaps, only a few field-tested examples exist to show how two tactics can be optimally integrated to suppress a single pest in large-scale cropping systems, and studies of the combination of a wider array of tactics are even rarer (Thomas 1999).

The spatial scale to be considered imposes additional constraints on the development of holistic IPM programmes. First, it is unclear what defines the IPM boundary in the farming landscape. Properties of the focal and neighbouring crop fields and their distribution pattern in the landscape, dispersal capacity of the pests, climatic and topographic considerations and many other factors will together determine the distance at which a particular operational IPM system is effective. Second, successful management of some pests may require collective action by neighbouring farmers, especially when the farm holdings are small and close together and pests are mobile. An IPM programme involving migrant pests that function as metapopulations may have to extend over a huge expanse of land. Such area-wide control of agricultural pests would require a centrally managed top-down approach with a regulatory component to ensure full participation and compliance of stakeholders within the region (Vreysen *et al.* 2007). This stands in sharp contrast to the bottom-up approach that has been the operational mode for IPM at the farm and community levels for years.

The dramatic impact of ecological complexity on the efficacy of IPM programmes is evident even when broad pest occurrence patterns, such as the effects of vegetation diversification on pest populations in the IPM landscape, have been demonstrated. The scientific literature generally suggests that plant diversification is a viable strategy for suppressing pests, in part by increasing the level of biological control (see meta-analysis by Letourneau *et al.* 2011). This positive impact of plant diversification was observed, for example, when blast-susceptible rice varieties were planted in combination with resistant varieties: the fungus *Pyricularia oryzae* was 94% less severe in mixtures than in pure rice stands (Zhu *et al.* 2000). However, many diversification schemes slightly but significantly reduce crop yields, in part because intercropping, or the inclusion of non-crop plants, removes some land area from production. Therefore, the potential ecosystem services (benefits) as well as disservices (costs) of vegetation diversification must be quantified for the management of harmful organisms, even though the positive effects usually outweigh the negative.

Another hindrance to the development and implementation of successful IPM programmes is limited and short-term governmental commitment. For the most part, IPM programmes rely on know-how that cannot be commercialized. As such, these programmes are developed by researchers in governmental organizations and public research institutes, such as universities, that are funded mostly by governments, grower associations and other public sources. Many programmes are then implemented through governmental extension services, farmer participatory research, and demonstration and educational programmes (Matteson 2000). Such programmes are the most effective way to disseminate good farming practices, especially, but not only, in developing countries. However, funding constraints, privatization of extension services and shifting attention to other sectors such as urban populations have reduced overall resources devoted to IPM research and implementation in many countries. This global trend is exemplified in the FAO-IPM programme in South and South-East Asian rice crops. This programme was extremely successful for some 20 years. It encompassed training farmers in 13 different countries and educational programmes supported by the respective governments to promote IPM and discourage unnecessary use of pesticides. But when public funding for these programmes dried up, farmers, in response to advocating chemical companies, were quick to revert to pesticide-dependent plant protection practices (Bottrell and Schoenly 2012; Heong and Hardy 2009). Although some IPM efforts have stood the test of time, many others have not, thus allowing the agrochemical industry to sway plant protection away from true IPM and back to the 'supervised control' of the 1950s.

An additional weakness aspect of plant protection research is the need to respond to constant changes in technology, production practices, markets and ecosystem conditions. New, higher yielding crops and cultivars that are more susceptible to pest attacks; novel cultivation practices such as irrigation technologies, no-till cultivation and fertilizer formulation; genetically modified crops; new pesticides and other pest control tools and other innovations force applied scientists to devise solutions to continuously emerging pest problems. Likewise, markets for agricultural produce are constantly in flux, with seasonal price changes, increased demands for produce free of pesticide residues and environmentally friendly food production practices, shifts in global trade in fruit, vegetable and flower crops, and other elements contributing to instability. All these factors influence both economic threshold levels and the arsenal of available pest control measures. In addition, major changes take place due to global warming and desertification, pest invasions, new regulatory actions and many additional factors.

Under these conditions, plant pathologists, weed scientists and entomologists have often only responded to the changes in their attempts to minimize pest-induced yield losses, instead of driving the field toward predetermined goals. In addition, applied scientists, perhaps because of their need to specialize and their appreciation of the uniqueness of their research objects (Rosenheim and Coll 2008), have found it difficult to view the agricultural production system as a whole. As a result, applied researchers rarely integrate multiple scales in their studies, be they multiple pests, several control tactics, several crops, larger spatial scales or long-term dynamics. They instead seek solutions to specific problems, responding to needs only at the local level. Unfortunately, such an approach may not be an optimal way to utilize limited resources and may even conflict with existing research incentives and institutional structures (Waage 1998).

1.3.2 The Impact of the Agro-Chemical Industry

The characteristics of pest management research described above leave the field highly susceptible to the influence of various powerful interest groups, particularly the agro-chemical industry. Until now, IPM has evolved in a bottom-up manner so that even public funding is highly sensitive to crises and is therefore not stable. When funding for research and extension is reduced, chemical companies increase pesticide use again. Similarly, plant protection scientists and professionals may influence national policy, sometimes even working against true IPM. As a case in point, in November 2012, the three professional societies most involved in pest management in the USA (Weed Science Society of America, American Phytopathological Society and Entomological Society of America) released a joint policy statement which clearly rejects the notion that pesticide use in IPM should be restricted to least toxic compounds, and that even those should be used only when no other options exists. They argue that 'suggesting that only "least toxic pesticides" be used, as a "last resort" ignores the extensive research, regulatory, educational and stewardship efforts that make important pesticide tools available and define their proper and safe use in Integrated Pest Management programmes' (www.entsoc.org/press-releases/issues-associated-least-toxic-pesticides-applied-last-resort). This statement appears to be heavily weighted in favour of the agro-chemical industry, and this approach may serve to hamper any effort to implement IPM on the ground.

Given all the obstacles described above, it is not surprising that sustainable IPM systems are extremely rare globally and pesticides use is once again on the increase. Commonly employed IPM practices offer no viable alternatives that would reduce pesticides use and farmers are easily swayed by the pesticide industry. The rate at which farmers revert to 'supervised control' has accelerated in recent years, particularly as inexpensive generic compounds have become available. Therefore, farmers are driven to apply these pesticides rather than scouting their fields. Scouting, after all, is more costly than applying pesticides manufactured in less developed countries where, generally speaking, few environmental, human health and labour regulations are enforced. As a result, global average pesticide use has increased by 8.1% over the last 15 years (Abrol and Shankar 2012). Interestingly, proportionate use of insecticides of all used pesticides is much higher in developing countries than in developed ones, whereas in the latter countries, proportionally more herbicides are used, likely because of the higher prevalence of herbicide-tolerant transgenic crops (Abrol and Shankar 2012).

1.4 A Call for Environmental Pest Management

The pesticide industry clearly has its own incentives and huge endowments to ensure that farmers buy its products. These should be countered by externalizing pesticide-inflicted costs: external costs to human health, the environment and society at large should be levied onto manufacturers, dealers and users of pesticides. The sustainable support of public sector-driven IPM must be guaranteed so that researchers and extension officers stay intimately involved on a long-term basis. The ultimate challenge is to harmonize IPM systems with the farming and consumer communities to ensure that it is compatible with the social, economic, marketing and political considerations that affect IPM adoption (Prokopy and Croft 1994). Toward this goal, constantly evolving scientific, social and economic constraints must be overcome to enable plant protection to become a sustainable component of agriculture with maximum value to farmers, society and the environment. It is apparent that these challenges cannot be met through the traditional, bottom-up approach to the development and implementation of IPM.

We argue that the way in which we approach agricultural pest management must change if we are to develop truly sustainable, environmentally compatible, safe and effective plant protection systems. We need to make the transition from a conventional pest- and crop-centric, bottom-up approach to a more holistic, system-centric, top-down scheme. The time has come to employ top-down tools through regulatory action, positive and negative incentive systems, and by imposing accountability for external costs. The external costs of pesticides have been estimated at US\$ 4–19 kg^{-1} of applied active ingredient (Pretty and Bharucha 2015). Adding these costs to the price of pesticides could help to reduce excessive applications. Such an approach would set desirable overall, ecosystem-wide goals and then devise ways to achieve them on the ground. Theoretical and empirical research will of course still be needed to generate predictive and practical tools, respectively.

While system-wide approaches of this sort are beginning to emerge and even mature in some countries, many of these agro-environmental schemes fail to consider the full range of mutual impacts between pest management and the environment, including effects on human health. A top-down approach would also address the most frequently cited obstacles to the adoption of IPM in developing countries, namely the 'lack of favourable government policies and support' and the need for 'collective action within a farming community' (Parsa *et al.* 2014).

This volume is intended to aid in the development and improvement of agro-environmental systems encompassing all major interactions between pest management practices and the environment. We argue that grassroots research, extension and farmer training efforts must be backed by legislative, regulatory and enforcement actions taken by governments. Governmental inputs acting to promote sustainable pest management practices and nature conservation should have four main objectives that are currently missing in most legislation: (1) the establishment of goal-based agro-environmental schemes that include pest management objectives, (2) externalizing true costs of pesticide use, (3) strengthening of the public extension service, and (4) soliciting goal-specific plant protection research.

Properties and methods used for the implementation of these objectives would certainly vary greatly among countries. Governmental and social structures, economic forces, traditions and other factors will shape needs, impose constraints and determine feasibility of means, and thus influence goals and approaches. However, in some cases, the required infrastructure already exists and needs only to be adjusted to the new objectives. For example, the State of California, USA, charges a "Mill Assessment" fee on pesticide sales that could be adjusted upward in order to discourage pesticide use and cover health and environmental costs related to pesticide application.

For practical, marketing or ideological reasons, growers should be allowed to meet regulatory requirements in different ways: through organic farming, permaculture, IPM, or by adopting just a few practices which promote desirable outcomes. Governmental involvement would also facilitate co-ordination and communication between landowners within a landscape and a thorough understanding of local and regional patterns of multi-scale ecosystem services and disservices. These are essential for sustainable pest management. Finally, centralized schemes and policies could be amended and fine-tuned as more information becomes available and with changes in agricultural production and market conditions. These continuous adjustments are crucial for the sustainability of safe and environmentally compatible pest management practices.

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Part I

General Background

2

Approaches in Plant Protection: Science, Technology, Environment and Society

Deborah K. Letourneau, Margaret I. FitzSimmons and Diego J. Nieto

2.1 Introduction

Our purpose in this chapter is to introduce Integrated Pest Management (IPM) as a desirable approach to plant protection, but one that requires an ecosystem-wide perspective and substantial shifts within the social, political and economic priorities of food production. In the words of van den Bosch and Stern (1962), 'it is the entire ecosystem and its components that are of primary concern and not a particular pest'. The reason for bringing attention to an even broader context is to understand what forces are shaping pest, disease and weed management today, and to argue that desirable changes in plant protection will require interdisciplinary strategies that foster bold transformations in food systems.

Plant protection approaches in agriculture are derived from a complex array of social and scientific factors, including access to capital, labour and technological tools, the agro-ecosystem and surrounding landscape, relationship dynamics along the commodity chain, market volatility, institutional price supports, regulations and loan stipulations. Yet on the ground, they may look like a series of simple decisions: prophylactically drench broccoli (*Brassica oleracera*) with chlorpyrifos to prevent yield losses from cabbage maggot (*Delia radicum*), sow mixed rice (*Oryza sativa*) varieties to optimize spider predation and virus resistance, grind up unharvested sugar cane (*Saccharum officinarum*) infested with stalk borers (*Diatraea saccharalis*), fumigate the soil to extend harvest cycles, etc. The outcomes of each plant protection decision then provide feedback to growers in terms of experience, knowledge, cultural norms, revenue and marketing options, while also extending out to affect less apparent aspects of the environment, such as microbial shifts in the soil, groundwater purity, allele selection and fixation in weed populations, diversity of parasitoids and dominance of suppressive micro-organisms. Environmental effects then come back to growers, farm workers and consumers indirectly in terms of promoting or disrupting agro-ecosystem health, ecosystem services, public health and food security. Examining pest control approaches in their social contexts highlights some of the barriers against, and opportunities for, integrated and sustainable crop protection solutions.

Environmental Pest Management: Challenges for Agronomists, Ecologists, Economists and Policymakers, First Edition. Edited by Moshe Coll and Eric Wajnberg.

2.2 History of Plant Protection Approaches

Humans have brought native plants into production, selected propagules with desirable traits, and dispersed them as crops into new ecological environments. Emerging in most of the world's regions out of local knowledge of plants and animals (Sauer 1952), early crop protection practices developed as adaptations to local ecological circumstances. As human dispersal transferred desired species into new ecological systems (Sauer 1993), cultural practices changed, in part because plants could be resited away from their natural enemies. The development of plantation agriculture in the 18th century benefitted from such relocation, as coffee (*Coffea* spp.), cotton (*Gossypium* spp.), banana (*Musa* spp.), pineapple (*Ananas comosus*) and other valued crops were freed from pest pressure in new colonial locations. New forms of economic management and control of labour were coupled to large-scale production in these new ecological-social complexes. Over time, specialized intensive production set the stage for new ecological and social challenges requiring different scientific and institutional innovations. The beginnings of standardized, broad-spectrum responses to these challenges were developed at research institutions for plant breeding and pest control and were disseminated through educational extension for farmer and public education.

The economic norms developed in plantation agriculture, such as increasing geographic separation of production and markets, creating powerful intermediate business between producers and consumers, standardizing varieties, and simplifying and intensifying farm activities, spread over a century from plantation and grain crops into horticulture (FitzSimmons 1986). We provide an historical overview of crop protection approaches within their social contexts in the changing production of fresh-market strawberry (*Fragaria ananassa*) in coastal California, USA, over the last 100 years. Major pests and crop protection approaches are listed at 20-year intervals from 1915 to 2015 (Table 2.1) for strawberry production in the Central Coast region of California (Figure 2.1). Our experience with this cropping system and location allows us to illustrate historical changes and social forces that determined the contents of a farmer's 'toolbox' and influenced decision making in plant protection strategies.

In 1915, intensive production of specialty crops in small parcels, including leafy greens, cole crops and strawberry, was initiated in the region by Japanese immigrants, bringing cultural norms, knowledge and production techniques from Asia. However, growing political anti-immigration sentiment in the USA (Higgs 1978) resulted in the Alien Land Law of 1913, which denied Asians in California the right to own, lease or otherwise enjoy land. By listing themselves as 'managers' affiliated with sympathetic growers with European heritage, the Isei (Japanese immigrant families) established and tended strawberry plantings that produced high-quality fruit for 4–6 years, and sold them in local markets. Patchy establishment of a new crop allowed for relatively low accumulation of pests in those early years. Although most pests were introduced species, such as strawberry root weevils from Europe and easily dispersed annual weeds (Mensing and Byrne 1998), native species such as oak root rot (*Armillaria mellea*) occasionally infected the crop, in this case after clearing of its woody hosts for berry production (see Table 2.1).

In 1935, producers in the region had diversified ethnically but were still commonly Nisei – sons of Japanese immigrants – tenant farmers who managed small parcels to grow berries and vegetables using family labour. Strawberries were transplanted in the spring into soil that had never before produced berries. Pest and disease pressure increased nonetheless, compared to the previous generation of growers, whose plants

Table 2.1 Changes in pest-related challenges and crop protection approaches over the last century, as illustrated by strawberry production on the central coast of California, USA.

	Major pests	**Crop protection tactics**
1915		Sources* include Smith and Goldsmith (1936), Darrow (1966), Farmers' Bulletins (e.g. USDA No. 2184)
Insects	Strawberry root weevil (*Otiorhynchus* spp.) (Eighme, L., pers. notes), strawberry leaf-roller (*Ancylis comptana*)	Conservation of natural enemies**; copper acetoarsenite (Paris Green), powdered arsenate of lead (Hinds 1913)
Mites	Possibly two-spotted mite (*Tetranychus urticae*)	Conservation of natural enemies***
Diseases	Gray mould (*Botrytis cinerea*), oak root fungus (*Armillaria mellea*)	Transplant clean nursery stock to land that has never been in strawberry production. These plants remain in production for 4–6 years with conservation of antagonistic microbes
Nematodes	Possibly root-knot nematodes (*Meloidogyne* spp.)	Naturally occurring *Bacillus thuringiensis* (Bt), predatory nematodes
Weeds	Unknown; few exotic species, some native species likely, such as coast wild cucumber (*Marah oreganus*)	Hand cultivation
1935		Sources* include Thomas (1932, 1939), Stevens (1933), Smith and Goldsmith (1936)
Insects	Strawberry rootworm (*Paria canella*), aphids (Aphididae), white grubs (Scarabaeidae)	Conservation of natural enemies**; top plant (remove leaves) before second spring to control mites and aphids; nicotine tannate, *Derris* plant extract (rotenone), pyrethrum (Ginsberg and Schmit 1932; Little 1931); lead arsenate dusts
Mites	Two-spotted spider mite, occasionally cyclamen mite (*Steneotarsonemus pallidus*)	Conserve natural enemies***; replace popular Nich Ohmer variety with Marshall-Banner varieties with resistance to cyclamen mite, but prone to diseases
Diseases	Red-stele root rot (*Phytophthora fragariae* var. *fragariae*) (Darrow 1966), *Verticillium* spp. wilts	Transplant clean nursery stock to levelled land that has never been in strawberry production; avoid land with a history of potato or tomato; these plants remain in production for 2–3 years with conservation of antagonistic microbes; top plant (remove leaves) before second spring to avoid leaf spot
Nematodes	Root-knot nematodes	Naturally occurring enemies such as the bacterium *Bacillus thuringiensis* (Bt) and predatory nematodes
Weeds	For example, red stem filaree (*Erodium cicutarium*), field bindweed (*Convolvulus arvensis*), pigweed (*Amaranthus* spp.), mustard (*Brassica* spp.)	Hand cultivation, pre-plant irrigation then low water in first year

(*Continued*)

Table 2.1 (Continued)

	Major pests	Crop protection tactics
1955		Sources* include Huffaker and Kennett (1956), Allen (1959), *California Agriculture* articles, e.g. Lange *et al.* (1967), and Smith *et al.* (1958)
Insects	Serpentine leaf miner (*Tischeria* sp.), strawberry aphid (*Chaetosiphon fragaefolii*), which vectors strawberry mild yellow-edge virus (SMYEV) (*Potexvirus*); secondary pests, such as the native western flower thrips (*Frankliniella occidentalis*) and western tarnished plant bug (WTPB) (*Lygus hesperus*)	Kelthane, phosdrin, TEPP, thiodan, chlordane, diazinon, malathion, parathion and methoxychlor; with less attention to conservation of natural enemies**
Mites	Two-spotted spider mite; cyclamen mite in second year plantings	Endrin, azobenzene and isodrin for cyclamen due to their persistence; conservation of natural enemies***
Diseases	Crown rot (*Phytophthora* spp.), SMYEV and crinkle virus (*Cytorhabdovirus*)	Sierra variety resistant to *Verticillium*; chlorobromopropene and methyl bromide soil fumigant, chloropicrin, Captan and phenyl mercury acetate
Nematodes	Root-knot nematode; possibly a secondary pest: root-lesion nematode (*Pratylenchus* spp.)	Chlorobromopropene soil fumigant
Weeds	For example, red stem filaree, field bindweed, pigweed, mustard, etc.	Hand cultivation, tractor cultivation, fumigation
1975		Sources include USDA (1972) and various *California Agriculture* articles, such as Welch *et al.* (1989)
Insects	Western flower thrips and WTPB	Organochlorines were mostly replaced by carbamates and organophosphates including carbaryl, methoxychlor, toxaphene and mevinphos for insects and mites
Mites	Two-spotted spider mite; cyclamen mite in second year plantings	Miticides; conservation or augmentation of predatory mites; release of artificially selected miticide-resistant predatory mites (Roush and Hoy 1980)
Diseases	Root rot (*Verticillium dahliae*)	Tioga variety tolerant to yellows and crinkle virus
Nematodes	Root-knot nematodes	Methyl bromide fumigation, allowed via special use permit
Weeds	For example, red stem filaree, field bindweed, pigweed, mustard, etc.	Monitoring, methyl bromide fumigation, hand and tractor cultivation
1995		Sources: Strand (1994), Gabriel (1989), Welch *et al.* (1989), Pickel *et al.* (1995), Gliessman *et al.* (1996)

Table 2.1 (Continued)

	Major pests	Crop protection tactics
Insects	Western flower thrips and WTPB	Malathion, naled; some organophosphates replaced by novaluron, pyrethroids, spinosyns, malathion; augmentation or conservation of natural enemies**; release of WTPB egg parasitoid *Anaphes iole*; removal of nearby host plants for overwintering WTPB, e.g. wild radish, shepherd's purse; monitor for WTPB on new plantings in fall to set biofix date to predict nymphal exposure and time insecticide spray after 242 degree-days accrue
Mites	Two-spotted spider mite; cyclamen mite in first and second year plantings	Bifenazate, abamectin, fenbutatin, oils; rotate active ingredients to retard resistance build-up; spray thresholds of 5–20 mites per leaflet unless predatory mites are half as abundant; augmentative releases of commercially available predatory mites *Phytoseiulus persimilis*, *Amblyseius californicus* and *Galendromus occidentalis*; conservation of natural enemies***
Diseases	Root rot and SMYEV	Methyl bromide fumigation, which controls white grubs and other previously common pests and diseases; rotation with rye or barley recommended
Nematodes	Northern root-knot nematode (*Meloidogyne hapla*)	Methyl bromide fumigation, hand and tractor cultivation
Weeds	Little mallow (*Malva parviflora*), burclover (*Medicago* spp.), common groundsel (*Senecio vulgaris*), sowthistle (*Sonchus* spp.), purslane (*Portulaca oleracea*), chickweed (*Stellaria media*), red stem filaree, burning nettle (*Urtica urens*), annual bluegrass (*Poa annua*); plants that host WTPB	Methyl bromide fumigation, plastic mulch and drip irrigation, except for field bindweed, sweetclovers, little mallow, burclover and common groundsel, the seeds of which survive methyl bromide and chloropicrin fumigation
2015		Sources: Strand (2008) and Koike *et al.* (2012), unless otherwise indicated
Insects	WTPB, western flower thrips and recently introduced exotic pests: light brown apple moth (*Epiphyas postvittana*), greenhouse whitefly (*Trialeurodes vaporariorum*), spotted-winged *Drosophila* (*Drosophila suzukii*)	Conservation, introduction and augmentation of natural enemies**; alfalfa trap crops (Swezey *et al.* 2014) and 'good bug blends' providing nectar and pollen for parasitoids and predators; introduction of WTPB braconid parasitoid *Peristenus relictus* (Pickett *et al.* 2009); rotation of insecticides with different modes of action, limited applications per season, spinosad, imidicloprid, diazinon; manage the 15 types of wild WTPB hosts; tractor-mounted vaccuums for insect removal on alfalfa or strawberry; organic: insecticidal soap, azadirachtin, neem oil, entomopathogenic fungus *Beauveria bassiana* and pyrethrin

(*Continued*)

Table 2.1 (Continued)

	Major pests	Crop protection tactics
Mites	Two-spotted spider mite, Lewis mite (*Eotetranychus lewisi*), cyclamen mite in organic production	Conservation and augmentation of natural enemies***; synthetic miticides in conventional production such as etoxazole, abamectin, acequinocyl
Diseases	Leaf spot (*Ramularia tulasneii*), crown and root rots, especially *V. dahliae*, SMYEV, and *Phytophthera* spp.	Albion variety for tolerance to major soil-borne pathogens; drip fumigation with an application of chloropicrin mixed with 1,3-dichloropropene followed by metam sodium or chloropicrin alone followed by metam sodium, some methyl bromide through critical use exemptions; cover cropping with mustards, anaerobic soil disinfection (Butler *et al.* 2014), mustard seed meal allelopathy or planting into coconut or rice hull
Nematodes	Root-knot nematodes	Conventional: fumigants, cereal rye or barley cover crops with broadleaf herbicides; organic: cereal rye or barley cover crops, anaerobic soil disinfection, cover-cropping or planting into coconut or rice hull
Weeds	Field bindweed (*Convolvulus arvensis*), burclover and yellow nutsedge (*Cyperus esculentus*) are resistant to fumigants; pigweed, filaree, mustards, radish (*Raphanus raphanistrum*), etc.; plants that host WTPB	Fumigants, flumioxazin and oxyfluorfen herbicides (Samtani *et al.* 2012), cereal rye or barley cover crops, solarization, anaerobic soil disinfection; organic: cover cropping, preirrigation, 12 rounds of tillage, drip irrigation and coverage of planting beds with opaque polyethylene mulch

* Determinations of major pests and likely management tactics used against them on the Central Coast of California, USA, between 1915 and 1955 are from Letourneau's readings of historical documents, including an assessment of what was listed, what common names meant, what was written about and left out in more than 50 sources found online in USDA archives, University of California archives, and on shelves at the Agricultural History Project in Watsonville, CA, USA. http://aghistoryproject.org/.
** Generalist predators, such as minute pirate bug (*Orius tristicolor*), big-eyed bug (*Geocoris* spp.), brown lacewing (*Hemerobius* spp.), ladybird beetle (e.g. *Hippodamia convergens*), predaceous fly larvae (Syrphidae), soil-dwelling beetles (e.g. Staphylinidae), spiders (e.g. Thomisidae) and insectivorous birds. Parasitoids, such as *Lysiphlebus testaceipes* (Braconidae), a strawberry aphid parasitoid (Oatman and Platner 1972) and *Trichogramma pretiosum* (Trichogrammatidae), a parasitoid of corn earworm (UC-IPM 2010).
*** *Phytoseiulus persimilis* and generalist predators, such as *Neoseiulus californicus*, rove beetle (*Oligota oviformis*) and six-spotted thrips (*Scolothrips sexmaculatus*) (Dara *et al.* 2012).

produced for up to six seasons. By the 1930s, cyclamen mite (*Phytonemus pallidus*) and soil-borne pathogens caused declines in yields in older plants, prompting growers to transplant into new ground every 2–3 seasons (Smith and Goldsmith 1936), and cosmetic standards would appear later in the decade (Thomas 1939).

By this time, crop protection practices were not usually devised by farmers acting independently. They were instead orchestrated by farmer co-operatives, which also facilitated marketing orders to nearby urban centres. The California Strawberry Advisory Council, later renamed the California Strawberry Commission (which is

Figure 2.1 Strawberry production on the Central Coast of California, USA, in 2014 showing strip cropping of alfalfa for control of the mirid bug *Lygus hesperus* via suction removal from alfalfa trap crop with tractor-mounted vacuums (a, b), hedgerows with native perennials that provide shelter and food resources for natural enemies of strawberry pests (c), comparison of plants protected with anaerobic soil disinfection (d) and growers' standard pre-plant practice (e) in an organic field infested with *Macrophomina* spp. and *Fusarium oxysporum* fungal diseases, and plastic mulch for weed control (f).