Rajinder Peshin
Ashok K. Dhawan
Editors

Integrated Pest Management: Innovation-Development Process

Volume 1

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Rajinder Peshin
Sher-e-Kashmir
University of Agricultural Sciences
and Technology of Jammu
Division of Agricultural Extension Education
FOA Chatha
Jammu-180009
India
rpeshin@rediffmail.com

Ashok K. Dhawan
Punjab Agricultural University
Department of Entomology
Ludhiana-141004
India
ashokdhawan@yahoo.com

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The fungal pathogen, *Hirsutella* sp., infecting the armyworm, *Spodoptera litura* (Fabricius). This fungus, along with other pathogens are important regulating agents is armyworm populations (Courtesy: Photo by G. R. Carner, Clemson University, Clemson, South Carolina, USA).

Larvae of the parasitic wasp *Cotesia congregata* (Say) (Hymenoptera: Braconidae) emerging from, and spinning coccoons on the back of a tobacco hornworm, *Manduca sexta* (L.) (Lepidoptera: Sphingidae). (Courtesy: Photo by Lisa Forehand, North Carolina State University, USA).

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For our teachers, farmers and colleagues

Preface

The book 'Silent Spring' written by Rachel Carson in 1962, is considered the landmark in changing the attitude of the scientists and the general public regarding the complete reliance on the synthetic pesticides for controlling the ravages caused by the pests in agriculture crops. For about five decades, the Integrated Pest Management (IPM) is the accepted strategy for managing crop pests. IPM was practiced in Cañete Valley, Peru in 1950s, even before the term IPM was coined. Integrated Pest management: Innovation-Development Process, Volume 1, focuses on the recognition of the dysfunctional consequences of the pesticide use in agriculture, through research and development of the Integrated Pest Management innovations. The book aims to update the information on the global scenario of IPM with respect to the use of pesticides, its dysfunctional consequences, and the concepts and advancements made in IPM systems. This book is intended as a text as well as reference material for use in teaching the advancements made in IPM. The book provides an interdisciplinary perspective of IPM by the forty-three experts from the field of entomology, plant pathology, plant breeding, plant physiology, biochemistry, and extension education.

The introductory chapter (Chapter 1) gives an overview of IPM initiatives in the developed and developing countries from Asia, Africa, Australia, Europe, Latin America and North America. IPM concepts, opportunities and challenges are discussed in Chapter 2. The world pesticide use, the environmental and economic externalities of pesticide use in agriculture, with case studies from the USA and India are covered in the next three chapters (Chapters 3, 4 and 5). The brief account of the advances in insect pests, disease pests and plant parasitic nematodes is given in Chapter 6. Crop plant manipulation to affect the pests through host plant resistance and transgenic crops is covered in Chapters 7 and 8. Content area on biological control and environmental manipulation to manage pests is the theme of the Chapters 9 and 10. The behavior modifying strategies in response to external stimuli for pest management are detailed in Chapter 11. The pesticides metabolized from botanicals, one of the first known pesticides, is covered in subsequent Chapter 12. The insect pest outbreaks and field level epidemiological issues of plant diseases and their management have been covered in Chapters 13 and 14. Chapter 15 covers the concepts and principles of integrated disease management of bacterial, fungal and viral diseases. The yield losses caused by insect pests are variable and dynamic.

The methods to measure yield losses with the example of rice crop are covered in Chapter 16. Cotton pest management has been a challenging task the world over, the historical perspective, components of cotton IPM program, insecticide resistance management and transgenic cotton is the focus of Chapter 17. Non-pesticide pest management, reality or myth- the experiences are analysed in Chapter 18. IPM systems for vegetable and fruit crops, their underlying concepts, advancements and implementation are covered in detail in the last three chapters (Chapters 19, 20 and 21).

IPM is a component of sustainable agriculture production, and was in vogue in agriculture before the introduction of synthetic pesticides. The renewed efforts are needed for the adoption of IPM by the end users. The farmers who did not fall in the pesticide trap in 1950s and 1960s were labeled as laggards, and, to use the words of E.M. Rogers (2003) – had the last laugh at plant protection scientists and extension workers. Due care should be taken with respect to euphoria generated by the introduction of transgenic crops in agriculture which may make us complacent as was the case after the introduction of DDT, lest we are caught into 'pesticide cum transgenic treadmill'. There is no permanent, normal professionalism, which can adopt for life, and especially not with complex interactive management systems like IPM (Robert Chambers). IPM-innovation-development process is dynamic, and is incomplete without the participatory development of farmers' compatible IPM systems and its adoption by the end users to its consequences in agriculture production system. Volume 2, Integrated Pest Management: Dissemination and Impact, analyses the success and failures of this aspect of IPM Innovation-Development process.

We are grateful and indebted to the contributing authors for their cooperation and guidance in compiling the book. We are also grateful to the reviewers for their comments on the book chapters. The book provides an invaluable resource material to graduate students, teachers, scientists working in the dynamic field of IPM in particular and agriculture in general.

Jammu, India — Rajinder Peshin
Ludhiana, India — Ashok K. Dhawan

Contents

Contributors

Rakesh S. Bandral, Krishi Vigyan Kendra, Sher-e-Kashmir University of Agricultural Sciences and Technology of Jammu, India, rsbandral@gmail.com

M.S. Chari, Centre for Sustainable Agriculture, 12–13—45, Street No. 1, Tarnaka, Secunderabad-500 015, India, chari_ms@yahoo.co.in

D.E. Conlong, Department of Conservation Ecology and Entomology, Faculty of AgriSciences, Stellenbosch University, Private Bag X1, Matieland. 7602. South Africa, Des.Conlong@sugar.org.za

Jeffrey Davis, Department Of Entomology, Louisiana State University Agricultural Center, Baton Rouge, Louisiana, USA, jeff.davis@agctr.lsu.edu

Ashok K. Dhawan, Department of Entomology, Punjab Agricultural University, Ludhiana-141004, India, dhawan@sify.com

W.G. Dilantha Fernando, Department of Plant Science, University of Manitoba, Winnipeg, MB R3T 2N2, Canada, D_Fernando@Umanitoba.ca

Gregory A. Forbes, International Potato Center, Apartado 1558, Lima 12, Peru, g.forbes@cgiar.org

Sanjay Guleria, Division of Biochemistry and Plant Physiology, Sher-e-Kashmir University of Agricultural Sciences and Technology of Jammu, Chatha-180 009, Jammu, India, guleria71@rediffmail.com

S.K. Gupta, Division of Plant Breeding and Genetics, Sher-e-Kashmir University of Agricultural Sciences and Technology of Jammu, Chatha, Jammu-180 009 India, guptaskpbg@rediffmail.com

Sachin Gupta, Division of Plant Pathology, Sher-e-Kashmir University of Agricultural Sciences and Technology of Jammu, Chatha, Jammu, 180 009, India, sachinmoni@gmail.com

Zakir Hussain, Centre for Sustainable Agriculture, 12–13—45, Street No. 1, Tarnaka, Secunderabad-500 015, India, zakircsa@gmail.com

Donn T. Johnson, Department of Entomology, Agriculture Experiment Station, University of Arkansas, Fayetteville, Arkansas 72701; USA, dtjohnso@uark.edu

Virender Kaul, Division of Entomology, Sher-e-Kashmir University of Agricultural Sciences and Technology of Jammu, Chatha, Jammu-180009, India, kaulvirender@yahoo.com

M.K. Khushu, Agrometeorology Research Centre, Sher-e-Kashmir University of Agricultural Sciences and Technology of Jammu, Chatha, Jammu-180009, India, dr_khushu@yahoo.co.in

K.R. Kranthi, Crop Protection Division, Central Institute for Cotton Research, PB. No. 2. Shankarnagar PO, Nagpur-440 010, India, krkranthi@satyam.net.in

Kavitha Kuruganti, Centre for Sustainable Agriculture, 12–13—45, Street No. 1, Tarnaka, Secunderabad-500 015, India, kavitha_kuruganti@yahoomail.com

Oscar E. Liburd, Entomology and Nematology Department, University of Florida, Gainesville, Florida 32611, USA, oeliburd@ufl.edu

James A. Litsinger, IPM and Farming Systems Specialist, 1365 Jacobs Place, Dixon CA 95620 USA, jlitsinger@thegrid.net

Eduardo S.G. Mizubuti, Departamento de Fitopatologia, Universidade Federal de Viçosa, Viçosa, MG, Brazil, mizubuti@ufv.br

S. Nakkeeran, Department of Plant Pathology, Krishi Vigyan Kendra Tamil Nadu Agricultural University Tindivanam-604 002, India, nakkeeransingai@yahoo.com

Teresia W. Nyoike, Entomology and Nematology Department, University of Florida, Gainesville, Florida 32611, USA, nyoiket@ufl.edu

David Orr, Department of Entomology, North Carolina State University, Raleigh, North Carolina, 27695-7613, USA, david_orr@ncsu.edu

Rajinder Peshin, Division of Agricultural Extension Education, Sher-e-Kashmir University of Agricultural Sciences and Technology of Jammu, Chatha, Jammu-180 009, India, rpeshin@rediffmail.com

David Pimentel, Department of Entomology, College of Agriculture and Life Sciences, Cornell University, Ithaca, New York, USA, dp18@cornell.edu

Aditya Pratap, Div. of Crop Improvement, Indian Institute of Pulses Research (ICAR), Kalyanpur-Kanpur (U.P.) 208 024, India, adityapratapgarg@gmail.com

T.A.V.S. Raghunath, Centre for Sustainable Agriculture, 12–13–45, Street No. 1, Tarnaka, Secunderabad-500 015, India, raghunathcsa@gmail.com

G.V. Ramanjaneyulu, Centre for Sustainable Agriculture, 12–13–45, Street No. 1, Tarnaka, Secunderabad-500 015, India, gvramanjaneyulu@gmail.com

Rajesh Ramarathnam, Southern Crop Protection and Food Research Centre, 1391 Sandford Street, London, Ontario, ON N5V 4T3, Canada. ramarathnamr@agr.gc.ca

V. K. Razdan, Division of Plant Pathology, Sher-e-Kashmir University of Agricultural Sciences and Technology of Jammu, Chatha, Jammu, 180 009, India, vijayrazdan@rediffmail.com

Cesar R. Rodriguez-Saona, Department of Entomology, Rutgers University, USA, PE Marucci Center for Blueberry & Cranberry Research & Extension, 125A Lake Oswego Rd., Chatsworth NJ 08019, USA. crodriguez@aesop.rutgers.edu

D.A. Russell, Natural Resources Institute, University of Greenwich, UK; Adjunct Professor, Department of Genetics, Bio-21 Institute, University of Melbourne, Parkville, Victoria 3010, Australia, Derek.russell@unimelb.edu.au

R.S. Rutherford, Crop Biology Resource Centre, South African Sugarcane Research Institute, Private Bag X02, Mount Edgecombe, 4300, South Africa, Stuart.Rutherford@sugar.org.za

Marium Sabitha, Advanced Research Institute, No. 386, 4th Cross, I Block, R.T. Nagar, Bangalore-560032, India, Sabimarium@gmail.com

J. Satyanarayana, Department of Entomology, College of Agriculture, Acharya N G Ranga Agricultural University, Rajendranagar, Hyderabad- 500 030, India, snjella@gmail.com

Nancy A. Schellhorn, Commonwealth Scientific & Industrial Research Organization (CSIRO) Entomology, Indooroopilly, Queensland, Australia 4068, Nancy.schellhorn@csiro.au

Uma Shankar, Division of Entomology, Sher-e-Kashmir University of Agricultural Sciences and Technology of Jammu, Chatha, Jammu-180009, India, umashankar_bhu@yahoo.com

P.K. Shetty, School of Natural Sciences and Engineering, National Institute of Advanced Studies, Indian Institute of Science Campus, Bangalore 560 012, India, pks@nias.iisc.ernet.in; pkshetty17@gmail.com

Dani Shtienberg, Department of Plant Pathology and Weed Research, ARO, The Volcani Center, PO Box 6, Bet Dagan 50250, Israel, danish@volcani.agri.gov.il

T.V.K. Singh, Department of Entomology, College of Agriculture, Acharya N G Ranga Agricultural University, Rajendranagar, Hyderabad- 500 030, India, tvksingh@yahoo.com

Lukasz L. Stelinski, Entomology and Nematology Department, University of Florida, Citrus Research and Education Center, 700 Experiment Station Rd., Lake Alfred FL 33840, USA, stelinski@ufl.edu

Michael Stout, Department Of Entomology, Louisiana State University Agricultural Center, Baton Rouge, Louisiana, 70803, USA, MStout@agcenter.lsu.edu

A.K. Tiku, Division of Biochemistry and Plant Physiology, Sher-e-Kashmir University of Agricultural Sciences and Technology of Jammu, Chatha-180 009, Jammu, India, dr_aktiku@yahoo.com

Lewis Wilson, Commonwealth Scientific and Industrial Research Organisation Plant Industry and Cotton Catchment Communities CRC, Australian Cotton Research Institute, Narrabri, NSW, Australia, 2390, lewis.wilson@csiro.au

WenJun Zhang, Research Institute of Entomology, School of Life Sciences, Sun Yat-sen University, Guangzhou 510275, China, zhwj@mail.sysu.edu.cn

Chapter 1
Integrated Pest Management: A Global Overview of History, Programs and Adoption

Rajinder Peshin, Rakesh S. Bandral, WenJun Zhang, Lewis Wilson and Ashok K. Dhawan

Abstract World-wide, integrated pest management (IPM) has become the accepted strategy for plant protection over the last five decades. Cotton growers in the Cañete valley, Peru were amongst the first to adopt a combination of pest management practices to save the cotton crop from the ravages caused by pests despite applying 16 insecticide sprays on average. However, it was not until 1959, that the concept of "integrated management" was born in the United States of America (USA). A panel of experts from the Food and Agriculture Organization (FAO) put the concept of IPM in operation in 1968. Advancements made in IPM systems for developing sustainable pest management strategies in the USA, Europe, Australia, Asia, Latin America and Africa have not generally resulted in wider adoption of IPM, though there have been some successes. Pesticides remain the main-stay of many IPM programs throughout the globe. In the USA and Europe, there is government legislation and mechanisms for implementation and evaluation of IPM programs, especially in Europe, where IPM innovation systems involving the government, researchers, farmers, advisory agencies and market forces are part of a system to reduce pesticide use. In the developing countries farmer education in IPM has gained impetus since 1989, through the Farmer Field School (FFS) extension methodology, originally developed for educating farmers in rice IPM. The FFS model of extension has spread from Asia to Latin America, Africa and Eastern Europe. In the developed countries the systematic periodic evaluation of IPM programs provides feedback for improving and formulating future strategies, but in many developing countries there is no periodic evaluation of IPM programs for assessing the extent of adoption and long term impact. This chapter provides a broad overview of IPM programs, policies and adoption of IPM practices in the North America, Europe, Australia, Asia, Latin America and Africa.

Keywords IPM-USA · Europe · Australia · Latin America · Africa · India · China · IPM history · IPM programs · IPM implementations · IPM adoption

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R. Peshin (✉)
Division of Agricultural Extension Education, Sher-e-Kashmir University of Agricultural Sciences and Technology of Jammu, Chatha, Jammu-180 009, India
e-mail: rpeshin@rediffmail.com

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1.1 Introduction

In the 1940s, with the introduction of synthetic pesticides, the whole scenario of pest management changed. The over reliance on synthetic pesticides from late 1940s to mid 1960s has been called "the dark ages" of pest control. The insecticidal properties of DDT (dichlorodiphenyltrichlorethane) discovered by the Swiss chemist Paul Muller, an employee of J.R. Geigy Co., in 1939 triggered this "dark age" of pest control. The discovery of the herbicide 2 4-D stimulated chemical weed control, and discovery of the dithiocarbamate fungicides during the 1930s led to the development of increased reliance on fungicides (Smith and Kennedy, 2002). The American Entomologists proclaimed in 1944, "…never in the history of entomology has a chemical (DDT) been discovered that offers such promise…" (Perkins, 1982). But the un-sustainability of pesticides was evident by the end of 1950s as complete reliance on pesticide intensive pest management was leading agriculture on a "pesticide treadmill". Resistance of pests to pesticides was observed during 1940s, the phenomenon of pest resurgence and development of minor pests to major pests due to killing beneficial insects was documented in late twentieth century (Norris et al., 2003). Soon after World War II few scientists realized that indiscriminate use of synthetic organic insecticides would be problematic.

Entomologists at the University of California, United States of America (USA) developed the concept of integrated pest management (IPM) during the 1950s in response to two major factors: the development of resistance to insecticides and the destruction of insect natural enemies by insecticides aimed at target pest insects. At the time of the first work on IPM, environmental pollution from insecticides was not a major factor in spurring entomologists to develop new practices, even though medical and environmental scientists recognized the widespread, unintended poisoning of people and other species (Perkins, 1982). So the Californian entomologists coined the concept of "supervised control", involving supervision of insect control by qualified entomologists (Smith and Smith, 1949). A decade later this concept had evolved and the concept of "integrated control" which combined and integrated biological and chemical control based on economic threshold concepts was put forward (Stern et al., 1959). Rachel Carson (1962) wrote the book *Silent Spring* that brought the problems caused by pesticides to the attention of the public and the scientists. *Silent Spring* also got the attention of the scientific community on negative externalities of pesticide use. She wrote in her book, "We have put poisonous and biologically potent chemicals indiscriminately in the hands of persons largely or wholly ignorant of their potential for harm."

The term "Integrated Pest Management" was used for the first time by Smith and van dan Bosch (1967) and in 1969 this term was formally recognized by the US National Academy of Sciences. In the 40 years since then there have been dramatic changes in the technologies available for pest management. In the 1970s, DDT was widely banned due to environmental risks. In 1972, insecticides based on the bacteria, *Bacillus thuringiensis, were* released for control of Lepidopteran pests. Transgenic pest resistant crops were released in 1996, representing the biggest step in technology since the development of pesticides in the 1940s. In the 1960s, the term "pest management" also came into existence and being broader it included other suppressive tactics such as semio-chemicals, host plant resistance and cultural control. But with the passage of time integrated pest control and pest management became synonymous and both were based on the concept of integrating a range of control tactics to manage pests, with insecticides as one of the tools rather than the only tool.

The basic tactics of IPM were proposed and applied to reduce crop losses against the ravages of pests long before the expression was coined (Jones, 1973; Smith et al., 1973). Throughout the early twentieth century, plant protection specialists relied on knowledge of pest biology and cultural practices to produce multi-tactical control strategies (Gaines, 1957). It was not until the incorporation of all classes of pests in the early 1970s that the modern concept of IPM was born (Kogan, 1998; Prokopy and Kogan, 2003). *Pest control was understood as the set of actions taken to avoid, attenuate, or delay the impact of pests on crops, as such goals and procedures of pest control were clearly understood* (Kogan, 1998). However, not until 1972, were "integrated pest management" and its acronym IPM incorporated into English literature and accepted by the scientific community (Kogan, 1998) and later, in November 1972, the report *Integrated Pest Management* prepared by the Council on Environmental Quality was published (Anonymous, 1972). IPM is the main strategy recommended for pest management under Agenda 21 of the United Nations Conference on Environment and Development (UNCED, 1992).

Pesticide use (active ingredients) in agriculture has decreased from 2.6 billion kg in 2004 (Allan Woodburn Associates, 2005) to 1.7 billion kg in 2007 (Agranova, 2008). Total sales in 2007 were estimated at US $35.85 billion (insecticides 26.4%, fungicides 23.2%, herbicides 45.6% and others 4.7%) (Agranova, 2008). The average growth rate of pesticide consumption world-wide during the period of 1993 to 1998 was in the order of 5 percent per year, exceeding that during the earlier period, 1983 to 1993. Global pesticide market recorded a negative average annual growth rate of 1.3 percent (after inflation) between 1998 and 2007 (Agranova, 2008). However, in 2007 there was a surge in the global sales of pesticides by 8.1 percent (after inflation) which is the largest single year growth for 10 years. The major markets for pesticides are the USA, Western Europe and Japan (Dinham, 2005). In Latin America sales of pesticides rose by 25% in 2004 (Allan Woodburn Associates, 2005) and since then recorded a growth rate of 20% between 2004 and 2007 (Agranova, 2008).

Despite these statistics there has been significant progress with the uptake of IPM in many countries. The theory and principles supporting IPM have evolved over the last 50 years. In addition new tools and strategies have been developed to support development of IPM systems: newer more selective insecticides, progress in the development of biopesticides, the development of semio-chemical based approaches (attract and kill, mating disruption), improved understanding of the deployment of trap and refuge crops, the use of "push-pull" strategies, techniques to conserve and attract beneficials in systems, use of augmentive biological control and most recently the advent of transgenic crops producing the Cry proteins from *Baccillus* *thuringiensis*. There are now many examples of successful IPM systems. The theory and components of IPM are discussed in this volume (Chapters 6 to 21, Vol. 1).

1.2 IPM: A Historical Overview

The term IPM is now more or less universally understood. Even before the term IPM was coined, the reasons for developing and propagating IPM are explained by citing some well documented historical cases. The main reliance on the use of pesticides led to creation of newer pest problems in all the crops and especially in the cotton crop. Due to lack of resistant cultivars, non-adoption of cultural control measures, and non-availability of effective biocontrol agents, the indiscriminate use of insecticides resulted in development of resistance in cotton pests such as American bollworm (*Helicoverpa armigera* (Hubner)), resurgence of pests such as spider mites (*Tetranychus* spp.) and whitefly (*Bemisia tabaci* (Gennadius)) and destruction of natural enemies, which ultimately led to crop failures in some countries. Such failures in cotton production systems were documented in Latin America (Cañete Valley, Peru), Sudan and other places even before the term IPM was coined.

Cañete Valley, Peru had been a successful cotton growing area with progressive farmers. In 1939, the tobacco bud worm (*Heliothis virescens* (Fabricius)) appeared in cotton crops. The spraying of arsenical insecticides and nicotine sulphate resulted in build-up of cotton aphid (*Aphis gossypii* (Glover)) and worsening of the tobacco bud worm problem. By 1949, cotton yields (lint) dropped from about 500 kg ha^{-1} to 365 kg ha^{-1} as natural enemies had disappeared owing to insecticide applications allowing pest populations to resurge after sprays were applied. A new program for pest control practices was introduced including banning the use of synthetic organic pesticides, the reintroduction of beneficial insects, crop diversification schemes, planting of early maturing varieties and the destruction of cotton crop residues. Pest problems subsequently declined dramatically and pest control costs were substantially reduced (Hansen, 1987).

Based on the same principles as IPM, efforts were for "harmonious control" in Canada in the 1950s (Pickett and Patterson, 1953; Pickett et al., 1958). The concept of integrated control in the USA was developed in the late 1950s and it consisted mainly of the use of insecticides in a manner that was compatible with biological control of insect pests (Norris et al., 2003). Cotton production in Sudan also suffered due to over reliance on insecticides. DDT induced outbreaks of cotton whitefly, *Bemisia tabaci* (Gennadius) and the use of parathion against this pest increased the occurrence of cotton bollworm (*Heliothis armigera* (Hüber)) which resulted in reduction in yields (Joyce and Roberts, 1959).

A key feature in the history of IPM is that the concept was first articulated by scientists from the Entomology Department at the University of California, USA. In the 1950s these scientists initiated the development of a new pest management strategy which brought applied ecologists and bio-control experts together (Perkins, 2002). Up to this time, applied entomology in the US had largely been taken over by a toxicology mind-set: find the right poison. The ecologists were ignored in most departments, the United States Department of Agriculture (USDA) had eliminated most classical biological control work, and only the University of California, Entomology Department still had both ecologists and biological control scientists. They worked together to solve the problems, especially resistance and destruction of natural enemies, caused by insecticides.[1] Sterile male releases were tested and demonstrated in 1950s against screw worm fly (*Cochliomyia hominivorax* (Fabricius)) and the second initiative in the USA was the development of the "integrated control" concept in the late 1950s by the entomologists at the University of California on alfalfa (Perkins, 1982). This concept aimed to integrate the use of biological control with chemical control was the beginning of IPM in the USA (Smith and Allen, 1954; Perkins, 2002). This early concept was based on the premise that pesticides could have a minimum impact on the natural enemies of the pest if applied at the correct time and under correct conditions. Economic thresholds, another important concept in IPM, were introduced at that time (Stern et al., 1959) and were the first attempt at providing a rational basis for deciding if a pest population warranted control, based on the value of expected loss from damage and the cost of control.

In the USA, IPM synthesized three strong ideas. First, USDA and California entomologists, plus some farmers, had great success in suppressing some pest insects by "classical" biological control. This method required an accurate taxonomy of the pest species, recognition of whether it was native or introduced, and, if introduced, the search of the original home of the invasive pest for its natural insect enemies followed by importation and release of the predatory or parasitic species. Control of cottony cushion scale (*Icerya purchase* – Maskell) by vedalia beetles (*Rodolia cardinalis*) imported from Australia in 1888 was the first great success and it had greatly benefited the California citrus industry and ignited interest in this practice in the State (Perkins, 1982; Sawyer, 1996).

Second, California entomologists were strong ecologists, i.e. they took seriously the need to understand the distribution and abundance plus the population dynamics of pest species. Consistent with the Entomology Department's strong interest in classical biological control, California entomologists understood that native pest species also had natural enemies, even though at times the natural predators and parasites did not suppress the pest population well enough to prevent economic damage. Thus these entomologists had a stronger appreciation for the value of natural enemies than did entomologists in other parts of the United States (Perkins, 1982).

Third, even though the University of California entomologists in the 1950s appreciated the power of classical biological control and careful ecological study, they also were intimately familiar with the many recently identified synthetic insecticides, such as DDT and methyl parathion. Their major insight in creating IPM in fact rested upon their realization that the best suppression practices lay in preserving natural enemies and using the new insecticides only when needed to supplement the suppressive effects of natural enemies. In other words, they developed "integrated

[1] Personal communication from Prof. John Perkins

control" that applied chemicals only if needed and in ways that did not decimate populations of natural enemies. This judicious use of insecticide also helped avoid the problems of resistance, which had begun appearing as early as 1908. By the 1950s, overuse of insecticides had generated numerous well recognized cases of resistance and destruction of natural enemies (Perkins, 1982).

These concepts remained the major themes of IPM throughout much of the 1970s. The United Nations Development Program (UNDP) together with the Food and Agriculture Organisation (FAO) has since 1975 initiated global programs for the development and application of IPM in rice, cotton, sorghum, millet and vegetable crops. All these developments in crop protection have been driven by changing pest problems faced by the farmers, the options available to them and their changing cash and labour requirements (Norton, 1993). Thus with the development of IPM started a search for a perfect definition. A broader definition was adopted by the FAO Panel of Experts in 1968. IPM has been defined by the Panel of Experts on Integrated Pest Control at Food and Agricultural Organisation (FAO), Rome, as:

> 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 (FAO, 1968).

This definition includes all the management tactics which fits best in the environment and was more oriented towards environment and ecology. A survey has recorded 64 definitions of IPM and the key words included in those 64 definitions suggests that authors attempted to capture (a) the appropriate selection of pest control methods, used singly or in combination; (b) economic benefits to growers and 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 impact of multiple pests (Kogan, 1998).

The focus of IPM began to shift to non-pesticidal tactics in the 1980s, including expanded use of cultural control, introduction of resistant varieties and biological control. In Asia, the Farmer Field School (FFS) approach for disseminating the IPM technology in rice crop was adopted in Indonesia in 1989. Since then, FFS has become a preferred extension methodology for implementing IPM programs in Africa, Latin America, Caribbean and Eastern Europe. FFS type model is also carried out in Australia through the Ricecheck Programs and in the USA on fruit trees (Braun et al., 2006).

1.3 IPM Initiatives in the Developed Countries

1.3.1 IPM Programs and Policies in the US

In the 1950s and 1960s, synthetic pesticides were the first choice for pest control. Development of IPM strategies emerged in the USA in 1950s to reduce pesticide use in agriculture (Discussed above in Section 1.2). Shortly after IPM first appeared, Rachel Carson's *Silent Spring* (1962) brought wide recognition to the fact that insecticides had become pervasive environmental pollutants. Both human health and the health of other animals were demonstrably harmed (Dunlap, 1981). Political leaders and the public understood the pollution problem better than they did the problems of resistance and destruction of natural enemies, and thus pollution due to insecticides helped entomologists gather political strength to win appropriations for research on IPM. The laws regulating the pesticides sales in the USA were made stringent. The US Congress overhauled its regulatory scheme for pesticides. After 1972, no pesticide could be sold or used unless it had undergone extensive tests for its environmental damages (Bosso, 1987). In the same year, the report "Integrated Pest management" was published (Council for Environmental Quality, 1972). In the early 1970s, IPM was accepted as the chosen approach for pest management (Geier and Clark, 1978). In 1971, Senate Bill 1794, approving special funding for IPM pilot field research programs was passed (Kogan, 1998). A number of other initiatives were taken as the bill provided the financial support and policy support to IPM programs. A number of IPM programs were implemented in the USA. The California entomologists vastly expanded research in 1970 by collaborating with cotton entomologists to win funding from the National Science Foundation. The multi-university grant became known as the "Huffaker Project," after its chairman, Carl Huffaker of the Entomology Department of the University of California at Berkeley (Perkins, 1982).

The United States Department of Agriculture (USDA), National Science Foundation (NSF) and Environmental Protection Agency (EPA) jointly financed a 5 year program of IPM to cover around 1.6 million hectares (Kogan, 1998) (the Huffakar Project). Six crops viz. – alfalfa, citrus, cotton, pines, pome and stone fruits and soybean were covered under the project (Huffakar and Smith, 1972) which spanned from 1972 to 1978. A second large scale project ran from 1979 to 1985, known as the Consortium for Integrated Pest Management (Frisbie and Adkisson, 1985). The adoption of IPM by growers in these crops led to a 40–50% reduction in the use of the more environmentally polluting insecticides within a five year period and a 70–80% reduction in 10 years (Huffakar and Smith, 1972). The coverage of the project was 5.76 million hectares. The main indicators of adoption were the use of scouting and economic injury levels for spray decisions and the use of selective pesticides (Frisbie, 1985).

In 1978, extension funding was provided to all states to implement educational IPM programs (Olsen et al., 2003). In 1979, this program was expanded to cover 50 states and 45 commodities (Blair and Edwards, 1979). By 1982, 42 states developed extension IPM education programs and the most successful of these were in California and Texas (Olsen et al., 2003). Regional IPM programs were launched with the Consortium for IPM which concluded in 1985.

Economic evaluation of 61 IPM programs conducted by Norton and Mullen (1994) reported that adoption of IPM methods resulted in lower pesticide use. Adoption of IPM strategies saved USA agriculture US$ 500 million per year due to reductions in pesticide use (Rajotte et al., 1987). In 1994, the adoption of IPM for field crops, vegetables, fruits and nuts in selected states covering most of the area

Table 1.1 Extent of adoption of IPM practices in the USA agriculture

Crop	1991–1994 (% area)	2000 (% area) USDA estimates
Cotton	29[1]	86[3]
Fruits and nuts	95[2]	62[3]
Vegetables	86[2]	86[3]
Soybeans	84[2]	78[3]
Corn	90[2]	76[3]
Barley	–	71[3]
Wheat	–	65[3]
Alfalfa-hay	–	40[3]
All other crops and pastures	–	63[3]

Sources: [1]Fernandez (1994); [2]Vandman et al. (1994) Data based on chemical use/cropping practices from 1991 to 1993; [3]USGAO (2001)

under the surveyed crops was least in case of cotton (29%) and the highest for fruits and nuts (95%) (Table 1.1).

National IPM initiatives for implementing IPM practices on 75% of the USA's crop area by 2000 were started in 1993 (Sorensen, 1994). The American Cooperative Extension Service (CES) plays a key role in dissemination of IPM in the United States (Frisbie, 1994). The IPM programs evolved and expanded to include the entire crop pest complex, and there was a greater emphasis on multidisciplinary team approaches to IPM, with CES and research cooperating at all phases of program development, implementation, and evolution (Kogan, 1998).

In the USA, the Government Performance and Results Act of 1993 (GPRA)[2] requires that federally funded agencies develop and implement an accountability system based on performance measurement, including setting goals and objectives and measuring progress toward achieving them. Accordingly, the performance of federally funded IPM program activities must be evaluated. During 2001, the United States General Accounting Office (USGAO) conducted an audit of the US IPM programs to ascertain if the USDA had achieved the targets of 1994 that 75% of the planted crop land should be under IPM by 2000. By 2000, farmer surveys conducted by the USDA indicated that IPM adoption across all crops had increased from 40% in 1994 to 71%. The area under IPM was: cotton-86%, fruit and nuts-62%, vegetables-86%, soybean-78%, corn-76%, barley-71%, wheat-65%, alfalfa-40% and other crops and pasture-63% (Table 1.1). However, total pesticide (technical grade material) use had increased by 4% (from 408.2 million kg in 1992 to 426.4 million kg in 2000), but there was a reduction of 14% in the use of pesticides (from 206.4 million kg to 176.9 million kg) categorized as risky by EPA during the same period (USGAO, 2001). The USGAO (2001) concluded that quantity of pesticide use may not be the most appropriate measure of the success of IPM programs. The methods for measuring IPM's environmental and economic results were questioned for not being well developed. The indicators for categorizing farmers as IPM practitioners are prevention, avoidance, monitoring and suppression (USDA, 1998).

[2] http://www.whitehouse.gov/omb/mgmt-gpra/gplaw2m.html

Table 1.2 Recommendations of USGAO for effective implementation of IPM

- Establish effective department-wide leadership, coordination, and management for federally funded IPM efforts;
- Clearly articulate and prioritize the results the department wants to achieve from its IPM efforts, focus IPM efforts and resources on those results, and set measurable goals for achieving those results;
- Develop a method of measuring the progress of federally funded IPM activities toward the stated goals of the IPM initiative; and
- Foster collaboration between EPA and USDA to support the implementation of pest management practices that may reduce the risks of agricultural pesticide use.

Source: USGAO, 2001

The United States General Accounting Office report 2001, made the recommendations for removing the leadership, coordination, and management deficiencies (Table 1.2).

In spite of all these efforts, however, there is little evidence that IPM (as originally envisioned) has been implemented to any significant extent in American agriculture (Ehler and Bottrell, 2000; Barfield and Swisher, 1994). The impact of IPM programs in terms of adoption of IPM practices by the growers is also questioned and the rate of adoption of IPM has been slow in the USA (Hammond et al., 2006). The failure or apparent failure of these programs can be traced to at least three constraints. Firstly, for farmers, IPM is time consuming and complicated; given the multiple demands of farm production, farmers cannot be expected to carry out the integration of multiple suppressive tactics for all classes of pests. Secondly, pest control consultants who might be hired by farmers usually have little time for closely monitoring pests and their natural enemies/antagonists; besides, many of them are employed by pesticide companies and have a built-in conflict of interest. Also, pesticides can be a cheap insurance policy when there is a possibility of losing an entire crop. Finally, pest scientists in the colleges of agriculture at the state (land-grant) universities have resisted the integration of the pest disciplines; most seem content to study individual ingredients of IPM, and this is reinforced by the incentive system in which they work. The result is a dearth of pest management programs that feature both vertical and horizontal integration (National Roadmap for IPM, May 17, 2004).[3] There are similar concerns at the international level.

The road map for a National IPM Program in the USA identified strategic directions for IPM research, implementation, and measurement for all pests, in all settings, throughout the country. This included IPM for all areas which include agriculture, structural, ornamental, turf, museums, and public and wildlife health pests. The goals of the National IPM Program are to improve the economic benefits of adopting IPM practices and to reduce potential risks to human health and the environment caused by the pests themselves or by the use of pest management practices. States receive a grant of US $10.75 million annually for IPM extension

[3] National Site for the USDA Regional IPM Centers Information http://www.ipmcenters.org/IPMRoadMap.pdf

Table 1.3 National Roadmap for implementation and adoption of IPM

In order to reach their full potential, IPM programs must be willingly adopted by agricultural producers, natural resource managers, homeowners, and the general public. The following activities will contribute to the adoption of IPM.

- Develop user incentives for IPM adoption reflecting the value of IPM to society and reducing risks to users. Work with existing risk management programs including federal crop insurance, and incentive programs such as NRCS Environmental Quality Incentive Program (EQIP) and other farm program payments to fully incorporate IPM tactics as rewarded practices.
- Provide educational opportunities for IPM specialists to learn new communication skills that enable them to engage new and unique audiences having specific language, location, strategy, or other special needs.
- Create public awareness and understanding of IPM and IPM programs through creative use of mass media and public service advertising.
- Leverage federal resources with state and local public and private efforts to implement collaborative projects.

Ensure a multi-directional flow of pest management information by expanding existing and developing new collaborative relationships with public and private sector cooperators

Source: National Road Map for Integrated Pest Management, 2004. http://www.ipmcenters.org/IPMRoadMap.pdf

programs. Implementation strategies as envisaged in the National Road Map for IPM Program are listed in Table 1.3. The National IPM Program focuses in three areas (i) production agriculture, (ii) natural resources, and (iii) residential and public areas. The USA Government created four Regional Pest Management Centers in the year 2000. These centers (North Central IPM Center, North Eastern IPM Center, Southern IPM Center and Western IPM Center) were established by the Cooperative Research Education and Extension Service (CSREES). These centers are playing a key role in implementing the National Roadmap for IPM which has identified strategic directions for IPM research and implementation. IPM tools are: (i) high-tech pest forecasting, (ii) sensible pest scouting practices, (iii) innovative biological control, and (iv) least toxic chemical option. Centers strengthen state IPM programs. A mid-term review[4] report of these centers has justified their establishment as "the Centers have engaged a wide spectrum of nontraditional partners and reinforced established IPM networks, thus facilitating IPM adoption across the nation." The success stories of these centers are the Great Lakes Vegetable IPM Program in nine states and Ontario, Canada being implemented on annual budget of US $30,000. In these areas 83.5 percent growers were moderate to high IPM adopters (North Central IPM Centre).[5] In the case of the Southern IPM Center, a national warning system designed to help soybean growers to protect their crop from Asian soybean rust (*Phakopsora pachyrhizi*) has saved US $299 million during 2005. The evaluation of the national roadmap (2002) for implementing and adoption of IPM practices in the US agriculture will provide the feedback about the progress of IPM in this decade.

[4] http://www.ipmcenters.org/IPMCenterReview2-06.pdf

[5] IPM success stories. 2008. http://www.ipmcenters.org/SuccessStoriesLowFinal.pdf

1.3.2 IPM Initiatives in Europe

In Europe, IPM programs were originally developed for orchards. In perennial crops IPM is the standard strategy but to a lesser extent in annual crops. The International Organization for Biological Control of Noxious Animals and Plants (IOBC) was established in 1956, for the development of bio-control strategies for major insect pests in Europe. In 1958, IOBC established the "Commission on Integrated Control" and in 1959 a working group on "Integrated Control in Fruit Orchards" (For details see Chapter 14, Vol. 2). Entomologists involved with apple production were the pioneers of IPM and later in the development of Integrated Production (IP) in Europe (Boller et al., 1998). In 1974, IOBC adopted the term "Integrated Plant Protection". IOBC developed IPM systems in all major crops of Europe. IOBC published the basic concept of Integrated Production in 1992, followed by crop specific IPM guidelines for all major crops. Farmers associations, Cooperatives, Non Governmental Organisations (NGOs) and retailers throughout Europe are implementing strategies for reducing pesticide and fertilizer use in European agriculture. Targets for pesticide use reduction have been adopted in Denmark, Sweden, the Netherland, France and Germany. Retailers are procuring low pesticide labeled food products and providing economic incentives to the farmers (Tresnik and Parente, 2007). A total of 65% of the total fruit area in Belgium is managed by a non-profit farmers' association which provides training to farmers in low pesticide use. Farmcare run by the cooperative group in the UK, SAIO and IP-SUISSE in Switzerland, and LAIQ in Italy are providing impetus to IPM. On June 23, 2008, Agriculture Ministers from Europe approved the creation of a European Union – wide pesticide blacklist. The pesticides linked with cancer, DNA mutation, reproductively toxicity and hormonal disruption, which together contaminate 22% of food items will be targeted (PAN, Europe, 2008). Romania, Hungary and Ireland were the only three countries not endorsing the proposal.

The European Union countries provide incentives to the growers for compliance with IPM tactics to reduce pesticide use. The European Commission considered levying taxes on plant protection products to encourage pesticide free or low pesticide farming. Norway and two European Union countries, Denmark and Sweden have levied taxes on pesticides. Sweden started pesticide taxation in 1986 under which pesticide tax was levied at the rate of US $3 (at 2008 rates) per kilogram (kg) technical grade material. Since 2004, the pesticide tax has been raised to US $4.7 per kg use of pesticide (PAN, Europe, 2004). Pesticide use was reduced by 67% during 1990s. A pesticide action plan to achieve 50% reduction in pesticide was launched in Denmark in 1986. In Denmark pesticide taxation was started in 1992 and incentives given to encourage low pesticide farming. In the case of insecticides a 54% tax was levied on the retail price and in the case of herbicides, fungicides and growth regulators a 33% tax was imposed (PAN, Europe, 2004). The pesticide treatment intensity decreased from 3.1 (1990–1993) to 2.1 applications (2001–2003) and is projected to be reduced to 1.4 by 2009 and pesticide use decreased by 25% by 1992, and 50% by 1997 (Cannell, 2007). Norway started a

Table 1.4 IPM initiatives in Europe

Country	Policy Initiatives
Belgium	1. Pesticides on red list totally prohibited as per IOBC norms 2. Since 1988 fruit growers initiative to promote IPM
Denmark	1. Pesticide Action Plan • 1986–1997, the first Pesticide Action Plan targeted a 25% reduction in total pesticide consumption by 1992 and 50% by 1997. It also included measures to encourage the use of less hazardous pesticides. Educating farmers to improve their knowledge and skills • 1997–2003 The second Plan introduced the indicator treatment frequency index. The target was to reach a treatment frequency of less than 2.0 before 2003 and establish 20,000 ha of pesticide-free zones along key watercourses and lakes. • 2003–2009 The objective of the third Pesticide Action Plan is to lower the treatment frequency below 1.7 by 2009, to promote pesticide-free cultivation and establish 25,000 ha pesticide-free zones along watercourses and lakes. This plan includes the fruits and vegetables sector for first time. 2. Pesticide tax a. Insecticide tax 54% of the retail price b. Herbicide, fungicide and growth regulator 34% of the retail price 3. Danish agriculture advisory service to educate farmers about IPM 4. Incentives to encourage IPM *The treatment frequency index expresses the average number of times an agricultural plot can be treated with the recommended dose, based on the quantities sold.
Germany	1986 – Germany makes IPM official policy through Plant Protection Act. Since 2004 the national Reduction Program Chemical Plant Protection encourages implementation of IPM in practice
Italy	1. Environmental NGO promoting pesticide free fruit and vegetables 2. NGO provides guidelines to farmers on IPM. Labeling of IPM produce LAIQ. 3. Transgenic crops not allowed
Netherland	1. 1991 – IPM for crop protection introduced by the cabinet decision in the Netherlands 2. New initiatives based on multi-stakeholders launched in 2003 with Euro 14 million for integrated crop management (ICM) 3. Experimental advisory service for low pesticide farming methods 4. Development of environmental impact cards with indicators 5. Development of best practice protocols for IPM in major crops 6. Market support to ICM. Farmers adopting ICM in apple, strawberry, Cabbage, lettuce etc. offered premium by the market. Supermarket Laurus supply ICM products.
Norway	1. In 1985 pesticide reduction program started 2. In 1988 levied banded tax system based on toxicity @ 2.4 Euro/ha 3. Inspection of spray equipments
Sweden	1. From 1985 to 2003 pesticide tax @ 2 Euro/kg 2. Since 2004 @ 3 Euro/kg 3. Active advisory service to reach farmers. It forecast, demonstrate, lays trials and conduct training

Table 1.4 (continued)

Country	Policy Initiatives
Switzerland	1. Development of low pesticide integrated production (IP) farming protocols 2. Euro 1.6 billion/year direct subsidy to farmers for adopting ecological standards 3. Pest warning services and pragnasis models for taking pest management decisions 4. Testing spray equipments at least once in 4 years 5. All market sell IP SUISSE products
United Kingdom	1. The UK cooperative group one of the largest consumers cooperative in the world manages 10000 ha of cooperative owned land and 20000 ha of farmland owned by land owners. Farmers provided guidelines on Integrated Farm Management and has prohibited use of 23 and restricted use of 32 pesticides which is aimed to reduce pesticide use by 50%. 2. Priority on adoption of biological and mechanical crop protection ahead of pesticides

After: PAN Europe (2005); IP SUISSE (2005); IP SUISSE (2006); PAN Germany (2004); Cannell (2007); Neumeister (2007); http://www.co-op.co.uk

pesticide reduction program in 1988 which employed a levied banded tax system based on toxicity at the rate of US $3.8/ha. This resulted in a 54% pesticide use reduction (PAN, Europe, 2004). Pesticide use was reduced from 8000 metric tons during 1981–1985 periods to 3000 metric tons in 2003 with an average consumption of 1.2 kg active ingredient per hectare (PAN, 2007). In the Netherlands, new initiatives based on multi-stakeholders were launched in 2003 with US $22 million for integrated crop management (ICM) (Cannell, 2007). Since 1985–2006, pesticide use in the Netherlands has been reduced by more than 50% from 21003 metric tons in 1985 to 9411 metric tons in 2006, but increased to 10741 metric tons in 2007 (Milieu en Natuur Planbureau, 2008). Similarly, in the UK the IPM initiatives taken by UK cooperative group by prohibiting 23 pesticides will reduce pesticide use by 50%. The details of the initiatives taken in the selected countries of Europe and their impact are given in Tables 1.4 and 1.5. In Eastern Europe, pesticide use is low as compared to Western Europe. In Poland, 10000 tones of apple (13% of total production) were certified as integrated production during 1999. Better contact with advisors helped the farmers to adopt IPM and 90% of farmers accepted IPM (Niemczyk, 2001). In Central and Eastern Europe, the Farmer Field School (FFS) model for implementation of IPM programs in maize was first introduced in 2003. In Central and Eastern Europe (CEE) the FFS approach was first introduced in seven countries (Bosnia-Herzegovina, Bulgaria, Croatia, Hungary, Romania, Serbia and Montenegroand Slovak Republic) in 2003 through an FAO project for managing an introduced pest on maize, the western corn rootworm (*Diabrotica virgifera* LeConte), by means of IPM (Jiggins et al., 2005). Two other projects have also been introduced in Armenia; one on rodent control through FAO funding and the other with support from USDA has triggered the establishment of an NGO that now coordinates a number of FFS projects in the country (Braun et al., 2006).

In the European Union, consumption of fungicides is on the higher side (61%) followed by herbicides (28%), insecticides (8%) and growth regulators (3%)

Table 1.5 Impact of IPM in European agriculture

Country	Crops	Area under IPM (ha)	Farmers adopted	Reduction in pesticide use (Technical grade material)	Reference (s)
Austria	Pome fruits	4770	51%	–	Cross et al., 1995
Belgium	All crops	In 2006, 2/3rd of the total area under fruit crops. 28634 ha organic farming	803 farms	–	FGOV, 2008
Belgium	Pome fruits	4510	31%	–	Cross et al., 1995
Belgium	Pear	–	98%	–	Schaetzen, 1996
Denmark	All crops	20000 (pesticide free)	–	Pesticide use frequency 1990–1993 −3.1, 2001–2003 −2.1, Projected 2009 −1.4	PAN Europe, 2007, Nielsen, 2005
Denmark	Pome fruits	960	17%	–	Cross et al., 1995,
Germany	Pome fruits	30440	27%	–	Cross et al., 1995
Italy	Potatoes, peach, apricot, onions, kiwi fruits, tomato, apple lettuce and figs	–	230	–	PAN Europe, 2007
Netherland	Pome fruits	14800	57%	–	Cross et al., 1995
Netherland	All major crops	–	–	50% reduction in pesticide use since 1995	PAN Europe, 2007

Table 1.5 (continued)

Country	Crops	Area under IPM (ha)	Farmers adopted	Reduction in pesticide use (Technical grade material)	Reference(s)
Norway	–	–	–	54% pesticide use reduction. Pesticide treatment intensity was reduced from 2.45 to 2.04 during 2000 to 2002. Projected 1.7 for 2004 to 2009	PAN, Europe, 2004
Sweden				No overall reduction in pesticide use (1991–2002)	PAN, Europe, 2004
Switzerland	Pome fruits	4350	39%	–	Cross et al., 1995
Switzerland	Cereals, rapeseed, potato, fruits, meat, poultry and milk	Cereals-11000 farms[1], Fodder – 13000 farms[1], Rapeseed – 2000 farms[1] Potato – 1200 ha[2]	18000 farmers members of IP SUISSE and 3000 out of 4000 fruit producers grow IP SUISSE fruits Apple-92% Strawberrie-85% Raspberries-70%	40% reduction in pesticide use (a.i) during the last 15 years (1990–2005) and was the most successful effort in Europe	Neumeister, 2007 [1]IP SUISSE, 2005 [2]IP SUISSE, 2006
UK	Carrot, potato, cauliflower, mushroom, avocado, pineapple	Cooperative 10000 ha land owned by land owners 20000 ha	–	50% reduction in pesticide use since 1994	Cannell, 2007

Table 1.6 Pesticide sale (technical grade material) in Europe (in tonnes)

Country	Year								Increase/ decrease over 1995 (%)
	1995	2001	2002	2003	2004	2005	2006	2007	
EU (15 countries)	279811	327642	–	–	–	–	–	–	+17
Belgium	10939	8845	9204	–	–	–	–	–	−16
Denmark	4809	2890	2722	–	–	–	–	–	−43
Germany	30468	27885	29531	30164	28753	29512	–	–	−3
Estonia	144	329	267	321	246	–	–	–	+71
Ireland	2291	2486	2796	2913	–	–	–		+27
Greece	8525	11111	–	–	–	–	–	–	+30
Spain	27852	35700	–	–	–	–	–	–	+28
France	84007	99635	82448	74524	76099	–	–	–	−9
Italy	48490	76346	94711	–	–	–	–	–	+95
Hungary	7698	6431	8232	–	–	–	–	–	+7
Netherlands	10924	7987	8073	7868	9071	9309	9411	10741	+2
Austria	3404	3133	3080	3386	3302	3404			0
Poland	6962	8855	10358	7184	8726	16039			+130
Portugal	11818	15491	17435	17046	16938	16346			+38
Finland	1035	1424	1614						+56
Sweden	1224	1738	1711	2049	942	1527	1707		+39
United Kingdom	33668	32971	31064						−8
Norway	931	518	818	689					−26

After: Eurostat (2008) June 9, 2008 http://epp.eurostat.ec.europa (Accessed on July 18, 2008)

(Eurostat, 2002). Pesticide consumption (active ingredients) in the European Union fell by 13% between 1991 and 1995, and it was the highest in Finland (−46%) followed by the Netherlands (−43%), Austria (−21%), Denmark (−21%), Sweden (−17%), Italy (−17%), Spain (−15%) and France (−11%) (Lucas and Pau Vall, 1999). Since 1995 total sales of pesticides (tons of active ingredients) have increased in the European Union except in Belgium, France, Denmark, Germany, Norway and the United Kingdom, and has remained almost static in the Netherlands (Table 1.6). Between 1992 to 1999, the consumption of fungicides decreased by 8% but the consumption of insecticides increased by 4% (Eurostat, 2002).

1.3.3 IPM Programs in Australia

IPM systems in Australia have been developed in pome and stone fruits (Williams, 2000a), cotton (Fitt, 1994, 2004), wine grapes (Madge et al., 1993), citrus (Smith et al., 1997) and vegetables (McDougall, 2007). In case of pome fruits there are national guidelines for integrated fruit production (IFP) in apples.

Progress with the horticultural crops has largely been driven through state based Departments of Primary Industries with support from Horticulture Australia Ltd, which is a national research, development and marketing organization that collects levies of horticultural producers and in partnership with the horticulture sector invests this in programs that provide benefit to Australian horticulture industries. These systems largely focus around the use of natural enemies, including native and introduced predatory mites and a range of hymenopteran parasites, and selective options including mating disruption, to manage introduced pests. Many use annual introductions of these predators or parasites which can be purchased commercially. Systems have been developed to ensure these introductions are effective, including the "pest in first" strategy that ensure beneficial insects (natural enemies) have prey to sustain them, rather than dying out.

There are some outstanding examples of IPM research and uptake in the horticultural industries. Citrus is an example where the introduction of bio-control agents for scale and mite pests, careful cultural control and limited use of selective insecticides has led to dramatic reductions in pesticide use (Smith et al., 1997). Similarly the conservation of native predatory mites in grapes has significantly reduced problems with mite pests of grapes (James and Whitney, 1993). IPM in apples is another example of IPM strategies being combined, including the use of introduced predatory mites, mating disruption and selective insecticides (Thwaite, 1997). In 2002, 80% of apple growers were adopting IPM (IFP).[6] The number of sprays in apple orchards was reduced by 30% (Williams, 2000b). In lettuce crops the advent of the current lettuce aphid, *Nasonovia ribisnigr*i (Mosley) created a significant challenge to IPM. However, this situation is being managed through an overall IPM strategy that emphasizes sampling, identification, management using non-chemical

[6] http://www.daff.gov.au/-data/assets/pdf

means (e.g. weed control, cultivation of crop residues, use of currant lettuce aphid resistant varieties) and selective insecticides (McDougall and Creek, 2007).

Sugar cane production has also been challenged by a range of pests, principally the cane grubs, rodents and soldier flies (Allsopp et al., 1998). Management of the cane grub complex has relied heavily on use of soil applied insecticides; however the loss of organochlorine based insecticides, drove change toward more diverse management systems. However, the cane grub complex includes species with quite different biology and pesticide susceptibility so different tactics are required for different species. Metarhizium fungus, is registered as a biological insecticide for control of the greyback canegrub, *Dermolepida albohirtum* (Waterhouse), as a result of Sugar Research and Development Corporation, Bureau of Sugar Experiment Stations, Commonwealth Scientific and Industrial Research Organisation (CSIRO Australia) and BioCare (now Becker Underwood) research and development funding (Milner et al., 2002). A tactic for helping to manage the intractable sugarcane soldier flies, *Inopus rubriceps* (Macquart) is to deprive them of food (Samson, 2006). Research to improve IPM for the cane grub complex continues and a range of cultural techniques, combined with strategic use of soil applied chlorpyriphos is the current recommendation (Allsopp et al.,2003).

Development of IPM systems has long been a target in grains cropping systems, which include winter cereals, summer and winter grain legumes and pulses and summer grains such as sorghum and maize and oilseeds such as sunflower and canola. A good account of the pests and beneficials in Australian grain crops can be found in (Berlandier and Baker, 2007; Brier, 2007; Franzmann, 2007a,b; Hopkins and McDonald, 2007; Miles et al., 2007; Murray, 2007). IPM in grains has been challenged by the variable climate, especially rainfall, fluctuating markets and crop diversity. This coupled with the low cost of highly effective synthetic pyrethroid insecticides has encouraged the use of prophylactic "insurance" insecticide applications which has unfortunately become common practice in many grain crops and resulted in significant selective pressure for the development of insecticide resistance. In some cases IPM has been perceived as a lower priority, especially in the course grains where there is a lower risk of pest attack. For instance, in the winter coarse grains, pests are only occasionally a problem, while in the summer coarse grains (sorghum and maize) *Helicoverpa armigera* (Hübner) is a pest, but rarely warrants control in maize and is readily controlled with *Helicoverpa* NPV in sorghum (Franzmann et al., 2008). Sorghum midge, *Stenodiplosis sorghicola* (Coquillett) has also been an important pest in late planted sorghum, but selection for plant resistance to this pest has been an outstanding success (Franzmann et al., 2008). However, the grain legumes and pulses are attractive to pests throughout their growing cycle and hence pest management and IPM in these crops is a higher priority. In these crops management of thrips, lepidopteran, hemipteran and mite pests poses a significant challenge which is being targeted by research.

There has been considerable investment in development of IPM systems in grains over many years although the diversity of grain crops and growth during both summer and winter has meant formulation of year-round IPM strategies has been challenging. The Grains Research and Development Corporation (GRDC) collects a levy from grain growers, matched by the federal government, that is used to co-ordinate and fund research and extension activities and IPM, and pest ecology and management has been an important component. Recently the GRDC has initiated the National Invertebrate Pest Initiative (NIPI) in an effort to bring together researchers, extension and industry representatives to help define the pest challenges across the range of grains crops and to develop coordinated IPM support materials and strategies. One outcome from the NIPI project has been the development of the PestFAX/PestFacts which is a free email information service alerting growers and farm advisers across southern Australia to invertebrate pest issues and IPM compatible solutions. A key focus has been on monitoring, including correct pest identification and use of selective control options to help conserve beneficial populations. A similar approach is being used with a 'blog' known as the Beatsheet developed by the Queensland Department of Primary Industries. Another development has been the identification of the need for IPM guidelines for grains which span the range of crops grown in regions throughout the year. Other initiatives include the Grain and Graze program which addresses enterprises with mixed animal and crop production. This is collaboration between the Grains Research and Development Corporation, Meat and Livestock Australia, Australian Wool Innovation Limited, and Land and Water Australia. The IPM component focuses on encouraging farmers to monitor pests, use more selective control options and to using other strategies such as baiting or seed dressings where appropriate. In many northern grain producing regions *Bemisia tabaci* (Gennadius) B-biotype is emerging as a significant issue and ironically, is driving the trend toward use of more selective insecticides to conserve beneficials as control of this pest is expensive and difficult if outbreaks are induced by use of broad-spectrum insecticides.

Rice production has also strived to improve and integrate production practices to improve yields. This has been implemented through the Ricecheck system, developed in the 1980s by New South Wales Department of Primary Industries, which provides rice growers with checks for production at critical phases of crop growth (Singh, 2005). It includes recommendations for control of rice pests, primarily snails and ducks, but also insect pests such as common armyworm *Leucania convecta* (Walker) and rice leaf miner *Hydrellia michelae* (Bock).

IPM has a rich history in Australian cotton (Fitt, 2000), with the failure of cotton production in the Ord River Irrigation Area in north-western Australian in the mid-1970s due to insecticide resistance providing a strong incentive for growers in eastern Australia to manage resistance and adopt more IPM compatible strategies. Accordingly, research on IPM has been supported strongly by the industry through levies on each bale of cotton which are matched by the federal government and administered by the Cotton Research and Development Corporation. In more recent years, the Co-operative Research Centre (CRC) initiative of the federal government has been important, with three successive cotton focused CRCs bringing together university, CSIRO, State Government and industry to collaboratively target issues challenging cotton production, including pest management. The CRC approach has facilitated strong co-operation and integration between agencies in the implementation of IPM in cotton.

Cotton is attacked by a range of pest, including the highly damaging *Helicoverpa armigera* and *Helicoverpa punctigera* (Wallengren) (Fitt, 1994). The need for season long control of these pests often disrupted natural enemy populations leading to outbreaks of secondary pests, in turn requiring control. High reliance on insecticides posed significant challenges in terms of public perceptions, environmental pollution, insecticide resistance and secondary pest management (Wilson et al., 2004). In the initial years (1960s and early 1970s) pest management advice mostly came from staff employed by the agrochemical companies. However, in the mid 1970s, independent consultants become more common – these were usually tertiary trained operators that sampled crops and provided growers guidance on the need to spray and the choice of insecticide. Most growers now use a consultant or employ their own agronomist. Innovative research in the late 1970s by CSIRO and State Department of Agriculture and University of Queensland researchers showed the value of more rigorous application of thresholds, selection of softer insecticides and use of cotton's capacity to compensate for pest damage to reduce insecticide use without reducing yield. This was captured in a computerized decision support system, SIRATAC (Brook and Hearn, 1990), that took into account pest abundance and used a *Helicoverpa* development and feeding model to predict crop damage and a crop model to simulate the crops productivity with and without this damage. Control was then recommended only if yield loss was predicted (Hearn and Bange, 2002; Room, 1979). This system was reasonably well adopted, with up to 30% of the industry using it. There was also an additional benefit as knowledge from SIRATAC seeped through the industry – increasing crop checking rigor and the use of valid thresholds by most consultants. In the early 1980s, pesticide resistance in *Helicoverpa armigera* to pyrethroids was detected in eastern Australia and prompted the development of an industry wide insecticide resistance management plan. This plan restricted use of insecticides to a set period during the season, with the aim to provide a generational break in selection of *H. armigera* for each product. This strategy evolved over time to include all insecticides used in cotton, and managing resistance to *H. armigera*, spider mites, aphids and silver leaf whitefly, and was managed by the Transgenic and Insecticide Management Strategies committee, which included research and industry members. The agrochemical industry, researchers, extension staff and consultants all played an important role in the implementation of insecticide resistance management (IRM) and in monitoring resistance levels to establish the effectiveness of the IRMS (Forrester et al., 1993).

In the late 1990s, the emphasis shifted from IRM (which was mainly based on reliance on chemical control) to sustainable and effective IPM, which incorporated IRM. This change was driven by escalating resistance levels and costs, despite the well implemented and adopted IRM strategy. However, IPM was difficult as most available control options were highly disruptive of beneficial populations. The availability of Bt-cotton (Cry1Ac) in the mid 1990s, initially capped to 30% of the area, and the registration of more selective control options for *Helicoverpa* control (e.g. spinosad, indoxacarb and emamectin) greatly helped uptake of IPM as growers could manage this pest with less effect on beneficials (Wilson et al., 2004). At the same time a set of guidelines for IPM were developed, which provided growers with a practical year round strategy to manage pests, conserve beneficials and communicate with each other to co-ordinate efforts (Deutscher et al., 2005). This was supported by well co-ordinated and highly focused extension effort from state and federal extension staff, including IPM field days, regular fact sheets and a well supported website.

Combined these factors led to a significant change in attitude toward IPM. This was further supported by economic analysis which showed that growers using more selective insecticides, which were more expensive, obtained yields similar to growers using cheaper, harder options, but made more money because they sprayed less (Hoque et al., 2000). This outcome, combined with a strong extension effort and the formation of regional IPM groups led to dramatically increased adoption of IPM and a significant decline in insecticide use (Wilson et al., 2004). However, overreliance on these selective compounds meant resistance appeared within 2–3 years of their introduction, so by the early 2000s resistance was again threatening the viability of IPM.

The advent of Bt-cotton with two genes (Cry1Ac and Cry2Ab) allowed the cap on area to be removed. From its initial release in Australia, Bt-cotton had a compulsory resistance management plan, developed in conjunction with industry, research and extension. The dramatic uptake of two gene Bt-cotton which now accounts for >85% of industry, has seen a further reduction in insecticide use by about 85% (Pyke and Doyle, 2006). This in turn has led to a dramatic reductions in insecticide resistance to insecticides (Rossiter and Kauter, 2006). However, the emergence of sucking pests, no longer controlled by insecticides applied against *Helicoverpa* now poses new challenges to IPM in Australian cotton and this is the focus of a concerted research effort (Wilson et al., 2004). Research continues to develop new tools to support IPM, including new biopesticides for the sucking pests, semio-chemical approaches, and the provision to industry of clear guidelines on the IPM fit of new insecticides.

1.4 IPM Initiatives in the Developing Countries

1.4.1 IPM Programs in Latin America

Cotton pest management in Peru and Nicaragua in the mid 1950s and early 1970s amply proved that sustainable pest management is possible by adopting a combination of pest management tactics. In Latin American countries there are many successful examples of IPM.

In Costa Rica, banana plantations were treated with aerial sprays of dieldrin granules against banana weevil, *Cosmopolites sordidus* (German) and rust causing thrips. The reliance on these aerial sprays resulted in outbreaks of banana stalk borer (*Castiomera humbolti*). By 1958, there were outbreaks of six major lepidopteran pests. Due to the oil crisis in 1973, pesticide sprays were stopped by the United Fruits Company managing the banana crop. Within two years, all pest species had almost disappeared and there were only occasional outbreaks of pests which did not reach economic thresholds due to increases in the natural enemy populations

(Stephens, 1984). In Brazil, in the 1970s and early 1980s, on average of 20–30 pesticide applications were given to tomato crops (around 2000 ha). An IPM program implemented in the Cauca valley (Colombia) in 1985, resulted in a reduction in pesticide applications of 2–3 sprays and savings of US $650/ha. Use of *Bacillus thuringiensis* combined with the release of natural enemies (*Trichogramma* spp.) and conservation of parasites (*Apanteles* spp.) reduced the population of a major pest, the fruit borer (*Scrobipalpula absoluta*) (Belloti et al., 1990). During the late 1970s, the agricultural research and extension services in Brazil initiated an intensive program to transfer IPM technology to cotton farmers (Bleicher et al., 1979). In Brazil in the late 1970s, the resistance of cotton boll worm, *Heliothis virescens* (Fabricius) to organophosphates was a major problem. At that time cotton received 15–20 insecticide applications per season. The launching of the IPM program in 1979, helped significantly to reduce insecticide applications on average to six sprays per season helping to optimize profits through lower production costs for the same level of yield (Pimentel and Bandeira, 1981; Seganmullar and Hewson, 2000). But in 1983, with the introduction of cotton boll weevil, *Anthonomas grandis* from Boheman to Brazil, the number of insecticide applications again rose to 10–12 applications per season. However, after local behavior patterns were established for the new pest, and IPM adapted accordingly, the number of applications decreased again to an average of 8 per season (Seganmullar and Hewson, 2000). IPM has produced excellent economic, social and ecological results in Brazil (Cruz, 1991). Later, the chemical pesticide industry began to collaborate in an IPM program which did not show desired results (Ramalho, 1994). The Latin American Association for Cotton Research and Development established working groups on research and extension in all member countries for exchange of information on IPM in cotton.

In Chile, over 120,000 ha of wheat were sprayed aerially with insecticides to control two aphid species (*Sitobium avenae* and *Metopolophium dirhodum*) in the early 1970s. Due to the high losses caused to the wheat crop, in 1976 the Chilean government in collaboration with FAO initiated an IPM program. Predators and parasitoids were introduced from South Africa, Canada, Israel, Europe and the USA. From 1976 to 1981, 4×10^6 parasitoids were distributed and the pest population was maintained below the economic threshold level (Zuñiga, 1986). Cuba was forced to adopt an IPM policy after the collapse of the socialist block in 1990, which resulted in 60% drop in pesticide imports. Under IPM, the focus was on biological control by establishing 218 centers for the production of biocontrol agents. These centers provided entomopathogens and *Trichogramma* wasps to the farmers (Rosset and Benjamin, 1994).

In Peru, the Peruvian Action Network of Alternatives to Agrochemicals (Spanish acronym RAAA) in 1992 started a training program in the Canete Valley to reawaken farmers' interest in IPM, under the theme "Ecological Pest Management for Cotton Growers". In 1997, a small project on organic cotton production was also set up (CABI, 2000). There is no government extension service in Peru. A Potato IPM Program in Peru has shown a net benefit of US $100–536 per hectare (for details see Chapter 12, Vol. 2). In Colombia in 1997, a growers' cooperative with 180 members, started working on 600 hectares to start an IPM program and in 1998 it had spread to over 2400 hectares (Williamson, 1999). The National Agricultural

Research Institute's (INRA) cotton IPM program in Argentina is researching and implementing, mass production of the predator *Chrysopa* spp. for aphid and cotton pest management. The IPM methods have succeeded in reducing insecticide applications from 11–12 per season to <4 (Williamson, 1999). In Peru, the IPM intervention in cotton resulted in reduction in pesticide use by 50–70% (Castro et al., 1997; Van Elzakker, 1999). Similarly, use of biological control in Argentina resulted in reducing pesticide applications from 11–12 to 4 (Williamson, 1999).

The first attempt to organize farmer training along discovery – learning methods was in Peru. Most training in IPM programs in Latin America had been based on result demonstration methods with little active farmer participation. The FFS approach for providing hands on experience to potato farmers in IPM was introduced by the International Potato Center (CIP) and its institutional partners in Peru in 1997. Between 1997 and 2005, a total of 747 FFS had been implemented in the Latin America and Caribbean countries of Bolivia, Brazil, Colombia, Dominica, Dominican Republic, Ecuador, El Salvador, Guatemala, Guyana, Haiti, Honduras, Jamaica, Mexico, Nicaragua, Peru, Suriname, and Trinidad and Tobago (Braun et al., 2006). The outcome of different IPM interventions in Latin American countries is given in Table 1.7.

1.4.2 IPM Programs in Africa

Egypt in the early 1970s developed effective integrated pest control (IPC) recommendations for cotton crop production consisting of cultural (timely sowing), biological, chemical methods, manual mechanical practice of removing egg-masses of cotton leaf worm, *Spodoptera littoralis* (Boisduval) and regulatory measures. These practices, in combination with some others have been very successful. The average number of sprays in 1975 and later years was less than one. The IPC programs were taken up due to development of insecticide resistance, development of secondary pests and the increasing costs of chemical control. IPC programs in cotton, sugarcane, maize and rice were taken up in Egypt. In Sudan, after the whitefly problem in 1979, when the problem spread out of control, a program for development and application of integrated pest control in cotton was implemented by FAO and financed by the Government of the Netherlands. The first phase was 1979–83; field studies on resistant cotton varieties to whitefly (*Bemisia tabaci*) and identification of suitable natural enemies were undertaken. The second phase continued from 1985 to 1989 under which demonstration trails and introduction of the parasite (*Trichogramma pretiosum*) of *Helicoverpa armigera* were implemented. Farmers were guaranteed compensation for eventual yield loss as 320 hectares were left unsprayed during 1986–1987. Under the third phase, results validated during the second phase were implemented (Oudejans, 1991). The IPM program in Sudan produced good results with more than a 50% reduction in insecticide use (Pretty, 1995; Morse and Buhler, 1997). Farmer field school IPM programs were first introduced in Sudan during 1993 and in Egypt during 1996 (Braun et al., 2006). Phase four of the program began in 1993 and was primarily devoted to IPM in vegetable crops. FFSs were implemented in the Sudan-Gezira Scheme from 1993 to 1996 under the FAO

Table 1.7 Outcome of IPM programs in Latin America

Country	Crop	IPM tactics	Outcome	References
Argentina	Cotton	Knap aerial sack or application of eggs of *Chrysoperla* spp. @ 20000 larva/ha and release of mated adults of *Chrysoperla* @ 100 female/ha	Reduced insecticide applications from 11–12 per season to less than 4	Williamson,1999
Bolivia and Peru	Potato	IPM – FFS	FFS graduates acquired knowledge necessary for the management of late blight, resulting in substantially increased income	van den Berg, 2004
Brazil	Soybean	Monitoring pest damage, establishing economic thresholds and application of specific insecticides	Insecticide application fell by 80–90% between 1974 and 1982	Campanhola et al., 1995
Brazil	Cotton	Manipulation of planting densities (9–10 plants per square meter)	Reduce the infestation of cotton stem borer and increased cotton yield	Santos, 1989
Chile	Wheat	Five species of predators and nine species of parasitoids were introduced against aphids (transmitting barley yellow dwarf virus), responsible for loss of 20% wheat production in 1975	Aphid populations maintained below threshold level by the action of bio-agents	Zuñiga, 1986
Colombia	Cotton	Use of pheromone traps, lure sticks, release *Trichogramma*, 2 *Bt* sprays and use of insecticides	Reduced average pesticide application to 2.3 per season instead of 18–20 application per season	Williamson, 1999
Columbia (Cauca Valley)	Tomato	IPM implemented in 1985, involved the use of microbial insecticides (*Bt*) combined with release of natural enemies such as *Trichogramma* spp. and conservation of natural population of parasite, *Apenteles* spp.	Reduced the pesticide application from 20–30 to 2–3 and saved US $650 per hectare	Belloti et al., 1990

Table 1.7 (continued)

Country	Crop	IPM tactics	Outcome	References
Peru (Ice Valley)	Potato	IPM training in pilot units	Significant reduction of key potato pests damage and reduction in pesticides	Cisneros et al., 1998
Peru	Cotton	Organic cotton	In 1988 yield dropped drastically due to excessive temperature and increased pest pressure (Whitefly – *Bemicia tabaci* (Gennadius) outbreak in particular) but organic farmers received far higher net income than conventional neighbours who increased pesticide application.	Williamson, 1999
Peru (Canete Valley)	Cotton	Manipulation of cultural practices along with spray of *Bacillus thuringensis (Bt)*, rotenone, oils, pheromones, sulfur and release of *Trichogramma* spp.	50% reduction in the cost of production	van Elzakker, 1999
Peru (Canete Valley)	Cotton	Organic cotton	35% less cost of pest management as compared to conventional cotton	Williamson, 1999
Peru (Ice Valley)	Cotton	Release of *Trichogramma* spp. and use of pheromone traps for Indian pink boll worm (*Pectinophora gossypiella* (Saunders))	Pesticides use reduced by 70%	Castro et al., 1997

vegetable IPM project. The long term impact was measured by comparing a baseline study (1993) to mid-term evaluation (1995) and impact evaluation (2001). The FFs trained farmers on an average applied 3.3 applications of pesticide compared to 12.5 by non-IPM farmers. The use of pesticide sprays had decreased from 4.3 to 3.3 in case of IPM farmers and increased from 9.6 to 12.5 in case of non-IPM farmers from 1995 to 2001 (Khalid, 2002). National support for the IPM project is tremendous, and the farmers unions are very supportive. During 1995, Sudan's IPM Steering Committee has been transformed into a permanent National IPM Committee (the report of the programs' 1995 annual review and planning meeting). In Ethopia, the Integrated Pest Management Collaborative Research Support Program (IPM CRSP) was initiated in 1993 with the financial support of the United States Agency for International Development (USAID).

In sub Saharan Africa, Integrated Production and Pest Management (IPPM) is the equivalent of IPM terminology used in other countries. It is broader in the sense that crop management strategies to enhance the very low productivity in African countries are also incorporated in the program. FAO Global IPM Facility is the partner in IPPM –FFS programs. In Zimbabwe, IPPM-FFS resulted in higher yields of cotton while average pesticide applications by IPPM-FFS farmers were 8.1 compared to 14.6 by non-IPPM farmers, and the percent pesticide cost to total cost of production was 33% and 67%, respectively (Mutandwa and Mpangwa, 2002).

There are no extensive periodic evaluation studies on the outcome and impact of IPPM-FFS programs in Africa and as of now no value judgment can be made about these programs. The challenge in sub-Saharan Africa is to increase productivity without pushing the farmers into a pesticide treadmill.

1.4.3 IPM Program in Commonwealth of Independent States

Major areas of cotton production in CIS are Uzbekistan, Turkmenistan, Azerbaijan and Tajaikistan (Sugonyaev, 1994). The IPM programs for cotton in the CIS have been developed on the basis of their practicality and economic expedience (For details refer Chapter 15, Vol. 2). IPM programs are flexible, open system aimed at achieving ecological stabilization. Natural enemies are considered a key component of IPM programs as they suppress 60–70 percent of the pest population (Niyazov, 1992). The pesticides shortages and dramatically increased costs (unlike in former USSR), coupled with public concern have created a sound environment for rapid progress of IPM.

1.4.4 IPM Programs in Asia

Widespread outbreaks of the rice brown planthopper, *Nilaparvata lugens* (Stål) in 1970s and 1980s was caused by the insecticides meant to control it and triggered the development of IPM strategies for pest management. The role of the FAO in dissemination of IPM is well documented. The FAO provided the coordination, leadership and resources to promote IPM, particularly in developing countries. The FAO Inter-country Program (ICP) for the Development and Application of Integrated Pest Control (IPC) in Rice in South and South-East Asia started in 1980. From 1977 to 1987, IPM moved from research towards extension. By 1988, the Training and Visit extension system in the Philippines, Indonesia, Sri Lanka, Bangladesh, India, Thailand and Malaysia attempted to introduce IPM to rice farmers through their system of "impact points" or through strategic extension campaigns (Kenmore, 1997). From 1988 to the present IPM has moved towards education rather than training. The introduction of IPM has been fostered by Farmer Field Schools (FFS), which provide "education with field based, location-specific research to give farmers the skills, knowledge and confidence to make ecologically sound and cost-effective decisions on crop health". The FFS training module is based on participatory experiential learning to help farmers develop their analytical skills, critical thinking and creativity, and help them learn to make better decisions (Kenmore, 1997). The trainer is more of a facilitator rather than an instructor (Roling and van de Fliert, 1994).

IPM-FFS was first started in Indonesia in 1989, after the banning of 57 broad-spectrum pesticides in 1986. IPM-FFS programs were carried out in 12 Asian countries after observing its success in Indonesia. Later on IPM-FFS were implemented in vegetable, cotton and other crops. The program spread to Africa, Latin America, the Middle East and Eastern Europe (van den Berg and Jiggins, 2007). FFS programs are being implemented in 78 countries and four million farmers have been trained under this program, with 91% of these from Bangladesh, China, India, Indonesia, the Philippines, and Vietnam (Braun et al., 2006).The coverage of IPM-FFSs was just 1–5% of all households in Asia (1989–2004). By 2002, ICP had spent US $45 million on training activities in Bangladesh, Cambodia, China, India, Indonesia, Laos, Malaysia, Nepal, the Philippines, Sri Lanka, Thailand and Vietnam. ICP also launched regional programs on IPM in cotton and vegetables. During the 15 year period (1989–2004) approximately US $100 million in grants were allocated to IPM projects in Asia (Bartlett, 2005). Preliminary pooled average results from seven studies on cotton IPM in five Asian countries indicate that FFS graduates increased their income by 31% in the year after training, due to 10% better yields and 39% lower pesticide expenditure, in relation to control farmers (FAO, 2004).

A Global IPM Facility with co-sponsorship of FAO, UN Development Program (UNDP), UN Environmental Program (UNEP), and the World Bank was established in 1995 (Kogan, 1998). A "Global IPM Field Exchange and Meeting" was held in 1993, where participants from Africa, the near East, Latin America, and Europe observed the success of Asian IPM farmers in South-east Asia (Kenmore, 1997). This experience has assisted the development of farmer-centered IPM programs in west, southern, and eastern Africa and is now working in the Near East, Central Asia, and Latin America (Anonymous, 1999). The FAO – European Union IPM program for cotton in Asia was established in late 1999. The program was implemented in six countries: Bangladesh, China, India, Pakistan, the Philippines and Vietnam (Ooi, 2003).

The studies on impact evaluation of IPM-FFS in Asia by the World Bank and FAO provide contradictory results due to methodological problems associated with impact evaluation. The World Bank study conducted by Feder et al. (2004) indicated that the IPM-FFS program in Indonesia did not have significant impact on the trained farmers and their neighbors. The complexity of the IPM information curtails the diffusion process from IPM trained farmers to others and abandoning of top-down approaches of extension by trainers in favor of facilitation mode is a challenge to the effectiveness of this program (Feder et al., 2004). Feder et al. (2004) on the basis of their study concluded that FFS in Indonesia have not induced a significant increase in yields or reduction in pesticides use by the trained farmers relative to other farmers. The farmer to farmer diffusion was not significant. Pesticide use expenditure had increased from 1990–91 to 1998–99 in case of IPM and non IPM farmers by 81 and 169%, respectively and yields had declined by 11 and 15%, respectively (Feder et al., 2004). Yamazaki and Resosudarmo (2007) evaluated the same data set as Feder et al. (2004). The performance of FFS farmers was declining through every cropping season thus the impact of the FFS on rice yield was phasing out over time but pesticide use expenditure reduced. Meta-analysis of 25 short term impact studies commissioned by FAO reported reduction in pesticide use (van den Berg, 2004). These studies have employed "before and after", "with and without" or combination of "with/without and before/after" to study the outcome (immediate impact) of IPM programs. The synthesis of selected studies is presented in Table 1.8.

In the developing countries there is no significant investment in farmer education, thus farmers and consumers have been exposed to environmental and health risks as a result of an induced reliance on synthetic pesticides (van den Berg and Jiggins, 2007). The farmer study groups in the Netherlands (van den Ban, 1957) "U-H clubs" in the USA, "farmer research and development groups" in Australia and the Netherlands, and "breed improvement societies" in England have been cited as examples in which organized farmer education and innovation has occurred (van den Berg, 2004; van den Berg and Jiggins, 2007). These efforts emphasize on field based observation and experimentation, shared learning and systematic evaluation of results. FAO should formulate a policy for extensive evaluation of IPM programs based on evaluation methodologies in the developing countries to measure the adoption, outcome and impact.

1.4.4.1 IPM Programs in India

In India, pest management before the synthetic pesticide era (pre green revolution period) was characterized by the use of cultural and manual mechanical practices based on a farmer's lifelong experiences. Experts of this era in most of the developing world (tropical areas) were involved in taxonomy, biology of pests, and advocacy of cultural practices (Muangirwa, 2002). With the advent of the green revolution in mid 1960s, a new technological paradigm use of pesticides (in addition to high yielding varieties and fertilizers) was adopted by India, largely imported from the USA. The surprising aspect of this paradigm shift is that insecticide based insect pest management as the sole pest control strategy was advocated by the agriculture policy planners, entomologists and extension agencies when the world had taken note of the negative impact of pesticide use brought forward by Rachel Carson in

Table 1.8 Outcome of IPM-FFS programs in Asia

Country	Crop	Outcome
China[1]	Cotton	A decline in insecticide use from 6.3 to 3.1 applications per season a year after training, whereas control farmers continued spraying around 6 times per season. Pesticide volume declined by 82% due to a combination of lower frequency, lower dosages and a shift towards less hazardous chemicals.
Bangladesh[1]	Egg plant	Reduction in pesticide applications from 7.0 to 1.4 applications per season. Increase in yield was also observed.
Cambodia[1]	Rice	Training caused farmers to reduce pesticide volume by 64% and to select relatively less hazardous compounds. FFS farmers were better aware of pesticide-related health risks than non-FFS farmers.
Vietnam[1]	Rice	Insecticide use reduced from 1.7 to 0.3 applications per season. Fungicide use was reduced after training in the North but was increased in the South, probably due to a combination of factors
Sri Lanka[1]	Rice	Insecticide applications reduced from 2.2 to 0.4 applications per season. A 23% yield increase and a 41% increase in profits. Consequently, the overall training costs could be recovered seven-fold within a single season. Impact was present six years after training.
Indonesia[2]	Rice	65% reduction in pesticide use and 15% increase in yield
Indonesia[1]	–	Training caused a change from preventative spraying to observation based pest management, resulting in an overall 61% reduction in the use of insecticides.
Thailand[1]	Rice	60% reduction in the use of insecticides and moluscicides and an increase in knowledge about pests and natural enemies.
Vietnam[1]	Tea	A 50–70% reduction in pesticide use and good prospects for improving crop management and to increase yield.
Sri Lanka[1]	Effect on health	FFS farmers spent considerably less time for spraying pesticides than non-FFS farmers and accordingly exhibited lower cholinesterase inhibition level in blood samples.

Sources: [1]van den Berg (2004); [2]Miller (2004)

her book "*Silent Spring*" in 1962, and entomologists were developing integrated control tactics (Stern et al., 1959). Pesticide use (mainly insecticide use) increased from 5640 tons in the pre-green revolution era to 21200 tons in 1968–1969 in the green revolution era and reached an all time high of 75418 tons in 1988–1989 (Fig. 1.1). Most of the pesticide was consumed in the green revolution areas of Punjab, Haryana, Andra Pradesh, Western Uttar Pradesh (around 103 districts) and 50 percent in cotton crops which were cultivated on a mere 5 percent of the total cultivable land of 176 million hectares.

In India, research on integrated pest management was started in 1974–75 on two crops, rice and cotton, under Operational Research Projects (ORP) (Swaminathan, 1975). Under this, location specific IPM technologies were developed in cotton and rice crops. But it was only in the mid 1980s that the Government of India re-oriented its plant protection strategy. India became a member country of the FAO

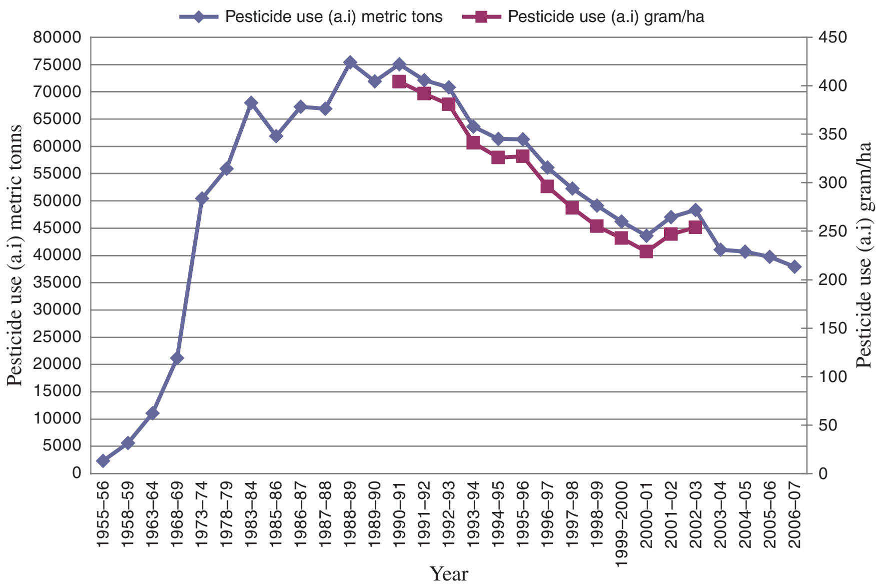

Fig. 1.1 Pesticide consumption in India (1955–56 to 2006–07)
Source: Directorate of Plant Protection Quarantine and Storage, Government of India

initiated Inter – Country Program in 1980, but IPM activities have been intensified only since 1993.

The results of ORP project were encouraging in reducing pesticide use and increasing productivity. The published literature of the ORP project in cotton (1976–1990) by the project agencies reported that adoption of IPM practices in cotton crop resulted in 73.7 and 12.4 percent reduction in the number of insecticide sprays for control of sucking pests and bollworms, respectively, in 15 villages of Indian Punjab (Dhaliwal et al., 1992). Under the same project in Tamil Nadu in the 1980s, the average quantity of insecticide used (technical grade material) was 3.8 kg/ha in six applications compared to 9.2 kg/ha in 11 sprays in non-ORP villages (Simwat, 1994). The IPM system increased the natural enemy population threefold. The spread of this program was limited to certain areas.

A number of IPM programs have been launched in India from 1993 onwards. These are the FAO-Inter Country Program for IPM in rice crops in 1993, Regional Program on cotton-IPM by Commonwealth Agricultural Bureau International (CABI) in 1993; FAO-European Union IPM program for cotton in 2000; National Agricultural Technology Project (NATP) for IPM in 2000 and Insecticide Resistance Management based IPM program by the Central Institute for Cotton Research (CICR), Nagpur in 2002 (Peshin et al., 2007). CICR, Nagpur; the Asian Development Bank (ADB) – Commonwealth Agricultural Bureau International (CABI) and Directorate of Plant Protection Quarantine and Storage, Government of India conducted season – long trainings for IPM – extension workers since 1994 to promote IPM (Bambawale et al., 2004). Central Integrated Pest Management

Centers (CIPMCs) were set up in 26 states which promoted the concept of IPM in cotton and rice since the 1990s. Various state departments of agriculture implemented IPM from mid – nineties. The Government of India launched the Technology Mission on Cotton in 2000 (Barik et al., 2002). FAO-EU launched an IPM program in cotton in India since 2000 for five years. Andhra Pradesh cotton IPM initiative is another active organization in IPM (Anonymous 2001). Multilocation trials have been carried out by the All India Coordinated Cotton Improvement Project (Anonymous, 2004). The Ashta IPM model is also being implemented in Central India. Agriculture Man Ecology (AME) funded by a bi-lateral agreement between the Indian and Dutch governments is implementing IPM farmer field schools in Karnataka, Andhra Pradesh and Tamil Nadu. Sir Ratan Tata Trust project (a private sector funded project) supports the Department of Entomology at Punjab Agricultural University, Ludhiana, India towards further developing, validating and disseminating cotton-IPM technology in cotton growing districts of Punjab since 2002.

In the mid 1990s, India abolished its insecticide subsidy resulting in a saving of US $30 million annually and imposed a 10% excise tax, which has resulted in a US $60 million annual revenue to the government. It spends US $10 million per year on IPM-FFS (Kenmore, 1997). In 1994, the Directorate of Plant Protection, Quarantine and Storage, Government of India, the nodal agency for implementing IPM programs, intensified its efforts and adopted FFS model for educating farmers through its 26 CIPMCs (presently there are 31 CIPMCs). These centers have completed pest monitoring in 10.20 million hectares and bio-control agents have been released in 7.79 million hectares up to 2006–2007. The IPM-FFS implemented during the same period are 10562, in which 318246 farmers and 43301 extension functionaries have been trained (DPPQ&S).[7] The IPM-FFS has mainly been conducted for rice (5930), cotton (2002), vegetables (951) and oilseeds (916) as well as other crops. The targets for next the five years (XI Plan Period: 2008–2012) are for conducting 3250 IPM-FFS. The IPM–FFS program was designed to be implemented by CIPMCs in collaboration with the state departments of agriculture (the main extension agency in India) with technical support from the state agricultural universities. No coordination between the state agricultural universities and CIPMCs was observed (Peshin and Kalra, 2000) and presently there is no functional coordination between CIPMCs, state departments of agriculture and state agricultural universities in jointly implementing IPM-FFS. These agencies are running their own IPM programs separately or in isolation and sometimes these agencies cater to the same village one after the other (Peshin, 2009). IPM initiatives are hampered by leadership, coordination, management of human and financial resources, and evaluation mechanism of these programs. The Central Government should manage, coordinate and draw a roadmap for IPM implementation; otherwise IPM programs will remain confined to projects and project reports, conference discussions, research journals and one-upmanship between state agricultural universities, state departments of

[7] Information received from Directorate of Plant protection Quarantine and Storage (DPPQ&S), Government of India

agriculture and CIPMCs. An outlay of US $2.8 million has been earmarked for state level training programs and FFS for the period 2008–2012 out of total outlay of US $266.7 million for "Strengthening and Modernising of Pest Management Approaches in India" which is meager.

In India, many agencies are involved with the implementation/dissemination of IPM technology, but the area covered under IPM is less than 5 percent (Ragunathan, 2005), and there is no extensive empirical impact evaluation of these programs. The actual spread of IPM practices being adopted by farmers is not well documented as was also pointed out by Luttrell et al. (1994) in a comprehensive review of cotton IPM systems of the world. The literature on impact of IPM programs in is mainly based on the project or annual reports of these programs compiled by the implementing agencies which are not based on the systematic evaluation of these programs on a larger scale. These reports lack both internal and external validity. Overall there is no documented evidence of the adoption and impact of different IPM programs in India, once the IPM training intervention has been withdrawn. The success of different IPM programs depends upon the widespread adoption of IPM practices by the farmers and for that "IPM Innovation System Approach" has to be adopted for coordination of research, extension, farmers, public sector and private sector. Results of the selected empirical studies based on the evaluation methodologies are given in Table 1.9.

Pesticide use (technical grade material) in Indian agriculture has steadily reduced since 1990–91 from 75033 tons to 37959 tons in 2006–07, which is a reduction of 49.41% (Fig. 1.1). There are four reasons for pesticide use reduction. First and the foremost is the banning of hexachlorocyclohexane (BHC) in April 1997, which accounted for 30 percent of total pesticide consumption in India, and the introduction of high potency newer molecules, like imidacloprid, spinosad, indoxacarb etc. The dosage of these chemicals per unit area is 10–35 fold lower than organophosphates. The second reason is the abolition of insecticide subsidies in the 1990s, and public extension agencies no longer selling insecticides from their input supply outlets. The third reason for the reduction is the introduction of Bt cotton in the 2002 season. India is the world's fifth largest grower of genetically modified crops with an estimated 6.9 million hectares (Bt cotton) sown in 2008. Since 2002, pesticide use has reduced from 48350 tons to 37959 tons in 2006, a reduction of 21.49%. The fourth reason is the implementation of multiple cotton IPM programs in high pesticide use states like Punjab, Haryana, Andra Pradesh, Maharashtra, Rajasthan and Tamil Nadu, which among them consume 55% of the total pesticide use. Insecticides account for 64% of the total pesticide consumption (Fig. 1.2). Consumption patterns in different states of India and different crops are highly uneven. In India, overall pesticide consumption per hectare (254 grams) is far less than in the USA, Europe and Japan, but the per hectare insecticide use in cotton is very high. For example in Punjab, agriculturally the most advanced state of India, it ranges between 5.602 and 8.032 kg/ha (Peshin, 2005).

Table 1.9 Outcome of IPM programs in India

Region/State	Crop	Intervention	Outcome	References
Central India	Cotton	IPM intervention	Cost of plant protection reduced by 31.3%. chemical pesticide consumption reduced by 94.3%	Bambawale et al., 2004
Tamil Nadu	Cotton	IPM intervention in four villages	Pesticide application reduced from 11 sprays to 6 sprays in IPM villages	Bambawale et al., 2004
Punjab	Rice	IPM-FFS in 10 villages	Average number of insecticide applications i. Before IPM – FFS = 1.88 ii. During IPM – FFS = 1.10–1.64 iii. After IPM – FFS = 1.44	Peshin and Kalra, 1998
Punjab	Cotton	Insecticide resistance management(IRM) based IPM intervention of Central Institute for Cotton Research, Nagpur, India	1. Average number of insecticide applications with/without IRM i. With IRM = 13.07 ii. Without IRM = 15.43 iii. Difference = 15.29% 2. Average number of insecticide applications before/after IRM i. Before IRM = 15.34 ii. After IRM = 13.07 iii. Reduction = 14.80% 3. Insecticide use (a.i) i. With IRM = 5.602 kg/ha ii. Without IRM = 8.032 kg/ha iii. Difference = 30.25% 4. No significant difference in yields with/without IRM	Peshin, 2005
Central India	Cotton	IPM intervention	Cost of plant protection reduced by 31.3%. Chemical pesticide consumption reduced by 94.3%	Bambawale et al., 2004
Andra Pradesh	Cotton	IPM-FFS	1. The adoption of IPM significantly reduced the use of pesticides. Trained farmers used one sixth of the pesticides to obtain the same yield levels. 2. The year after the FFSs, all farmers decreased the use of highly and moderately toxic pesticides. 3. Number of pesticide applications by IPM-FFS farmers reduced from 7.9 to 1.7 while no significant reduction (From 8.2 to 7.2) in case of non-IPM farmers.	Mancini et al., 2008

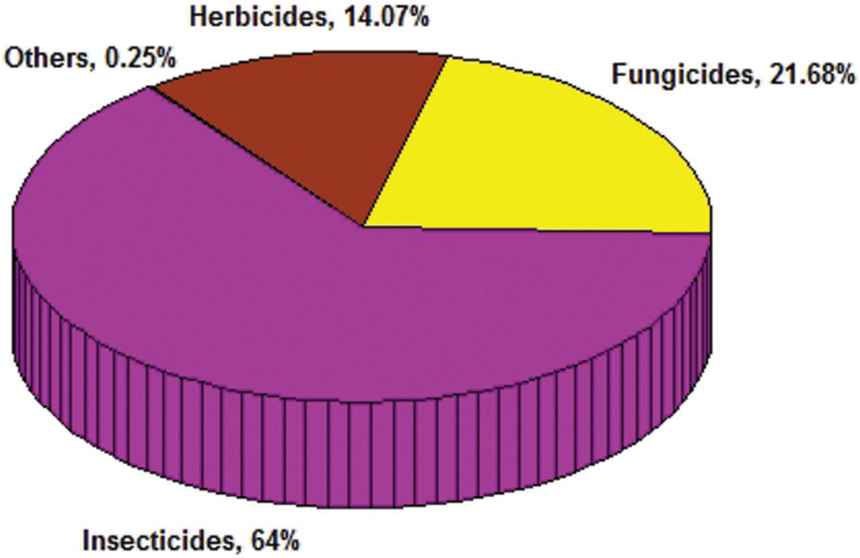

Fig. 1.2 Consumption pattern of different groups of pesticides in India (2003–04)

1.4.4.2 IPM Programs in China

Development Process of IPM Framework in China

China was one of the earlier countries to promote integrated control of plant diseases and insect pests. As early as the early 1950s, China put forward the concept "integrated control" in the relevant literature (Jing, 1997). In 1975, Chinese plant protection scientists formulated the principle of plant protection "Focus on Prevention and Implement Integrated Control", namely the IPM framework. Lately this framework was included or realized in some agriculture-related policies, regulations and provisions in China. Meanwhile the country coordinated and arranged a number of research and promotion programs on IPM and has made great achievements (Zhang et al., 2001).

According to China's level of implementing IPM, the development process of IPM framework in China can be generally divided into three stages (Wang and Lu, 1999):

(i) Pest-centered IPM, i.e., the first-generation IPM. For example, during the period of "The Sixth Five Year Plan" (1981–1985), each of the main pests on a certain crop was controlled to below the economic threshold using physical, chemical and biological control methods.
(ii) Crop-centered IPM, i.e., the second-generation IPM. For example, during "The Seventh Five Year Plan" (1986–1990), with crop as the center, a variety of major pests on the crop were controlled. At this stage, IPM gave full play to the full value of natural control in the agro-ecosystem and IPM systems began to be established. During "The Eighth Five Year Plan" (1991–1995), a large number of IPM systems were developed, assembled, improved and applied in China. In

this period, IPM was demonstrated on more than 200,000 ha of farmlands and promoted on more than 6,670,000 ha, and achieved certain positive results.

(iii) Ecosystem-centered IPM, i.e., the third-generation IPM. The entire field or regional ecosystem was the focus of IPM; a large quantity of advanced scientific information and data were collected and used, and advanced technologies were developed in IPM practices. Overall and global benefit was expected to be increased with the natural control of ecosystems as the main force. At present, China is in the transition phase of the second- and third-generation IPM.

Dissemination and Impact of IPM

The migratory locust, *Locusta migratoria manilensis* (Meyen), was historically a serious insect pest in China. With focus on environmental conditions and farming systems in an IPM framework, specific methods to eradicate locust disaster were presented in early 1957. The eradication program was organized and invested in by government. The growth and reproduction of locusts was finally inhibited and the locust population sustainably controlled by transforming habitats, constructing irrigation systems, stabilizing water table, reclaiming wastelands, implementing crop rotation, planting beans, cotton, sesame, and greening lands (Chen, 1979; Ma, 1958, 1979). The rice stem borer, *Scirpophaga incertulas* (Walker), is a serious rice insect pest across South China. As early as the 1950s, it was found that adjusting farming systems and selecting appropriate planting dates were the main methods to suppress this pest (Zhao, 1958), which has now been applied in IPM practices for this pest. In terms of radiation-sterilizing technologies, during the late 1980s about 150,000 radiation sterilized male *Bactrocera minax* (Enderlein) were released into a citrus orchard with more than 30 hm^2 in Huishui, Guizhou Province, which reduced the citrus injury from 7.5% to 0.005% (Wang and Zhang, 1993). Insect-resistant breeding has also been used since the 1950s. Insect-resistant wheat varieties "Xinong 6028" and "Nanda 2419" have been bred and planted to successfully control the wheat midges (*Sitodiplosis mosellana* and *Comtarinia tritci* (Kiby)) in north China (Wang et al., 2006). During the 1990s, under the support of government, transgenic Bt cotton varieties were bred and used to control cotton bollworm and have achieved remarkable success (Zhang et al., 2001; Chapter 18, Vol. 2). In recent years the application of insect-resistant varieties of cotton, rice, wheat, rapeseed and other crops have also achieved great success in China. According to the statistical data, the total area of transgenic insect-resistant cotton in China has reached 4.667 million ha, with an average income of US $304.3–342.9/ha (US $1 = 7 RMB Yuan). Annual reduction of chemical pesticide applications reaches 20,000–31,000 tons, equivalent to 7.5% of China's annual total production of chemical insecticides (Chapter 18, Vol. 2). In general, past years' IPM programs supported by Chinese government have demonstrated the positive and significant impact of IPM (Table 1.10).

Beginning in 1988, funded by the FAO Inter-Country Rice IPM Program, the Asian Development Bank (ADB) Cotton IPM Program and World Bank Crop IPM Program, a number of FFS-based training courses were organized in China. During 1993–1996, the ADB Cotton IPM Program was implemented in Tianmen, Hubei Province, under the auspices of the National Agricultural Technology Promotion Center of China (Zhang et al., 2002). Since 1996, the FAO Inter-Country Rice IPM

Program was implemented in Gaoming, Guangdong Province (Chen and Du, 2001). Starting in 2000, the EU Cotton IPM Program was implemented in Yingchen, Tianmen and Xiantao of Hubei Province. During the implementation of these programs, training courses to train qualified teachers (TOT) and standardized FFS were held (Zhang et al., 2002). Through running FFS, establishing IPM associations, sponsoring community-based IPM activities, establishing IPM demonstration gardens, and developing and producing pesticide-free agricultural products, a preliminary way to promote IPM was constructed in China (Zhang et al., 2001). Through the above rice programs implemented in China, up till 1999 in total of 2,017 FFS had been sponsored, 66,112 rice farmers, cadres and promotion households had been trained, and hundreds of thousands of farmers were triggered to use IPM technologies. Various IPM programs have made certain achievements: (i) A large number of agricultural extension personnel were trained and a network to promote IPM technologies was initially established. (ii) A number of IPM demonstration gardens were established, which facilitated the development of IPM in local regions. Trained farmers organized farmers' organizations and used IPM technologies of rice and cotton to high valuable and high-dosage pesticide used fruits, vegetables and other specific crops and established demonstration gardens, and tried to produce pollution-free agricultural products. For example, the IPM programs were implemented over 4,000 ha and radiated to 34,000 ha of farmlands in 28 counties, cities and districts around Jianghan Plain of Hubei Province. (iii) The village-based agricultural technology service network systems on the basis of farmers – IPM trained farmers – IPM

Table 1.10 Outcome of some IPM programs in China

Region and period	Crop	IPM intervention	Outcome	References
North China: Jilin Province (1995–1999)	Maize	Pest-resistant varieties, seed-coating technique, fungus and insecticide use, parasitic natural enemy, etc.	Yield increase: 630–1708.5 kg/ha. Ratio of cost *vs.* benefit: 1:18.9–28.1. Crop loss reduction: 7% from 15–20%.	Jin et al., 2000
South China: Guangdong Province (2000–2004)	Rice	Pest-resistant varieties, cultivation techniques, fertilizer use, seed selection and pesticide treatment, selected use of insecticides, etc.	Pesticides reduction: 3–4 times of annual applications' reduction, 28.3–32.4% of dosage reduction, US $14.6–18/ha of pesticides cost reduction, US $15.6–16.3/ha of labour-spraying reduction. Income increase: US $120.2/ha. Natural enemy protection: 5–8 more spiders per hundred rice clusters.	Zeng, 2006

farmers' organizations were initially formed, which linked town stations-county stations-provincial station for plant protection in order to strengthen the liaison and information technology support services (Zhang et al., 2001). (iv) Cultivation benefits of rice and cotton increased by implementing IPM. For example, implementing IPM on rice and cotton can increase income by US $123.4 and 206.4/ha, respectively and reduce the use of chemical pesticides. Pesticide applications on rice and cotton were reduced by 1.8 and 12.2 times, respectively. According to the survey, there were totally 2,325 predatory natural enemies on IPM cotton but only 1,168 predatory natural enemies on non-IPM cotton (Zhang et al., 2002).

Problems in IPM Implementation

On the whole the applications of IPM technologies in China are still highly localized. Pesticide misuses are still common and pesticide residue problems are serious (Figs. 1.3 and 1.4). The chemical pesticide use per unit land is 2.6 times of some developed countries (Liu, 2000; Zhang, 2001). According to a report, in 1999 Anhui Province alone exhausted pesticide 9,650.89 tons (active ingredient), application

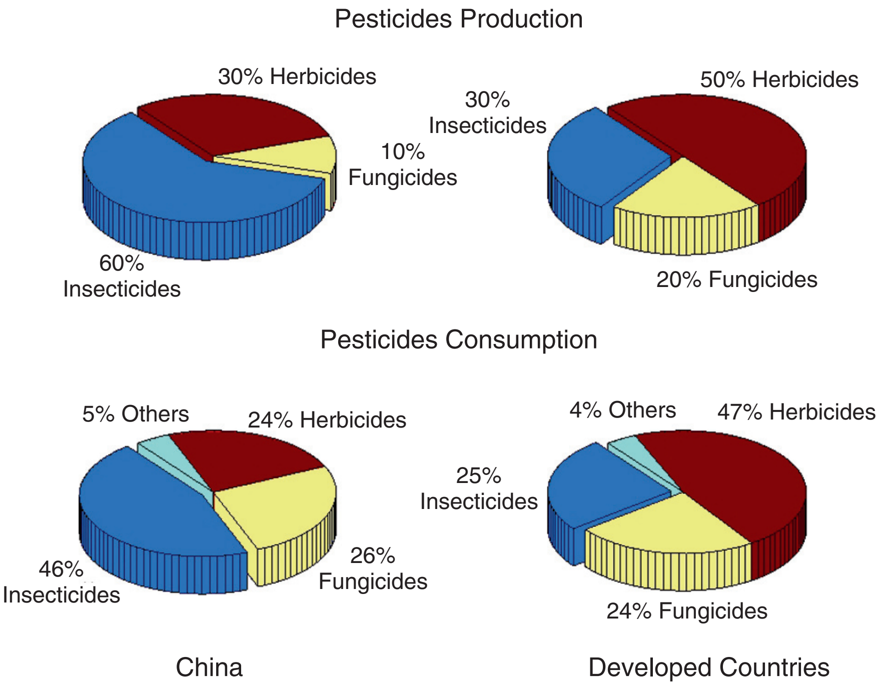

Fig. 1.3 Production and consumption percentages of various pesticides for China and developed countries in past years. Proportion consumption of insecticides in China was much higher than the developed countries. However, a large number of high poisonous insecticides have been banned for using in China since 2007. An ideal development trend is expected in the future.
Sources: http://www.5ilog.com/cgi-bin/sys/link/view.aspx/6329967.htm; http://www.moneychina.cn/html/67/76/76336/1.htm

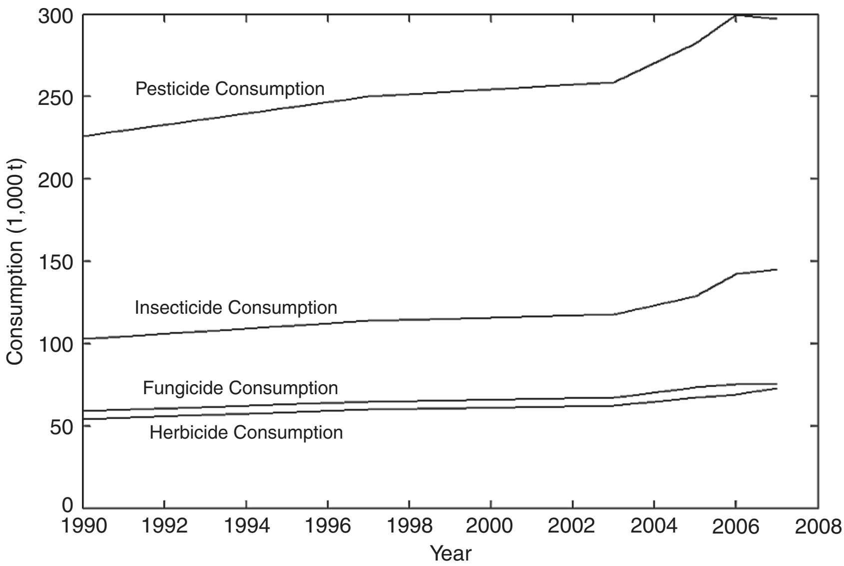

Fig. 1.4 Dynamic changes of pesticides consumption in China. A declining trend in pesticides (total pesticides, insecticides, fungicides) consumption growth is expected in China, although pesticide misuses are still common and pesticide residue problem is serious. Herbicides consumption in China is largely increasing in recent years
Sources: Yu (2006); http://www.1nong.com/info/list40702.html; http://www.chinawz.cn/Report/06-07bg/07nongyao.htm; http://www.toponey.com/Html/20061129151626-1.Html; http://www.chemdevelop.com/Trade/trade2.asp

dosage reached 0.22 g/m^2, increasing by 43.7% and 24.16% over the "The Eighth Five Year Plan" (1991–1995) (Zhang, 2001). Excessive use of pesticides in rice and cotton production reached 40% and 50%, respectively (Chen and Han, 2005). In recent years the annual pesticide poisoning number of farmers in Guangdong Province alone has reached 1,500 and is increasing annually. The lack of application of IPM in China is attributed to the following: (i) under the household contract system, agricultural intensification and on-scale operation could not be realized easily, the farmers have less demand on IPM technologies. (ii) IPM technical extension services systems are insufficient. (iii) Pesticides markets are not ordered, the social environment for IPM application has not yet been established. (iv) We are short of theoretical researches and application technologies of IPM. At present, IPM technologies are not perfect, and monitoring effectiveness and forecasting accuracy are at a lower level (Chen and Han, 2005).

1.5 Experiences, Problems and Perspectives

The relative success of the IPM extension programs is ultimately judged on the adoption rate of the IPM systems (or components *thereof*) and the improvements in the production associated with this (Dent, 1995). Without a unanimously accepted definition there is considerable difficulty in determining the extent to which IPM has been adopted (Norris et al., 2003). The use of truly integrated pest management (based on the definition of IPM discussed in Section 1.2) is still relatively low as a worldwide review of the IPM literature suggests (Kogan and Bajwa, 1999) and as discussed in this chapter. Pest management practices in different agro ecosystems have changed dramatically since the late 1960s in some developed countries (Norris et al., 2003) and since 1980s in most of the developing countries IPM philosophy has made major contribution in that regard.

The constraints in adoption have been in terms of inappropriateness of technology, economic implications, non-availability of appropriate information, acquiring of knowledge and skills by farmers for applying the IPM in their fields, dissemination of IPM, and vast network of chemical industry to lure farmers into using pesticides and the lack of coordination among implementing agencies. Due to the complexities of carrying out IPM, it has been difficult for farmers in carrying out IPM practices like ETL (Goodell, 1984; van de Fliert, 1993; Escalada and Heong, 1994; Matteson et al., 1994; Malone et al., 2004; Peshin, 2005). The compatibility of an IPM practice also plays a role in its adoption. If an IPM practice is not compatible like "*trash trap*" in maize (Bentley and Andrews, 1991) it is a limitation in its adoption. Economic returns/implications of IPM need to be improved and demonstrated to the farmer so that the farmer learns that even buying information and advice can be more profitable than buying chemicals (Lacewell and Taylor, 1980). Growers perceived that IPM practices are more risky than conventional pest management in both the developed countries and developing countries (Grieshop et al., 1990; Norris et al., 2003; Peshin, 2005) so the risk associated must be decreased to make farmers sure of its economic viability. In Europe, the countries where the government policy initiatives in terms of pesticide taxation and providing incentives to farmers for adopting IPM, farmers associations, NGOs and retail market chains all work in unison to promote low pesticide crop production has reduced pesticide use and increased adoption of IPM. Dissemination of IPM technology related information in a top down approach is also a constraint in many developing countries (Kenmore et al., 1995) and lack of proper knowledge about different aspects of IPM like agro – ecosystem analysis and not acquiring required skills for its use acted as barriers (van de Fliert, 1993, Merchant and Teetas, 1994). Vast network of pesticide companies in developed and developing world also lured back the IPM practioners. The company agents scouting farmers' field and assisting them in sampling acts as a barrier for IPM adoption. Counteracting forces even in public extension services confuse the farmers and the lack of commitment of extension agencies to IPM limit its spread and adoption (van de Fliert, 1993) and lack of master trainers acts as an obstacle in the adoption of IPM (Matteson et al., 1994; Peshin and Kalra, 2000).

In developing countries the policy planners are not well conversant with IPM programs and implementation. Similarly, input suppliers are not farmers but traders. They do not have any idea of IPM and are a big hurdle in the implementation of IPM. Farmers are not prepared to adopt simple IPM practices but often are provided with simple solutions with the use of insecticides. The wide gap in technology generated and implemented results in loss of confidence among farmers. The time-lag in technology dissemination is great and in era of fast changing technology, the old system of transfer of technology will not serve the purpose. The use of modern information technology, e-learning, decision support systems, mobile phones, text messaging and video conferencing around the globe can revolutionize the concept of IPM. The IPM technology needs to be farmer friendly. The introduction of transgenic crops creates an opportunity to enhance implementation of IPM, because the need to control a key pest with insecticides is reduced, and this has been the case in some countries (e.g. Australia, India). However, this technology can be seen as a "silver bullet" that replaces the need for IPM, hence diminishing interest. Further, the technology, though offering many benefits is at risk from target pests developing resistance, necessitating complex resistance management strategies in some countries. The current monopoly of this technology by a few large multi-national companies also creates a challenge as farmers in developing countries may be very susceptible to the lure of simplified pest control the transgenics offer but have a poor understanding of the technology's benefits and risks. The inputs are controlled by private sector and are mainly concerned with profit and ignore long term consequences of the technology as was and is the case with pesticides. Farmers in developing and under developed countries will face new problems in implementation of IPM program unless they have access to fast means of transfer of technology so they can have ready access to up-to-date information, government invests in farmers education and agriculture innovation system is put in place.

The constraints for development and uptake of IPM in different agricultural systems can vary. For instance, in most of the Latin American countries there is no public service extension so the farmers are more dependent on agents of chemical industry for information. In the USA the constraints are in terms of IPM adoption which is often more expensive than conventional pesticide based management, due to increased need for population assessment and record keeping. However, where it meets the economic interest of growers adoption is high. In developing countries counteracting approaches, lack of proper dissemination of technology in a participatory mode are the barriers in adoption of IPM. For different crops also the constraints differ.

1.6 Conclusion

Globally the disappointing aspect of the IPM programs is the confusion in actually assessing the adoption and success of IPM programs – what constitutes the adoption of IPM? In many instances IPM programs target small groups of farmers and may achieve considerable success in increasing yield and reducing pesticide use, but do these successes ripple out to the wider farming community? The adoption of IPM has been generally slow in both the developed and the developing world, despite some successes. Pesticides are still the main strategy of many IPM programs. Overall use of pesticides has not decreased in most of the countries with the exception of a few. IPM research and extension programs must be evaluated to formulate strategies to overcome the "real-world" impediments experienced by the farmers (Hammond et al., 2006).

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Chapter 2
Integrated Pest Management: Concept, Opportunities and Challenges

Ashok K. Dhawan and Rajinder Peshin

Abstract Integrated Pest Management (IPM) has a prominent place on the policy agenda. Due to continuing concerns regarding unsustainable trends in pest management, promoting the adoption of IPM has been a priority in developed and developing countries. The history of IPM, however, can be traced back to the late 1800s when ecology was identified as the foundation for scientific plant protection. The priorities in IPM shifted from calendar-based use of insecticides to need base, and thereafter, reduce use of insecticides with safety concerns to environment and human health. The development, validation, and dissemination of site-specific IPM and adoption by farmers are key elements for the success of IPM programs. The IPM means do right thing based on a value-based decision system and use of multiple tactics. Because, information delivery is a key part of IPM, the spread of the internet rapidly has enhanced knowledge transfer and access to options. The knowledge acquisition tools are essential for the successful implementation of IPM. Knowledge and information transfer are key to correct pest management. IPM emphasizes correct decisions based on available information on pest management. Internet-based interactive decision support can play a significant role in developing countries. With new innovations coming fast and increasing awareness of the internet, more farmers are using IPM informatics and decision support systems. Environmental risk in IPM is an important issue. Pesticides will continue to dominate IPM in developing and under-developed countries as the target is to produce more for food security. Environmental quality in pest management will continue the focus on alternatives to pesticides and environmentally-safe tactics. Recent developments have the potential to contribute to greater significance of IPM for sustainable development in agriculture. New technological innovations and new modes of delivery have given a new direction to IPM. Biotechnology, including genetic engineering, offers new tools for reducing dependency on chemical pesticides. New products for biological control are becoming more widely applied, and the agrochemical industry is developing more specific and target products. Participatory approaches for farmer training and awareness rising are increasingly employed to ensure sustainability of

A.K. Dhawan (✉)
Department of Entomology, Punjab Agricultural University, Ludhiana-141004, India
e-mail: dhawan@sify.com

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pest management practices. Requirements of the food industry regarding pesticide residues have become a major force that encourage adoption of IPM practices, and the rising public demand for food safety and quality is creating niche and market opportunities for certified products, such as organic foods. Pest and pesticide management problems affect most countries and many externalities are global in scope. IPM is gaining recognition as a global policy issue and there is increased involvement of the relevant stakeholders in the IPM policy debate at both the national and international levels. To develop IPM programs for the 21st century, directional research and extension seems to be needed, as well as the development of new technology.

Keywords Integrated pest management · IPM implementation · Pest control

2.1 Introduction

Policy makers and scientists globally are addressing the need for sustainability in agriculture, in order to satisfy changing human needs and enhancing the quality of the environment. The sustainable practices have to be ecologically-sound, economically viable, socially-justifiable, and adaptable. During the next two decades, the world will have to feed 2.5 million people with less land and renewable resources. Over half of the world population growth will occur in Asia and one third in African countries. The challenges will be more in under-developed countries, where the population growth is very high compared to the growth in the agriculture sector. Moreover, growing awareness about the quality of food will further through challenge on increasing quality production. The economic liberalization, globalization, and the World Trade Organization policies have necessitated a paradigm shift in agriculture to meet the needs in food requirements of the growing population.

Insect pests are one of the limiting factors in increasing food productivity worldwide. The global losses due to various insect pests vary with crop, geographical location, and pest management options. Immigration of new pest, introduction of new crops/cropping systems, and crop intensification has resulted in significant change in pest populations. The estimated losses due to insect pests are 500 billion US$; by adopting better pest management practices these losses can be reduced by 42.6%. In the case of no insect control losses can be as high as 69.8% (Dhaliwal et al., 2004). Challenges are to reduce the losses due to pests by integrating various management options. The development of high yielding agro-cultivars during the green revolution increased the availability of food grains through the use of high yielding varieties, use of energy inputs like pesticide, fertilizers, and irrigation. With the introduction of improved technologies, the food production has outstripped population growth in the last few decades. Besides the increased productivity, the improved technologies resulted in an increased use of synthetic fertilizers and pesticides. Over-reliance on the use of pesticides has resulted in environmental pollution, ground water contamination, pest resurgence, and poisoning of food material, animals and human beings. In addition, it also affected the agricultural trade where several agricultural commodities were rejected due to the accumulation of pesticide residues.

Introduction of sustainable farming practices, including integrated pest management (IPM), created a paradigm shift in agriculture. “Integrated pest management is a pest management system that in the socio-economic context of farming systems, the associated environment and the population dynamics of the pest species, utilizes all suitable techniques in as compatible manner as possible and maintains the pest population levels below those causing economic injury” (Dent, 1995). Pest management is an ecological approach of reducing the pest damage to a great extent and determines the management strategy. However, if pest management is faulty it will help the pests to develop and expand their populations or, conversely, make natural enemies ineffective. Therefore, for an effective pest management program, it is essential to consider ecological concepts that can be applied to the design and management of the system to better manage pests and their parasitoids and predators.

Integrated Pest Management is an effective and environmentally-sensitive approach to pest management that relies on a combination of common-sense practices. The concept of IPM excelled during mid 1970s to reduce the over-dependence on pesticides that were used for reducing losses due to pests. IPM programs use current, comprehensive information on the life cycles of pests and their interaction 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 least possible hazard to people and the environment. The nature of IPM in the waning years of the 20th century is such that it has become a household term, generally understood, and frequently used. IPM, being a knowledge-intensive and farmer-based decision making process, encourages natural control of pests and diseases from reaching economically-damaging levels. It prevents pest outbreaks and the development of pest resistance. The pesticide-free agricultural commodities from the IPM-practiced fields have a great scope to increase the income of farmers. In spite of several advantages, the levels of adoption of IPM by the farmers are very slow. Hence, there is a challenging task for the government, researchers, and extension functionaries to identify the reasons for poor adoption and to design policies that motivate the farming community to adopt the IPM practices.

2.2 Historical Perspective of Pest Control

In agriculture, a phytophagous insect is a pest when its population is high enough to cause significant damage in yield or quality to any of the economic plants grown by man. Over the centuries, farmers developed a number of mechanical, cultural, physical, and biological control measures to minimize the damage caused by phytophagous insects. Synthetic organic insecticides developed during the mid 20th century initially provided spectacular control of these insects and resulted in the abandonment of traditional pest control practices. The increasing insect pests problems encountered with the use of insecticides resulted in the origin of integrated pest management (IPM).

The various events in pest management can help in understanding the concept of pest management and provide better options for pest management (Table 2.1). Pest management has three historical periods which laid the foundation of the IPM era.

Table 2.1 The history of pest management

Period	Landmark
8000 BC	Beginning of agriculture
4700 BC	Silkworm culture in China
2500 BC	First records of insecticides e.g. the sulphur compounds to control insects and mites
1500 BC	First descriptions of cultural controls, especially manipulation of planting dates
1200 BC	Botanical insecticides were being used for seed treatments and as fungicides in China
950 BC	First descriptions of burning as a cultural control method
200 BC	Oil spray for pest control
300 AD	Biological control on citrus orchard in China by predatory mites
400 AD	Root application of arsenic in rice to protect against insect pests
1750–1880	Discovery of the botanical insecticides pyrethrum and derris
Early 1800s	Appearance of books and papers devoted entirely to pest control covering cultural control, biological control, varietal control, mechanical and chemical control
1848–1878	Introduction of *Viteus vitifoliae* from Americas and release of the natural enemy *Tyroglyphus phylloxerae* to France from North America in 1873
1880	First commercial spraying machine
1883	*Apanteles glomeratus* was imported from the UK to the USA to control cabbage white butterfly
1888	First major success with imported biological control agents *Cryptochetum iceryae* and the coccinellid beetle *Rodolia cardinalis* from Australia for the control of cottony-cushion scale in US citrus fruits
1890s	Lead arsenate for insect control
1893	Recognition of arthropods as vectors of human diseases
1901	First successful biological control of a weed (lantana in Hawaii)
1920–1930	More than 30 cases of natural enemy establishment were recorded throughout the world
1921	First aerial application in insecticide against *Catalpa sphinx* moth in Ohio, USA
1929	First area-wide eradication of an insect pest against Mediterranean fruit fly in Florida, USA
1930	Introduction of synthetic organic compounds for plant pathogen control
1932	“History of the Development of Organophosphate Poisons”
1939	Recognition of insecticide properties of DDT
1942	Release of wheat variety resistant to the Hessian fly.
	Rediscovery of the insecticidal properties of benzene hexachloride and in particular its gamma isomer (BHC)
1950s	First applications of systems analysis to crop pest control
1959	Introduction of concepts of economic thresholds, economic levels, and integrated control by V.M. Stern, R.F. Smith, R. van den Bosch, and K.S. Hagen
1960	First insect sex pheromone isolated, identified and synthesis in the gypsy moth
1962	Publication of “Silent Spring” by Rachel Carson

Table 2.1 (continued)

Period	Landmark
1965	Release of carbamate insecticide pirimicarb and pirimiphos ethyl
1967	Introduction of the term "Integrated Pest Management" by R.F. Smith and R. van den Bosch and "Life Systems" was introduced by L.R. Clark, P.W. Geier, R.D. Hughes and R.F. Morris
1969	US National Academy of Sciences formalized the term Integrated Pest Management
1970s	Widespread banning of DDT
1972	Release of *Bacillus thuringiensis* insecticide based on isolate HD-1 for control of lepidopteran pests
1975	Development and release of the synthetic pyrethroid insecticides permethrin and cypermethrin
1988	Major IPM successes in rice systems in Indonesia
1992	Concept of "Environment Injury Level" by L.P. Pedigo and L.G. Higley
1992	World Food Prize for developing sterile-insect technique to E.F. Knipling and R.C. Bushland
1992	Pivotal role of IPM in agriculture and policy as part of Rio de Janerio, Brasil (part of agenda 21)
1996	Commercialization of first transgenic crop – cotton
2004	Resistance of *Helicoverpa zea* to Bt cotton

Modified after Dhaliwal et al., 2004

2.2.1 Prior to World War II

This was an era of traditional approaches for pest management. Pest control consisted of crop rotations and other cultural and mechanical practices like field sanitation, deep ploughing, flooding, and collection and destruction of damaging insects and/or insect-infested plants. These practices were developed by farmers through experience and were among the oldest methods developed by humans to minimize the damage caused by insect pests (Smith et al., 1976). For example, the Chinese used chalk and wood ash for the control of insect pests in enclosed spaces and botanical insecticides for seed treatment. They also used ants for biological control of stored grain as well as foliage feeding insects. In India, neem leaves were placed in grain bins to keep away troublesome pests. In the Middle and Near East Asia, powder of chrysanthemum flowers was used as an insecticide. A number of synthetic inorganic insecticides containing arsenic, mercury, tin, and copper were also developed towards the end of the 19th and the beginning of the 20th century. With the development of these insecticides, the focus of research shifted from ecological and cultural control to chemical, even before the development of synthetic organic insecticides (Perkins, 1980).

2.2.2 Post World War II

This was the era of pesticide use. DDT was widely used in World War II and saved many lives by preventing outbreaks of yellow fever and other arthropod vectored diseases commonly associated with war conditions. DDT became the solution to all pest problems. After World War II, DDT and other organic insecticides were used worldwide to control insect pests. The period from the late 1940s through to the mid-1960s has been called the "Dark Ages" of pest control (Newsom, 1980). Pesticides were the basis of pest control practices on almost all farms in industrialized countries in the early 1950s, and the focus of scientist and farmers was shifted to the development and application of pesticides in a fixed spray schedule. By the 1970s, farmers had come to rely on pesticides, and other control methods were not even considered. Regular spray programs were developed on a routine preventive basis, which provided a shield of pesticide protection whether the pest was present in damaging numbers or not. Shortly after the introduction of control programs based on pesticides, however, resistance, resurgence, and residual problems began to emerge. Some farmers experienced problems because they could not cultivate crops any more, since no pesticide could control the pests in their farms, or the cost of pesticides use became too high. Perhaps the most alarming example of this is the cotton fields in Peru, Egypt, Central America, and Texas (USA). In an effort to control pests in cotton, some farmers increased the application of highly toxic pesticides to 60 applications during the growing season. Under these conditions, the cost of pest control made the production of cotton profitless, and the industry collapsed in some areas. Similar situation was observed in irrigated cotton system in Punjab, India (Dhawan, 1993, 2001)

2.2.3 Silent Spring

Silent Spring (a book by Rachel Carson published in 1962) criticized pest control methods, and mentioned that toxic chemicals should not be called "insecticides" but "biocides".

Rachel Carson view point was that:

- Insecticides are numerous and more deadly biocides.
- Pesticides are contaminating the environment.
- Toxicity to non target species shift the balance of nature and result in loss of biodiversity thereby making the agro ecosystem more viable to pest outbreak.
- Safety problems of pesticides are underestimated.
- Toxicological testing is done with single chemicals and does not consider the mixture of compounds that people are exposed to.
- Insects are developing resistance to insecticides and the proposed solution is to use more frequent and/or greater quantities of insecticide, leading to a "pesticide treadmill".

2.2.4 Integrated Pest Management

The theory and principles supporting IPM have been developed over the last 40 years. Integrated control (IC), the term first applied to IPM, was developed and introduced as a concept in the United States in the late 1950s. IC was developed to harmonize chemical control and biological control. Smith and Allen (1954) proposed IC as a new trend in economic entomology. The early concept was based on the premise that pesticides could have a minimum impact on the natural enemies of the pest if applied at the correct time and under the correct conditions.

"Economic threshold", another important concept in IPM, was introduced at that time. It is based on knowledge of the pest biology and ecology, and how the populations fluctuate naturally. The control measures should only be used to prevent an increasing pest population from reaching the economic injury level. The "economic injury level" was defined as the lowest density that will cause economic damage. These concepts remained the major theme of IPM throughout much of the 1970s. The focus of IPM began to shift to non-pesticidal tactics in the 1980s, including expanded use of cultural controls, introduction of resistant plants, and biological control. Research results on the effectiveness of IPM were published during the 1970s and 1980s; IPM was not implemented by farmers on a large scale before the 1990s. One of the major reasons was the lack of extension support. In the 1990s, extension techniques and policy have been emphasized strongly in the development of IPM.

The history of agricultural pest control, thus, has four distinct phases, viz., the era of traditional approaches, the era of pesticides, the era of IPM, and the era of transgenic.

2.3 Genesis of IPM

Stern et al. (1959) introduced the *Integrated Control* concept based on ecological balance in the ecosystem. In nature, pest outbreaks are not very common as the population of insects pests are subject to population control by natural enemies. This concept should be the basis of any interventions in crop ecosystem. Any irrational use of artificial control mechanisms may result in serious pest problems. With the non availability of resistant cultivars, effective bio-control agents, and constraints in adoption of cultural and other non-chemical approaches, the main reliance was on use of insecticides as a major component of IPM. With the release of high-yielding pest susceptible cultivars, chemical approach became the main component of IPM. This resulted in many insecticide-induced pest problems. The concept of "Economic Injury Level" formed the basis of insecticide use, keeping in view of all the ecological, economical and sociological cost of such practices. After a decade of the pioneering work Stern et al. (1959), Stone and Pedigo (1972) first demonstrated the economical and biological formula for calculating economic injury level (EILs) and presented a research methodology as the basis for transforming "theory" to "practice". Pest management programs should be based on maintaining the pest below EILs, on diverse tactics, and on sound ecological principals. In pest management programs no preference is given to one class of tactic over the other, except where value can be demonstrated. After implementation of IPM using the above criteria, several issues may emerge. Perhaps the most common is the reduction in pesticide inputs and indeed this can and has happened in many instances. A valid IPM program does not have to decrease pesticide inputs, but has to promote judicious use of insecticide within an IPM framework. Even an increase in insecticide use can be considered IPM if the use of pesticides (or other tactics) results in a better understanding and realization of the injury (I) or damage (D) potential for pests.

IPM is experiencing an identity crisis. Within academia and many branches of government, IPM has become somewhat of a "buzzword" used to convince granting agencies that their research proposals have merit as a means to the misguided goals of reducing pesticide use. Many of the proposals do in fact relate to the key EIL biological variables of injury (I) and damage (D), many more do not and contribute to the confusion and diffusion of IPM research objectives. In addition to academia, IPM also experiences a socio-political identity crisis – there is an errant belief that IPM is an "acceptable" public policy only to reduce pesticides. Obviously, this identity is clearly wrong and not consistent with the management objectives or qualifying elements of the concept and practice. The IPM is to reduce the indiscriminate use of insecticide and promote the use of safe chemistry as component of IPM in integration with other options. The use of transgenic crop as component of IPM is also as debatable as the use of pesticides to those organizations that oppose the genetically-modified (GM) crops.

2.4 Origin of IPM Concept

Basic tactics of IPM were proposed and used to defend crops against the ravages of pests long before the IPM concept was coined (Jones, 1973; Smith et al., 1976). "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. In the early 1940s with the advent of organic synthetic insecticides in 1980, the protection specialists began to focus on pesticides as a key component of pest management and little consideration was given to non-insecticidal methods of control. The period from the late 1940s through the mid-1960s has been called the "dark ages" of pest control (Newsom, 1980). By the late 1950s, however, warnings about the risks of the preponderance of insecticides in pest control were highlighted. The main concern of over-dependence on insecticide as component of IPM arose mainly from traditional centers of excellence in biological control, particularly in California (Ripper, 1956), and from cotton groups in North and South America (Dout and Smith, 1971) and deciduous tree fruit in Canada, the United States, and Europe (MacPhee and MacLellan, 1971). The IPM is centered on the use of behavioral and biological control, plant resistance to insects, and cultural controls. It employs intensive monitoring and the judicious use of pesticides. The main concern was the potential risk associated with an insect population density, host susceptibility, loss of biodiversity, and the environment.

2.5 Defining IPM

The search for a perfect definition of IPM has endured since integrated control was first defined (Stern et al., 1959). IPM, as it was originally conceived, proposed to manage pests though an understanding of their interactions with other organisms and the environment. Most of the 77 definitions for IPM listed in The Database of IPM Resources (DIR) Web site, despite some differences in emphasis, agree with this idea and have the following elements in common:

2.5.1 Appropriate Selection of Pest Control Methods, Used Singly or in Combination

Management actions are taken to restore and enhance natural balances in the system, not to eliminate species. Regular monitoring makes it possible to evaluate the populations of pest and beneficial organisms. Before action all the available pest management options are considered. IPM strategies will integrate a combination of all suitable techniques in as compatible a manner as possible and it is important that one technique not conflict with another.

2.5.2 Economic Benefits to Growers and to Society

IPM incorporates ecological and economic factors into decision making, and addresses all concerns about environmental quality and food safety. The decisions are made on management for long term gains. The benefits of implementing IPM can include reduced chemical input costs, reduced on-farm and off-farm environmental impacts, and more effective and sustainable pest management. In less developed countries the traditional approaches, which are farmers' friendly, should be integrated in a pest management strategy.

2.5.3 Benefits to the Environment

The indiscriminate/unwanted use of synthetic pesticides in crop protection programs around the world has resulted in disturbances to the environment, pest resurgence, pest resistance to pesticides, and lethal and sub-lethal effects on non-target organisms, including humans. This has shattered the economy of many cropping systems and farmers lost what they have gained with the use of an insecticide-based IPM. These side effects have raised serious concerns about the routine use and safety of pesticides. With increasing population and concern about food security with ever-greater demands of "ecological services" like provision of clean air, water and wildlife habitat, the farmers and researchers will have to manage their land with greater attention to direct and indirect off-farm impacts of various farming practices on water, soil, and wildlife resources. Reducing dependence on toxic chemical pesticides in favor of ecosystem manipulations is a good strategy for farmers. Safe chemistry can play an important role to overcome the gap created as a result of withdrawal of toxic chemicals.

2.5.4 Decision Rules that Guide the Selection of the Control Action

Conventional IPM strategies help to prevent pest problems from developing, and reduce or eliminate the use of chemicals in managing problems that arise. IPM lays more stress on use of non-chemical approach as first option. Traditional practice of pest management should be a part of IPM to keep balance in productivity and safe the environment.

2.5.5 Need to Consider Impacts of Multiple Pests

IPM lay stress on management of pest complex not on an individual pest. All decisions about management are based on the impact of management options on the pest complex. Thus, IPM programs should be based on cropping system as a whole. Among many definitions for IPM, the most often cited definition is Stern et al. (1959) for Integrated Control. A wider definition was adopted by the FAO, which is: "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 is referred as entomological bias in IPM because of the emphasis on pest populations and economic injury levels. The former definition, however, 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 (Zadoks, 1985; Backman and Jacobi, 1996; Mertensen and Coble, 1996). Based on an analysis of definitions spanning the past 35 years, Kogan (1998) defined IPM as "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. Integrated pest management is a well-known innovation that accords with modern environmental management's best practice".

The definition of IPM does not only include strategy but also to educate and encourage agricultural producers to grow crops using pest management methods that aimed at:

- Reducing, if not replacing, the use of synthetic organic pesticides
- Environment safety and posing minimal risk to human health
- Enabling growers to obtain a reasonable return or investment
- Ensuring consumers a supply of high quality, safe and economical foods and other agriculturally related products.

2.6 Developing IPM Systems

Many components of IPM were developed in late 19th and 20th centuries. Stephen W. Pacala was probably the pioneer in the application of ecological studies for dealing with insect problems in agriculture. By the early 1920s, a highly complex and sophisticated system evolving the use of multiple component suppression techniques, viz., resistant varieties, sanitation practices and chemical treatments with calcium arsenate at fixed population levels, was already developed for cotton boll weevil control in the USA. In fact, IPM is a dynamic and constantly evolving approach to minimize crop losses in which all the suitable management tactics and available surveillance and forecasting information are utilized to develop a holistic management program as part of a sustainable crop production technology (Dhaliwal and Arora, 1996). Here it needs to be emphasized that the aim of IPM program should not be restricted to a mere efficient use of pesticides and product substitution within an agricultural system that essentially remains unchanged.

- Environmental problems caused by widespread/indiscriminate application of pesticides, alternative technologies especially integrated pest management (IPM) should be pursued.
- The importance of basic ecological studies for IPM can hardly be overemphasized. The clear understanding of the functioning of agro ecosystem under different environmental conditions has a key role in developing ecological sound IPM program. Only then ecosystem can be manipulated to the detriment of the pests and/or in favour of natural enemies.
- Bioagents like parasitoids, predators and pathogens should be effective and farmer friendly component of IPM. The natural enemies should be thoroughly evaluated in the laboratory and screen house conditions for their adaptability to micro- and macro-environment. The field releases should be done only after thorough evaluation of crop phenology, pest ecology and behavior of natural enemies. The availability of effective natural enemies should be ensured.
- Genetic engineering has a place in IPM, but it should not be considered a panacea for solving all pest problems in the future. In the disturbed agro-ecosystem due to loss in biodiversity, as a result of excessive use of pesticides new pest problems emerged in the past. Genetically modified crops may also result in new pest problems or minor pests gaining status of major pests due to decline in use of insecticide. Many minor pests were controlled with the use of insecticide for management of key pests. Moreover, GM crops will provide management of one type of pest complex and management for other pest complex will redefine IPM strategy in GM crops. The best of traditional techniques should be exploited to maintain balance of arthropods and other fauna in agro ecosystems.
- Resistant varieties have many ecological advantages over those of insecticidal control as it conserves the population of beneficial insects and microorganisms thus strengthening natural control of pests in the agro ecosystem assuming that resistant varieties have minimal effects on natural enemies. The biodiversity is

maintained, which make the cropping system more stable, and can better withstand abiotic stresses, reducing the chance of pest outbreak.

- Botanical pesticides with multiple toxic, behavioral and physiological effects should find a place in IPM in order to reduce the synthetic pesticides. These chemicals have multiple actions including antifeedant, insect growth regulatory, and ovipositional deterrent effects. Botanical do not give immediate kill as pesticides but can be an important component of IPM when used at the right time. The plant allelochemicals can also be used for improving colonization by the natural enemies. It is, therefore, of utmost importance to study multi-trophic interactions involving host plants-pests-natural enemies.
- Most IPM study today focus mainly on insects, and insufficient attention is given to diseases, weeds and other organisms that damage the crops. Also, much of the IPM technology applies to a single pest/crop. Little information is available in the literature on IPM of weeds and diseases. A more holistic or ecosystem approach is necessary in future IPM programs (Dhaliwal et al., 1998).

2.7 Components of IPM

Pest management practices have a preventive character, or a curative effect. Therefore, one needs to learn the advantages and disadvantages of all components which might be applied in an IPM system in order to make an appropriate choice (Oudejans, 1991).

2.7.1 Cultural Control

Cultural and crop management practices provide means to manipulate the environment to make it less favorable for pests, while maintaining the best possible conditions for high productivity, thereby achieving economic control of pests or reducing their rate of increase and damage. These are the simple modification or adoption of regular farm practices and are the most important method for controlling pests and preventing crop losses. These control practices may not inflict direct mortality on pest species, but these practices more often are oriented at prevention of pest build up and outbreaks. They are effective component of IPM as these interventions does not eliminate pest thus help in conservation of natural enemies. Although cultural control is often associated only with mechanical methods such as tillage or burning, it involves many aspects of crop and soil management, crop rotation, time of planting and harvesting, trap cropping system diversification (Metcalf and Luckman, 1975; Luna and House, 1990). The timing of options is critical for success of these options and is major constraint in adoption of as component of IPM. Area wide adoption is another critical factor for success of these pest crop and area specific operations.

2.7.1.1 Crop Rotation and Intercropping

Crop rotation and intercropping increase and maintain the temporal and spatial diversity, respectively. These practices offer numerous advantages in soil structure, fertility and erosion management, as well as aiding in control of various pest species. The principle of rotating cropping pattern is to interrupt the specific relationship between pests and host plants which favours or limits the development of these damaging organisms (Oudejans, 1991). It is important that crops in rotation should be genetically different so that they do not have same pest complex and consists of a planting pattern alternating susceptible and non-susceptible crops. This practice does not have any economic or ecological disadvantage. Crop rotation plays a significant role in management of major soil pests as they have limited mobility. This approach seems to be most effective for soil pests like white grubs (Youm et al., 1996). Similarly white fringed weevil complex can be effectively managed by soybean (susceptible host)/maize rotation (Zehnder, 1997).

The growing of two or more crops on the same plot or field is a common practice in subsistence farming of many tropical countries. The inherent increase in biodiversity of multiple cropping system increases the quality and quantity of natural enemy complex (Altieri, 1994; Wratten and van Emden, 1995; Landis et al., 2000). The high biodiversity provide more stability to cropping ecosystem and make them more stable. The mixed planting of food crops, vegetables and fruit tree often provides relatively high yields owing to the optimum use of soil, nutrients, water, space and other factors (Oudejans, 1991). Inter-planting of trap crops reduces, on a large scale, the development of pests without giving them a chance to complete their life cycle because of resistance, or because the trap crop is destroyed by man to save the main crop.

2.7.1.2 Planting and Harvesting Dates

One of the oldest methods used to avoid excessive pest damage is manipulation of planting and harvesting dates. Planting before or after certain dates can disrupt synchronized crop-pest association and enable the plant to escape damage from pest during the susceptible growth stage. Many cotton insect pests, especially those that attack fruit, cause greater damage during later parts of the growing season. Therefore, the tactic of advancing the planting date on an area-wide basis has been quite successful in minimizing damage. In north India the cotton crop escapes the damage of *Helicoverpa armigera* by early planting of cotton (Dhawan, 1999). A classical example is the delayed planting of wheat as a mean of controlling the Hessian fly. The early harvest of alfalfa can often be used to control alfalfa weevil and potato leaf hopper (Luna, 1987). Sorghum planted during first half of May mature early and escapes the damage due to panicle inhibiting insects as compared to crop sown in June in Texas (Archer et al., 1990). Alteration of harvest date can also result in reducing the pest damage. Early termination of cotton crop helps in reducing the damage due to pink bollworm in north India (Dhawan, 1999).

2.7.1.3 Solarization and Phytosanitaion

Covering the soils with plastic sheets for the purpose of raising temperature and thereby killing noxious soil organisms is called solarization (Porter, 1992). Mulching with vegetative matter or polythene film (plastic) plays a very important role in reducing evaporation of soil and conservation of moisture which enhance the population of beneficial soil organisms and in suppressing weed growth (Oudejans, 1991). Phytosanitation includes measures aimed at the removal and destruction of infected plant material as the potential source from which the pest or disease could spread. Collecting or burning crop residue and stubble from the field removes many diapausing larvae, eggs and pathogens. Eradication of weeds deprives many noxious organisms of their intermediate hosts. Removal of weed in off season can reduce the incidence of cotton leaf curl virus, carryover of mealy bugs and spotted bollworm in cotton – wheat crop ecosystem (Dhawan, 1999; Dhawan et al., 2007). Furthermore, cleaning and disinfecting planting tools and machines, containers and soil, are necessary measures to prevent the spreading pathogens, nematodes and weeds.

Many regional specific agronomic practices like judicious use of fertilizers and irrigation water, plant spacing, soil tillage, seed rate etc are used as component of IPM.

2.7.2 Quarantine and Regulatory Control

New insect pests and diseases are often introduced from sources of infestation within or outside a country by the movement of people, commodities and equipment carrying the contaminant. Plants and plant products to be imported into a country must be free from pests and diseases; and plants with the potential of becoming weeds must be strictly prohibited. Quarantine and containment law or regulations, and other legislations, have been enacted and enforced in many countries to overcome this problem. Regulating the prohibition to grow certain trees, plants, or crops which are intermediate hosts to important insect pests or diseases of the economically most important crops of an area can help in reducing the damage. Governments are responsible for overseeing such regulatory control programs, which include eradication, containment, and suppression.

The plant quarantine regulations around the world aim at enforcing legal provisions on the movement of plants/plant materials between countries (Foreign quarantine) and between states within the country (Domestic quarantine) to check the infiltration/spread of exotic pests/diseases. Several quarantine measures to prevent the spread of insect pests and diseases across national boundaries are enacted but never implemented properly and new insect pests and diseases are introduced to new area. The Government of India enacted the "Destructive Insects and Pests Act" in 1914 (DIP Act 1914). Plants/plant materials are imported into the country as per regulations enshrined under "The Plants, Fruits, and Seeds" (Regulation of lmport into India) order, 1989 aiming at preventing the introduction of exotic insect pests/diseases and weeds into the country (Upadhyay et al., 1996a).

2.7.3 Biological Control

One of the most successful, non-chemical approaches to pest management is that of biological control which promotes the use of control agents, where the active principle is living organism or virus for regulating the incidence of insect pests or pathogens (Oudejans, 1991 and Upadhyay et al., 1996b). Biological control emphases the conservation of natural enemies, use of parasitoids (specific natural enemies), predators (non-specific natural enemies), the sterile male method, micro-organisms and sex attractants. Biocontrol through importation, augmentation and/or conservation of natural enemies can provide long term regulation of pest population. Crop ecosystem has numerous natural enemies which in nature feed upon, or infects insect pests, pathogens, and weeds. These organisms provide a significant level of "natural control", in many cases preventing many insect species from reaching pest status. The high level of human safety, stability of control and renewable nature, make biopesticides very attractive candidates for pest management (Jayaraj et al., 1994). The IPM should provide environmental conditions allowing the agro ecosystem to sponsor its own natural protection against pests (Altieri, 1994). However, the pest management interventions harmful to natural enemy complex result in increased losses due to pests with the use of more sophisticated pest management tools (Dhawan, 1999). The destruction of natural enemy populations by indiscriminate use of insecticides caused the emergence of minor pests as key pests due to the lack of natural control. Thus natural control is defined as the "suppression, maintenance or regulation of organisms by natural enemies sufficient to maintain pests below the action level (economically damaging levels)" also defined as inaction level by Fillman and Sterling (1985). The establishment of inaction levels for natural enemies is suggested as one of the first steps in optimizing pest management decision so that the impact of mortality factors that act on pests can be considered. Management decisions based solely on the abundance of pests can result in unneeded expenses for chemical insecticides and can harm the environment. Augmentations of natural enemies through rearing and mass release have been used extensively for pest control, including release of predatory phytoseid mites for control of spider mites in strawberries (Oatman et al., 1968), mass release of a coccinellid predator for control of avocado brown mite (McMurthy et al., 1969), and, control of bollworm and bud worm in cotton through release of green lacewing larvae (Ridgeway and Jones, 1969).

Biological control by means of entomopathogens and other microbial pest control agents involves the application of micro-organisms on the crop for ingestion by insect pest or directly on the noxious insects, fungus, or weed with the objective of destroying them. These biocontrol agents include bacteria, protozoa, fungi, viruses and nematodes. Although these microbials probably play an important role in pest control, their density is not generally monitored to assist in making pest management decisions. *Bacillus thuringiensis* and the nuclear polyhedrosis virus, applied to fields as insecticides, have been used in the management of *Heliothis* species in many areas of the world (Hoftman et al., 1992; Cherry et al., 2000). The major advantage of using microbial pathogens to control pests is that they inflict little or no harm to other natural enemies. Fungi have long been recognized as having the potential of killing insects. *Beauveria bassiana* is reportedly used in Russia for the control of Colorado potato beetles in fields (Lipa, 2008). A synergistic interaction between *B. bassiana*- and *B. thuringiensis tenebrionis*-based biopesticides applied against field populations of colorado potato beetle larvae was observed in potato as the maximum control was produced by combination of two products (Wraight and Ramos, 2005).

2.7.4 Host-Plant Resistance and Biotechnology

Host plant resistance is a vital component of IPM as this concept is environment friendly, compatible with other pest management tactics and provides inherent protection against insect pests. Many new resources of resistance to major pests have been identified and incorporated in high yielding varieties (Dhaliwal et al., 2004). Crop breeding and selection has been an important element in the evolution of agriculture since pre-historic times and the choice of cultivar probably is the single most important management decision the grower makes in an integrated crop management system. Resistant cultivars provide the cornerstone for a successful IPM system. Even those cultivars with low to moderate levels of resistance, are highly compatible with all other control tactics; they contribute to crop stability and offer several advantages to IPM. Host-plant resistance may either be a contributing factor, or the primary means, for controlling pests. Ecological and environmental benefits arise from increase in species diversity in crop ecosystem due to less use of insecticides. The main advantage of resistance varieties is compatibility with other options of pest management. The built in mechanism in resistant varieties function at the basic level and disrupt the normal association from the initial stage. Genetic resistance is more likely to be used in relation to other pest control measures, which include cultural, biological, and chemical approaches. Resistant cultivars may not require as many treatments or as high rates of pesticide application to achieve adequate pest control. This may result in reduced production costs, and thus increased profits. More than 500 cultivars resistant to crop pests of economic importance have been developed and grown in many countries and have proved to be ecologically and economically superior insect pest management tools in global agriculture for over 30 years (Chelliah and Uthamasamy, 1998). Genetic resistance is recognized as the most effective, economical, and reliable means of maintaining healthy plants and reducing crop losses.

Development and use of pest resistant varieties has a tremendous impact on global agricultural production. Recent advances in genetic engineering (Biotechnology) have raised hopes of greatly accelerating classical crop breeding efforts, as well as incorporating new resistance mechanisms. Transgenic cultivars are viable tool of pest management technology and therefore must be used within framework of IPM. Genetically-engineered pest resistance in crops could offer powerful economic and environmental incentives for large-scale adoption by growers. The need is to understand the interaction between transgenic crops, herbivores and natural enemy complex to use transgenic as main component of IPM. Adoption of Bt cotton as a component of IPM has drastically reduced the use of insecticide on cotton and provided better economic return to cotton growers as compared to pesticide dominated IPM strategies (Dhawan, 2004).

2.7.5 Pesticides

The insecticides have played and will continue to play a significant role in food security. Little doubt exists that insecticide use will increase further with the intensification of agriculture. Moreover, there is an increasing awareness among the farmers about the judicious use of insecticides. These control agents have been, currently are, and will continue to be the future basic tools in pest management. Pesticides are the effective option for pest management once the pest builds up on crop (Dhawan, 2001). But the judicious use can overcome the negative impact of pesticides such as resurgence of pests, development of resistance in insects, management of pesticides residue, conservation of natural enemy complex and biodiversity in crop ecosystem. Pesticides provide a dependable, rapid, effective, and economical means of controlling whole complexes of crop pests. The basis of using pesticides as pest management options and the consequences of misusing them be carefully analyzed in order to obtain maximum benefits from their application, while at the same time preventing and minimizing their possible hazardous effects on non-target organisms and the environment. The proper, restrained and further refined use of pesticides must be a major objective of any integrated pest management strategy in order to delay resistance and to avoid harmful interactions with biological control agents and the environment.

The need is to educate the farmers about the right crop protection technology. This can only be achieved with the active participation of industry. The coordination among scientist, government agencies, industry and farmers is essential. The pesticides are biological poisons and farmers in developing and under developed countries do not follow safety norms in handling of these toxic chemicals. The need of the hour is transformation from totally chemical-based farming practices to eco-friendly alternatives to reduce the dependence on expensive and hazardous chemical inputs. Pesticides industry, distributors, farmers and pesticide enforcement and regulatory agencies need to work together at various levels of pesticide production and use. Adoption of safety norms and effective pesticide stewardship practices would go a long way to preserve environment and prevent agricultural community from catastrophic situations.

2.7.6 Push-Pull Strategies

This strategy involves combination of behavior-modifying stimuli to manipulate the distribution and abundance of pest and/or beneficial insects for pest management

(Cook et al., 2007). The stimuli for "push" components is grouped on basis of visual or chemical cues, synthetic or plant- or insect-derived semiochemicals, These stimuli are usually used to affect host recognition and selection over a relatively long range (visual cues, synthetic repellents, non-host volatiles, host volatiles, anti-aggregation pheromones, and alarm pheromones) or shorter-range host acceptance (antifeedant, ovipositional deterrents, and deterring pheromones). The pests are repelled or deterred away from this resource (push) by using stimuli that mask host appearance or those are repellent or deterrent. The stimuli for "pull" components include visual stimulants, host volatiles, sex and aggregation pheromones, gustatory and ovipositional stimulants. The pests are simultaneously attracted (pull), using highly apparent and attractive stimuli, to other areas such as traps or trap crops where they are concentrated, facilitating their elimination (Cook et al., 2007).

2.8 Assessment of IPM

Based on the aim and goal of IPM program, the three main areas identified are: profitability, human health and environmental quality. Swinton and Williams (1998) reviewed the economic impact of IPM and laid emphases the development of simple indicators to assess the impact of IPM on human health and environment.

2.8.1 Expected Profit

Various measures of expected profit are used to assess the benefits of IPM. The IPM does not insist on eradication of pests but on keeping the pest densities below level that do not threaten the profitable production of agricultural commodities. Some studies use gross revenue minus the costs of IPM ("gross margin over pest management cost"), while others include additional production costs ("gross margin over variable costs" or "gross margin over specified costs"). Costs arising from the health impacts of pesticide use (Antle and Pingali, 1994; Pingali et al., 1994; Crissman et al., 1998) and expenditures to reduce exposure to pesticides (e.g., safety equipment; Harper and Zilberman, 1992), and variable production costs in addition to pest management costs (Boggess et al., 1985) should also be considered while working out the expected profits. One important profitability impact that has been omitted from many studies is the effect of pesticide management on development of pesticide resistance (Higley et al., 1992).

Most information-based IPM methods, select a pest management option measure based on expected pest damage which may be somewhat unpredictable. The three efficiency criteria applied in most of the cases includes first-degree stochastic dominance which ranks technologies according to profitability across many different production conditions; second-degree stochastic dominance, which ranks technologies according to profitability and outcomes under the least profitable conditions; and mean-variance dominance (Barry, 1984).

2.8.2 Environmental Impacts

Different criteria used to assess environmental impacts and risks include the quality of water, air, and soil, as well as the health of non-target species of mammals, birds, fish, insects, plants, and other life forms. Kovach et al. (1992), environmental impact quotient (EIQ) for pesticides, uses eight criteria in calculating the environmental components of the indices including dermal and chronic toxicity, toxicity to fish, bee, beneficial arthropod, soil and plant surface half life and systematicity. Mullen et al. (1997) use five separate criteria to characterize environmental risks from insecticides and herbicides in calculating their environmentally adjusted EILs. Teague et al. (1995) and Crissman et al. (1998) approach environmental risk assessment but they add site-specific criteria. Hoag and Hornsby (1992) developed a trade-off frontier for pesticide costs and a groundwater hazard index (GHI). The criteria used to develop the GHI include pesticide specific criteria and site-specific criteria that might affect the likelihood of contamination of groundwater by pesticides. Teague et al. (1995) compare the EIQ with environmental risk. Crissman et al. (1998) also included site-specific information on soil types and rainfall in their measure of pesticide leaching risk. Environmental impacts of IPM adoption are mainly related to use of pesticides. However, no weightage is given to class of pesticides used and is based on assumption that any pesticide use must harm the environment (Reichelderfer and Bender, 1979).

2.8.3 Human Health Impacts

Research on the human health of pest management has mostly focused on the acute toxicity of pesticides and pesticide exposure. Most studies dealing with health impacts used LD_{50} as acute toxicity risk estimates (Higley et al., 1992; Hoag and Hornsby, 1992; Kovach et al., 1992; Mullen et al., 1997; Penrose et al., 1994 and Teague et al., 1995). However, the risk of nonchemical pest management practices is not considered. Risk of pesticide exposure depends on movement in the environment (e.g. water, air, soil). The EIQ is a result of three separate calculations of likely risk and exposure for consumers, farm workers, and the environment. Harper and Zilberman (1992) divide worker health risks according to form of exposure to aerially sprayed pesticides (mixers/loaders vs. pilots vs. flaggers on the ground). Epidemiological research has begun to consider the chronic effects of pesticide exposure on carcinogenicity and the human neurologic, endocrine, immune, and reproductive systems and is focused largely on risk to farmers and pesticide applicators (Blair and White, 1985; Hoar et al., 1986; Blair et al., 1997; Zahm, 1997).

2.9 Impact of IPM in India – A Case Study

Integrated pest management programs are implemented by various agencies of Government of India, Ministry of Agriculture (Directorate of Plant Protection, Quarantine and Storage, and Indian Council of Agricultural Research) and state governments (Agricultural Universities for research, education and training activities and State Departments of Agriculture for extension work). Various objectives were defined during national five year plans to promote IPM in different crops. Based on the experiences gained through biocontrol program, survey and surveillance of insect pests, diseases, weeds and natural enemies and IPM demonstrations at farmer's field, IPM was adopted as the core of plant protection activities of during 1987–1992. During VIIIth plan (1992–93 to 1996–97), IPM gained a momentum and attained the status of social movement under the ambit of total crop production program, during 1992–1997, particularly with the help of externally aided projects sponsored by FAO, Asian Development Bank and UNDP.

The greater emphasis is being given to human resource development in IPM technology through rigorous field oriented training of state extension functionaries and farmers. These training programs included (i) residential training to master trainers through Season Long Training, (ii) training of agriculture extension officers and farmers through farmers' field schools and (iii) popularization of IPM practices among the farmers through conduct of lPM demonstrations. The field demonstrations of site specific IPM package of practices at the farmers' field to train farmers were key component of dissemination of technology among masses. Working group for agriculture principle has recommended for giving major emphasis to IPM under crop production program for the safety of human and environmental health as well as to restore biodiversity and to reduce cost of cultivation (Upadhyay et al., 1998). Introduction of IPM has brought the following changes in the approach and strategy of scientists, technocrats, farmers, and policy makers with regards to crop protection.

2.9.1 Policy Change

The government of India has withdrawn all kinds of subsidy and encouragement aimed for the enhanced use of pesticides. Instead, the government is promoting exploitation of natural biocontrol potential, use of resistant/tolerant varieties and cultural operations so as to minimize pesticide usage. This encourages the use of non chemical approach by providing subsides/demonstrating the use of biopesticides as component of IPM. Bio-control laboratories are set up in different states to promote the use of bio-agents for management of pests. Under National Horticulture Mission bio-agents are promoted as component of pest management strategies.

2.9.2 Awareness Towards Health of Environment and Man

Recent upsurge insecticide related social environmental and economic problems forced society at large and farmers and pest managers specifically, to relook and to rethink about their decision to use pesticide. Now, knowledgable progressive farmers in villages are aware of food chain getting contaminated with pesticides and their impact on human health. As a result, farmers have started taking utmost care while making pest management decision and go for pesticide use only when other options are already exhausted.

2.9.3 Decline in Pesticide Use

There is substantial reduction in pesticide consumption, which declined from 75033 metric tons (1990–91) to 61357 metric tons (1994–95). During 1995–96, the pesticides consumption is anticipated to be around 60,000 metric tons. In irrigated cotton belt the number of sprays declined from 20–25 to 8–12 with the adoption of insecticide resistance management technology and to 3–5 with use of Bt cotton as a component of IPM.

2.9.4 Banning of Hazardous Pesticides

More emphasis is given to the use of safe insecticide to conserve the natural enemies. The highly toxic chemicals are withdrawn from recommendation wherever alternative pest management options are available. Contamination of ecosystem with pesticides and associated hazards to human health, environment and deleterious effects on biocontrol agents inspired the government to ban already registered but most hazardous pesticides. Consequently 20 pesticides have already been banned, 18 pesticides have been refused registration, 25 are under review and 11 are allowed for restricted use only.

2.9.5 Promotion of Biopesticides

The liberal policy of registration of biopesticides encouraged the use of microbial pesticides and pesticides of plant origin in IPM. These are being popularized by the government and non-government organizations among farmers. Government has liberalized registration process while considering grant of registration to such pesticides. As a result, neem products, *Bacillus thuringiensis* and *B. sphaericus* have been granted registration. The provision of liberal funding for research and dissemination of biopesticides based IPM modules will help in the promotion of biopesticides as a component of IPM.

2.10 Constraints in IPM Implementation

IPM has been accepted in principle as the most attractive option for the protection of agricultural crops from the ravages of insect and non-insect pests. However, implementation at the farmers' level has been rather limited particularly in developing and under developed countries. The Consultant Group of the IPM Task Force has conducted an in-depth study of the constraints on the implementation of IPM in developing countries and this section is largely based on the Consultants' Report (NRI, 1992). The important constraints to wider adoption of IPM, and suggested measures to overcome them, are discussed below.

2.10.1 Institutional Constraints

Research on IPM is interdisciplinary and multi-functional approach to solve pest problems. Lack of coordination between disciplines, research, extension and implementation agencies is a major constraint in generation of adequate technical information and technologies. IPM programs lack the technology that meets the needs and capabilities of farmers. Secondly, both the national programs of developing countries and the donor agencies (National government, multilateral agencies and charitable organizations) have lacked a policy commitment to IPM in the context of national economic planning and agricultural development (Dhaliwal et al., 2004). This has resulted in a low priority for IPM from national government and donors alike. Thirdly, the research must be field oriented. Traditional top-down research in many cases does not address the real needs of farmers, who eventually are the end-users and who may adopt or reject the technology based on its appropriateness. Institutional barriers (formal, informal, environmental and skills) to research scientists in national programs conducting on-farm research in developing countries are real and need to be addressed.

2.10.2 Informational Constraints

The lack of IPM information with policy planners, the farmers and by extension workers is a major constraint in implementation. The information on various management options is well known but different strategies are rarely integrated. The gap in generation of technology and adoption by end users is very wide. Many a time when the information reaches farmers it has no relevance to current pest scenario. Lack of training materials, curricula and experienced teachers on the principles and practice of IPM is another major constraint. Human resource development should receive special consideration in IPM.

2.10.3 Sociological Constraints

The projection of pesticide as important tool of pest management during green revolution era as panacea for all pest problems advocated the misuse of insecticides. Chemicals are offered as first choice to farmers and extension workers by pesticide agency as effective and easy tool of pest management. This acts as a major constraint in IPM implementation. The industry's objective of more sales and the IPM message of rational pesticide use is a major hurdle in implementation of IPM. Development of resistance to bollworm complex in cotton to insecticides is the outcome of irrational use of insecticides in cotton. As a result of this farmer lost confidence in pest management options and was major constraint in implementation of IPM without effective pesticides as a component of IPM. There is a need for private industry, non government organizations and the extension agencies to work in a more complementary manner.

2.10.4 Economic Constraints

Funding of IPM programs is crucial and may come from external or national sources. Different agencies should collaborate in funding of IPM programs. Textile industry is the major beneficiary of IPM in cotton but do not contribute to research, extension and implementation of IPM in cotton. Another major constraint in implementation of IPM is the economic condition of farmers. Even if they have knowledge of IPM, they have no finance to adopt. They depend on private sector for inputs including the pesticides. Moreover, the funding for research, extension and implementation of IPM should be properly managed for an accelerated growth of IPM program. IPM programs may become self-generating in long term due to savings on resource inputs for production.

2.11 Measures for Improving IPM Implementation

Acceleration of IPM implementation in developing countries requires farmers' participation, increased government support, legislative measures, improved institutional infrastructure, and a favorable environment.

2.11.1 Farmer Participation

Farmers have developed many cultural, mechanical, and physical control practices for the protection of their crops from insect and non-insect pests (Smith et al., 1976). Farmers' are closely associated with the cultivation of crops and have excellent understanding of crop ecosystem, changing pest scenario and effective management practices. Farmers' innovations were the only source of improvements in crop production and protection technology until formal research by scientists started complementing it during the late 18th and 19th centuries (Harverskort et al., 1991). Unfortunately, with the advent of modern high-tech agriculture comprising high yielding varieties, inputs like fertilizers, water and pesticides, farmers have been completely displaced from the research and development process. Instead this role has been usurped by the private industry and government agencies. The technology generated by scientists is being transferred through the extension agencies to the farmers and there is wide gap in dissemination of technology. Improper adoption of new technology package has also created a number of ecological and environmental problems.

The sustainable agriculture requires farmers' participation at every step of the research and development process in order to evaluate the technology under local conditions and constraints. Farmers' innovativeness and skills can make the best possible use of limited resources. IPM can be successful by making the farmer a confident decision maker, free from dependence on a private profit making organizations. The threat to IPM is dependence of farmers on traders for agricultural inputs who guide them on the basis of business interest in developing and under developed countries. The role of researchers, extension and non-government organizations (NGOs) and field workers is to act as consultants, facilitators and collaborators, stimulating and empowering the farmers to analyze their own situation, to experiment and to make constructive choices. A number of terms have been proposed for the new approach. These include: "Farmer-first-and last", "farmer participatory research", "people-centered technology development (P-CTD)", transfer of technology (ToT), season long training (SLT) and "participatory technology development (PTD)" (Chambers et al., 1991; Harverskort et al., 1991). PTD serves to improve the experimental capacity of farmers and helps in the development of locally-adapted improved technologies. The approach has been used in the development of Farmers' Field Schools (FFS) in Indonesia, India and the Philippines. The FFS are designed to build up farmers' understanding of agro-ecological relationships and to improve their capacities to systematically observe, document, and interpret these.

2.11.2 Government Support

The government must address the IPM research, education and technology transfer of IPM in participatory mode. The strategy should involve policy and regulatory development and implementation with respect to pesticides and genetically modified crops, trade policy (including sanitary and phyto-sanitary issue) and IPM adoption. Both the national programs of developing countries and the donor agencies must have a policy commitment to IPM in the context of national economic planning and agricultural development. The conditions laid out by the FAO "Code of Conduct on the Regulation, Distribution, and Use of Pesticides" should be adopted. National policies to promote IPM require close regulation at all stages related to the importation and/or manufacture, distribution, use and disposal of pesticides. In case of pesticides that do not meet prescribed standards for safety, persistence, etc. import and manufacturing bans should be enacted. Sale of pesticide of highly toxic category should be regulated and subsidies need to be eliminated in order to make IPM an attractive alternative. National policy for monitoring the impact of pesticide and transgenic crop in ecosystem should be formulated. Similarly beneficiary of IPM programs should be encouraged to fund such program. The availability of good IPM technology and providing resources for adoption by the poor farmers should be the priority of developing and under developed countries. Additional monetary resources may be generated through cooperation with bilateral/multilateral agencies willing to support such programs (NRI, 1992).

2.11.3 Legislative Measure

IPM is an information system and its adoption reduces not only the pest control costs but also make the crop ecosystem more stable. The adoption of IPM program on wider area can further reduce the plant protection cost. The alternative to IPM is the indiscriminate use of broad spectrum synthetic organic pesticides. Unfortunately, while pesticide manufacturers and users (farmers) derive full benefits from the use of these chemicals, they pass on the environmental and ecological costs of their use to society as a whole. However, the long term negative effects will be passed on to the farmers as a result of which failure of crops may occur. In order to revive cultivations government has to subsidize the inputs. If they are made to bear the full cost of the use of these toxicants, they may find IPM a more economical and attractive alternative. This could be achieved by enforcing suitable legislative measures. The success of an IPM program in any geographical region depends upon its implementation at community level. A few farmers may voluntarily adopt an IPM program but still some farmers may hold out. Such farmers called "spoiler holdouts" may impair the success of a program by failing to adopt a necessary practice thus causing damage to adjacent areas. Besides these, some farmers may have a free-ride and thus shift the costs of implementing and managing a program to a group of participating farmers. To overcome "spoiler holdouts" and "free riders", it may be necessary to impose a program upon an unwilling minority through suitable legislative measures (Tarlock, 1980).

2.11.4 Improved Institutional Infrastructure

IPM cannot be implemented unless research findings are put into practice. The proper infrastructure for dissemination and validation of IPM technology is key to success. All the countries are adopting and implementing the concept of IPM. There is a basic infrastructure for plant protection in a country and there is a need to develop and support national program capabilities for on-farm dissemination, testing and technology extrapolation. At the international level, establishment of a Global IPM facility to coordinate and monitor funding of IPM projects is required to provide impetus to the implementation of IPM. With the fast changing pest scenario and awareness among consumers, IPM a predominantly knowledge based technology, the use of which requires training of all the groups involved. There is currently little scientific based quality training material for most of these groups including farmers, extension personnel, and researchers. If IPM is to become the major approach for pest management in the developing world, this deficiency must be remedied (NRI, 1992). Another aspect requiring greater attention is coordination of efforts within and among state, regional and national research, training and implementation institutes/programs, and amongst international development agencies. Due to the lack of coordination different agencies are operating in same region which many a time creates confusion among farmers. A reliable source of accurate information on the status of crops and pests in farmers' field is necessary for many IPM activities. Most of the successful IPM programs, both in developed and developing countries, have a reasonably accurate system of monitoring and evaluating various biological and environmental parameters in the agro ecosystem. A reliable data base on crop yield and pest losses is required for planning and resource allocation at the national and international level. The internet based pest management decision system needs to be evolved for faster and accurate transfer of information. The current use of this media lacks accuracy in dissemination of IPM technology. However, this can be an effective tool for passing basic information about the concept of IPM. The institution should look into the possibility of e-learning for faster transfer of technology.

2.11.5 Improved Awareness

Policy makers and planners need to be convinced that without IPM current agricultural production systems are not sustainable. Similarly, much important information that might induce a farmer to adopt IPM is not immediately observable and is, therefore, not sought by him/her. A manufacturer of pesticides has no incentive to recommend a program that propogates less amount of pesticide use, or even selective pesticides that kill a limited range of pests (Tarlock, 1980). Increased education and awareness regarding the objectives, techniques, and impact of IPM programs is required at all levels including policy makers, planners, farmers, consumers, and the general public. Pesticide and now biotech seed industry are utilizing the services of not only their salesmen but also agricultural scientists, administrators, and planners to promote their interest. Consumer groups and the general public may also be able to support the implementation of IPM programs by demanding residue-free commodities. There is now a distinct market for organically-produced food and other products. There is not yet a strong market for dissemination of IPM information.

2.12 New Challenges and Future Prospects

Integrated pest management has many challenges in future with the fast changing pest scenario and pest problems related with transgenic crops and sudden decline in use of insecticide in certain cropping systems. During the last two decades IPM has moved from a peripheral position to the central stage of agricultural production programs and the urgency of managing the pests by the use of integrated pest management. A variety of farmer friendly and easily adoptable techniques have been developed and refined for controlling different insect pests. Farmer-centered methods have resulted in successful implementation of IPM in rice in parts of South-east

Asia and cotton in India and South America. As agriculture is further intensified, insect and non-insect pest problems are expected to become more serious. Increased emphasis on IPM is the only sensible option under these conditions. IPM implementation faces a number of institutional, informational, socio-economic, and political constraints (NRI, 1992). These problems could be overcome by increased farmers' participation, government support, legislative measures, improved institutional infrastructure, creating greater awareness and use of the electronic media.

Crop losses from pests vary on an average between 30 and 45%, but can reach 100%. The value of pesticides in protection of crops can be questioned when it is noted that estimated percentage losses in food production attributed to pests are as great today as they were 50 years ago when organic pesticides began to be widely used. Further, it has been estimated that pesticide use could be reduced by 35–50% without decline in crop yields or causing an appreciable increase in the price of food (Pimentel, 1991). With increasing population pressure and need for more food from same area, pesticide will be important component of IPM. However, the safe and judicious use of pesticide will be the priority. In future and that greater reliance will be placed on biologically-based technologies. Nevertheless, without pesticides we could not produce certain crops economically. The pesticides debate will continue and pesticides will contribute to pest control for some time. Transgenic crops will alter the pest scenario and will pose greater challenge for validation of IPM technologies. Environmental issues are debated for use of pesticide and transgenic crops as dominant component of pest management. The scientist extension workers and policy planners must learn to work with farmers who have better understanding of their land and what is needed to improve. The future prospect and challenges of IPM are:

1. Emphasis should be placed on the development of pesticides that are active at lower doses, more specific for the target organisms, less toxic to the user, consumer, wildlife, biocontrol agents, and less persistent in the environment. Compatibility of pesticides with other pest management options should be improved. Pesticides must be integrated with other pest control technologies including genetic resistance in plants, cultural practices, biological control, and biotechnology. Pesticides must be integrated with other pest control technologies including genetic resistance in plants, cultural practices, biological control, and biotechnology. Continued improvements are needed in pesticide application technology and in methods to manage or prevent pesticide resistance in pests and misapplication of pesticides. Thresholds need to be revised and further exploration on the basis of biological, economical, or psychological considerations.
2. Research must continue on genetic approaches to pest resistance in plants, which is facilitated by preserving land races with better resistance gene pool as source of resistance, and biotechnology comprising of recombinant DNA technology. These techniques result in transgenic plants with resistance to viruses, insects, and herbicides. Transgenic crops are an alternative to pesticide dominated IPM and therefore it is imperative to use these on the basis of IPM principles.

3. Biological control is an emerging technology to control insect pests, diseases and weeds. Genetic engineering will play a vital role in production of transgenic biocontrol agents having biocontrol potential and ecological acceptability.
4. Integration of IPM must be done in the context of agro-ecosystem management. IPM and other forms of pest management were built on the pre-existing research basis. The challenge before us is to develop new science, new technology, new management skills and new concepts of integration in order to control plant pests, protect our environment and provide a continuous supply of safe and nutritious food in abundance for a rapidly expanding world population.
5. Digital technology and high speed telecommunication should be used to increase networking among scientist, institutions, extension workers and farmers. Knowledge based system on pest management should designed to improve IPM communication.

For the success of IPM, entomologists should work hand-in-hand with other agricultural scientists, environmentalists and farmers to develop and implement innovative IPM strategies targeted towards a sustainable crop production technology in the coming years.

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Chapter 3
Pesticides and Pest Control

David Pimentel

Abstract About 3 billion tons of pesticides are applied each year in the world. However, despite this large amount of pesticide applied worldwide, pests, insects, weeds and plant pathogens destroy about 40% of all crops.

Keywords Insects · Pests · Pesticides · Plant pathogens · Weeds

3.1 Introduction

From the beginning of agriculture about 10,000 years ago pests have been a major problem for crop production and continues today. In one sense food lost to pests is more critical today because there are 6.5 billion people on earth (PRB, 2006). In addition, nearly 60% of the world population is malnourished (WHO, 2007).

In the US prior to 1945, farmers were able to control some pests by using cultural methods such as crop rotation, tillage, and field sanitation. Only a few chemically based products such as lead arsenate, nicotine, rotenone, and pyrethrums were available for use on crops.

In 1945 with the development of DDT, 2,4-D, and later BHC, dieldrin, and other synthetic chemical pesticides, began a new era in chemical pest control. Initially, DDT and the other pesticides fulfilled their promise in pest control. The chemicals were easy to apply, fast acting and killed most target pests. Enthusiasm for these new chemical weapons was great, and their use spread rapidly throughout the US and the remainder of the world.

However, problems soon developed related to the effectiveness of DDT and other pesticides against insect pests. In addition, declines were noted in the numbers of some bird and fish populations. Within two years after the first use of DDT, resistance to the chemical was observed in houseflies and other insect pests (Pimentel et al., 1951). Over time, this resistance meant that more and higher

D. Pimentel (✉)
Department of Entomology, College of Agriculture and Life Sciences, Cornell University, Ithaca, New York, USA
e-mail: dp18@cornell.edu

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dosages of more insecticides had to be used to ensure control of the pests. In addition, not all pests were susceptible to the chlorinated insecticides. In the US today, resistance to pesticides costs the nation about $1.5 billion per year.

In addition to the resistance problem, several species of natural enemies were killed by these insecticides which allowed many previous non-pest species to increase in numbers and become serious pests themselves. For instance, pest mite species increased in apple orchards and other crops. As a result, apple trees turned brown from the heavy feeding of the mites and apple yields declined.

In addition to on-site crop problems caused by DDT and other insecticides, their impacts extended beyond the croplands and into the natural environments. Significant kills of sport fish and various birds, including the bald eagle were declining in numbers due to the heavy use of DDT and other insecticides. Concern heightened when milk and other foods were found to be heavily contaminated with insecticides, herbicides, and fungicides.

Then in 1972, the use of DDT and related chlorinated insecticides were banned in the United States. Production and use of pesticides continued, but many of the newer chemicals are extremely potent based on current dosages per hectare. Thus, while small amounts are applied per hectare, their toxicity is much greater than the earlier pesticides. In some cases the dosages of the newer pesticides are used at one/thousandth the dosage DDT and related chlorinated insecticides.

3.2 Crop Losses to Pests

Worldwide an estimated 70,000 different pest species damage agricultural crops. Included in this estimate are approximately 9,000 species of insects and mites, 50,000 species of plant pathogens, and 8000 species of weeds. In general, less than 10% of these organisms are considered major pests. In many instances, the insect and mite pests specific to a particular region have moved from feeding on native vegetation to feeding on crops which were introduced into the region (Pimentel, 1988; Hokkanen and Pimentel, 1989). Approximately 99% of the crops grown in most nations are introduced crops (Pimentel et al., 2005).

Despite the yearly investment of about $40 billion for the application of 3 million metric tons of pesticides worldwide (Table 3.1), in addition to the use of various biological and other non-chemical controls, between 35% and 42% of potential crop production is destroyed by pests (Pimentel, 1997). Worldwide, insect pests cause an estimated 14% loss, plant pathogens cause a 13% loss, and weeds a 13% loss. The value of this crop loss is estimated to be $2,000 billion per year, yet there is still about a $4 return per dollar invested in pesticide control.

In the United States, yearly crop losses caused by pests is nearly the same as the world figure or about 37% (13% = insects, 12% = plant pathogens, and 12% = weeds). In total, pests in the US are destroying an estimated $200 billion per year in food and fiber crops, despite all efforts to control them with pesticides and various non-chemical controls. Currently, the U.S. invests about $13 billion in pesticide

Table 3.1 Annual estimated pesticide use in the world

Country/region	Pesticide use 10^6 metric tons
United States	0.5
Canada	0.2
Europe	1.0
Other developed	0.5
China	0.2
Asia, developing	0.3
Latin America	0.2
Africa	0.1
Total	3.0

controls, which saves about $52 billion in crops per year. Biological and cultural controls also save an estimated $52 billion per year.

Without pesticides and non-chemical controls, the damage inflicted by pests would be more severe than it is at present. Oerke et al. (1994) estimated that crop losses would increase from about 40% to 70%. Such an increase would cause a significant economic loss and have negative impacts on world food supply. Similarly, estimates are that US crop losses would increase to about 63% along with significant economic losses.

Although pesticide use has increased over the past nearly six decades, US crop losses have not shown a concurrent decline, mainly because various changes have occurred in agricultural practices that encouraged pest outbreaks. According to survey data collected from 1942 to present, losses from weeds fluctuated, but declined only slightly from 13.8% to 12% (Pimentel, 1991). A combination of improved chemical, mechanical, and cultural weed control practices were responsible for the decline. Over the that same period, losses from plant pathogens, including nematodes, have increased slightly from 10.5% to about 12%. This happened, in part, because crop rotations were abandoned, field sanitation was reduced and more stringent cosmetic standards for many crops were implemented by the government, wholesalers and retailers.

Unfortunately, the share of crops lost to insects has nearly doubled from about 7% to 13% during the last 50 years (Pimentel et al., 1993), despite a more than 10-fold increase in both the amount and the toxicity of synthetic insecticides applied (Arrington, 1956; USBC, 1971, 1994). This increase in crop losses is associated with several major changes taking place in US agricultural practices. These include: the planting of some crop varieties that are more susceptible to insect pests than those planted previously; the destruction of natural enemies by insecticides that increased the need for added insecticides; resistance to insecticides developing in insect populations; reductions in crop rotations which increased insect pest populations; increased monocultures of crops and reduced crops diversity; lowering of Food and Drug Administration tolerances for insects and insect parts in foods; and the enforcement of more stringent “cosmetic Standards” by fruit and vegetable wholesalers, retailers, and processors; increased use of aircraft application technology; reduction in field sanitation, including less attention to the destruction of pest-infected fruit and crop residues; no-till and the leaving of crop residues on the surface of the land; culturing crops in climatic regions where they become more susceptible to insect attack; use of herbicides that alter the physiology of some crop plants that increases their attractiveness as a food for some insect pests.

Added to the damage pests inflict during the growing season are the substantial losses that occur during transport and storage of the crop prior to their use. Worldwide, an estimate of 25% food losses occur during transport and storage of crops due to microbes, insects, rodents, and birds. In the US, post harvest food losses to pests are estimated to be about 10%. Thus, despite all pesticide use and other non-chemical pest controls, we are losing from 50% to 60% of all potential food production to pests worldwide.

3.3 Worldwide Pesticide Impacts on the Environment and Public Health

Good data are lacking on the impact of pesticides on public health and the environment. An assessment was recently completed of the impacts of pesticides on the environment and public health in the United States and a copy of that study can be found in Chapter 4. For the public health impacts of pesticides worldwide, the best estimate is there are 26 million human pesticide poisonings with about 220,000 deaths per year (Richter, 2002). There are no estimates of deaths from cancer and depression of learning from being exposed to pesticides.

In our chapter on pesticide impacts in the US, I reported an estimate of 72 million bird kills in agriculture from pesticides annually. Worldwide, my estimate would be more than 800 million bird kills associated with pesticides applications to agricultural lands. Mammals, fish, and other animals are also being affected, but with the current limited data it would be difficult even to attempt a rough estimate of the impacts on other animals.

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Chapter 4
Environmental and Economic Costs of the Application of Pesticides Primarily in the United States

David Pimentel

Abstract An obvious need for an update and comprehensive study prompted this investigation of the complex environmental costs resulting from the nation's dependence on pesticides. Included in this assessment of an estimated $12 billion in environmental and societal damages are analysis of pesticide impacts on public health; livestock and livestock product losses; increased control expenses resulting from pesticide-related destruction of natural enemies and from the development of pesticide resistance in pests; crop pollination problems and honeybee losses; crop and crop product losses; bird, fish, and other wildlife losses; and governmental expenditures to reduce the environmental and social costs of the recommended application of pesticides. The major economic and environmental losses due to the application of pesticides in the USA were: public health, $1.1 billion year-1; pesticide resistance in pests, $1.5 billion; crop losses caused by pesticides, $1.1 billion; bird losses due to pesticides, $2.2 billion; and ground water contamination, $2.0 billion.

Keywords Agriculture · Costs · Crops · Environment · Livestock · Natural resources · Pesticide · Pesticide resistance · Public health

4.1 Introduction

Worldwide, about 3 billion kg of pesticides are applied each year with a purchase price of nearly $40 billion per year (Pan-UK, 2003). In the U.S., approximately 500 million kg of more than 600 different pesticide types are applied annually at a cost of $10 billion (Pimentel and Greiner, 1997).

D. Pimentel (✉)
Department of Entomology, College of Agriculture and Life Sciences, Cornell University, Ithaca, New York, USA
e-mail: dp18@cornell.edu

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Despite the widespread application of pesticides in the United States at recommended dosages, pests (insects, plant pathogens, and weeds) destroy 37% of all potential crops (Pimentel, 1997). Insects destroy 13%, plant pathogens 12%, and weeds 12%. In general, each dollar invested in pesticide control returns about $4 in protected crops (Pimentel, 1997).

Although pesticides are generally profitable in agriculture, their use does not always decrease crop losses. For example, despite the more than 10-fold increase in insecticide (organochlorines, organophosphates, and carbamates) use in the United States from 1945 to 2000, total crop losses from insect damage have nearly doubled from 7% to 13% (Pimentel et al., 1991). This rise in crop losses to insects is, in part, caused by changes in agricultural practices. For instance, the replacement of corn-crop rotations with the continuous production of corn on more than half of the corn acreage has nearly resulted in an increase in corn losses to insects from about 3.5% to 12% despite a more than 1,000-fold increase in insecticide (organophosphate) use in corn production (Pimentel et al., 1991). Corn today is the largest user of insecticides of any crop in the United States.

Most benefits of pesticides are based on the direct crop returns. Such assessments do not include the indirect environment and economic costs associated with the recommended application of pesticides in crops. To facilitate the development and implementation of a scientifically sound policy of pesticide use, these environmental and economic costs must be examined. For several decades, the U.S. Environmental Protection Agency pointed out the need for such a benefit/cost and risk investigation (EPA, 1977). Thus far, only a few scientific papers on this complex and difficult subject have been published.

4.2 Public Health Effects

4.2.1 Acute Poisonings

Human pesticide poisonings and illnesses are clearly the highest price paid for all pesticide use. The total number of pesticide poisonings in the United States is estimated to be 300,000 per year (EPA, 1992). Worldwide, the application of 3 million metric tons of pesticides results in more than 26 million cases of non-fatal pesticide poisonings (Richter, 2002). Of all the pesticide poisonings, about 3 million cases are hospitalized and there are approximately 220,000 fatalities and about 750,000 chronic illnesses every year (Hart and Pimentel, 2002).

4.2.2 Cancer and Other Chronic Effects

Ample evidence exists concerning the carcinogenic threat related to the use of pesticides. These major types of chronic health effects of pesticides include neurological effects, respiratory and reproductive effects, and cancer. There is some evidence that pesticides can cause sensory disturbances as well as cognitive effects such as memory loss, language problems, and learning impairment (Hart and Pimentel, 2002). The malady, organophosphate induced delayed poly-neuropathy (OPIDP), is well documented and includes irreversible neurological damage.

In addition to neurological effects, pesticides can have adverse effects on the respiratory and reproductive systems. For example, 15% of a group of professional pesticide applicators suffered asthma, chronic sinusitis, and/or chronic bronchitis (Weiner and Worth, 1972). Studies have also linked pesticides with reproductive effects. For example, some pesticides have been found to cause testicular dysfunction or sterility (Colborn et al., 1996). Sperm counts in males in Europe and the United States, for example, declined by about 50% between 1938 and 1990 (Carlsen et al., 1992). Currently, there is evidence that human sperm counts continue to decrease by about 2% per year (Pimentel and Hart, 2001).

The U.S. data indicate that 18% of all insecticides and 90% of all fungicides are carcinogenic (NAS, 1987). Several studies have shown that the risks of certain types of cancers are higher in some people, such as farm workers and pesticide applicators, who are often exposed to pesticides (Pimentel and Hart, 2001). Certain pesticides have been shown to induce tumors in laboratory animals and there is some evidence that suggest similar effects occur in humans (Colborn et al., 1996).

A UFW (2003) study of the cancer registry in California analyzed the incidence of cancer among Latino farm workers and reported that per year, if everyone in the U.S. had a similar rate of incidence, there would be 83,000 cases of cancer associated with pesticides in the U.S. The incidence of cancer in the U.S. population due to pesticides ranges from about 10,000 to 15,000 cases per year (Pimentel et al., 1997).

Many pesticides are also estrogenic – they mimic or interact with the hormone estrogen – linking them to increase in breast cancer among some women. The breast cancer rate rose from 1 in 20 in 1960 to 1 in 8 in 1995 (Colborn et al., 1996). As expected, there was a significant increase in pesticide use during that time period. Pesticides that interfere with the body's endocrine – hormonal – system can also have reproductive, immunological, or developmental effects (McCarthy, 1993). While endocrine disrupting pesticides may appear less dangerous because hormonal effects rarely result in acute poisonings, their effects on reproduction and development may prove to have far-reaching consequences (Colborn et al., 1996).

The negative health effects of pesticides can be far more significant in children than adults, for several reasons. First, children have higher metabolic rates than adults, and their ability to activate, detoxify, and excrete toxic pesticides differs from adults. Also, children consume more food than adults and thus can consume more pesticides per unit weight than adults. This problem is particularly significant for children because their brains are more than 5 times larger in proportion to their body weight than adult brains, making chloinesterase even more vital. In a California study, 40% of the children working in agricultural fields had blood cholinesterase levels below normal, a strong indication of organophosphate and carbamate pesticide poisoning (Repetto and Baliga, 1996). According to the EPA, babies and toddlers are 10 times more at risk for cancer than adults (Hebert, 2003).

Table 4.1 Estimated economic costs of human pesticide poisonings and other pesticide related illnesses in the United States each year

Human health effects from pesticides	Total costs ($)
Cost of hospitalized poisonings	
5000[a] × 3 days @ $2,000/day	30,000,000
Cost of outpatient treated poisonings	
30,000[c] × $1,000[b]	30,000,000
Lost work due to poisonings	
5,000[a] workers × 5 days × $80	2,000,000
Pesticide cancers	
10,000[c] × $100,000/case	1,000,000,000
Cost of fatalities	
45 accidental fatalities[a] × $3.7 million	166,500,000
Total	1,228,500,000

[a]Estimated.
[b]Includes hospitalization, foregone earnings, and transportation.
[c]See text for details.

Although no one can place a precise monetary value on a human life, the economic "costs" of human pesticide poisonings have been estimated (Table 4.1). For our assessment, we use the EPA standard of $3.7 million per human life (Kaiser, 2003). Available estimates suggest that human pesticide poisonings and related illnesses in the United States cost about $1 billion per year (Pimentel and Greiner, 1997).

4.2.3 Pesticide Residues in Food

The majority of foods purchased in super markets have detectable levels of pesticide residues. For instance, of several thousand samples of food, the overall the assessment in 8 fruits and 12 vegetables is that 73% have pesticide residues (Baker et al., 2003). In 5 crops (apples, peaches, pears, strawberries and celery) pesticide residues were found in 90% of the crops. Of interest is the fact that 37 different pesticides were detected in apples (Groth et al., 1999).

Up to 5% of the foods tested in 1997 contained pesticide residues that were above the FDA tolerance levels. Although these foods violated the U.S. tolerance of pesticide residues in foods, these same foods were consumed by the public. This is because the food samples were analyzed after the foods were sold in the super markets.

4.3 Domestic Animal Poisonings and Contaminated Products

In addition to pesticide problems that affect humans, several thousand domestic animals are accidentally poisoned by pesticides each year, with dogs and cats representing the largest number (Table 4.2). For example, of 250,000 poison cases involving

Table 4.2 Estimated domestic animal pesticide poisonings in the United States

Livestock	Number × 1000	$ per head	Number ill[e]	$ cost per poisoning[f]	$ cost of poison-ings	Number deaths[d]	$ cost of deaths × 1,000[g]	Total$ × 1,000
Cattle	99,000[a]	607[a]	100	121.40	12,140	8	4,856	16,996
Dairy cattle	10,000[a]	900[a]	10	180.00	1,800	1	900	2,700
Dogs	55,000[c]	125[h]	55	25.00	1,375	4	500	1,875
Horses	11,000[b]	1,000[c]	11	200.00	2,200	1	1,000	3,200
Cats	63,000[c]	20[h]	60	4.00	240	4	80	320
Swine	53,000[a]	66.30[a]	53	13.26	703	4	265	968
Chickens	8,000,000[a]	2.50[a]	6000	.40	2,400	500	1,250	3,650
Turkeys	280,000[a]	10[c]	280	2.00	560	25	250	810
Sheep	11,000[a]	82.40[a]	11	16.48	181	1	82	263
Total	8,582,000				21,599			30,782

[a] USDA (1989)
[b] Estimated
[c] USBC (1990)
[d] Based on a 0.008% mortality rate (see text).
[e] Based on a 0.1% illness rate (see text).
[f]Based on each animal illness costing 20% of total production value of that animal.
[g] The death of the animal equals the total value for that animal.
[h] Estimated.

animals, a large percentage of the cases were related to pesticides (National Animal Poison Control Centers, 2003). Poisonings of dogs and cats are common. This is not surprising because dogs and cats usually wander freely about the home and farm and therefore have greater opportunity to come into contact with pesticides than other domesticated animals.

The best estimates indicate that about 20% of the total monetary value of animal production, or about $4.2 billion, is lost to all animal illnesses, including pesticide poisonings. It is reported that 0.5% of animal illnesses and 0.04% of all animal deaths reported to a veterinary diagnostic laboratory were due to pesticide toxicosis. Thus, $21.3 and $8.8 million, respectively, are lost to pesticide poisonings (Table 4.2).

This estimate is considered low because it is based only on poisonings reported to veterinarians. Many animal deaths that occur in the home and on farms go undiagnosed and unreported. In addition, many are attributed to other factors than pesticides. Also, when a farm animal poisoning occurs and little can be done for the animal, the farmer seldom calls a veterinarian but, rather either waits for the animal to recover or destroys it. Such cases are usually unreported.

Additional economic losses occur when meat, milk, and eggs are contaminated with pesticide. In the United States, all animals slaughtered for human consumption, if shipped interstate, and all imported meat and poultry, must be inspected by the USDA. This is to insure that the meat and products are wholesome, properly labeled, and do not present a health hazard.

Pesticide residues are searched for in animals and their products. However, of the more than 600 pesticides in use now, the National Residue Program (NRP) only searches for about 40 different pesticides, which have been determined by FDA, EPA, and FSIS to be of public health concern. While the monitoring program records the number and type of violations, there might be little cost to the animal industry because the meat and other products are sometimes *sold and consumed by the public* before the test results are available. For example, about 3% of the chicken with illegal pesticide residues are sold in the market (NAS, 1987).

In addition to animal carcasses, pesticide-contaminated milk cannot be sold and must be disposed of. In some instances, these losses are substantial. For example, in Oahu, Hawaii, in 1982, 80% of the milk supply, worth more than $8.5 million, was condemned by the public health officials because it had been contaminated with the insecticide heptachlor (Baker et al., 2003). This incident had immediate and far-reaching effects on the entire milk industry on the island.

4.4 Destruction of Beneficial Natural Predators and Parasites

In both natural and agricultural ecosystems, many species, especially predators and parasites, control or help control plant feeding arthropod populations. Indeed, these natural beneficial species make it possible for ecosystems to remain "green." With the parasites and predators keeping plant feeding populations at low levels, only a relatively small amount of plant biomass is removed each growing season by arthropods (Hairston et al., 1960; Pimentel, 1988).

Like pest populations, beneficial natural enemies and biodiversity (predators and parasites) are adversely affected by pesticides (Pimentel et al., 1993a). For example, the following pests have reached outbreak levels in cotton and apple crops after the natural enemies were destroyed by pesticides: cotton = cotton bollworm, tobacco budworm, cotton aphid, spider mites, and cotton loopers; apples = European red mite, red-banded leafroller, San Jose scale, oyster shell scale, rosy apple aphid, wooly apple aphid, white apple aphid, two-spotted spider mite, and apple rust mite. Major pest outbreaks have also occurred in other crops. Also, because parasitic and predaceous insects often have complex searching and attack behaviors, sub-lethal insecticide dosages may alter this behavior and in this way disrupt effective biological controls.

Fungicides also can contribute to pest outbreaks when they reduce fungal pathogens that are naturally parasitic on many insects. For example, the use of benomyl reduces populations of entomopathogenic fungi, resulting in increased survival of velvet bean caterpillars and cabbage loopers in soybeans. This eventually leads to reduced soybean yields.

When outbreaks of secondary pests occur because their natural enemies are destroyed by pesticides, additional and sometimes more expensive pesticide treatments have to be made in efforts to sustain crop yields. This raises the overall costs and contributes to pesticide-related problems.

Table 4.3 Losses due to the destruction of beneficial natural enemies in U.S. crops ($ millions)

Crops	Total expenditures for insect control with pesticides[a]	Amount of added control costs
Cotton	320	160
Tobacco	5	1
Potatoes	31	8
Peanuts	18	2
Tomatoes	11	2
Onions	1	0.2
Apples	43	11
Cherries	2	1
Peaches	12	2
Grapes	3	1
Oranges	8	2
Grapefruit	5	1
Lemons	1	0.2
Nuts	160	16
Other	500	50
Total	$1,120	$257.4 ($520)[b]

[a]Pimentel et al. (1991)
[b]Because the added pesticide treatments do not provide as effective control as the natural enemies, we estimate that at least an additional $260 million in crops are lost to pests. Thus the total loss due to the destruction of natural enemies is estimated to be at least $520 million per year.

An estimated $520 million can be attributed to costs of additional pesticide application and increased crop losses, both of which follow the destruction of natural enemies by various pesticides applied to crops (Table 4.3).

As in the United States, natural enemies are being adversely affected by pesticides worldwide. Although no reliable estimate is available concerning the impact of this in terms of increased pesticide use and/or reduced crop yields, general observations by entomologists indicate that the impact of loss of natural enemies is severe where pesticides are heavily used in many parts of the world. For example, from 1980 to 1985 insecticide use in rice production in Indonesia drastically increased (Oka, 1991). This caused the destruction of beneficial natural enemies of the brown planthopper and this pest population exploded. Rice yield decreased to the extent that rice had to be imported into Indonesia. The estimated cost of rice loss in just a 2-year period was $1.5 billion (FAO, 1988).

After this incident, Dr. I.N. Oka, who had previously developed a successful low-insecticide program for rice pests in Indonesia, was consulted by the Indonesian President Suharto's staff to determine what should be done to rectify the situation. Oka's advice was to substantially reduce insecticide use and return to a sound "treat-when-necessary" program that protected the natural enemies. Following Oka's advice, President Suharto mandated in 1986 on television that 57 of 64 pesticides would be withdrawn from use on rice and sound pest management practices implemented. Pesticide subsidies were also reduced to zero. By 1991, pesticide applications had been reduced by 65% and rice yields increased 12%.

Dr. Rosen (Hebrew University of Jerusalem, PC. 1991) estimates that natural enemies account for up to 90% of the control of pests species in agroecosystems. I estimate that at least 50% of the control of pest species is due to natural enemies. Pesticides provide an additional control, while the remaining 40% is due to host-plant resistance in agroecosystems (Pimentel, 1988).

Parasites, predators and host-plant resistance are estimated to account for about 80% of the nonchemical control of pest arthropods and plant pathogens in crops (Pimentel et al., 1991). Many cultural controls, such as crop rotations, soil and water management, fertilizer management, planting time, crop-plant density, trap crops, polyculture, and others provide additional pest control. Together these non-pesticide controls can be used to effectively reduce U.S. pesticide use by more than 50% without any reduction in crop yields or cosmetic standards (Pimentel et al., 1993a).

4.5 Pesticide Resistance in Pests

In addition to destroying natural enemy populations, the extensive use of pesticides has often resulted in the development and evolution of pesticide resistance in insect pests, plant pathogens, and weeds. An early report by the United Nations Environmental Program (UNEP, 1979) suggested that pesticide resistance ranked as one of the top 4 environmental problems of the world. About 520 insect and mite species, a total of nearly 150 plant pathogen species, and about 273 weeds species are now resistant to pesticides (Stuart, 2003).

Increased pesticide resistance in pest populations frequently results in the need for several additional applications of the commonly used pesticides to maintain crop yields. These additional pesticide applications compound the problem by increasing environmental selection for resistance. Despite efforts to deal with the pesticide resistance problem, it continues to increase and spread to other species. A striking example of pesticide resistance occurred in northeastern Mexico and the Lower Rio Grande of Texas (NAS, 1975). Over time extremely high pesticide resistance had developed in the tobacco budworm population on cotton. Finally approximately 285,000 ha of cotton had to be abandoned, because the insecticides were totally ineffective because of the extreme resistance in the budworm. The economic and social impact on these Texan and Mexican farmers dependent on cotton was devastating.

The study by Carrasco-Tauber (1989) indicates the extent of costs associated with pesticide resistance. They reported a yearly loss of $45 to $120 per ha to pesticide resistance in California cotton. A total of 4.2 million hectares of cotton were harvested in 1984; thus, assuming a loss of $82.50 per hectare, approximately $348 million of the California cotton crop was lost to resistance. Since $3.6 billion of U.S. cotton was harvested in 1984 (USBC, 1990), the loss due to resistance for that year was approximately 10%. Assuming a 10% loss in other major crops that receive heavy pesticide treatments in the United States, crop losses due to pesticide resistance are estimated to be about $1.5 billion per year.

Furthermore, efforts to control resistant *Heliothus* spp. (corn ear worm) exact a cost on other crops when large, uncontrolled populations of *Heliothus* and other pests disperse onto other crops. In addition, the cotton aphid and the whitefly exploded as secondary cotton pests because of their resistance and their natural enemies' exposure to high concentrations of insecticides.

The total external cost attributed to the development of pesticide resistance is estimated to range between 10% and 25% of current pesticide treatment costs (Harper and Zilberman, 1990), or more than $1.5 billion each year in the United States. In other words, at least 10% of pesticide used in the U.S. is applied just to combat increased resistance that has developed in several pest species.

Although the costs of pesticide resistance are high in the United States, the costs in tropical developing countries are significantly greater, because pesticides are not only used to control agricultural pests, but are also vital for the control of arthropod disease vectors. One of the major costs of resistance in tropical countries is associated with malaria control. By 1985, the incidence of malaria in India after early pesticide use declined to about 2 million cases from a peak of 70 million cases. However, because mosquitoes developed resistance to pesticides, as did malarial parasites to drugs, the incidence of malaria in India has now exploded to about 60 million cases per year (Malaria, 2000). Problems are occurring not only in India but also in the rest of Asia, Africa, and South America. The total number of malaria cases in the world is now 2.4 billion (WHO, 1997).

4.6 Honeybee and Wild Bee Poisonings and Reduced Pollination

Honeybees and wild bees are vital for pollination of fruits, vegetable, and other crops. Bees are essential to the production of about one-third of U.S. and world crops. Their benefits to U.S. agriculture are estimated to be about $40 billion per year (Pimentel et al., 1997). Because most insecticides used in agriculture are toxic to bees, pesticides have a major impact on both honeybee and wild bee populations. D. Mayer (Washington State University, PC, 1990) estimates that approximately 20% of all honeybee colonies are adversely affected by pesticides. He includes the approximately 5% of U.S. honeybee colonies that are killed outright or die during winter because of pesticide exposure. Mayer calculates that the direct annual loss reaches $13.3 million per year (Table 4.4). Another 15% of the honeybee colonies either are seriously weakened by pesticides or suffer losses when apiculturists have to move colonies to avoid pesticide damage.

According to Mayer, the yearly estimated loss from partial honeybee kills, reduced honey production, plus the cost of moving colonies totals about $25.3 million per year. Also, as a result of heavy pesticide use on certain crops, beekeepers are excluded from 4 to 6 million ha of otherwise suitable apiary locations, according to Mayer. He estimates the yearly loss in potential honey production in these regions is about $27 million each year (Table 4.4).

Table 4.4 Estimated honeybee losses and pollination losses from honeybees and wild bees

Colony losses from pesticides	$13.3 million/year
Honey and wax losses	$25.3 million/year
Loss of potential honey production	$27.0 million/year
Bee rental for pollination	$ 8.0 million/year
Pollination losses	$210.0 million/year
Total	$283.6 million/year

In addition to these direct losses caused by the damage to honeybees and honey production, many crops are lost because of the lack of pollination. In California, for example, approximately 1 million colonies of honeybees are rented annually at $55 per colony to augment the natural pollination of almonds, alfalfa, melons, and other fruits and vegetables (Burgett, 2000). Since California produces nearly half of our bee-pollinated crops, the total cost for honeybee rental for the entire country is estimated at $40 million per year. Of this cost, I estimate that at least one-tenth or $4 million is attributed to the effects of pesticides (Table 4.4).

Estimates of annual agricultural losses due to the reduction in pollination caused by pesticides may be as high as $4 billion per year (J. Lockwood, University of Wyoming, PC, 1990). For most crops, both yield and quality are enhanced by effective pollination. Several investigators have demonstrated that for various cotton varieties, effective pollination by honeybees resulted in yield increases from 20% to 30%.

Mussen (1990) emphasizes that poor pollination will not only reduce crop yields, but equally important, it will reduce the quality of some crops, such as melon and fruits. In experiments with melons, E.L. Atkins (University of California [Davis], PC, 1990) reported that with adequate pollination melon yields increased 10% and melon quality was raised 25% as measured by the dollar value of the melon crop.

Based on the analysis of honeybee and related pollination losses from wild bees caused by pesticides, pollination losses attributed to pesticides are estimated to represent about 10% of pollinated crops and have a yearly cost of about $210 million per year (Table 4.4). Clearly, the available evidence confirms that the yearly cost of direct honeybee losses, together with reduced yields resulting from poor pollination, are significant.

4.7 Crop and Crop Product Losses

Basically, pesticides are applied to protect crops from pests in order to increase yields, but sometimes the crops are damaged by the pesticide treatments. This occurs when (1) the recommended dosages suppress crop growth, development, and yield; (2) pesticides drift from the targeted crop to damage adjacent crops; (3) residual herbicides either prevent chemical-sensitive crops from being planted; and/or (4) excessive pesticide residue accumulates on crops, necessitating the destruction of the harvest. Crop losses translate into financial losses for growers, distributors, wholesalers, transporters, retailers, food processors, and others. Potential profits as well as investments are lost. The costs of crop losses increase when the related costs of investigations, regulation, insurance, and litigation are added to the equation. Ultimately the consumer pays for these losses in higher market place prices.

Data on crop losses due to pesticides are difficult to obtain. Many losses are never reported to the state and federal agencies because the parties settle privately (Pimentel et al., 1993a).

Damage to crops may occur even when recommended dosages of herbicides and insecticides are applied to crops under normal environmental conditions. Recommended dosages of insecticides used on crops have been reported to suppress growth and yield in both cotton and strawberry crops (ICAITI, 1977; Reddy et al., 1987; Trumbel et al., 1988). The increase in susceptibility of some crops to insects and diseases following normal use of 2,4-D and other herbicides has been demonstrated (Oka and Pimentel, 1976; Pimentel, 1994). Furthermore, when weather and/or soil conditions are inappropriate for pesticide application, herbicide treatments may cause yield reductions ranging from 2% to 50% (Pimentel et al., 1993a).

Crops are lost when pesticides drift from the target crops to non-target crops located as much as several miles downwind (Barnes et al., 1987). Drift occurs with most methods of pesticide application including both ground and aerial equipment; the potential problem is greatest when pesticides are applied by aircraft. With aircraft from 50% to 75% of the pesticide applied never reaches the target acre (Akesson and Yates, 1984; Mazariegos, 1985; Pimentel et al., 1993a). In contrast, 10% to 35% of the pesticide applied with ground application equipment misses the target area (Hall, 1991). The most serious drift problems are caused by "speed sprayers" and ultra low volume (ULV) equipment, because relatively concentrated pesticide is applied. The concentrated pesticide has to be broken into small droplets to achieve adequate coverage.

Crop injury and subsequent loss due to drift are particularly common in areas planted with diverse crops. For example, in southwest Texas in 1983 and 1984, nearly $20 million in cotton was destroyed from drifting 2,4-D herbicide when adjacent wheat fields were aerially sprayed with the herbicide (Hanner, 1984). Because of the drift problem, most commercial applicators carry insurance that costs about $245 million per year (Pimentel et al., 1993a; Table 4.5).

Table 4.5 Estimated loss of crops and trees due to the use of pesticides

Impacts	Total costs (in millions of dollars)
Crop losses	136
Crop applicator insurance	245
Crops destroyed because of excess Pesticide contamination	1,000
Governmental investigations and testing	10
Total	$1,391

When residues of some herbicides persist in the soil, crops planted in rotation are sometimes injured. This has happened with a corn and soybean rotation. When atrazine or Sceptor herbicides were used in corn, the soybean crop planted after was seriously damaged by the herbicides that persist in the soil. This problem also has environmental problems associated. For example, if the herbicide treatment prevents another crop from being grown, soil erosion may be intensified (Pimentel et al., 1993a).

An average 0.1% loss in annual U.S. production of corn, soybeans, cotton, and wheat, which together account for about 90% of the herbicides and insecticides used in U.S. agriculture, was valued at $35.3 million in 1987 (NAS, 1989). Assuming that only one-third of the incidents involving crop losses due to pesticides are reported to authorities, the total value of all crop lost because of pesticides could be as high as 3 times this amount, or $106 million annually.

However, this $106 million does not take into account other crop losses, nor does it include major events such as the large-scale losses that have occurred in one season in Iowa ($25 to $30 million), in Texas ($20 million), and in California's aldicarb/watermelon crisis ($8 million) (Pimentel et al., 1993a). These recurrent losses alone represent an average of $30 million per year, raising the estimated average crop loss value from the use of pesticides to approximately $136 million each year.

Additional losses are incurred when food crops are disposed of because they exceed the FDA and EPA regulatory tolerances for pesticide residue levels. Assuming that all the crops and crop products that exceed the FDA and EPA regulatory tolerances (reported to be 1% to 5%) were disposed of as required by law, then about $1 billion in crops would be destroyed because of excessive pesticide contamination.

Special investigations and testing for pesticide contamination are estimated to cost the nation more than $10 million each year (Pimentel et al., 1993a).

4.8 Ground and Surface Water Contamination

Certain pesticides applied at recommended dosages to crops eventually end up in ground and surface waters. The 3 most common pesticides found in groundwater are aldicarb, alachlor, and atrazine (Cornell, 2003). Estimates are that nearly one-half of the groundwater and well water in the United States is or has the potential to be contaminated (Holmes et al., 1988; USGS, 1996). EPA (1990) reported that 10% of community wells and 4% of rural domestic wells have detectable levels of at least one pesticide of the 127 pesticides tested in a national survey. Estimated costs to sample and monitor well and groundwater for pesticide residues costs $1,100 per well per year (USGS, 1995). With 16 million wells in the U.S., the cost of monitoring all the wells for pesticides would cost $17.7 billion per year (Well-Owner, 2003).

Two major concerns about ground water contamination with pesticides are that about one-half the human population obtains its water from wells and once groundwater is contaminated, the pesticide residues remain for long periods of time. Not only are there extremely few microbes present in groundwater to degrade the pesticides, but the groundwater recharge rate is less than 1% per year (CEQ, 1980).

Monitoring pesticides in groundwater is only a portion of the total cost of groundwater contamination. There is also the high cost of cleanup. For instance, at the Rocky Mountain Arsenal near Denver, Colorado, the removal of pesticides from the groundwater and soil was estimated to cost approximately $2 billion. If all pesticide-contaminated groundwater were to be cleared of pesticides before human consumption, the cost would be about $500 million per year. Note the cleanup process requires a water survey to target the contaminated water for cleanup. Thus, addition the monitoring and cleaning costs, the total cost regarding pesticide-polluted groundwater is estimated to be about $2 billion annually. The $17.7 billion figure shows how impossible it would be to expect the public to pay for pesticide-free well water.

4.9 Fishery Losses

Pesticides are washed into aquatic ecosystems by water runoff and soil erosion. About 13 t/ha/yr are washed and/or blown from pesticide-treated cropland into adjacent locations including rivers and lakes (Unnevehr et al., 2003). Pesticides also can drift during application and contaminate aquatic systems. Some soluble pesticides are easily leached into streams and lakes.

Once in aquatic ecosystems, pesticides cause fishery losses in several ways. These include high pesticide concentrations in water that directly kill fish; low doses that may kill highly susceptible fish fry; or the elimination of essential fish foods, like insects and other invertebrates. In addition, because government safety restrictions ban the catching or sale of fish contaminated with pesticide residues, such fish are unmarketable and are an economic loss.

Only 6 to 14 million fish are reported killed by pesticides each year (Pimentel et al., 1993a). However, this is an underestimate because fish kills cannot be investigated quickly enough to determine accurately the cause of the kill. Also, if the fish are in fast-moving waters in rivers, the pesticides are diluted and/or the pesticides cannot be identified. Many fish sink to the bottom and cannot be counted.

The best estimate for the value of a fish is $10. This is based on EPA fining Coors Beer $10 per fish when they polluted a river (Barometer, 1991). Thus, the estimate of the value of fish killed each year is only $10 to $24 million per year. This is an under estimate and I estimate $100 million per year minimum.

4.10 Wild Birds and Mammals

Wild birds and mammals are damaged and destroyed by pesticides and these animals make excellent "indicator species". Deleterious effects on wildlife include death from the direct exposure to pesticides or secondary poisonings from consuming contaminated food; reduced survival, growth, and reproductive rates from exposure to sub-lethal dosages; and habitat reduction through the elimination of food resources and refuges. In the United States, approximately 3 kg of pesticide is applied per hectare on about 160 million hectares of cropland each year (Pimentel et al., 1993a). With such heavy dosages of pesticides applied, it is expected that wildlife would be significantly impacted.

The full extent of bird and mammal kills is difficult to determine because birds and mammals are often secretive, camouflaged, highly mobile, and live in dense grass, shrubs, and trees. Typical field studies of the effects of pesticides often obtain extremely low estimates of bird and mammal mortality (Mineau et al., 1999). This is because bird and small mammal carcasses disappear quickly, well before the dead birds and small mammals can be found and counted. Even when known numbers of bird carcasses were placed in identified locations in the field, from 62% to 92% of the animals disappeared overnight due to vertebrate and invertebrate scavengers (Balcomb, 1986). Then in addition, field studies seldom account for birds that die a distance from the treated areas. Finally, birds often hide and die in inconspicuous locations.

Nevertheless, many bird kills caused by pesticides have been reported. For instance, 1,200 Canada geese were killed in one wheat field that was sprayed with a 2:1 mixture of parathion and methyl parathion at a rate of 0.8 kg/ha (White et al., 1982). Carbofuran applied to alfalfa killed more than 5,000 ducks and geese in five incidents, while the same chemical applied to vegetable crops killed 1,400 ducks in a single application (Flickinger et al., 1980, 1991). Carbofuran is estimated to kill 1 to 2 million birds each year (EPA, 1989). Another pesticide, diazinon, applied to three golf courses killed 700 Atlantic brant geese of the wintering population of just 2,500 birds (Stone and Gradoni, 1985).

EPA reports that there are 1100 documented cases of bird kills each year in the United States (ABCBirds, 2003). Birds are not only killed in the U.S. but they are killed as they migrate from North America to South America. For example, more than 4,000 carcasses of Swainson's hawks were reported poisoned by pesticides in late 1995 and early 1996 in farm fields of Argentina (CWS, 2003). Although it was not possible to know the total kill, conservatively it was estimated to be more than 20,000 hawks.

Several studies report that the use of some herbicides has a negative impact on some young birds. Since the weeds would have harbored some insects in the crops, their nearly total elimination by herbicides is devastating to particular bird populations (Potts, 1986; R. Beiswenger, University of Wyoming, PC, 1990). This has led to significant reductions in the grey partridge in the United Kingdom and in the common pheasant in the United States. In the case of the partridge, population levels have decreased more than 77% because the partridge chicks (also pheasant chicks) depend on insects to supply them with needed protein for their development and survival.

Frequently the form of a pesticide influences its toxicity to wildlife (Hardy, 1990). For example, treated seed and insecticide granules, including carbofuran, fensulfothion, fonofos, and phorate, are particularly toxic to birds. Estimates are that from 0.23 to 1.5 birds per hectare were killed in Canada, while in the United States the estimates of kill ranged from 0.25 to 8.9 birds killed per hectare per year by the pesticides (Mineau, 1988). Pesticides also adversely affect the reproductive potential of many birds and mammals. Exposure of birds, especially predatory birds, to chlorinated insecticides has caused reproductive failure, sometimes attributed to eggshell thinning (Elliot et al., 1988). Most the affected predatory birds, like the bald eagle and peregrine falcon, have recovered since the banning of DDT and most other chlorinated insecticides in the U.S. (Unnevehr et al., 2003). Although the U.S. and most other developed countries have banned DDT and other chlorinated insecticides, other countries, such as India and China, are still producing, exporting, and using DDT (Asia Times, 2001).

Habitat alteration and destruction can be expected to reduce mammal and bird populations. For example, when glyphosphate (Roundup) was applied to forest clear cuts to eliminate low-growing vegetation, like shrubs and small trees, the southern red-backed vole population was greatly reduced because its food source and cover were practically eliminated (D'Anieri et al., 1987). Similar effects from herbicides have been reported on other mammals. Overall, the impacts of pesticides on mammal populations have been inadequately investigated.

Although the gross values for wildlife are not available, expenditures involving wildlife made by humans are one measure of the monetary value. Nonconsumptive users of wildlife spent an estimated $14.3 billion on their sport (USFWS, 1988). Yearly, U.S. bird watchers spend an estimated $600 million on their sport and an additional $500 million on birdseed, or a total of $1.1 billion (USFWS, 1988). For bird watching, the estimated cost is about 40¢ per bird. The money spent by hunters to harvest 5 million game birds was $1.1 billion, or approximately $216 per bird (USFWS, 1988). In addition, the estimated cost of replacing a bird of an affected species to the wild, as in the case of the Exxon Valdez oil spill, was $800 per bird (Dobbins, 1986).

If it is assumed that the damages that pesticides inflict on birds occur primarily on the 160 million ha of cropland that receive the most pesticide, and the bird population is estimated to be 4.4 birds per ha of cropland (Boutin et al., 1999), then 720 million birds are directly exposed to pesticides. Also, if it is conservatively estimated that only 10% of the bird population is killed by the pesticide treatments, it follows that the total number of birds killed is 72 million birds. Note this estimate is at the lower range of the range of 0.25 to 8.9 birds killed per hectare per year mentioned earlier.

The American Bald Eagle and other predatory birds suffered high mortalities because of DDT and other chlorinated insecticides. The Bald eagle population declined primarily because of pesticides and was placed on the endangered species list. After DDT and the other chlorinated insecticides were banned in 1972, it took nearly 30 years for the bird populations to recover. The American Bald Eagle was recently removed from the endangered species list (Millar, 1995).

I assumed a value of a bird to be about $30 based on the information presented, plus the fact that the cost of a fish is about $10, even a 1 inch fish. Thus, the total economic impact of pesticides on birds is estimated to be $2.1 billion per year. This estimate does not include the birds killed due to the death of one of the parents and in turn the deaths of the nestlings. It also does not include nestlings killed because they were fed contaminated arthropods and other foods.

4.11 Microbes and Invertebrates

Pesticides easily find their way into soils, where they may be toxic to arthropods, earthworms, fungi, bacteria, and protozoa. Small organisms are vital to ecosystems because they dominate both the structure and function of ecosystems (Pimentel et al., 1992).

For example, an estimated 4.5 tons per hectare of fungi and bacteria exist in the upper 15 cm of soil. They, with the arthropods, make up 95% of all species and 98% of the biomass (excluding vascular plants). The microbes are essential to proper functioning in the ecosystem, because they break down organic matter, enabling the vital chemical elements to be recycled (Atlas and Bartha, 1987; Pimentel et al., 1997). Equally important is their ability to "fix" nitrogen, making it available to plants and ecosystems (Pimentel et al., 1997).

Earthworms and insects aid in bringing new soil to the surface at a rate of up to 200 tons/ha per year (Pimentel et al., 1993a). This action improves soil formation and structure for plant growth and makes various nutrients more available for absorption by plants. The holes (up to 10,000 holes per square meter) in the soil made by earthworms and insects also facilitate the percolation of water into the soil (Edwards and Lofty, 1982).

Insecticides, fungicides, and herbicides reduce species diversity in the soil as well as the total biomass of these biota. Stringer and Lyons (1974) reported that where earthworms had been killed by pesticides, the leaves of apple trees accumulated on the surface of the soil and increased the incidence of scab in the orchards. Apple scab, a disease carried over from season to season on fallen leaves, is commonly treated with fungicides. Some fungicides, insecticides, and herbicides are toxic to earthworms, which would otherwise remove and recycle the fallen leaves.

On golf courses and other lawns, the destruction of earthworms by pesticides results in the accumulation of dead grass or thatch in the turf (Potter and Braman, 1991). To remove this thatch special equipment must be used and it is expensive.

Although these microbes and invertebrates are essential to the vital structure and function of both natural and agricultural ecosystems, it is impossible to place a money value on the damage caused by pesticides to this large group of organisms. To date, no relevant quantitative data on the value of microbe and invertebrate destruction by pesticides are available.

4.12 Government Funds for Pesticide Pollution Control

A major environmental cost associated with all pesticide use is the cost of carrying out state and federal regulatory actions, as well as pesticide-monitoring programs needed to control pesticide pollution. Specifically, these funds are spent to reduce the hazards of pesticides and to protect the integrity of the environment and public health.

About $10 million is spent each year by state and federal governments to train and register pesticide applicators. Also, more than $60 million is spent each year by the EPA to register and reregister pesticides. In addition, about $400 million is spent to monitor pesticide contamination of fruits, vegetables, grains, meat, milk, water, and other items for pesticide contamination. Thus, at least $470 million is invested by state and federal governmental organizations.

Although enormous amounts of government funds are being spent to reduce pesticide pollution, many costs of pesticides are not taken into account. Also, many serious environmental and social problems remain to be corrected by improved government policies.

4.13 Ethical and Moral Issues

Although pesticides provide about $40 billion per year in saved U.S. crops, the data of this analysis suggest that the environmental and social costs of pesticides to the nation total approximately $10 billion. From a strictly cost/benefit approach, it appears that pesticide use is beneficial. However, the nature of the environmental and public health costs of pesticides has other trade-offs involving environmental quality and public health.

One of these issues concerns the importance of public health vs. pest control. For example, assuming that pesticide-induced cancers number more than 10,000 cases per year and that pesticides return a net agricultural benefit of $32 billion per year, each case of cancer is "worth" $3.2 million in pest control. In other words, for every $3.2 million in pesticide benefits, one person falls victim to cancer. Social mechanisms and market economics provide these ratios, but they ignore basic ethics and values.

In addition, pesticide pollution of the global environment raises numerous other ethical questions. The environmental insult of pesticides has the potential to demonstrably disrupt entire ecosystems. All through history, humans have felt justified in removing forests, draining wetlands, and constructing highways and housing in various habitats. L. White (1967) has blamed the environmental crisis on religious teachings of mastery over nature. Whatever the origin, pesticides exemplify this attempt at mastery, and even a noneconomic analysis would question its justification. There is a clear need for a careful and comprehensive assessment of the environmental impacts of pesticides on agriculture and natural ecosystems.

In addition to the ethical status of ecological concerns are questions of economic distribution of costs. Although farmers spend about $10 billion per year for pesticides, little of the pollution costs that result are borne by them or the pesticide producing chemical companies. Rather, most of the costs are borne off-site by public illnesses and environmental destruction. Standards of social justice suggest that a more equitable allocation of responsibility is desirable.

These ethical issues do not have easy answers. Strong arguments can be made to support pesticide use based on social and economic benefits. However, evidence of these benefits should not cover up the public health and environmental problems. One goal should be to maximize the benefits while at the same time minimizing the health, environmental and social costs. A recent investigation pointed out that U.S. pesticide use could be reduced by one-half without any reduction in crop yields (Pimentel et al., 1993b). The judicious use of pesticides could reduce the environmental and social costs, while it benefits farmers economically in the short-term and supports sustainability of agriculture in the long-term.

Public concern over pesticide pollution confirms a national trend toward environmental values. Media emphasis on the issues and problems caused by pesticides has contributed to a heightened public awareness of ecological concerns. This awareness is encouraging research in sustainable agriculture and in nonchemical pest management.

Granted, substituting nonchemical pest controls in U.S. agriculture would be a major undertaking and would not be without its costs. The direct and indirect benefits and costs of implementation of a policy to reduce pesticide use should be researched in detail. Ideally, such a program should both enhance social equitability and promote public understanding of how to better protect public health and the environment, while abundant, safe food is supplied. Clearly, it is essential that the environmental and social costs and benefits of pesticide use be considered when future pest control programs are being considered and developed. Such costs and benefits should be given ethical and moral scrutiny before policies are implemented, so that sound, sustainable pest management practices are available to benefit farmers, society, and the environment.

4.14 Conclusion

An investment of about $10 billion in pesticide control each year saves approximately $40 billion in U.S. crops, based on direct costs and benefits. However, the indirect costs of pesticide use to the environment and public health need to be balanced against these benefits. Based on the available data, the environmental and public health costs of recommended pesticide use total more than $9 billion each year (Table 4.6). Users of pesticides pay directly only about $3 billion, which includes problems arising from pesticide resistance and destruction of natural enemies. Society eventually pays this $3 billion plus the remaining $9 billion in environmental and public health costs (13.6).

Table 4.6 Total estimated environmental and social costs from pesticide in the United States

Costs	Millions of $/year
Public health impacts	1, 140
Domestic animals deaths and contaminations	30
Loss of natural enemies	520
Cost of pesticide resistance	1, 500
Honeybee and pollination losses	334
Crop losses	1, 391
Fishery losses	100
Bird losses	2, 160
Groundwater contamination	2, 000
Government regulations to prevent damage	470
Total	9, 645

Our assessment of the environmental and health problems associated with pesticides was made more difficult by the complexity of the issues and the scarcity of data. For example, what is an acceptable monetary value for a human life lost or a cancer illness due to pesticides? Equally difficult is placing a monetary value on killed wild birds and other wildlife; on the dearth of invertebrates, or microbes lost; or on the price of contaminated food and groundwater.

In addition to the costs that cannot be accurately measured, there are many costs that were not included in the $12 billion figure. If the full environmental, public health and social costs could be measured as a whole, the total cost might be nearly double the $12 billion figure. Such a complete and long-term cost/benefit analysis of pesticide use would reduce the perceived profitability of pesticides.

The efforts of many scientists to devise ways to reduce pesticide use in crop production while still maintaining crop yields have helped but a great deal more needs to be done. Sweden, for example, has reduced pesticide use by 68% without reducing crop yields and/or the cosmetic standards (PCC, 2002). At the same time, public pesticide poisonings have been reduced 77%. It would be helpful, if the United States adopted a similar goal to that of Sweden. Unfortunately with some groups in the U.S., IPM is being used as a means of justifying pesticide use.

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Chapter 5
Economic and Ecological Externalities of Pesticide Use in India

P.K. Shetty and Marium Sabitha

Abstract India is among the largest agricultural societies in the world as the agricultural sector provides livelihood to the majority of its one billion people. Modern agriculture use inputs such as chemical fertilizers, pesticides, seeds of high yielding varieties and mechanization that aided in increased yields ushering an era of green revolution in the country. Synthetic pesticides are one of the major agro-inputs that significantly contributed to the agricultural production in the country. These chemicals have become an inevitable input and constitute an integral part of modern crop-management practices. Pesticides may have helped in enhancing agricultural production, but at the same time these chemicals have caused adverse effects. This paper discusses the economic and ecological implications of pesticide use in India.

Keywords Pesticide stewardship · Ecological implications · Crop-management · Integrated pest management

5.1 Introduction

India is among the largest agricultural societies in the world and since independence agricultural development is given top priority. The agricultural sector contributes nearly 26% of GDP and it provides livelihood to the majority of its one billion people. Even though India is growing in several other sectors such as IT, service sectors etc., India remains predominantly as a farming society. From an employment viewpoint, agriculture provides 115 to 130 million jobs, which is comparable to almost the entire employed population of the United States. According to Government of India Planning Commission report, 650 million Indians rely on agriculture, directly or indirectly for their livelihood (Landes and Govindan, 2004).

P.K. Shetty (✉)
School of Natural Sciences and Engineering, National Institute of Advanced Studies, Indian Institute of Science Campus, Bangalore 560 012, India
e-mail: pks@nias.iisc.ernet.in; pkshetty17@gmail.com

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Agricultural production has recorded remarkable growth over the past few decades. Food grain production increased from 62.5 million tons in 1965 to 209 million tons in 2004–2005. This increase is attributed to the adoption of modern farming techniques in India involving improved irrigation, high-yielding varieties, agrochemicals and farm mechanization. Even though these factors have contributed to the overall growth of agricultural production, studies point out that this may not be the case in future. The high yielding varieties are more demanding as their use increased the need for inputs such as irrigation, pesticides and fertilizers. Pressures on the agro-ecosystems are ever increasing from the overload of chemicals. The very agro-inputs, responsible for increasing agricultural production, are slowly showing signs of threats to environment, health and socio-economic well being of the community. Additionally, monoculture and continuous cultivation of improved varieties, overlapping of cropping seasons, and excessive application of agro-chemicals, have resulted in high incidences of insect pests and diseases in many parts of the country.

5.2 Pesticide Use in India

Indian pesticide market is the twelfth largest in the world with a value of US $0.6 billion, which is 1.6% of the global market. Western Europe and the USA are the world leaders with shares of about 30.2% and 22.7%, respectively. There is a boom in the global pesticide market as new insecticides, herbicides and fungicides and their formulations are being introduced with greater level of activity (TIFAC, 2004). The Indian pesticide industry has made remarkable progress having achieved the status of second largest basic pesticide manufacturers in Asia after Japan. TIFAC reported that there is encouraging developments in recent years, which include almost total self-reliance, with imports constituting less than 5% of total consumption, indigenous development of several new products and processes, and on penetration into overseas markets with exports of about Rs.1.5 billion (US $33 million, 1US $ = Rs. 45).

Pesticide consumption in India varies with the cropping pattern, intensity of insect pests and diseases and agro-ecological regions. The crop-wise and state-wise consumption of pesticides also vary considerably. Besides, since Indian agriculture is dominated by small farms, pesticides used by each of them may vary in quantity, quality and its effectiveness. This restricts one from getting a correct picture of the exact amount of pesticide used in the country. However, the overall pesticide consumption in India between 1955 and 2006 indicates that the use of pesticides remained quite high in the initial years of the green revolution, and reached a peak in the year 1988–89 (Fig. 5.1). Between 1988–89 and 2000–2001, there was significant decline in pesticides use from 75,418 to 43,584 tons. This decline began with the banning of a few organochlorine insecticides such as DDT and BHC for use in agriculture. After the Government of India decided to ban BHC in April 1997, an estimated 300,000 tons of BHC has been eliminated from use. BHC represented 30% of

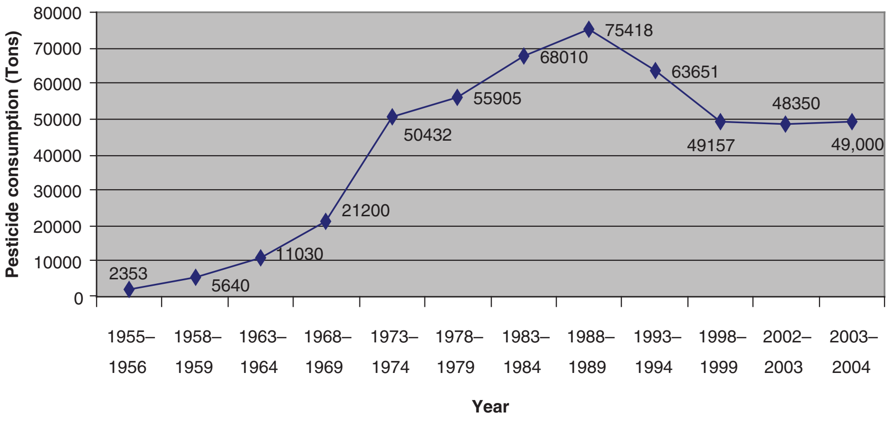

Fig. 5.1 Pesticide consumption pattern in India

India's total pesticide consumption. Another reason for the decline is probably due to the increased cost of pesticides following the removal of subsidies on them. However, the consumption of pesticides between 2001–2002 and 2003–2004 is showing a slight increase.

Plant protection chemicals currently cover about 30 percent of the total cultivated area in India (IIRD, 2001), wherein, insecticides account for 61.39%, followed by fungicides (19.06%), herbicides (16.75%) and others (2.80%). The trend in pesticide usage pattern is changing. For instance, from 1995 to 2001, herbicide usage has increased by almost 21%. However, consumption of insecticides, fungicides and other pesticides has decreased during this period (Table 5.1). In terms of value, Organophosphates dominate at 50% of total insecticide use followed by Synthetic Pyrethroids (19%), Organochlorines (16%), Carbamates (4%) and Biopesticides (1%). Pesticides such as Monocrotophos, Endosulfan, Phorate, Chlorpyriphos, Methyl Parathion, Quinalphos, Mancozeb, Paraquat, Butachlor, Isoproturon and Phosphamidon are still in use in India. Most of these harmful chemicals are replaced by much safer ones in the developed countries. India is moving gradually into the production and use of high performance low volume products as the R&D

Table 5.1 Percent change in pesticide (group-wise) use (tech. grade) from 1995–96 to 2000–01

	Pesticide use (in tons)		
Pesticide group	1995–96	2000–01	Percentage change
Insecticide	38,788	26,756 (61.39%)	−31.01
Fungicide	10,563	8,307 (19.06%)	−21.35
Herbicide	6,040	7,299 (16.75%)	+20.84
Others	5,869	1,222 (2.80%)	−79.17
Total	61,260	43,584	−28.85

Figures in parenthesis show consumption percentage of pesticide groups activities of the research laboratories and the pesticide manufacturers are yielding good results. Processes have been developed for several important products.

5.3 Important Crop Pests

While the pesticide usage pattern has changed over the years, agricultural pests have also undergone changes. For instance, the number of pests has increased in almost all the crops, existing pests have developed resistance and pest resurgence is a major problem in different crops and different agro-ecosystems. One of the important stumbling blocks for increasing productivity is the yield loss due to crop pests. It is essential to assess these losses quantitatively, in order to frame strategies to overcome them. The losses caused by individual pests are not distinguished from the whole pest complex as yield loss estimates vary depending on crop variety, density of pest population, time of pest attack in relation to crop stage (fruiting/pod bearing stage) and cultural practices followed.

A survey carried out during the 1950s revealed that fruits, cotton, rice and sugarcane suffered significant yield losses due to insect pests (Pradhan, 1964). Introduction of high yielding varieties and agro inputs during the green revolution period increased the productivity of land with a concomitant increase in the proportion lost to insect pests in India and other developing countries in Asia (Dhaliwal and Arora, 1994). Trend of crop losses between the 1950s and 1994 showed that the crop loss in paddy and cotton respectively increased from 10% to 25% (accounting for 150% increase) and 18% to 50% (accounting for 178% increase). Similarly, there was a significant increase in crop loss in maize, sugarcane and millets (Fig. 5.2).

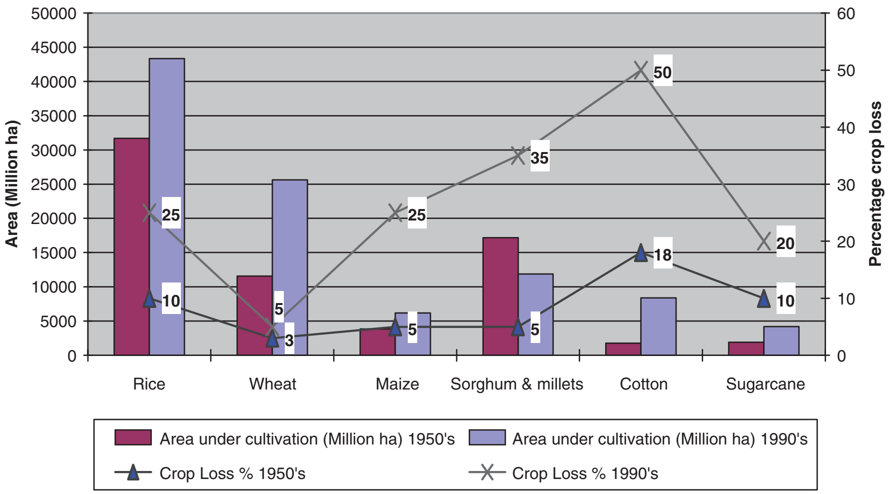

Fig. 5.2 Area vs crop loss due to insect pests in India

A study by Reddy and Zehr (2004) indicates that during the last 15 years, the periodical unabated explosions of aphids, whiteflies, bollworms, pod borers, defoliators, coccids, cutworms, plant hoppers etc., and now mealy bug on cotton as direct crop damagers and disease transmitters in different regions of the country have made agriculture less profitable and highly risk prone (Table 5.2). Many insect species have developed resistance and there are more than 500 insect and mite species that are immune to one or more insecticides. Similarly, about 150 plant pathogens such as fungus and bacteria are shielded against fungicides. Some of the herbicides found effective earlier now fail to control weeds.

Table 5.2 Major pests and percentages of crop loss in India

Crop	Major pests	Percentage crop loss
Rice	Stem borer (*Scirpophaga incertulas*)	10–48
	Leaf folder (*Cnaphalocrocis medinalis*)	10–50
	Whorl maggot (*Hydrellia* spp)	20–30
	Gall midge (*Orseolia oryzae*)	8–50
	Hispa (*Dicladispa armigera*)	6– 5
Wheat	Ghujia weevil (*Tanymecus indicus*)	NA*
	Army worm (*Mythimna separata*)	20–42
Pigeonpea	Pod borer (*Helicoverpa armigera*)	14–100
	Pod webber (*Maruca testulalis*)	20–60
	Pod fly (*Melanagromyza obtusa*)	10–60
Sunflower	Capitulum borer (*Helicoverpa armigera*)	30–60
Cotton	Spotted bollworm (*Earias vittella*)	30–40
	American bollworm (*Helicoverpa armigera*)	20–80
	Pink bollworm (*Pectinophora gossypiella*)	20–95
	Tobacco caterpillar (*Spodoptera litura*)	NA
Cabbage	Diamond back moth (*Plutella xylostella*)	20–52
	Cabbage webber (*Crocidolomia binotalis*)	NA
	Cabbage borer (*Hendula undalis*)	NA
Cauliflower	Diamond back moth (*Plutella xylostella*)	20–52
Okra	Shoot and fruit borer (*Earias vittella*)	NA
	Fruit borer (*Helicoverpa armigera*)	NA
Brinjal	Shoot and Fruit borer (*Leucinodes orbonalis*)	25–92
	Stem borer (*Euzophera perticella*)	NA
Chilli	Fruit borer (*Helicoverpa armigera*)	NA
	Fruit borer (*Spodoptera litura*)	NA

NA* = Not available
Source: Reddy and Zehr, 2004

Insects are a major problem in agriculture as these are acquiring resistance and incidences of resurgence are increasing especially in areas where pesticides are extensively used. The losses caused by insect pests like *Spodoptera, Helicoverpa*, whitefly and aphids are so enormous that farmers use insecticides excessively and as a result disturb the ecological balance. The current annual loss due to insect pests and diseases in agricultural sector in India is around Rs. 150 billion

(US $3.3 billion) and in addition over 20 million man days are lost due to the vector borne diseases (TIFAC, 2004).

5.4 Pesticide Use and its Implications: World Scenario

Global pesticide use has also been a major issue in the agricultural world. According to the EPA estimates, world pesticide expenditures totaled more than $32.5 billion in 2001. Among all the pesticides, the expenditures on herbicides accounted for the largest portion of total expenditures – more than 40%, followed by expenditures on insecticides, fungicides, and other pesticides, respectively (Fishel, 2007). Though awareness of impacts of pesticides has been growing since the green revolution period, it has become a cause of concern in most part of the world. Estimates also suggest that pesticide used exceeded 5.0 billion pounds in 2000 and 2001 in the world. Herbicides accounted for the largest portion of total use, followed by insecticide, and fungicide use (EPA, 2007).

One of the reasons for the increasing use of pesticides is that, these chemicals are the final inputs for any crop cultivation. Farmers invest on land, seeds, labor and fertilizers and finally on pesticides. Pesticides are the final input in the agricultural operation, which protects all the other inputs, when considerable investment is already done. Hence they put in their full potential to save the crops from insect pests and diseases. While pesticides have helped farmers to save crops, its indiscriminate use has created ecological, economic, social and health problems in the different parts of the world.

Occupational and environmental exposures to pesticides cause a range of human health problems. Estimates suggest that approximately 10,000 deaths annually are attributed to use of chemical pesticides worldwide, with about three fourths of these occurring in developing countries (Horrigan et al., 2002). Additionally, it is important to consider external costs due to pesticide use such as damage to the health of consumers, contamination of water sources, damage to off-farm beneficial organisms such as reptiles, fish, pollinators, etc., increase of pest resistance, loss of biodiversity and contribution to global loads of persistent pollutants in the environment (Fleischer, 2004).

5.5 Pesticide Use and its Implications in India

5.5.1 Ecological Implications

Tremendous benefits have been derived from the use of pesticides in forestry, public health and the domestic sphere – and, of course, in agricultural sector. The evidence accumulated over the last few decades point out that the use of such chemicals in agriculture has much greater health and environmental consequences. Pesticide use in crop production has been a major contributor to environmental pollution.

There are problems directly linked with the basic resources of air, water and soil pollution. Besides, problems directly related to the biological counter parts are also enormous. These include loss of crop, wild plant, and animal genetic resources, elimination of natural enemies of pests, pest resurgence and genetic resistance to pesticides, chemical contamination, and the complete destruction of natural control mechanisms (Conway and Pretty, 1991).

Continual and liberal use of pesticides has disturbing consequences on agro-ecosystems and human health. One of the important pesticide-induced problems is the development of resistance by the insect pests. Pesticide resistance is a dynamic phenomenon dependent on biochemical, physiological, genetic and ecological factors (Mehrotra, 1992). Resistance development is higher with pests having shorter lifecycles (Agnihotri et al., 1999). The use of insecticides over a long period has resulted in the development of cross-resistance in insect pests. When an insect develops resistance to a particular insecticide, it automatically becomes resistant to all the other insecticides having the same target or activity.

Globally, about 504 insects and mites, 150 plant pathogens and 273 weeds are known to have developed resistance. Large-scale and repeated application of pesticides over a long period in different parts of the country for the control of BPH in paddy, Helicoverpa in cotton and DBM in vegetables have led to the development of resistance in these pests. Defective spraying and over-dosages coupled with spraying of spurious insecticides have also aggravated the problem of pest resistance. To overcome this problem, farmers apply more than the optimum dose and also resort to unscientific combinations of pesticides. Sequential application of pesticides from different chemical groups and also adopting integrated pest management (IPM) practices are some viable techniques for managing the problem of resistance.

Resurgence is yet another problem faced by farmers. It is an abnormal increase in pest population often exceeding the economic threshold level, following the insecticide application. Resurgence of pests occurs in two ways (1) rapid resurgence of pest populations exposed to the pesticide, and (2) minor pests or unimportant target species developing into major pests as a result of decreased competition for food and shelter (Dudani, 1999). The phenomenon of resurgence of insect pests has resulted in serious economic loss in crops like cotton and rice. The loss due to bollworm is estimated at around 50–60% in cotton, and loss from BPH is estimated to be 10–70% on paddy (Puri et al., 1999). This is mainly due to excessive use of agrochemicals, particularly nitrogenous fertilisers, which enhances the vegetative growth of the host plants, thereby harbouring numerous insect pests.

Use of pesticides over a long period has resulted in the decline of the natural enemies of pests, which is one of the reasons for resurgence of insect pests. The large-scale use of broad-spectrum pesticides for the suppression of cotton bollworm led to the mortality of the natural enemies of the insect pest and resulted in the resurgence of cotton bollworm in 1977, 1983, 1993 and 1997 (Dhawan, 1999). In addition, unpredicted or delayed rains and other changes in climatic conditions are also identified as causes for the resurgence of insect pests. It was reported that application of sub-lethal doses of insecticides brings about changes in reproductive cycles of the insect pests leading to their resurgence (Chelliah, 1979).

Pesticides are potent poisons and have an adverse effect on any organism having physiological functions similar to the target organism. Some pesticides have greater detrimental effect on non-target organisms than on target organisms. With the present pesticide use pattern, the sustenance of non-target organisms, especially the beneficial organisms, natural enemies of pests, parasites and pollinators are greatly jeopardised. Pesticides that reach water bodies as runoff kill fish, water bugs, snails and aquatic plants, which are a part of the food web and play an important role in maintaining eco-balance. Some of the major socio-ecological concerns among small and marginal farmers include the declining population of beneficial organisms, natural enemies of pests and also the increased expenditure on synthetic pesticides (Shetty, 2003).

5.5.2 Social and Economic Implications

In many developing countries like India, incentives for pesticide use often conflict with efforts to ensure the rational and safe use of plant protection chemicals. It is difficult to assess the impact of pesticides on health in developing countries because of lack of data, non-availability of hospitals and monitoring facilities. However, there are several studies that show pesticides can cause health problems, such as birth defects, nerve damage, cancer, and other effects that might occur over a long period of time. These problems are magnified because of the socio-economic conditions prevalent in these countries. The following are some of the examples of these conditions: the lack of access to clean water for drinking; absence of medical facilities or access to antidotes; lack of training; shortage of technical and cultural controls to minimize pesticide hazards; inability to afford protective clothing or equipment; high rates of illiteracy and inability to read complex label instructions; labels not written in a user-friendly language; the virtual impossibility of wearing protective clothing in hot and humid climates; mixing of hazardous active ingredients by hand; and reuse of containers for food or water storage (Dinham, 1996).

The World Health Organization (WHO) has estimated about three million acute cases of pesticide poisoning and as many as 20,000 unintentional deaths occur each year, primarily in developing countries (WHO, 1990). A WHO study indicated that three percent of agricultural workers in developing countries suffered a poisoning incident each year, resulting in 25 million occupational poisonings (Jeyaratnam, 1990). Farmers take short-term assessments of pesticide use. In the process, they put their efforts to maximize the net returns by minimizing the crop losses. They take into account the money saved from preventing crop loss versus the cost of pesticide and other farm resources required for pesticide application. Unfortunately, important factors such as the health risks involved, loss of money spent on health care, loss of labor due to sickness, decreasing efficiency of work, long-term health effects of pesticides and downstream effects are not given equal attention. Studies in the USA and Philippines have shown that farmers spend as much money on health care as they do on pesticides themselves (Pimentel et al., 1993; Rola and Pingali, 1993). Further, the harmful effects of pesticides in the form of residues in food and the environment is also aggravating day-by-day. The external costs incurred due to illnesses due to pesticide residues are a major cause of concern.

There is now overwhelming evidence that some of these chemicals do pose potential risk to humans and other life forms and unwanted side effects to the environment (Forget, 1993; Igbedioh, 1991; Jeyaratnam, 1985). No segment of the population is completely protected against exposure to pesticides and its serious health effects (WHO, 1990). No agency regularly monitors pesticide residues in market samples or undertakes diet basket surveys to assess actual exposure of consumers from pesticide residues in food or water and project the health risk, if any. Such activity comes under the purview of Ministry of Health but no comprehensive regular monitoring program is being conducted in India (JPC Report, 2004).

To analyse the possible side effects of pesticide use on human health, a distinction has to be made between occupational health hazards and pesticide residues in food products and drinking water. Meeting the minimum requirements of occupational health standards is regarded as one of the elements of sustainable agricultural development. Apart from a limited number of case studies, there are no countrywide statistics on the extent of poisoning of farmers due to pesticide application. At least four reasons are responsible for this. (1) Farmers seek medical attention only in cases of serious health problems due to the costs involved. (2) Most of the farmers are not aware of the specific symptoms of pesticide poisoning, so health workers are not informed and therefore cannot draw the right conclusions. (3) The system of health statistics does not clearly specify cases of poisoning. (4) In many cases of poisoning or death no further investigations are done due to the lack of technical facilities for autopsies.

WHO has classified chemical pesticides into four different groups based on (lethal dose) LD_{50} values. The LD_{50} value is a statistical estimate of the toxicity in terms of milligram of toxicant/kg of the body weight required to kill 50 percent of a large population of test animals. Of the main class of insecticides used, organophosphorous compounds are the most hazardous and affect the nervous system. Organochlorines are highly persistent in nature, and most of these are banned in India, but there is illegal marketing of banned pesticides, like DDT for agricultural purposes in different parts of the country.

The well-known controversy in the village Padre in Kasaragod district of North Kerala is an example of far more destructive impacts of aerial spray of endosulfan. Several studies conducted in this region say that endosulfan spraying on cashew trees has affected the people in the village causing serious health problems. Additionally, children of that area have been perplexed with very high incidence of central nervous system disorders such as cerebral palsy, mental and/or physical retardation, epilepsy and congenital abnormalities like stag horn limbs. There are also reports of increase in blood and liver cancer, infertility, un-descended testis, miscarriages, menstrual irregularities, skin disorders, asthma, etc. Psychiatric problems and suicidal tendencies have also been rising (Punjabilok).

Making an assessment of health hazards related to pesticide use in agricultural production raises some difficulties. On one hand, if poisoning cases do occur, it is difficult to identify beyond doubt a specific pesticide as the source of poisoning.

On the other hand, many poisoning cases are never reported to a doctor and will therefore never appear in the official occupational poisoning statistics. Interestingly, in the pesticide use predominant areas it was observed that record on serious pesticide poisoning cases were available in a few Government hospitals, but such details were not accessible from private hospitals as pesticide poisoning are medico-legal cases. Many were hesitant to share information on pesticide poisoning and deaths in these regions. The Poison Information Centre in National Institute of Occupational Health (NIOH), Ahmedabad reported that organophosphate (OP) compounds were responsible for the maximum number of poisoning (73%) among all agricultural pesticides (Dewan and Saiyed, 1998). In a study on patients of acute OP poisoning ($N = 190$), muscarinic manifestations such as vomiting (96%), nausea (82%), miosis (64%), excessive salivation (61%), and blurred vision (54%) and CNS manifestations such as giddiness (93%), headache (84%), disturbances in consciousness (44%) were the major presenting symptoms (Agarwal, 1993). Cardiac manifestations such as sinus tachycardia (25%), sinus bradycardia (6%) and depression of ST segments with T wave inversion (6%) were also observed. The incidence of intermediate syndrome in cases of OP poisoning has also been reported (Samuel et al., 1995; Shailesh et al., 1994). There were number of reports from northern India on the abuse of aluminium phosphide, a grain preservative taken for self-poisoning (Saraswat et al., 1985; Singh et al., 1985; Raman et al., 1991).

In human beings, the pesticide residue level is an index of exposure, which may be acute, occupational or incidental. In acute exposure, the residue level has a diagnostic potential, and in the occupationally exposed, the residue level merits an insight reflective of industrial exposure. However, in the general population, the residue level is a measure of the incidental exposure and/or average levels of the persistent pesticides, which is mainly through the food chain. Residues of OC insecticides, especially DDT and HCH have been detected in man and his environment the world over (Hayes and Laws, 1991; Jensen, 1983). However, by comparison very high levels of these pesticides have been reported in human blood, fat, and milk samples in India (ICMR, 2001).

Consumers may be affected by relatively low doses of pesticide residues in drinking water and through food products (long-term effects) or acutely through high doses caused by misuse, wrong application or overdose at the farm level. Different groups and segments of a population are exposed to pesticides in different ways and to different degrees. These are intentional (suicides and homicides) and unintentional exposures (occupational and non-occupational exposure to the pesticide-affected water, air and food). The occupational hazards in industrial settings and the ecological repercussions in the environment could be grouped as under: (i) Operational hazards, which arise during production and formulation of pesticides in industrial settings and their distribution and use in field conditions. (ii) Direct toxic effects on non-target animal life such as pollinators, predators and wild life during application of pesticides. (iii) Post application hazards or indirect toxic effects which involve risk to non-target animals due to toxic residues of pesticides in food or due to pollution of the ecosystem and habitat as a whole, such as water bodies or soil (ICMR, 2001).

5.6 Stewardship Initiatives

It is a well-known fact that pesticide use cannot be stopped overnight. However, till the time pesticides are being used, good stewardship practices can help to reduce its harmful implications for health and environment. Good practice begins at the point of analyzing the pest problem and identifying the right approach for the problem. In many cases chemical pesticides will be a favoured option, but consideration should be given to alternative strategies. If pesticide use is unavoidable, it is important that the products purchased for use are of acceptable quality, are correctly packaged and labeled. Besides, it is also important that the end users are well trained in safe use practices (Pesticide Action Network, 1998a).

In developing countries like India pesticides are often used under conditions, which generate or exacerbate the hazards to health and the environment. These conditions include: lack of protective clothing, poor quality spray equipment, lack of training, inappropriate or inadequate advice, illiteracy or poor literacy, labels not in local languages, lack of water for washing after spraying, and for regular washing of clothes and inaccessible medical facilities (Pesticide Action Network, 1998b). End user protection must be given top priority. The risk to small-scale farmers and agricultural workers is high. It is also important for users to wear appropriate clothing, masks, gloves and boots while handling harmful chemicals. Risk is at the peak during mixing and loading where good measuring devices are of at most importance. Risk is magnified with the use of poor quality spray equipment, lack of protective clothing and use by untrained operators.

It is important to follow stewardship practices such as pesticide drift management and triple rinse procedure before disposal of pesticide containers, which is followed in developed nations like UK and US. In those regions where pesticides will continue to be used, investment in the ability to use them safely and effectively has to be taken into account as part of the cost of the products. The farmers have little knowledge of better pest management, and this gap in knowledge must be filled up. It is very essential for all the stakeholders including industry, government, farming community and the public to share a responsibility to protect health and the environment during all phases of pesticide handling, use and storage.

There is a growing demand for organic foods in India. According to a study conducted by Food and Agriculture Organisation (FAO) in mid-2003, India had 1,426 certified organic farms producing about 14,000 tons of organic food/produce annually. Government of India statistics of the year 2005 reports that approximately 190,000 acres were under organic cultivation and the total production of organic food in India as per the same reference was 120,000 tons annually. This also largely included certified forest collections. India has tremendous potential for organic farming in 65% of non-irrigated cropped areas as in these regions high-input driven crops are rarely grown for obvious reasons. These non-chemical farms can be converted easily into an organic one providing excellent yields and without the necessity and effort of a lengthy conversion period which will be required for chemical farms (Satavic Farms, 2006).

Integrated Pest Management (IPM) has been defined by the FAO International Code of Conduct on the Distribution and Use of Pesticides, as an economically viable, environmentally sound and socially acceptable approach to crop protection. It is an important component of sustainable agriculture. IPM is an approach to pest management based on ecologically sustainable control measures, which are cost effective and safe for the farmer and consumer.

IPM has been promoted as an alternative pest control strategy in India since the 1960s. Adoption of some of the successful IPM programs in recent years has produced many economic benefits. These include lowering the cost of cultivation and improving ecological sustainability by conserving natural enemies of pests. IPM is knowledge intensive, takes time, money and one needs to have patience to see the results. Currently, only 1% of 143 million hectares of cropped area and about 2500 villages out of over 6 lakhs villages in India have been covered under IPM (Singh and Sharma, 2004). This indicates the efforts required to promote IPM and also the magnitude of investment of time and finances that would be required to train more than 125 million cultivators in IPM (Anonymous, 2002). With sustained efforts by Government and non-governmental organizations, between 1996–97 and 2001–02 consumption of bio-pesticides such as *neem* and *Bacillus thuringiensis* increased from 0.39 percent to 1.88 percent (Table 5.3).

The Government of India promoted the IPM in the mid 80s, as an eco-friendly strategy of pest containment by utilizing natural control agents and forces in harmony with other pest management practices. IPM was adopted as a national policy in 1995 and it was implemented as large-scale demonstrations cum training in farmer fields in a wide range of crops including cotton. In 1994–95 the Government withdrew the subsidy on pesticides to facilitate promotion of IPM. In India, 26 central IPM centres have been established in various states for pest surveillance and monitoring, promotion of bio-control methods of conservation, promotion of non-chemical methods of pest control, and training of extension workers and farmers.

During 1994–95 and 2001–02, the Government of India spent nearly Rs. 14,926 million (US $ 331.68 million) for biocontrol of pests on different crops, covering a land area of 4.3 million hectares. Besides, an additional amount of Rs. 59 million (US $ 1.3 million) was spent for pest monitoring (Table 5.4). Some States such as Madhya Pradesh, Maharashtra, Uttar Pradesh, Andhra Pradesh, Punjab and Karnataka, rank highest in accomplishing IPM. As a result during this period, there was significant reduction in the consumption of synthetic pesticides in the country

Table 5.3 Consumption of pesticides and bio-pesticides in India

	Pesticide in tons	Bio-pesticide in tons	Percentage of bio-pesticide
1996–97	56,114	219	0.39
1997–98	52,239	395	0.75
1998–99	49,157	482	1.00
1999–00	46,195	874	1.89
2000–01	43,584	683	1.56
2001–02	47,929	902	1.88

Table 5.4 IPM In India: Accomplishments during 1994–95 to 2001–02

Status	Amount spent on pest monitoring (Million US$)	Biocontrol		Training & demonstration on IPM		
		Area coverage (million ha)	Release (Million US$)	Number of FFSs	AEOs trained	Farmers trained
Achievement	1.31	4.26	331.68	7 257	30 381	219 141
Target	1.20	3.85	311.11	7 620	37 560	224 960

Note: FFSs: Farmer's field schools. AEOs: Agriculture extension officers
1US$ = Rupees 45

from 61,357 MT (Tech. Grade) to 47,929 MT (Tech. Grade). Various steps taken by the Government of India to promote the usage of biopesticides include encouraging farmers, local entrepreneurs, NGOs in production of biopesticides; simplification of the guidelines for registration of biopesticides; provision of assistance as grants-in-aid for research, development, and production; provision of grants-in-aid provided to the States for infrastructural development for production of biocontrol agents and biopesticides; and allowing commercialisation of biopesticides during the validity of provisional registration for two years.

It is extremely important to ensure the availability of trained extension workers to promote this approach at village level. In farmer participatory systems, farmers are trained through Farmers' Field Schools (FFSs) to enable them to analyse the situation in the field as the key decision-maker in pest management. Between 1994 and 2001, approximately 1.38 million manpower resources were created with the efforts of Government in IPM and these included, master trainers, extension functionaries, farmers, women farmers and NGOs (Prasad, 2001).

Successful IPM modules are available for a few important crops and the farmers are responding positively for these initiatives. For instance, farmers in a remote village Ashta located in the Nanded district of Maharashtra took the advantages of IPM on cotton. Ashta earned the tag of 'Bollworm free village' by virtue of collective participation of farmers in implementing IPM practices, easy availability of quality components and also effective dissemination of information. Many farmers are practicing subsistence farming of coarse cereals, millets, pulses and green vegetables in the country. As there is not much emphasis given to pest management, there is very little use of pesticides in subsistence farming. Enhancement of food production and security will be possible if these crops are brought under IPM umbrella (Shetty, 2004). IPM modules were also developed for *Bt* cotton, for example, in a collaborative study conducted in the Nanded district, highest yields and economic gains were recorded to farmers using IPM when compared to non-IPM farmers (Bambawale et al., 2004). Similarly, the strategies for insecticide resistance management (IRM) were successfully implemented and accepted in a large number of villages in Maharashtra, Andhra Pradesh, Punjab and Tamilnadu. The IRM strategies place emphasis on efficient use of insecticides to conserve the ecosystem for better pest management. These have been extensively tested for 4–5 years in hundreds of acres and were found to reduce insecticide use by 50–90% with increases in yield by 10–25% (Kranthi, 2004).

Implementation of IPM practices in developing countries like India requires increased farmers' participation, government support, improved institutional infrastructure and a coordinated effort among farmers, researchers, policy makers, industries and non-governmental organizations. Establishment of IPM units at village level will help to monitor crop pests on a day-to-day basis and also to provide information about the economic threshold level. Unemployed educated youths need to be encouraged to participate in IPM activities and to produce IPM inputs at the village level by providing necessary assistance and training. In addition, it is important to encourage NGOs, self help groups, women's organizations, *Panchayat Raj* institutions etc. in promoting IPM. Government needs to ensure appropriate private sector participation in promoting the IPM by providing necessary incentives.

Utilization of Information Technology could be helpful in evolving more efficient dynamic agricultural systems in the country. This would include dissemination of information regarding latest developments in identifying insect pests, diseases and natural enemies, pest management, updated information on pest monitoring and disease forecasting, availability of biocontrol agents, successful IPM packages and access to online database on IPM. Besides, IPM program can also be promoted through recently introduced toll free *Kisan* Call centers.

Over a period of time, pesticide companies have established excellent market network and gained the confidence of farmers. These companies can play a vital role in promoting IPM through their involvement in the supply, production and marketing of eco-friendly inputs. Furthermore, success in IPM depends on full participation and co-operation of farmers and they need to be trained as the key decision makers in pest management. Currently, several IPM packages are available for major crops and farmers are responding positively to these initiatives. Mass adoption of IPM programs needs pro-active policies from Governments, participation of crop protection industry and training of extension personnel and farmers.

Green revolution aided by the seeds that respond well to large doses of inorganic fertiliser and chemical pesticides supported the agricultural growth in most of the countries. Unfortunately these new seed varieties have displaced a wide range of traditional seeds, which in other words eroded the crop biodiversity. In the recent years there is also mounting evidence of, and growing concern with, other ecological problems, such as increasing soil infertility, chemical pollution of land and water resources, pesticide poisoning, and pest infestation due to growing pest resistance to pesticides and resurgences. It is important to understand that these are not *ad hoc* problems, but symptoms of gradual failure of the green revolution technological system. It is high time that we adopt sustainable approaches such as organic farming, integrated pest and disease management and the emerging field of biotechnology.

5.7 Conclusion

Good pesticide management practices are essential to minimize the negative effects of these toxic chemicals on the environment, health and socio-economic well being of the community. No single central agency undertakes post registration monitoring of pesticide use in India. Developed countries such as the United Kingdom have post registration monitoring which has been a legal requirement since 1985 and it helps to study the long-term impact and actual trend in the use of these chemicals. In India, though pre-registration requirements (testing of chemical before introduction in the market) are mandatory, post registration studies have not gained much importance. The pre-registration studies are done for a limited period of time and cannot be used to predict the long-term impact of these chemicals. In addition, the individual crop-wise and chemical-wise consumption data of pesticide up to district level is yet to be established. This means we do not know the exact pattern of pesticide usage. Hence, it is important to take adequate steps for pre and post registration monitoring.

Although several alternative strategies continue to evolve in pest management, pesticides will continue to be used in agriculture in the near future. Hence, there is an urgent need for proper control on their use through good stewardship practices. It is essential for all the stakeholders, including industry, government, the farming community and the public to share the responsibility to protect public health and the environment during all phases of pesticide production and its use.

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Chapter 6
Advances in Crop Protection Practices for the Environmental Sustainability of Cropping Systems

W.G. Dilantha Fernando, Rajesh Ramarathnam and S. Nakkeeran

Abstract The era of green revolution has witnessed a tremendous change in the outlook of agriculture development. Green revolution emphasized the increased availability of food grains through the use of high yielding varieties, plant protection measures, and application of increased dosage of synthetic fertilizers, coupled with irrigation management. It not only increased the food grain production but also the utilization of synthetic fertilizers and pesticides. Over-reliance on the use of pesticides during green revolution has resulted in environmental pollution, ground water contamination, resurgence of pests, and poisoning of food sources, animals and human beings. Extensive application of fertilizers has changed the soil properties and acts as a major barrier in sustainable agriculture production. Farmers and agro-based industries could thrive only through the technological innovation that goes in harmony with IPM practices. Several advances have been made in the research and implementation of control strategies for the management of pests and diseases, which could be integrated into a sustainable agricultural system. The chapter focuses on these advances in various control measures and gives an account of various successful IPM programs from around the world. The success of any IPM program would depend on the understanding and acceptance from the farmers, and the integrated approach needed in form of policy making, communication and networking from the governmental and non-governmental agencies. The policy makers have to be advised to allocate budget for the extensive training, motivation of farmers and promotion of IPM through the establishment of IPM networks. Restructuring, both research and policy issues, will pave way for sustainable agriculture production through IPM.

Keywords Biological control · Bacteria · Fungi · Plant diseases · Antibiotics · IPM

W.G.D. Fernando (✉)
Department of Plant Science, University of Manitoba, Winnipeg, MB R3T 2N2, Canada
e-mail: D_Fernando@Umanitoba.ca

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6.1 Introduction

Agriculture development over years has witnessed a marvelous change after the inception of green revolution. Green revolution ensured the increased availability of food grains through the use of high yielding varieties, plant protection measures, application of increased dosage of synthetic fertilizers coupled with irrigation management. With the introduction of improved technologies, the food production has outstripped population growth in the last few decades and continues to grow. Besides the increased productivity, the improved technologies resulted in the increased consumption of synthetic fertilizers and pesticides. In developing countries like India, agricultural statistics emphasized that the consumption of pesticides before green revolution was around 2330 MT, however the same during green revolution in the 1960s increased to 75,000 MT (Raghunathan, 2005). Expenditure on pesticides in U.S. agriculture increased eight-fold from 1950 to 1999 to $8.8 billion (in year-2000 dollars). Pesticide expenditures rose from 1.6% to 7.5% of total purchased inputs. This increase was widespread across crops and regions (United States Department of Agriculture, Economic Research Service, 2001) much had become a mainstay in many countries. Over reliance on the use of pesticides has resulted in environmental pollution, ground water contamination, and development of resurgence in pests, and poisoning of food material, animals and human beings. In addition, it also affected the agricultural trade where several agricultural commodities were rejected due to the accumulation of pesticide residues.

The economic liberalization, globalization and the WTO policies have necessitated a paradigm shift in agriculture. To meet the stringent demands put forth by WTO, and the phytosanitary standards prescribed by the importing countries, the environment policy has to be restructured so as to minimize the extensive usage of pesticides. However, recent agricultural policies emphasize agriculture as an engine for growth by accelerating the development of commercial agriculture, agro-industry and agro-exports. The need for sustainability in agriculture, to satisfy changing human needs and enhancing the quality of the environment is being addressed by policy makers and scientists globally. To be sustainable the practices have to be ecologically sound, economically viable, socially justifiable and adaptable.

Introduction of sustainable farming practices, including integrated pest management (IPM), will create a paradigm shift in agriculture. "Integrated pest management is a pest management system that in the socio-economic context of farming systems, the associated environment and the population dynamics of the pest species, utilizes all suitable techniques in as compatible manner as possible and maintains the pest population levels below those causing economic injury" (Dent, 1995).

IPM being a knowledge-intensive and farmer based decision making process, encourages natural control of pests and diseases from reaching economically damaging levels. It prevents the outbreak of resurgence among the pests and development of resistance among the plant pathogens. The pesticide free agricultural commodities from the IPM practiced fields have a great scope to increase the income of farmers. In spite of several advantages, the levels of adoption of IPM by the farmers are very slow. Hence, there is a challenging task for the government, researchers and extension functionaries to identify the reasons for poor adoption and to design policies that motivate the farming community to adopt the IPM practices.

6.2 Management of Insects Pests and Diseases

Implementation of effective pest and disease management programs demands achievement of goals and allowing the system to evolve with experience. Although the future demands for quality food production and export requires residue free food products, the usage of pesticides and fungicides has to be appropriate, that it not only controls pest and diseases but at the same time ensures that the residue accumulation is under permissible limits as prescribed by the importing countries. These goals can be achieved by introducing IPM/IDM, which adheres to the following basic principles:

- The maximum use of production inputs that are internal to the system, i.e. incorporating indigenous knowledge on pest control, enhancing natural control process via vegetation management, and wise and judicious use of pesticides.
- The development or redevelopment of germplasm well adapted to local conditions and pest problems.
- The development of farmer-participatory process by researchers to stimulate the acquisition and use of technological information by farmers.

Maintaining crop habitat diversity, adoption of various cultural and behavioral methods, growing of resistant varieties, rationalization of pesticides use and integration of biopesticides have been demonstrated in management of pests and are attractive tools in IPM in view of their ecofriendly nature (Jayaraj et al., 1994).

6.2.1 Habitat Diversification

The cropping system approach in IPM is a low input system, which existed in subsistence farming. This traditional method of farming practice needs a modern touch in view of plant-host-natural enemy relationship. The existing habitat structure should be designed considering the complex system of the biodiversity of the host plants, pests/ pathogens/ weeds, their natural enemies and their interaction.

Sustainable systems of agricultural production are seen in areas where proper mixes of crops and varieties are adopted in a given agroecosystem. Monocultures and overlapping crop seasons are more prone to severe outbreak of pests and diseases. One of the reasons for adoption of mixed cropping in marginal farming and in rainfed ecosystem is due to the low incidence of pests and diseases (Jayaraj, 1987) which was due to the increased activity of natural enemies (Bhatnagar and Davies, 1980). The diversity of natural enemies that attack pests at various stages of the life cycle is greater in poly crop systems, which also tends to prevent severe pest outbreaks. The cropping system approach proliferates natural enemies by providing food and shelter and prevents the evacuation of these biological control agents from the agroecosystem by biological (host plant, prey density) and physical (protection from wind, hiding, shading) interference mechanisms.

6.2.2 Integration of Host Plant Resistance

Technical advancements in containing the crop pests have been successful in the area of host plant resistance. More than 500 cultivars resistant to crop pests of economic importance have been developed and grown in many countries and have proved to be ecologically and economically superior insect control tools in global agriculture for over 30 years (Chelliah and Uthamasamy, 1998). In the context of integration of resistant cultivars in crop protection, continuous cultivation of resistant varieties with a narrow genetic base for a long period might lead to development of biotypes. Strategies include sequential release of varieties with major genes, pyramiding of genes, use of multiline varieties, incorporation of polygenes and wide hybridization (Jayaraj, 1990). With the advent of genetic transformation techniques, it has become possible to insert exotic genes into the plant genome that confers resistance to insects. Genes from bacteria, trypsin inhibitor, lectins, ribosome inactivating proteins, secondary plant metabolites, vegetative insecticidal proteins and small RNA have been in use for resistance buildup in crops (Sharma and Ortiz, 2000). In India, at least 12 research organizations are involved in plant transformation work for developing novel plants with new genetic traits for resistance to insects (Ghosh, 1999). While host plant traits for resistance has so far been practiced as the principle method of pest management by farmers, they have added advantage in crop protection of being complementary to biological and insecticidal control (Uthamasamy, 1998) and botanical pest control (Abdul Kareem and Gunasekaran, 1998). Huang et al. (2003) reported that Bt cotton significantly reduces the number of sprayings, the quantity of pesticides used and the level of pesticide expenditures. They also state that such reductions in pesticides also likely lead to labour savings, more efficient overall production, as well as positive health and environmental impacts. Modern cropping practices need adjustments in growing resistant crop varieties under polycrop situations in which greater habitat diversification is possible. The main crops can be attractive to the natural enemies, while the pests are deterred away from causing economic damage. A two year field study in Manitoba, Canada, evaluated the effect of wheat cultivar mixtures on disease levels. It was found that wheat cultivar mixtures provided yield stability and resulted in lower disease levels than some varieties of monocropped wheat (Natural Systems Agriculture, 2007).

6.2.3 Biological Control of Pests

Biopesticides like pathogens, parasitoids, predators and antagonistic organisms have become invaluable components in agricultural IPM systems. In addition to the natural biocontrol operating in many crop habitats, applied biocontrol can bring about a successful suppression of crop pests, diseases and nematodes without disrupting the ecosystem, The high level of human safety, stability of control and renewable nature, make biopesticides very attractive candidates for pest management (Jayaraj et al., 1994). In recent times, biological control has expanded from the use of entomophagous insects to the use of a whole range of organisms to control insects and nematodes. Biological control has been used as an end in itself rather than as a synergistic component of integrated pest management. After nearly two decades of intensive teaching and field level training, farmers have understood the value of biological control. Some of the notable success achieved with entomophagous insects and microbials in India is presented. (Tables 6.1 and 6.2).

6.2.3.1 Bio-Control of Pests Worldwide

Biological control has been well adopted as a mean of pest control in many parts of the world. Biocontrol strategies which involve the use of parasitoids, predators and pathogenic microbes have been success stories in many countries. A brief summary of some case studies are presented.

Cotesia rubecula (Marshall) has demonstrated the reduction of population of *Pieris rapae* L., a European butterfly that infests garden cabbage and other cole crops. The parasitoid has been an important source of mortality of the pest in the USA. The study also found that population of one non-native butterfly was also reduced in the northeastern USA by another introduced parasitoid *C. glomerata* L. This proves that introduction of natural enemies often focus on the eradication of

Table 6.1 Potential entomophages in IPM systems

Pest	Parasitoids
Scirpophaga incertulas (Walker)	*Trichogramma chilonis* (Ishii),
Chilo infuscatellus (Snellen)	*T. japonicum* (Ashmead), *Tetrastichus schoenobii* (Ferr).
Chilo sacchariphagus indicus (Kapur)	*Epiricania melanoleuca* (Fletcher)
Pyrilla perpusilla (Walker)	*Adelencyrtus mayurai* (Subba Rao)
Earias vitella (Sherborn)	*Rhogas aligarhensis* (Qadri)
Plutella xylostella (Linnaeus)	*Apanteles plutellae* (Kurdjumov)
Opisina arenosella (Walker)	*Goniozus nephantidis* (Musebeck)
Pest	Predators
Grapevine, citrus and coffee mealy bugs	*Cryptolaemus montrouzieri* (Mulsant), *Chrysoperla carnea* (Stephens), *Cheilomenes sexmaculata* (Fabricius),
Aphids, whiteflies, young larvae of Lepidoptera on cotton	*Coccinella arcuata* (Fabricius), *Syrphus indicus* *Lycosa pseudoannulata* (Bosenberg and Strand),
Rice brown planthopper, Green leafhopper, White-backed planthopper.	*Cyrtorhinus lividipennis* (Reuter),

Table 6.2 Potential entomophages in IPM systems

Pest	Pathogens
Helicoverpa armigera (Hubner), *Spodoptera litura* (Fabricius), *Amsacta albistriga* (Walker), *Plutella xylostella* (Linnaeus), *Spilosoma oblique* (Walker), *Hyblaea puera* (Cramer)	Respective Nuclear Polyhedrosis Viruses (NPVs)
Chilo infuscatellus (Snellen) *Chilo sacchariphagus indicus* (Kapur) *H. armigera* (Hubner) *Oryctes rhinoceros* (Linnaues)	Respective Granulosis Viruses (GV)
Nilaparvata lugens (Stal)	Non-occlusion virus, *Metarhizium anisopliae* (Metsch).
H. armigera, P. xylostella, Cnaphalocrocis medinalis (Guenee)	*Beauveria bassiana* (Bals.), *Nomuraea rileyi* (Farlow) Samson, *Bacillus thuringiensis* (Berliner)

the pest, rather than on the bigger project of incorporating pre and post introduction evaluations on the target and related non-target organisms (Driesche, 2007). Biocontrol of *Mononychellus tanajoa* (Bondar), the cassava green mite, by *Typhlodromalus aripo* (DeLeon), a phytoseiid predator, in more than 20 countries of sub-Saharan Africa is a great example of classical biological control using introduced natural enemies (Yaninek, 2007). Biocontrol mediated by *Harmonia axyridis* (Pallas) (ladybird beetle), through predation, has been a success story in the USA: *Monellia caryella* (Fitch) (blackmargined aphid) and *Monelliopsis pecanis* (Bissell) (yellow pecan aphid) in pecan orchards in Georgia, USA (Tedders and Schaeffer, 1994); *Diaphorina citri* (Kuwayama) (Asian citrus psyllid) in citrus groves in Florida, USA (Michaud, 2004); *Macrosiphum euphorbiae* (Thomas) (potato aphid) in potato crops in northern Maine, USA (Alyokhin and Sewell, 2004). The decimation of *Lymantria dispar* L, the gypsy moth, the pest responsible for severe defoliation of decudious forests and shade trees in N. America, by *Entomophaga maimaiga* is a good example of the "enemy release hypothesis". This is so because high populations of this pest are not common in its areas of origin but severe outbreaks occur in North America where gypsy moth has invaded without its native natural enemies. The gypsy moth populations have remained at much lower levels after the introduction of the entomopathogenic fungus (Hajek, 2007). Biocontrol of the native New Zealand grass grub, *Costelytra zealandica* (White), by *Serratia entomophila* (Grimont) is also a success story. The bacteria cause Amber disease, which is caused by ingestion of pathogenic bacteria, rapidly causing cessation of feeding and gut clearance, which give the larvae their amber appearance (Jackson, 2007). In Brazil, an IPM project successfully implemented the use of a naturally occurring nucleopolyhedrovirus for the control of the velvetbean caterpillar, *Anticarsia gemmatalis* (Hubner), one of the most devastating pests of soybean. The virus is presently used in two million hectares of soybean production area in Brazil, representing the largest program worldwide for the use of an entomopathogen to control a pest in a single crop, which generated substantial economic, ecological and social benefits to Brazil (Moscardi, 2007). Biopesticide products based on the entomopathogenic nematodes and their symbionts are at present aimed almost exclusively at relatively small niche markets. Research outputs in the last decade points the potentiality of these organisms. Nematodes belonging to the groups viz., mermethids, neoaplectanids, sphaerulariids and entaphelenohids hold promise. Biological control of scarabaeid larvae, the pest of plantation trees and nursery plants, by entomopathogenic nematodes of the genera *Steinernema* and *Heterorhabdis* living in a close symbiotic association with bacteria of the genera *Xenorhabdus* and *Photorhabdus*. The dauern juveniles of the nematodes enter the insect host and release the symbiotic bacteria, which release toxins that kill the insect host. The bacteria proliferate in the insect cadaver, and are in turn fed on by the larvae, which develop to adults to produce off springs. The off springs develop into dauer juveniles which leave the insect cadaver in search of new hosts (Ehlers, 2007).

6.2.3.2 Efficacy of Biocontrol of Pests Under Field Conditions

Within the field of microbial control of agricultural pests, the use of entomopathogenic fungi has a special role, rather than nuclear polyhedrosis virus. They can develop independent of their host, which presents the opportunity for large-scale production of these fungi on liquid or solid media, which makes the use of entomopathogenic fungi as biocontrol agents technically and economically viable. Due to the ease of technical production, their host range, their capability of triggering epizootics, their temperature optimum and other ecological criteria, *Beauveria bassiana* (Bals.) Vuil. (Deuteromycotina: Hyphomycetes) and *Metarhizium anisopliae* (Metsch.) Sorok. (Deuteromycotina: Hyphomycetes) are the two species most frequently employed. The production of conidia on cereals has a long tradition in Latin America. In the 1970s, applications of *Metarhizium* covered an area of 100,000 ha/yr (Marques et al., 1981). In Cuba, 220 centers for the reproduction of entomophages and entomopathogens were created by the state. In 1994, 500 t of *B. bassiana* were applied to 400,000 ha of crops to control banana root weevil, *Cosmopolites sordidus* (Germ.) (Coleoptera: Curculionidae), citrus root weevil *Pachnaeus litus* (Germar) (Coleoptera: Curculionidae), and sweet potato weevil *Cylas furmicarius* Fabricius (Coleoptera: Apionidae).

Entomophthoralean fungi pathogenic to insects and mites cause and encourage spread of disease using different strategies. For example, insects infected by fungal pathogens may be induced to climb to the top of plants and firmly grip branches immediately before death, which enhances spread of the fungus in the field. Also, as the host sickens and dies, rhizoids sometimes grow through the insect's ventral surface to anchor the body firmly to the substrate. The conidiophores, in most species, forcibly discharge conidia. The entomophthoralean fungi *Batkoa* sp. and *Furia* sp. occur at epizootic levels in Brazil in spittlebug pests (Hemiptera: Cercopidae). *Neozygites oridana* has been found in many countries suppressing populations of some important mite pests in agriculture, including two-spotted spider mite, *Tetranychus urticae* (Koch.). *B. bassiana* is one of the most commonly occurring entomopathogenic fungal species, and shows strong pathogenicity to Lepidoptera, Hymenopterta, Coleoptera, and Leptinotarsa (Fernandez et al., 2001).

There have been some attempts to develop entomophthoraleans as practical biopesticides. The two most studied genera, *Zoophthora* and *Erynia*, have been produced through liquid fermentation, formulated as mycelium, and introduced into field conditions as an inoculating strategy. However, the research on the use of insect fungal pathogens for the management of pests in India is very limited, which requires an intensive search for the identification of fungal pathogens suited well for the tropical situations. Nevertheless, to develop as practical biopesticides, it is necessary to develop culture media and methods that not only maximize production, but also at an economical cost. This effort will entail in selecting the most favorable inexpensive components for pathogen growth, as well as the lowest concentrations that afford high yield.

6.2.4 Microbial Bio-Control of Plant Diseases

Steady increase in the global population demands a steady and healthy food supply. The demand for food production requires further intensification of agricultural practices, which in turn may increase the pressure on crop plants. To have a healthy cropping system to meet the demands of increased food production, yield losses resulting from plant diseases need to be curtailed. Practices involving improving the genetic resistance of the host plant, management of the plant and its environment, and use of synthetic pesticides play a key role in the control of plant diseases (Strange, 1993). Intensification of agricultural practices would result in increases in use of synthetic pesticides such as fungicides, which is of great concern. Use of synthetic chemicals is under extreme pressure due to their hazardous effects on the environment, and concern over non-target effects (Felton and Dahlman, 1984; Elmholt, 1991) and; development of resistance in pathogen populations (Ishii, 2006). Especially, the use of site – specific systemic fungicides has brought about numerous cases of fungicide resistance (Schumann, 1991). Also, there have been concerns over pesticide residues in food, which could lead to serious health concerns (Picó et al., 2006).

Biological control, which is a natural phenomenon, involving the use of microorganisms for disease control, seems to be a good alternative to chemical control. First and foremost, the highly diverse microbial community in the environment provides an endless source for this purpose (Emmert and Handelsman, 1999). Various studies have shown that increasing the population of a particular microbial strain in the vicinity of a host plant can control the disease without altering the rest of the microbial community or causing any adverse effects on other organisms in the ecosystem (Gilbert et al., 1993; Osburn et al., 1995; Ravnskov et al., 2002). In addition to this inundative approach, management and manipulation of natural communities of antagonistic microbes through crop rotation and organic amendments have proven to be highly effective forms of biological control (Hoitink and Boehm, 1999; Kurle et al., 2001; Coventry et al., 2005 (from Janvier et al., 2007)). It is also believed that the complexity in the interaction between the organisms in the ecosystem, the multiple mechanisms of disease suppression by a single microorganism, and the capability of the antagonist to adapt itself to the environment in which it is used, could make biological control a more durable system than synthetic chemicals (Cook, 1993; Benbrook et al., 1996; Weller, 2007).

6.2.4.1 Significance of Crop Growth Stage

The dynamics of PGPR, yeast, actinomycetes and pathogenic microbes are influenced by the exudates of roots in the rhizosphere region, which in turn alters the communication network and interaction between the beneficial, deleterious microflora and the plant system as a whole (Picard et al., 2000). Plant roots release a wide variety of compounds into the surrounding soil, including ethylene, sugars, amino acids, organic acids, vitamins, polysaccharides, and enzymes. These materials create unique environments for the microorganisms living in association with plant roots in the rhizosphere. Bacteria respond differently to the compounds released by the plant root, and thus different compositions of root exudates are expected to select different rhizosphere communities (Garbeva et al., 2004). On the other hand, rhizosphere bacteria will also influence plants, as wide ranges of bacteria in the rhizosphere can promote plant growth via chemical signals such as auxins, gibberellins, glycolipids, and cytokinins. Genera such as *Pseudomonas, Agrobacterium, Bacillus, Variovorax, Phyllobacterium*, and *Azospirillum* are among the most efficient plant growth – promoting bacteria (Bertrand et al., 2001). For example, *Azospirillum brasilense* (Tarrand) can exert a positive effect on the growth of common bean and soybean, and *Agrobacterium tumefaciens* (Smith and Townsend) can have a strong effect on plant root development (Burdman et al., 1997; Molla et al., 2001). The composition of root exudates is strongly affected by the plant developmental stage, which in turn can affect rhizosphere communities over time (Yang and Crowley, 2000). Picard et al. (2000) showed that the presence of 2,4-diacetylphloroglucinol (DAPG)-producing bacteria in the rhizosphere of maize was significantly affected by plant age. The frequency of DAPG producers was very low in the first stage of plant growth and increased over time. Plant age effects were also observed by di Cello et al. (1997) and Seldin et al. (1998), who showed that populations of *Burkholderia cepacia* ((Palleroni and Holmes) Yabuuchi) and *Peanibacillus azotofixans* in the maize rhizosphere changed during plant growth. Furthermore, Gyamfi et al. (2002) also confirmed that the plant growth stage had a strong impact on total bacterial as well as *Pseudomonas* communities. Yang and Crowley (2000) later confirmed these observations. The main sources of easily accessible substrates are sites at root tips and young roots. Thus, young plants provide the highest amount of organic carbon available for microbial growth. Young roots and root tips might therefore represent excellent niches suitable for colonization by r-strategists. Hence, understanding the distribution of genetic structure and the activity of a microbial community existing in the rhizosphere has a practical importance in the selection of a potential candidate for the management of plant diseases. This would facilitate to estimate the fate of released strains and their impact on both pests and disease causing organisms in the rhizosphere and phyllosphere due to the production of antibiotics (Picard et al., 2000).

6.2.4.2 Role of Antibiotic Producers

Direct antagonism of the pathogen through antibiosis is one of the mechanisms by which disease suppressive bacteria achieve disease control. Antibiosis is mediated through the production of a chemically heterogeneous group of organic, low-molecular mass compounds (Raaijmakers et al., 2002), which at low concentrations are deleterious to the growth or metabolic activities of other microorganisms (Fravel 1988; Thomashow et al., 1997).

Numerous studies on the role of antibiotics in biocontrol of plant pathogens have led to the isolation and characterization of numerous antibiotics from various bacterial genera. Some prominent examples are: control of *Gaeumannomyces graminis* var *tritici* (Walker) in wheat by phenazine produced by *Pseudomonas chlororaphis* PCL1391 (Chin-A-Woeng et al., 1998); control of multiple pathogens such as *Pythium aphanidermatum* ((Edson) Fitzpatrick), *Botryodiplodia theobromae* (Patouillard), and *Alternaria solani* ((Ellis et Martin) Sorauer) by phenazine produced by *P. chlororaphis* PA23 (Kavitha et al., 2005); control of *Rhizoctonia solani* (Kuhn) in cotton by pyrrolnitrin produced by *P. fluorescens* BL915 (Ligon et al., 2000); control of *Rhizoctonia solani* in poinsettia by pyrrolnitrin produced by *Burkholderia cepacia* (Hwang et al., 2002); control of *Thielaviopsis basicola* ((Berkeley et Broome) Ferraris) and *Pythium ultimum* (Trow) in cotton by pyoluteorin produced by *P. fluorescens* CHA0 (Maurhofer et al., 1992); control of *G. graminis* var *tritici* in wheat by 2–4, diacetylphloroglucinol produced by *P. fluorescens* Q8r1-96 (Raaijmakers and Weller, 2001); control of *Phytophthora medicaginis* in alfalfa by zwittermicin A produced by *B. cereus* UW85 (Silo-Suh et al., 1994); control of *Erwinia herbicola* (Lohnis) in apple by pantocin A and B produced by *P. agglomerans* EH318 (Wright et al., 2001); control of *P. ultimum* in sugar beets by xanthobaccins produced by *Stenotrophomonas* SB-K88 (Nakayama et al., 1999).

Pseudomonas chlororaphis strains PA23 (PA23) and DF190 are strong antagonists of *Sclerotinia sclerotiorum* de Bary and *Leptosphaeria maculans* (Desmazieres) Cesati et De Notaris, respectively. The bacteria were identified as producers of the antifungal antibiotics phenazine and pyrrolnitrin (Ramarathnam and Fernando, 2006; Zhang et al., 2006). The production of phenazines and pyrrolnitrin corresponds to the antifungal activity of PA23 culture extracts in the inhibition of sclerotial and/or spore germination of several plant pathogens. Production of multiple antibiotics, with overlapping or different degrees of activity, may account for the suppression of specific or multiple plant pathogens (Raaijmakers et al., 2002). Characterization of a PA23Tn5 mutant, called PA23-63, revealed a Tn insertion in *phzE*, which forms part of the phenazine biosynthetic cluster. Despite producing no phenazines, this strain exhibited wild-type levels of antifungal and biocontrol activity against *S. sclerotiorum* and *L. maculans* (Poritsanos, 2005; Ramarathnam, 2007). Our findings indicate that phenazine production is not essential for PA23 biocontrol of these two pathogens. MutantPA23-63 produces pyrrolnitrin at levels equal to that of the wild type (Paulitz, personal communication). Therefore, we believe that pyrrolnitrin is mainly, but not exclusively, responsible for the antibiosis-mediated biocontrol of *S. sclerotiorum*, the stem rot pathogen (Poritsanos, 2005), and *L. maculans*, the blackleg pathogen of canola (Ramarathnam, 2007). *Bacillus cereus* strain DFE4, and *B. amyloliquefaciens* strains BS6 and DFE16 exhibited agar-diffusible antifungal activity, and greenhouse and field suppression of sclerotina stem rot and blackleg of canola (Fernando, 2005; Ramarathnam, 2007). All three *Bacillus* strains harbour biosynthetic genes for the lipopeptide antibiotics iturin A, bacillomycin D and surfactin. Moreover, cell extract analysis by MALDI-TOF-MS (Matrix-Assisted Laser Desorption Ionization – Mass Spectrometry) confirmed the production of iturin A, bacillomycin D and surfactin by these biocontrol agents (Ramarathnam, 2007).

6.2.4.3 Role of Mycorrhizal Fungi

Arbuscular mycorrhizal (AM) fungi are ubiquitous soil microbes that form symbiotic associations with plant root systems. In forming such symbiotic associations, they colonize within and around the plant root system, forming internal structures that facilitate the transfer of photosynthetically derived carbon to the fungus. AM fungi are obligate symbionts and are dependent on this source of carbon for the completion of their life-cycle (Harrier and Watson, 2004). There is an apparent lack of host specificity with about 150 species of AM fungus demonstrating a wide host range for each individual species. This wide host range is deceptive, since there is a level of functional compatibility, shown by symbioses between different isolates of AM fungi and different plant species varying in compatibility. Therefore, selection of the isolate of AM fungus is critical for the optimisation of the benefits of the symbiosis *in situ*. It is now widely recognised that the soil conditions prevalent in sustainable agriculture are likely to be more favourable to AM fungi than those under conventional agriculture (Bethlenfalvay and Schüepp, 1994; Smith and Read, 1997). AM fungi have not been shown to interact directly with pathogens through antagonism, antibiosis and/or mycoparasitism. Cordier et al. (1996) and Davies and Menge (1980) demonstrated localised competition between AM fungi and *Phytophthora*, as *Phytophthora* development was reduced in AM fungal-colonised and adjacent un-colonized root system regions. Vigo et al. (2000) found that the number of infection sites was reduced within mycorrhizal root systems and that the colonisation by the AM fungus had no measurable effect on the spread of necrosis, thus suggesting that the number of infection sites was important for subsequent pathogen infection. The increase in lignification is thought to protect the roots from penetration by other pathogens, and results from an elevation of phenolic metabolism within the host plant (Morandi, 1996). Cordier et al. (1998) and Pozo et al. (2002) demonstrated that induced resistance against the pathogen *Phytophthora parasitica* (Dastur) in AM fungal-colonised tomato roots resulted from localised defence responses in arbuscule containing cells and systemic defence responses in non-mycorrhizal parts of mycorrhizal roots. The local induced resistance comprised the formation of cell wall appositions reinforced by callose adjacent to intercellular hyphae. The systemic resistance of non-mycorrhizal components of a mycorrhizal root system was characterised by the elicitation of host wall thickenings containing non-esterified pectins and PR-1a proteins in reaction to intercellular pathogen hyphae and by the formation of callose rich encasement material around *P parasitica* hyphae that were penetrating root cells. Therefore, the bioprotection conferred by AM fungal-colonisation of host plant root systems is both localised and systemic. De la Peña et al. (2006) reported that root infection and multiplication of *Pratylenchus penetrans* (Cobb) were significantly reduced by the native inoculum of AMF in *Ammophila arenaria* L. (pioneer dune grass). Plant preinoculation with AMF further decreased nematode colonization and reproduction. Nematode suppression by AMF did not occur through a systemic plant response but through local mechanisms. In contrast, Khaosaad et al. (2007) reported that the root infection by *G. graminis var. tritici* was systemically reduced when barley plants showed high degrees of mycorrhizal, *Glomus mosseae*, root colonization, whereas a low mycorrhizal root colonization exhibited no effect on infection. A clear systemic bioprotectional effect depending on the degree of root colonization by the mycorrhizal fungus was established. At a higher mycorrhizal colonization rate the concentration of salicylic acid (SA) was increased in roots colonized by the mycorrhizal fungus but no systemic increase of SA could be measured in nonmycorrhizal roots of mycorrhizal plants, indicating that the systemic bioprotectional-effect against *G. gramminis* is not mediated by salicylic acid. Pozo and Azcon-Aguilar (2007) support the theory mycorrhiza mediated systemic induction towards disease control. They describe the steps involved in the process of mycorrhiza mediated systemic induction. Upon germination, AM fungi grow toward the root and form appresoria at the root surface. At this stage, the plant reacts with an increase in SA levels. (i) In a compatible interaction, SA levels decrease as the fungus colonizes the cortex. (ii) JA biosynthesis occurs in arbuscule containing cells. Priming seems to be the main mechanism operating in mycorrhiza induced resistance. The lack of systemic activation of cellular or biochemical defense mechanisms in mycorrhizas and the stronger defense reactions observed upon pathogen challenge support this hypothesis.

6.2.4.4 Integration of Microbial Bio-Control Agents in IPM

The success of microbial biocontrol agents in plant disease control depends on their efficient integration into a disease management system. This can be achieved by efficient formulation, optimization of delivery system, and integration with other control strategies such as host resistance, combination with fungicides and bactericides, combination with other microbial biocontrol agents, and in strategies that involve prevention of pathogen resistance development towards fungicides and other chemical control.

Fluorescent pseudomonads were first developed as talc based formulation for the treatment of potato seed tubers for growth promotion (Kloepper and Schroth, 1981). Talc based formulation of *Pseudomonas fluorescens* strain Pf1 and Pf 2 increased grain yield of pigeonpea besides the control of pigeonpea wilt (Vidhyasekaran et al., 1997). Seed treatment of groundnut and pigeon pea with peat based formulation of *Bacillus subtilis* supplemented with 0.5% chitin or with 0.5% of sterilized *Aspergillus* mycelium controlled crown rot and wilt of groundnut and pigeon pea respectively. It also increased growth promotion even in the presence of inoculum pressure (Manjula and Podile, 2001). Application of talc based strain mixture formulation of fluorescent psedomonads through seed, root, soil and foliage to rice crop suppressed sheath blight disease under field conditions better than individual strains based formulations. The average disease reduction for mixtures was 45.1% compared to 29.2% for individual strains. In addition to disease reduction, strain mixtures increased biomass production and yield compared to individual strains (Nandakumar et al., 2001). Combined application of *Pichia guilermondii* and *Bacillus mycoides* (B16) reduced the infection of *Botrytis cinerea* (Persoon) by 75% on fruits in strawberry plants grown commercially under greenhouse conditions. But the individual application of either antagonist resulted in 50% reduction of strawberry fruit infection. Population of yeast increased when applied as mixture rather than single application (Guetsky et al., 2002). Raupach and Kloepper (1998), reported that *Bacillus subtilis* isolate INA7 when used in combination with *Bacillus subtilis* isolate GBO3 and *Curtobacterium flaccumfaciens* isolate ME1 as seed treatments, demonstrated greater growth promotion and numerically better angular leaf spot control of cucumber where methyl bromide fumigation was used compared with that of nonfumigation. This latter mixture of BCAs is the basis for the BioYield product marketed by Gustafson Inc., Plano, TX.

Formulation can affect many aspects of biocontrol performance, shelf life, and safety. As with any biological system, three parameters that greatly affect success are water, food, and environment. Water activity can profoundly affect survival of biocontrol agents in formulations (Connick et al., 1996). A dry product is less weight to ship and at lower risk of possible contamination. Some biocontrol agents form life stages that are relatively simple to formulate, such as bacterial endospores, yeasts, and the resting-spore stages of many fungi (Fravel, 2005). Delivery systems that are well thought-out as to time and place can greatly reduce the amount of biocontrol agent needed. The time and place to deliver the biocontrol agent depends on the biocontrol agent, the pathosystem, and the cropping system (Fravel, 2005). Steddom and Menge (2001) determined that ten repetitive applications of *Pseudomonas putida* at low concentrations through irrigation water resulted in soil populations similar to those from a single application at a tenfold greater concentration. *Bacillus subtilis* applied 1–5 days before infection by *Cercospora* increased control (Collins and Jacobsen, 2003). A double spray of *Pseudomonas chlororaphis* strain PA23 at the flowering stage reduced *Sclerotinia* stem rot to levels not significantly different from the fungicide treatment (Fernando et al., 2007). Similarly, bacterial application at the cotyledon stage of canola, i.e. the stage most susceptible to pathogen infection, plays an important role in the prevention of blackleg infection (Ramarathnam, 2007). This phenomenon was clearly established in our field study where *B. amyloliquefaciens* strain DFE16 applied at the cotyledon stage suppressed the disease as efficiently as the fungicide which was tested. Bacteria seem to prevent early infection of the cotyledon leaves, reducing the chances for systemic infection, and girdling and cankering of the stem. Populations of *Trichoderma harzianum* (Rifai) on strawberry flowers were half as large when delivered by bumblebees or honeybees than by spray applications, but the bee-delivered inoculum provided better control in a 4-year field study (Kovach et al., 2000). However, we still have a long way to go to standardize delivery system and frequency of application to ensure sustainable disease management.

Integration of *Bacillus*-based biological control agents (BCAs) with disease resistant hosts has proven to be useful in management of several disease problems, particularly where high levels of disease resistance is not available, or where high yielding, highly resistant cultivars are not available. Hervas et al. (1998) showed that suppression of Fusarium wilt caused by race 5 of *Fusarium oxysporum* f. sp. *ciceris* ((Padwick) Matuo et Sato) was greater and more consistent on partially resistant cv. PV 61 with *Bacillus subtilis* isolate GB03 seed treatment than on the more susceptible cv. ICCV 4. In a 3-year study, Larson (2004) showed that a BCA, *Bacillus mycoides* isolate Bm J, provided control of *Cercospora* leaf spot equal to synthetic fungicides as measured by AUDPC on a sugarbeet hybrid that had a moderate level of resistance, but isolate Bm J provided only 41% of the control afforded by four fungicide sprays on the susceptible cultivar.

Today nearly all cotton planted is treated with Kodiak (*Bacillus subtilis* isolate GB03) and fungicides (Brannen and Kenney, 1997). Brannen and Kenney (1997) indicated that combining Kodiak with fungicides provides control of pathogens that are not controlled by available fungicides, and the BCA provides control via colonization of the rhizosphere long after the fungicides have degraded. Brannen and Kenney (1997) suggest that success of Kodiak in the cotton market is due to integration with fungicides. *Bacillus pumilis* isolate 341-16-5 has been used as a seed treatment for the control of sugarbeet damping-off and root rot caused by *Aphanomyces cochlioides* (Drechsler), *P. ultimum*, and *R. solani* in combination with varying rates of hymexazol (Jacobsen, 2004). In 14 location-years of testing, this isolate increased both stand at harvest and yield when combined with 20, 30, or 45 g of hymexazol per 100,000 seed compared with that of hymexazol treatments alone. In addition, the 20-g rate was as effective as the 45-g rate when combined with the BCA. *Bacillus pumilis* isolate 341-16-5 was not as effective as hymexazol when used alone, and the 20-g rate was not as effective as the 45-g rate when used alone. In a study of control of avocado black spot caused by *Pseudocercospora purpurea* ((Cooke) Deighton), Korsten et al. (1997) showed that, in eight location-years of research, *Bacillus subtilis* isolate B246 applied with copper oxychloride or with benomyl and copper oxychloride provided more consistent control than either the BCA or the fungicides alone. The integrated program allowed for fewer fungicide sprays, and Korsten et al. (1997) suggested that the integration of fungicides acted as a safeguard in those years unfavourable to BCA activity. Some heavy metal-resistant mutants of *Trichoderma* spp. selected on heavy metal-rich artificial media were effective antagonists of *Fusarium* spp., *Pythium* spp. and *Rhizoctonia* spp. (Kredics et al., 2001). These mutants might be of value for use with heavy metal containing pesticides, as part of an integrated plant protection system. Combination treatments of *Trichoderma viride* (L4 and S17A) with either tebuconazole or compost enhanced control of *Allium* white rot (AWR) caused by *Sclerotium cepivorum* (Berkeley) and, in some treatments, disease was almost eliminated. Combining S17A and tebuconazole resulted in a similar level of AWR to using tebuconazole alone (Clarkson et al., 2006). By using chemical and biological control measures together, the duration of active disease control will be extended and the chances for the development of fungicide resistance can be reduced.

Integration of BCAs into pesticide resistance management strategies has not been well explored. However, use of different modes of action in sequential fungicide applications is considered a keystone of resistance management programs (Jacobsen, 2004; Koeller, 2004). Since *Bacillus*-based BCAs have modes of action different from that of synthetic chemical fungicides, it is logical that they can be used in fungicide resistance management programs. *Bacillus*-based BCAs have modes of action that include antibiosis, parasitism, and induced systemic resistance (Bargabus et al., 2002; Jacobsen and Backman 1993). Matheron and Porchas (2000) reported on the use of Serenade (*Bacillus subtilis* isolate QST 713) alternated with sulfur (Microthiol 80DF), myclobutanil (Rally 40W), or trifloxystrobin (Flint 50WG) for control of powdery mildew of lettuce. Thus, alternate sprays with the BCA Serenade saved 8.96 to 20.16 kg of sulphur per ha, 139 g ai of trifloxystrobin per ha, or 141 g ai/ha and achieved the same results. In addition, by using different modes of action, Matheron and Porchas (2000) proposed that the BCA contributed to a fungicide resistance management program.

6.2.5 Role of Organic Soil Amendments

Cover crops are typically grown during the off-season with an annual cash crop. Cover crops have usually been turned under prior to planting the cash crop. When they are incorporated into the soil they become a "green manure." Cover crops may or may not have any harvestable yield value. However, they have been demonstrated to reduce erosion (Wall et al., 1991; Creamer et al., 1997), improve the physical characteristics of the soil (Reid and Goss, 1981), and reduce plant diseases (Sumner et al., 1981). Root rot is a major disease complex of beans grown in New York, causing substantial economic losses annually (Abawi et al., 1985). This diseases complex is caused by several pathogenic fungi (*Fusarium solani* f. sp. *phaseoli, R. solani, P. ultimum*, and *Thielaviopsis basicola*) and the plant-parasitic nematode (*Pratylenchus* spp.) individually or in any possible combination. A recent test demonstrated that a previous cover crop of grain rye incorporated as a green manure resulted in the highest bean yield and slightly lower root rot severity ratings. Viaene and Abawi (1998) found that sudangrass was effective, as a green manure, in reducing reproduction of *Meloidogyne hapla* (Chitwood) and, therefore, its damage to lettuce plants. In field microplots filled with organic soil infested with *M. hapla*, incorporation of sudangrass grown as a cover crop from late summer to fall resulted in 20–30% increase in the weight of lettuce planted the following spring as compared to lettuce planted in nematode-infested soil that was left fallow.

Composting is becoming an effective way to manage and recycle municipal and industrial waste. It converts organic wastes into a stabilized form, reduces the volume of waste material, destroys human pathogens, provides a way for recycling valuable plant nutrients, and can be used as an effective and desirable soil organic amendment (Hoitink and Fahy, 1986; Dick and McCoy, 1993). In addition to increasing organic matter of the soil, amending with composts also increases soil microbial populations (Pera et al., 1983; Perucci, 1990), which leads to an improvement of the soil quality. Chen et al. (2000) found that the application of brewery compost reduced root galling severity and egg production of *M. hapla* and increased yield of lettuce by 13% in fumigated soil and 23% in nonfumigated soil.

Common root rot (causal agent *Aphanomyces euteiches* (Drechsler)) is a major disease of commercially grown snap bean (*Phaseolus vulgaris* L.). The disease was suppressed by both fresh and composted paper-mill residuals, but the composted residuals at high rates had the lowest disease incidence (<40%) and produced healthiest plants (Leon et al., 2006). Brassica crops used in crop rotations and as green manures have been associated with reductions in soilborne pests and pathogens. These reductions have been attributed to the production of volatile sulphur compounds through a process known as biofumigation, and to changes in soil microbial community structure (Larkin and Griffin, 2006). Indian mustard was found to be most effective for reducing powdery scab and common scab diseases, whereas rapeseed and canola were most effective in reducing *Rhizoctonia* diseases, thus indicating that Brassica crops have potential for use as green manures for the control of multiple soilborne disease problems.

6.2.6 Role of Push-Pull Strategies in IPM

Push-pull strategies use a combination of behavior-modifying stimuli to manipulate the distribution and abundance of pest and/or beneficial insects for pest management (Cook et al., 2007). The pests are repelled or deterred from this resource (push) by using stimuli that mask host apparency or are repellent or deterrent. The pests are simultaneously attracted (pull), using highly apparent and attractive stimuli, to other areas such as traps or trap crops where they are concentrated, facilitating their elimination. The stimuli for "push" components have been grouped according to whether they are visual or chemical cues, whether they are synthetic or plant- or insect-derived semiochemicals, and whether they are usually used to affect host recognition and selection over a relatively long range (visual cues, synthetic repellents, non-host volatiles, host volatiles, anti-aggregation pheromones, and alarm pheromones) or shorter-range host acceptance (antifeedants, oviposition deterrents, and deterring pheromones). The stimuli for "pull" components include visual stimulants, host volatiles, sex and aggregation pheromones, gustatory and oviposition stimulants (Cook et al., 2007).

6.2.6.1 Push-Pull Strategies in Subsistence Farming

Control of Stem Borers in Maize and Sorghum

Maize (*Zea mays*) and sorghum (*Sorghum bicolor*) are principal crops for millions of the poorest people in eastern and southern Africa, and lepidopterous stem borers, e.g., *Chilo partellus* (Swinhoe), *Eldana saccharina* (Walker), *Busseola fusca* (Fuller), and *Sesamia calamistis* (Hampson), cause yield losses of 10% to 50% (Kfir et al., 2002; Khan and Pickett, 2004). The strategies involve the combined use of intercrops and trap crops, using plants that are appropriate for the farmers and that also exploit natural enemies. The push-pull strategy has contributed to increased crop yields and livestock production, resulting in a significant impact on food security in the region (Khan and Pickett, 2004).

6.2.6.2 Push-Pull Strategies in Intensive Arable Agriculture

Control of *Helicoverpa* in Cotton

Helicoverpa species are polyphagous lepidopterous pests of a wide range of crops. The potential of combining the application of neem seed extracts to the main crop (push) with an attractive trap crop, either pigeon pea (*Cajanus cajan*) or maize (*Z. mays*) ("pull") to protect cotton (*Gossypium hirsutum*) crops in Australia from *Helicoverpa armigera* (Hubner) and *H. punctigera* (Wallengren) has been investigated (Pyke et al., 1987). Trap crop efficiency was increased by application of a sugar-insecticide mix.

Control of *Sitona lineatus* in Beans

Sitona lineatus L., the pea leaf weevil, is a pest of field legumes in Europe, the Middle East, and the United States. Adult feeding reduces leaf area, while larvae damage the nitrogen-fixing root nodules. Commercially available neem antifeedant (push) and synthetic aggregation pheromone 4-methyl-3,5-heptanedione (Blight et al., 1991) released from polythene dispensers (pull) were effective as components of a push-pull strategy for control of *S. lineatus* in field trails using faba beans (*Vicia faba*) (Smart et al., 1994).

6.2.7 *Role of Botanicals in IPM*

Plant products, being indigenous resources, are in use for over a century in India to minimize losses in grain storage due to insect pests. Many plant species show selective action against a number of pests through a variety of biological activities including production of behavior-modifying chemicals such as pheromone analogues, repellents, attractants, antifeedants, direct toxicants and insect growth regulators. Such substances are found in many plants for natural defense from their enemies.

Research designed to discover these defensive mechanisms have led to applications that have been integrated with existing pest management programs.

A number of these plants were recommended for pest control in developing countries including those that were not safe to non-target organisms. However, research on botanicals for pest control has continued during the last two decades mostly on neem, *Azadirachta indica* (Juss) and *Chrysanthemum* sp. Many botanical have been studied extensively for integration with biological control (Rabindra et al., 1997), chemical pesticides (Dhaliwal et al., 2000), host plant resistant (Ragumoorthy, 1996) and safety to natural enemies has been recorded (Arora and Dhaliwal, 1994). Jayakumar et al. (2007) reported the effectiveness of combining plant extracts with antifungal microorganisms in the control of red rot of sugarcane, caused by *Colletotrichum falcatum* (Went). Leaf extracts of *Abrus precatorius* L. and *Bassia latifolia* (Roxb.) and the rhizome extract of *Curcuma longa* L. in combination with *Pseudomonas fluorescens* MD1 effectively controlled the disease in greenhouse and field conditions.

For the management of major viral diseases antiviral principles (AVP's) have been successfully employed. The antiviral principles are successfully used for the management of rice tungro virus (RTV), tomato spotted wilt virus (TSWV), groundnut bud necrosis and chilli mosaic virus. Among the AVP's *Croton sparsiflorus* (Morong.), *Euphorbia thymifolia* L., *Prosopis chilensis* ((Mol) Stuntz) (10%) and dried leaf powder of coconut and sorghum has been employed for the management of TSWV in tomato in field condition. These AVP's caused more than 80% reduction of disease incidence and increased the yield up to 26% over control. (Manickam and Rajappan, 1999). In AVP's treated plants, the bio chemical studies revealed that there is induction of new proteins, which will help to reduce the viral disease incidence. Attempts are being made to locate the genes responsible for the induction of antiviral proteins through application of AVP, and to clone these genes thereby enabling the production of transgenic for the control of viral diseases.

6.2.8 Biopesticides for the Management of Nematodes

Commercially available *Pseudomonas fluorescens* was tested against *Pratylenchus zeae* (Graham) in maize and sorghum, *Heterodera cajani* (Koshi) in pulses; *Rotylenchulus reniformis* (Linford and Oliviera) in castor and papaya and root knot nematode, *M. incognita* in tomato and brinjal under field condition. Seed treatment with *P. fluorescens* @ 10 g/kg of seed was effective in suppressing the population by 61.40% and 58.24% in maize and sorghum respectively and increases the grain yield of maize (69.04%) and sorghum (98.57%). Soil application of *P. fluorescens* at 2.5 kg/ha along with chitin and neem cake was found to be very effective against the rice root nematode *Hirschmanniella oryzae* ((van Breda de Haan) Luc & Goodey) recording 51 percent decrease in root population (Swarnakumari, 1996). In Florida field trials, two Gram-positive PGPR isolates (*B. subtilis* strain GB03 and

Bacillus amyloliquefaciens (*ex* Fukumoto) Priest et al. strain IN937a) in a formulation containing chitin-reduced *Meloidogyne incognita* ((Kofoid and White) Chitwood) galling and improved root condition of bell pepper and muskmelon when added to transplant media at seeding (Kokalis-Burelle et al., 2002, 2003). Eggs of plant parasitic nematodes were reported to be parasitized by fungal bioagents viz., *Paecilomyces lilacinus* ((Thom) Samson), *Verticillium lecanii* ((Zimmermann) Viegas), *V. chlamydosporium, Trichoderma harzianum, T.viride* and *Gliocladium virens* (Miller) (Rao and Reddy, 1992). The mode of action of their destructive activity is due to be enzymatic disruption of egg shell and larval cuticle and also by physiological disturbances brought about by biosynthesis of diffusible toxic metabolites (Morgan-Jones and Rodriguex-Kabana, 1985). *Paecilomyces lilacinus* is the most promising and practicable biocontrol agent for the management of root-knot and cyst nematodes. In cut flowers like carnation, gerbera, gladiolus and asiatic lily, the application of the fungus at 0.5 g/kg soil was found to check the root knot nematode *M. incognita*.

6.3 Examples of Successful IPM Programs from Around the World

Stern et al. (1957) were the first to assemble the various concepts that make up what is now referred to as IPM. They called for the integration of biological and chemical control strategies based on greater knowledge of the ecosystem; science-based monitoring and prediction of pest populations to identify economic thresholds; the augmentation of natural enemies; and the use of selective insecticides. The management of pests is a key issue for profitability of agriculture and for human and environmental health. Undoubtedly, advances in pest management contributed to the 1.9% per annum growth in agricultural productivity in the United States from 1949 to 1991 (Acquaye et al., 2003). The use of chemical pesticides is a common component of pest-management strategies. Expenditure on pesticides in U.S. agriculture increased eight-fold from 1950 to 1999 to $8.8 billion (in year-2000 dollars). Pesticide expenditures rose from 1.6% to 7.5% of total purchased inputs. This increase was widespread across crops and regions (United States Department of Agriculture, Economic Research Service, 2001).

6.3.1 IPM in Germany for the Control of Fungal Leaf Diseases in Sugar Beet

Cercospora beticola (Saccardo) is the primary leaf pathogen of sugar beets in Germany, where economic losses may reach US $1,500/ha (Wolf and Verreet, 2002). Powdery mildew, caused by *Erysiphe betae* ((Vanha) Weltzien), is also common, however, sugar losses (about 5 to 15%) tend to be lower than for *Cercospora* leaf spot (Ahrens and Breustedt, 1984). In the past, sugar beet leaf diseases were often controlled by applying fungicides on fixed-calendar schedules or growth stages. In many cases, these treatments were applied without regard to cultivar resistance or weather conditions. Additionally, management decisions were often adversely affected by poor disease diagnosis. A new approach was needed to provide adequate disease control while effectively reducing the chemical load on the environment. Proper diagnosis is a key component of the IPM program. The implementation and acceptance of the sugar beet IPM model was based on the ability to accurately diagnose foliar diseases and to transmit the disease warning system to the farmer in a user-friendly system. In the past, misidentification of foliar diseases, particularly between leaf blotching caused by *Pseudomonas syringae* and *Cercospora* leaf spot, often resulted in unnecessary fungicide treatments. Symptoms associated with *P. syringae* are already common in June but are temporary and originate from physical injuries such as hail. Fungicide applications are neither necessary nor do they have any effect against the bacterium. Hence, accurate diagnosis at early stages of the epidemic is very important. The most important advantage of the model is the potential for reducing or eliminating fungicide applications. The model also links the fungicide treatment and damage thresholds to develop forecasts of damage risk. The damage threshold alone is not suitable for optimization of timing fungicide applications, because even the new generation of fungicides is not effective in suppressing disease development once the damage threshold is reached. Therefore, there is a need to define special thresholds that allow optimum fungicide efficacy. The yield risk potential forecast of the IPM model takes this into account.

6.3.2 IPM in California

This IPM system focuses on the five major commodities of California, almonds, cotton, oranges, processing tomatoes, and lettuce. Also, it has been a subject of case study by Mullen et al. (2005) which illustrates the impacts of public investment in research and extension in pest management on the economic efficiency of agricultural production and on the risks to human and environmental health. IT also estimates the returns to University of California (UC) investments in pest management in these industries.

6.3.2.1 Almonds

Navel orangeworm (*Amyelois transitella* Walker) is the most significant pest of almonds causing extensive damage to the nuts. In the late 1970s, growers relied heavily on pesticides such as azinphosmethyl and carbaryl but resistance was an emerging problem. Monitoring of pest populations and post-harvest orchard sanitation the removal of mummy nuts to break the breeding cycle have been key components of an IPM package. The cumulative investment in developing and maintaining this IPM package from 1970 to 1999 was $65.3 million. The main benefit has been a reduction in insect damage, totaling $375 million since 1980. Also, a savings of $282 million in the use of pesticides was recognized.

6.3.2.2 Cotton

The cotton IPM program has the typical features of regular monitoring of pest and predator populations based on scientific protocols, and resistance management in the choice of pesticides. The IPM in cotton has been successful in reducing the use of broad-spectrum pesticides by supplementing them with other technologies based on monitoring populations of pests and their predators. The total value of UC research and extension investments in pest management in cotton from 1970 to 1997 compounded forward to 2000 was $162 million. Benefits to the cotton industry from IPM technologies come in the form of pesticide savings.

6.3.2.3 Oranges

The citrus industry in southern California has a long history of successfully employing biological pest control. Morse and Luck (2000) noted that thirteen exotic pests of oranges had been controlled biologically in southern California. The two most important pests of citrus have traditionally been California red scale, *Aonidiella aurantii* (Musk), and citrus thrips, *Scirtothrips citri* (Grafton-Cardwell). The real savings in pesticide expenditures, from the use of biological control agents, compounded forward to 1999, were $66.8 million in Southern California and $5.6 million in the San Joaquin Valley, giving a total benefit stream worth $72.4 million.

6.3.2.4 Processing Tomatoes

The IPM program reduced losses due to worm damage by 40% while annual savings in pesticides to combat nematodes totaled $100 per acre ($40/ha) over 40% of the crop. The value (in year-2000 dollars) of the stream of benefits from 1990 to 1999 from the development of nematode-resistant varieties was $134 million. The benefits from better management of insects and mites between 1981 and 1999 were $48 million. Total benefits amounted to $182 million.

Information-based management strategies have been particularly important for the control of arthropods in California. IPM technologies have allowed growers to make more profitable pest-management decisions, particularly about pesticides, through the use of information about pest populations and knowledge of their interactions with their natural enemies and cultural and chemical control measures.

6.3.3 IPM Program for Managing Fungal Leaf Blight Diseases of Carrot in New York

Fungal leaf blight diseases caused by *Cercospora carotae* ((Passerini) Solheim) and *Alternaria dauci* ((Kuhn) Groves et Skolko) occur annually on processing carrot in New York, with growers applying up to eight fungicide sprays to manage these diseases. An integrated pest management (IPM) program involving the use of a 25% disease incidence threshold to prompt the first fungicide application and timing subsequent sprays by monitoring for increases in disease severity and weather forecasts in conjunction with a 10- to 14-day spray interval was evaluated in grower fields in 1997 and 1998 (Gugino et al., 2007). The IPM plots, compared with the grower plots, required two to six fewer fungicide applications but showed no yield reduction. From 1999 to 2004, the IPM program was validated and the effect of crop rotation and carrot cultivar susceptibility also were assessed. Carrot plants growing in fields with 2-year or longer crop rotation intervals reached the 25% disease incidence threshold later in the season and required fewer fungicide applications. The less-susceptible carrot cultivars also reached the 25% disease incidence threshold later, required fewer fungicide applications, and were less severely diseased than more susceptible cultivars. Growers in general are interested in adopting IPM practices (Hollingsworth and Coli, 2001) and reducing fungicide applications, but they must be convinced that the diseases and their resultant losses are prevented by using IPM. Therefore, continued demonstration and outreach regarding the effectiveness of this IPM program for carrot leaf blights is necessary to promote its further adoption among New York carrot growers.

6.3.4 Successful IPM Strategies in Canada

By 1994, the apple ermine moth, *Yponomeuta malinellus* Zeller (Lepidoptera: Yponomeutidae), was a serious pest of apple, which had spread into the commercial apple-producing regions of Okanagon and Similkameen valleys and most of British Columbia, including Washington and Oregon to the south of the border (Cossentine and Kuhlmann, 2000). *Ageniaspis fiscicollis* (Hymenoptera: Encrytidae), has been successfully released and used in the control of the apple ermine moth in British Columbia. The parasitoid is a oligophagous, specific to Yponomeutidae, synchronized with its host species and occupies a wide geographic range (Affolter and Carl, 1986). Apple ermine moth has decreased in areas where *A. fuscicolis* was released, especially in Vancouver island where the moth is consistently found, mean parasitism of *A. fiscicolis* was as high as 23% (Cossentine and Kuhlmann, 2001). Cossentine and Kuhlmann (2007) also note that similar studies were also carried in the USA, for the control of the pest, and recommend that international introductions could be better handled through collaborative classical biological control projects.

Generalist natural enemies can be key members of biological control, and programs would adapt and offer better control of pests that imported generalist predators. Dicyphus Hesperus Knight, is an endemic generalist predator that has been used in the greenhouse tomato crops in Ontario, Quebec and British Columbia (Gillespie et al., 2007). It appears to be particularly useful when tomatoes are grown under lights in winter. In winter, when growers interplant new plant among mature plants, *D. hesperus* moves readily to the new plants and provides control of pests moving from the old plants. It provides excellent control of whitefly and thrips in tomato crops (Gillespie et al., 2007).

Sporothrix flocculosa Traquair, a yeast-like fungus, was isolated from mildew infection sites and found to be an exceptional control agent of powdery mildew on a number of crop plants (Jarvis et al., 2007). Sporodex® performed as well as the best recommended fungicides (such as dodemorph acetate and microfine sulphur) under commercial conditions of greenhouse cucumbers in Ontario, Quebec, USA, Netherlands, France and Greece. It increased yield in cucmber without evident residues and improved the flower quality of roses (Belanger et al., 2002). Its also compatible with other pest control products and is used in integrated pest management systems for greenhouse crops. Sporodex® was registered as a biofungicide in Canada in 2002 and in the USA in 2003 (Jarvis et al., 2007).

In temperate climates, greenhouses, owing to their enclosed structure and highly sophisticated crop production systems, provide the ideal conditions for the implementation of biological control. The stable growing conditions can be manipulated to maintain the populations of the biocontrol agents and reduce the invasion of pests and diseases. By creation of excellent partnerships that brought together Canadian researchers, biological control companies and greenhouse growers organizations, the Canadian greenhouse industry has almost completely transitioned from total chemical control to a balance of biological control and integrated pest management for managing pests of greenhouse vegetables (Shipp et al., 2007).

6.4 Transfer of Technology

There is renewed interest in the use of eco-friendly methods for pest management. The implementation will be possible through appropriate knowledge empowerment in a situation where exploitative practices are still in vogue. The "do how" processes are more relevant. Therefore farmer-led and participatory programs are very essential if desired goals of eco-friendly production and commodity export are to be achieved. Depending upon the cropping systems and agro-ecological zones "tailor-made" programs can be evolved and farmers scientists have to be involved in the production programs. This will enable the farmers to learn methodological skills and develop scientific and durable solutions. To make it as a realistic one, community based IPM program is a prerequisite for the success. Though several FFS programs are organized at national level, the farmers have to be motivated to participate in the program, because without the involvement of the farmers, the program is not going to succeed. Only then the IPM programs can be implemented at local level. Presently in general the cooperation from the farmer's side at rural level is not satisfactory. In addition, the scientists and extension workers should dedicate themselves for the betterment of the farmers so as to educate farmers not to use excess pesticides and not to pollute environment. The importance of farmer involvement and the success of IPM has been has been proved by the Insecticide Resistance Management Program launched in India (Peshin et al., 2007). The Central Institute of Cotton Research, Nagpur—India (CICR), launched IPM program in ten cotton-growing states of India, called Insecticide Resistance Management (IRM) in 2002, focusing on 26 districts, which between them consume 80% of insecticides for cotton crops (Russell, 2004). IRM based IPM program is directly being implemented by the scientists at Punjab Agricultural University, Ludhiana, India (PAU), so that there is direct information flow from scientists to farmers (from research sub-system to farming sub-system). IRM program is being implemented in Punjab since 2002, covering main cotton-growing areas of Punjab. The majority of the farmers gained knowledge about the major insect-pests, natural enemies, judicious use of insecticides according to good agricultural practices, regular field monitoring, the presence of predators in the cotton fields and their role in insect pest management. The farmers reported the knowledge gain about insect pests, natural enemies, and proper use of insecticides, as the first reward of the IRM program. The farmers possessed pre-training knowledge about timely sowing of cotton crop and its benefits viz-a-viz pest management, but farmers did not gain substantially with respect to the role of cultural practices in management of pests. This could be due to the fact that training program picked up momentum in later stages of crop cycle, when majority of these cultural operations were over. The program needs the same intensity in the initial crop stages as observed 70 days after sowing. The aggressive campaign launched by the project staff to popularize IPM philosophy using all channels of communication acted as a barrier for pesticide agents of chemical companies to lure the farmers into their net. Experimental learning in the "field laboratory" (farmers' field) will go a long way in making farmers move to higher levels of cognitive domain: comprehension, application, synthesis and evaluation of the IPM practices, with which farmers were not comfortable (Peshin et al., 2007).

6.5 Conclusions

Decline in crop productivity due to the outbreak of pests and diseases, increase in production cost, degradation of natural resources, health hazards and environmental pollution necessitate a paramount shift in production technology. Farmers and agro-based industries could thrive only through the technological innovation that goes in harmony with IPM practices. To achieve technological innovation several researchable issues related to IPM have to be addressed for better adoption of IPM. Issues pertaining to cost benefit analysis of IPM, human health risk assessment, development of improved bioformulations, development of resistant cultivars and the constraints in commercialization of biocontrol has to be addressed for the successful implementation of IPM. However, IPM will come into reality only through the support of Government policies. The policy makers have to be advised to allocate budget for the extensive training, motivation of farmers and promotion of IPM through the establishment of IPM network coordinated by various government and non-governmental agencies. The restructuring of both research and policy issues will pave the way for sustainable agriculture production.

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Chapter 7
Keys to the Increased Use of Host Plant Resistance in Integrated Pest Management

Michael Stout and Jeffrey Davis

Abstract Host-plant resistance as a management tactic involves both the exploitation of intraspecific variation in genetically based plant resistance to breed crop varieties that support lower populations of herbivores or that better tolerate injury by herbivores and the integration of said varieties with other management tactics such as insecticide applications and biological control. There are several barriers to the increased development and use of resistant cultivars in IPM. Many of these barriers arise from the complex genetic and phenotypic nature of plant resistance. In addition, insufficient attention has been given to the integration of plant resistance with other IPM tactics, and to quantifying the benefits of plant resistance in multi-tactic IPM programs. Three keys to overcoming these barriers are described: increased understanding of the causal bases of plant resistance, increased application of modern genetic tools, and a more quantitative approach to implementing host-plant resistance.

Keywords Host-plant resistance · Integrated pest management · Causal basis · Insecticides · Biological control · Polygenic · Gene-for-gene resistance

7.1 Introduction

Integrated pest management (IPM) entails the manipulation of plant-herbivore interactions with the goal of regulating populations of the herbivore at levels below those at which economic losses occur. Plant genotype strongly influences the abundance, distribution, and fitness of herbivores on a plant and the amount of damage (loss) that results from injury by herbivores to the plant (Kennedy and Barbour, 1992; Marquis, 1992; Peterson and Higley, 2001; Hochwender et al., 2005). Moreover, significant variation in genetically based resistance exists within most crop plant species (Kennedy and Barbour, 1992; Clement and Quisenberry, 1999). There is

M. Stout (✉)
Department of Entomology, Louisiana State University Agricultural Center, Baton Rouge, Louisiana, 70803, USA
e-mail: MStout@agcenter.lsu.edu

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thus a sense in which plant resistance is always a factor in a pest management program. However, the phrase "host-plant resistance" has generally been reserved to describe the IPM tactic in which intraspecific variation in plant resistance is intentionally exploited to achieve the goals of IPM. It is in this latter sense that the phrase is used here.

The use of host-plant resistance in an IPM program can be a fairly straightforward matter of avoiding the use of varieties with high levels of susceptibility to an arthropod pest (Eigenbrode and Trumble, 1994). In Louisiana sugarcane, for example, widespread use (ca. 90% of the acreage in Louisiana) of a variety highly susceptible to the sugarcane borer (*Diatreae saccharalis* (F.)) has forced producers to rely heavily on chemical insecticides for borer control, which in turn has probably contributed to the development of insecticide resistance in *D. saccharalis* populations (Akbar et al., 2008). Adoption of more resistant varieties would likely lead to area-wide reductions in sugarcane borer populations and reduced reliance on insecticides (T.E. Reagan, personal communication; Posey et al., 2006). Historically, however, the best-known applications of host-plant resistance have involved the targeted breeding of varieties with higher levels of resistance to arthropods and the use of these resistant varieties in IPM programs. Examples include the development and implementation of wheat varieties resistant to Hessian fly and rice varieties resistant to brown planthopper (Wiseman, 1999) (Table 7.1).

Development and implementation of resistant varieties has been accompanied, to varying extents in different crop-pest systems, by research focused on elucidating the causal bases of resistance and on characterizing the impacts of plant resistance on individual herbivores and on populations of herbivores. In the applied literature, this type of research has largely consisted of efforts to classify resistance as antixenosis (a type of plant resistance that affects herbivore behavior and results in reduced preference for the resistant plant), antibiosis (a type of resistance that results in negative effects on insect biology such that herbivore performance is reduced on the resistant plant), or tolerance (a term that refers to the ability of some plants to sustain injury from herbivores without losses in fitness or yield) (Kogan, 1986; Wiseman, 1994; Smith, 2005). A parallel body of more fundamental research has sought to explain, at several levels of analysis, how biochemical, physiological, and morphological plant characters function singly and in combination to reduce herbivore fitness and herbivore populations. It is clear from both the fundamental and applied literatures that any plant character involved in mediating the interaction between an herbivore and a plant can contribute to host plant resistance, and, as a consequence, host-plant resistance almost always has a complex phenotypic (causal) basis.

There are several advantages to the use of host-plant resistance in IPM, as well as a number of disadvantages. Among the former, host-plant resistance is generally compatible with other IPM tactics, is often easy and inexpensive for producers to implement, and is cumulative in its impact on herbivore populations. The disadvantages include the sometimes long, difficult, and expensive process of developing (breeding) resistant varieties, the instability inherent in some types of plant

Table 7.1 Selected examples of host-plant resistance cited in this chapter

Host plant (crop)	Pest	Selected reference
Resistance conditioned by one or a few genes		
Wheat, *Triticum aestivum* (L.)	Hessian fly, *Mayetiola destructor* (Say)	Harris et al., 2003
Rice, *Oryza sativa* (L.)	Brown planthopper, *Nilaparvata lugens* (Stål)	Alam and Cohen, 1998
Cucumber, *Cucumis sativus* (L.)	Spider mite, *Tetranychus urticae* Koch	Agrawal et al., 1999
Rice, *Oryza sativa* (L.)	Rice gall midge, *Orseolia oryzae* (Wood-Mason)	Harris et al., 2003
Tomato, *Solanum lycopersicum* Mill.	Sweetpotato whitefly, *Bemisia tabaci* (Gennadius)	Nombela et al., 2003
Melon, *Cucumis melo* (L.)	Cotton aphid, *Aphis gossypii* Glover	Pitrat and Lecoq, 1982
Resistance likely conditioned by many genes		
Sugarcane, *Saccharum* spp.	Sugarcane borer, *Diatraea saccharalis* (F.)	Posey et al., 2006
Rice, *Oryza sativa* (L.)	Rice water weevil, *Lissorhoptrus oryzophilus* Kuschel	Heinrichs and Quisenberry, 1999
Rice, *Oryza sativa* (L.)	Stem borers (many species)	Heinrichs and Quisenberry, 1999
Potato, *Solanum tuberosum* (L.)	Colorado potato beetle, *Leptinotarsa decemlineata* (Say)	Flanders et al., 1993
Potato *Solanum tuberosum* (L.)	Potato leafhopper, *Empoasca fabae* (Harris)	Kalazich and Plaisted, 1991
Cotton, *Gossypium hirsutum* (L.)	Reniform nematode, *Rotylenchulus reniformis*	Robinson et al., 2007
Soybean, *Glycine max* (L.)	Soybean aphid, *Aphis glycines* Matsumura	Hesler and Dashiell, 2007
Soybean, *Glycine max* (L.)	Defoliating Lepidopterans	Zhu et al., 2008
Peanut, *Arachis hypogaea* (L.)	Southern corn rootworm, *Diabrotica undecimpunctata howardi* Barber and other pests	Campbell and Wynne, 1985

resistance, and, occasionally, incompatibility of plant resistance with other IPM tactics. These advantages and disadvantages have been discussed at length elsewhere (for example, see Smith, 2005) and will not be rehearsed in detail here. Rather, we will present here several obstacles or barriers to the increased and more effective use of host-plant resistance in IPM, and will suggest several keys to overcoming these barriers so that the promise of host plant resistance as the foundation for effective IPM (Wiseman, 1994, 1999) can be realized.

7.2 Obstacles to Increased Use of Host-Plant Resistance

7.2.1 Typical Nature of Plant Resistance

Perhaps the most important barriers to the increased use of host-plant resistance in IPM arise from the intrinsic nature of plant resistance to insects. We will initially consider important characteristics of polygenic resistance, because plant resistance to insects typically has a complex genetic basis (Smith, 2005; Nunez-Farfan et al., 2007). Resistance conditioned by single genes will then be considered, followed by a discussion of some of the consequences of the typical nature of plant resistance for the development and use of resistant varieties.

7.2.1.1 Characteristic Features of Polygenic Plant Resistance

First, as with other polygenic traits, variation in plant resistance to arthropods is usually continuous rather than discrete and, when two genotypes differ substantially in their resistance to an arthropod, this difference is usually due to the contribution of several genes (Simms and Rausher, 1992). Second, polygenic resistance often occurs at low frequencies in the germplasm collections of crop species, and high levels of resistance to many arthropod pests are apparently absent from the germplasm collections for many crop species. This may be either because the germplasm collections do not contain the full range of resistance variation present in the crop species, or because high levels of resistance simply do not exist in the crop species. This aspect of plant resistance, as well as the polygenic nature of most plant resistance, can be verified by consulting the synopses of resistance variation in important crop species found in Maxwell and Jennings (1980), Kennedy and Barbour (1992), and Clement and Quisenberry (1999).

Third, the level of expression of polygenic plant resistance is often strongly context-dependent. One aspect of the context-dependence of plant resistance is the strong influence often exerted by abiotic factors on the expression of plant resistance (Smith, 2005; see Huberty and Denno, 2004, for a comprehensive review of the effects of one such abiotic factor, water availability, on plant resistance). In agroecosystems, the effects of agronomic and cultural practices such as irrigation, seeding rate and fertilization deserve special attention because these practices systematically alter the environment in which the plant-herbivore interaction takes place, and thus cultural practices are often important influences on plant resistance. Another aspect of the context-dependence of plant resistance is the phenomenon of induced resistance, defined here as a type of plant phenotypic plasticity in which prior attack by an arthropod herbivore causes an increase in the resistance of the plant to subsequent herbivores (Stout, 2007). Induced resistance is generally thought to be a strategy to minimize the cost of plant resistance by restricting the full expression of resistance to times at which the plant is under attack (see below; Walters and Heil, 2007); however, phenotypic plasticity *per se* may be an important feature of plant resistance that contributes to its effectiveness (Karban et al., 1997). Finally, the level of resistance realized by a plant also depends on the activities of the third trophic level. Plant traits may have a strong effect on natural enemies, and in fact plants may actively manipulate the activities of natural enemies to their benefit (Cortesero et al., 2000).

Finally, expression of plant resistance may incur costs to the plant. These costs can be of several types (Simms, 1992; Purrington, 2000; Strauss et al., 2002), including autotoxicity of resistance mechanisms and tradeoffs among resistances to different pests or tradeoffs among different mechanisms of resistance. Perhaps most important is the direct effect of the expression of resistance on yields resulting from the diversion of resources from reproductive functions (e.g., grain yields) or other functions that are directly related to crop yield.

7.2.1.2 Features of Single Gene Resistance

Although plant resistance to insects usually has a complex genetic basis, there are cases in which single genes are strong determinants of the level of expression of resistance, and some of these cases are well-known and important. In cucurbits, for example, resistance to many arthropods is strongly influenced by the presence or absence of cucurbitacins, the expression of which are controlled by one or a few genes (Agrawal et al., 1999; Balkema-Boomstra et al., 2002; Kennedy and Barbour, 1992).

Then there are the crop-arthropod interactions in which resistance is governed by so-called gene-for-gene interactions (Harris et al., 2003; Kaloshian, 2004). Gene-for-gene resistance is quite common in plant-pathogen interactions. Gene-for-gene resistance is rarer in plant-insect interactions, but appears to be much more common in plant-herbivore interactions involving piercing/sucking and galling herbivores than in interactions involving chewing herbivores. In gene-for-gene interactions, expression of resistance is controlled by specific resistance genes (R genes) in the plant that directly or indirectly recognize the products of corresponding avirulence genes in the arthropod (Walters and Heil, 2007). Perception of the avirulence gene product by the plant triggers a response in the plant that is often highly effective at killing the attacker or otherwise preventing the exploitation of the plant (i.e., the level of resistance is usually very high, often approaching immunity). It should be noted here that the response triggered in the plant by the recognition of the attacking arthropod can involve changes in the expression of hundreds or thousands of genes and in comprehensive changes in plant metabolism (Kaloshian, 2004). Thus, the mechanism by which the plant protects itself (the phenotype associated with resistance) can be very complex, even when expression of the resistance phenotype is regulated by a single gene.

7.2.1.3 Consequences for the Development of Resistant Varieties

One important consequence of the typical nature of polygenic plant resistance is that it makes discovering donors or sources of resistance for breeding purposes a difficult process. The low frequencies of often low levels of resistance in germplasm collections necessitate the evaluation of large numbers of genotypes. This may, in turn, necessitate the development of high-throughput screening methods (often in a laboratory or greenhouse) which require maintenance of plants and insect colonies. These screening techniques must be congruent with the potential mechanisms of resistance. The environmental contingency of plant resistance may complicate this evaluation process, especially in the field, if environmentally-induced resistance obscures the presence of true resistance. Furthermore, insect populations are notoriously variable in space and time, and often manipulation of populations by various techniques is required. For further discussion of the difficulties encountered in the screening process, see Smith and Quisenberry (1994) and Smith (2005).

Incorporation of polygenic resistance into agronomically acceptable varieties by traditional breeding practices is also difficult because not all genes involved in resistance may be transferred during crosses, resulting in dilution of the desired resistance. This is especially problematic when resistance involves many genes and when levels of resistance in the donor are low to moderate. In practice, low frequencies of resistance and low levels of resistance in the germplasm of a crop species often force reliance on unimproved germplasm or wild accessions that possess higher levels of resistance but undesirable agronomic traits. In such cases, genetic linkage between the resistance locus and alleles responsible for undesirable agronomic traits may be extremely difficult to eliminate (linkage drag) (Purrington, 2000). As a result, it may take many years, diverse expertise and considerable infrastructure and resources to develop resistant varieties (Sadasivam and Thayumanavan, 2003).

Yet another consequence of the nature of plant resistance is that resistance and high agronomic quality may be, in some cases, incompatible goals. This may be the case if the mechanisms that impart resistance involve plant traits that are undesirable from an agronomic perspective. This is also the case if resistance involves substantial allocation costs, such that expression of resistance leads to reduced yields or quality. Such direct costs may be quite common: over half of the studies reviewed by Strauss et al. (2002) detected direct costs of constitutive resistance ranging from 6% to 50% or greater reductions in fitness correlates (mostly non-crop species were reviewed). Similarly, many of the recent studies in which fitness correlates were compared in experimentally induced versus non-induced plants have shown that activation of induced resistance is costly to the plant in the absence of herbivores (Strauss et al., 2002; Walters and Heil, 2007).

The challenges associated with introducing single-gene resistance into agronomically acceptable varieties are different. In many cases of single-gene resistance, discrete, often very marked, differences in the phenotypes of resistant and susceptible genotypes facilitate the screening of large numbers of genotypes. Also, the frequency of single-gene resistance in germplasm collections may be higher than the frequency of high levels of polygenic resistance (Harris et al., 2003;

Heinrichs, 1986). Once resistant genotypes are discovered, the task of introducing a single gene into an acceptable agronomic background is simpler than is the introduction of polygenic resistance. However, the expression of single-gene resistance by a plant may, like polygenic resistance, incur costs to the plant (Brown, 2002). Moreover, the use of single-gene resistance is complicated by the development of populations of herbivores (biotypes) that overcome the R gene (Smith, 2005). The biochemical basis underlying the development of resistance-breaking biotypes in insects is not completely understood, but probably involves changes in the production of elicitors (products of avirulence genes) that are involved in the recognition of the attacker by the plant (Harris et al., 2003; Kaloshian, 2004). The development of resistance-breaking biotypes may or may not be a direct response to selective pressures imposed by the widespread planting of resistant varieties (Smith, 2005). The development and spread of biotypes (time to adaptation) can be quite rapid; in the wheat-Hessian fly system, for example, time to adaptation may be as rapid as three to eight years (Harris et al., 2003). The need for the continual development and introduction of varieties with new R genes to combat the development of biotypes is a significant drawback to the use of single-gene resistance.

7.2.1.4 Illustrations from Selected Crops for Insect Resistance

The development and implementation of rice varieties over the past 40 years nicely illustrates many of the points made above. Rice has a relatively large and diverse germplasm collection (Heinrichs and Quisenberry, 1999) which has been used to good effect in breeding programs for arthropod resistance, notably for Asian rice gall midge (*Orseolia oryzae* Wood Mason), brown planthopper (*Nilaparvata lugens* (Stål)), and green leafhopper (*Nephotettix virescens* (Distant)). For these pests, high levels of resistance, conditioned by one or a few genes, are present in the germplasm collections at relatively high frequencies (Heinrichs, 1986; Alam and Cohen, 1998; Heinrichs and Quisenberry, 1999). The relative ease of identifying resistant phenotypes has contributed greatly to the development of efficient screening methods, the relatively high frequency of resistance in the germplasm collections has resulted in the identification of numerous lines with resistance, and the relatively simple genetic basis of resistance has facilitated the breeding of resistant varieties (Heinrichs, 1986). These resistant varieties have been used successfully in Asia over the past 35 years, although development of biotypes has necessitated the development and release of new varieties with different major genes for resistance (Cohen et al., 1997). In contrast to the success in breeding varieties resistant to gall midges and planthoppers, little progress has been made in breeding rice varieties resistant to other major pests such as the yellow stem borer (*Scirpophaga incertalus* (Walker)) and the rice water weevil (*Lissorhoptrus oryzophilus* Kuschel) (Heinrichs and Quisenberry, 1999). For these pests, only low to moderate levels of resistance appear to be present in germplasm collections at relatively low frequencies, and inheritance of resistance to these pests is probably polygenic (Heinrichs, 1986). These features complicate all stages of variety development, as described above.

Efforts to breed potatoes resistant to insects illustrate how introgression of resistance into commercially acceptable backgrounds can compromise crop quality and desired production characteristics. As in most crop breeding programs, potato breeders must create cultivars which are agronomically acceptable and commercially marketable. In potato breeding, market standards specify cultivar selection, and new releases must exceed current yield potential, have superior tuber appearance and fry qualities, and be suitable for long term storage. Efforts to incorporate insect resistance into potato have failed to produce a marketable cultivar. Incorporation of potato leafhopper, *Empoasca fabae* (Harris), resistance based on trichomes has resulted in lower yields due to fewer tubers and poor tuber appearance (Kalazich and Plaisted, 1991). Field resistance to Colorado potato beetle, *Leptinotarsa decemlineata* (Say), and potato leafhopper has been associated with the glycoalkaloid, tomatine (Flanders et al., 1992). Excessive glycoalkaloid levels can cause undesirable flavors and mammalian toxicity (Gregory et al., 1981). The potato cultivar Lenape was removed from the market due to harmful glycoalkaloid levels (Zitnak and Johnston, 1970).

A recent example of the difficulties involved in introgressing resistance from wild species into an agronomically acceptable variety, albeit involving nematode resistance, was provided by Robinson et al. (2007) in cotton. In this example, resistance to the nematode species *Rotylenchulus reniformis* Linford & Oliveira was introduced into cotton, *Gossypium hirsutum* (L.), from the wild cotton species *G. longicalyx* J.B. Hutch and B.J.S. Lee by means of a long (>10 years) and difficult process involving the creation of trispecies hybrids and repeated backcrossing.

The commercial use of many resistant lines and varieties has been limited by lower yield potentials of the resistant varieties relative to widely grown susceptible varieties; this is the case, for example, for soybean lines resistant to Mexican bean beetle (Lambert and Tyler, 1999), wheat cultivars resistant to wheat stem sawfly and cereal leaf beetle (Webster and Kenkel, 1999), and sugar beet lines resistant to nematodes (Zhang et al., 2008). Similarly, yield penalties associated with disease resistance have been reported for many crops (Brown, 2002). However, in many, if not most, of these cases, it is not clear whether low yields are a direct effect of expression of resistance or whether they are due to linkage drag.

7.2.2 *Need for Multiple Pest Resistance and the Problem of Tradeoffs*

Another barrier to the development and implementation of resistant varieties relates to the fact that all crops encounter multiple pests and stresses, not only arthropods of different types but also pathogenic microorganisms, nematodes, weed competitors, etc. In addition to the difficulties inherent in breeding multiple traits into plants, special problems are presented when the mechanisms that impart resistance to one pest lead to susceptibility to others. One well-known example occurs in cultivated cucumber, in which the tetracyclic triterpenoid cucurbitacins impart resistance to many generalist herbivores (e.g., spider mites) but susceptibility to specialist Diabrotica beetles (Agrawal et al., 1999; Balkema-Boomstra et al., 2002).

Another, similar, type of tradeoff, perhaps widespread in occurrence, stems from antagonistic relationships between signal transduction pathways for induced resistance. Activation of the response pathway mediated by salicylic acid (involved in resistance to biotrophic pathogens) is known to antagonize the response pathway mediated by jasmonic acid (involved in resistance to many types of insects and some pathogens). This inhibition by salicylate of jasmonate-induced responses in dicots is mediated by the NPR1 gene (Beckers and Spoel, 2006). According to the currently accepted model, NPR1 ordinary exists in plant cells as an oligomeric complex but is converted to its active, monomeric, form when elevated levels of salicylic acid alter cellular redox states. Monomeric NPR1 inhibits the biosynthesis of jasmonic acid as well as events downstream of jasmonate biosynthesis, and also enters the nucleus, where it activates expression of salicylate-dependent genes via interaction with transcription factors. The inhibitory effect of salicylate on jasmonate-mediated responses at the biochemical level is manifested at the organismal level as a reduction in the magnitude of induced resistance in plants with elevated levels of salicylic acid. For instance, Preston et al. (1999) found that tobacco plants infected with tobacco mosaic virus (and presumably with higher levels of salicylate) had suppressed induction of jasmonic acid and decreased resistance to *Manduca sexta* (L.). Increased susceptibility of TMV-infected tobacco plants was correlated with reduced ability of plants to produce nicotine after wounding. Field grown tomato plants treated with an inducer of systemic acquired resistance had lower expression of a jasmonate-dependent protein and were less resistant to some but not all insect herbivores (Thaler et al., 1999). However, the significance of these tradeoffs to the use of host-plant resistance in IPM are not well understood because the relative importance of induced resistance in structuring communities on plants is not well understood (Agrawal, 2005).

Other types of tradeoffs may exist and may impact the development and use of resistant varieties, including possible tradeoffs between resistance and tolerance (Nunez-Farfan et al., 2007) and between resistance to herbivory and tolerance of stresses (e.g., the presence of competitors; Cipollini, 2004).

7.2.3 *Insufficient Understanding of the Role of Host-Plant Resistance in IPM*

Another major impediment to the increased and more efficient use of host-plant resistance in IPM is an insufficient understanding of the relationship of host-plant resistance to other IPM tactics (Cuong et al., 1997). This point has been raised in broader context by Thomas (1999), who noted that most IPM programs, which in theory involve the strategic combining of two or more tactics, in practice often rely heavily on single tactics. This reliance on single tactics is attributable to a lack of attention to the interactions of component tactics in IPM programs during the development and implementation of IPM programs (and, probably, to the ease by which insect pests have been controlled by insecticides).

Insufficient attention has been given to the integration of host-plant resistance with both insecticides and biological control. The benefits of the use of resistant varieties are often not fully realized in practice because insufficient information (e.g., variety-specific treatment thresholds or rates) is available to convince risk-averse producers to modify their use of insecticides on resistant varieties (Eigenbrode and Trumble, 1994; Teetes, 1994). Similarly, host-plant resistance and biological control have mostly been developed as “parallel but independent” tactics (Cortesero et al., 2000) in the past, with little thought to integrated deployment. Moreover, even in those cases in which compatibilities (or the lack thereof) have been explored, the explorations have mostly consisted of laboratory, greenhouse and small-plot field studies designed to maximize the probability of detecting effects. Although these studies are helpful, verification on a farm-level scale is often lacking in the literature. When information on the combined effects of two or more strategies on a farm-level scale is available, it indicates that the combined use of two or more strategies on a farm-level scale can be more durable than reliance on single tactics; for example, the relative stability of IPM programs against brown planthoppers in some parts of Asia has been attributed to the combined use of moderately or highly resistant rice varieties and the use of insecticides in a manner that preserves populations of predators (Cohen et al., 1997; Cuong et al., 1997).

7.2.4 Lack of Estimates of the Benefits of Host-Plant Resistance in IPM

Yet another shortcoming is the fact that estimates of the economic, environmental, and societal benefits of host-plant resistance are not common (see Wiseman and Webster, 1999). This is a critical lack, as estimates of the benefits of plant resistance are needed to justify continued or increased investment in the development and implementation of resistant varieties, an area of diminishing support over the past few decades (Bradsher and Martin, 2008). Estimating the benefits of plant resistance is a difficult endeavor involving the collaboration, at minimum, of entomologists, economists, breeders, agronomists, and social scientists (Webster and Kenkel, 1999; Wiseman and Webster, 1999). Not surprisingly, then, most of the best estimates of the value of plant resistance have come from systems in which strong, single gene resistance functions as the primary or sole pest management tactic (e.g., Hessian fly; Webster and Kenkel, 1999; Roberts et al., 1988). Much rarer are studies which estimate the value of host-plant resistance (particularly low levels of resistance) in the context of a multi-tactic IPM program (e.g., Buntin et al., 1992; Hansen et al., 2002).

7.3 Keys to Increased Use of Host-Plant Resistance in IPM

7.3.1 Mechanistic Understanding of the Phenotypic Basis of Plant Resistance

Historically, detailed knowledge of the mechanisms underlying plant resistance has not been considered essential to the development and implementation of resistant varieties (Kogan, 1986). However, consistent with the recent emphasis on IPM as a "knowledge-intensive" endeavor (Thomas, 1999), it has become increasingly clear that more effective use of host-plant resistance in IPM will require a more detailed understanding of the mechanisms of plant resistance (i.e., the phenotypic or causal bases of resistance). In this section, we suggest several ways that a greater understanding of the mechanistic basis of plant resistance may contribute to its more effective use in the future. Induced resistance warrants special mention in this context, as rapid advances are being made in our understanding of all aspects of this phenomenon, from recognition of attackers by the plant and consequent elicitation of responses in the plant (Schmelz et al., 2006; Chen et al., 2004) to the molecular, genetic, and biochemical nature of plant responses to the role of induced resistance in structuring communities of herbivores, plants, and natural enemies (Agrawal, 2005).

One area that would likely benefit from increased knowledge of mechanisms is the integration of plant resistance and biological control. Recent research has demonstrated that plants are active mediators of the interactions between herbivores and their natural enemies, for example by providing volatile cues that signal the location of herbivores to natural enemies. Such indirect defenses can strongly reduce the impact of herbivores on plant fitness (Kessler and Baldwin, 2001). However, there are still many gaps in our understanding of indirect defense (Cortesero et al., 2000; Degenhardt et al., 2003). More knowledge of the ways that plant attributes impact natural enemies will facilitate the development of plants that promote the activities of the third trophic level (Cortesero et al., 2000). The development of such plants may be accomplished by genetic manipulation (e.g., of patterns of terpene emission; Degenhardt et al., 2003). However, the development of such plants may also be achievable by traditional breeding practices. Recently, Rasmann et al. (2005) demonstrated that North American and European maize lines, developed by traditional breeding practices, differed in the amount of caryophyllene released from their roots following feeding by Western corn rootworm larvae, and that higher rates of caryophyllene release were correlated with increased attractiveness to an entomopathogenic nematode.

An in-depth characterization of plant resistance may also improve integration with insecticides by enabling the development of treatment recommendations that are appropriate for resistant cultivars (Eigenbrode and Trumble, 1994). For example, the biochemical and morphological traits that contribute to plant resistance are not expressed uniformly by plants in space or time, and hence plant resistance affects the distribution as well as the abundance of herbivores. Soybean aphids (*Aphis glycines* Matsumura) distributed themselves differently on unifoliate leaves and shoot structures of soybean lines that differed in resistance (Hesler and Dashiell, 2007).

Similarly, caterpillar feeding was more concentrated (less dispersed) on a tomato line with reduced ability to mount a response to damage than on a wild-type line, indicating that herbivore-induced responses influenced patterns of herbivore feeding on the more resistant plants (Rodriguez-Saona and Thaler, 2005). Studies such as these are needed for the development of sampling methods that are specific to resistant cultivars.

Detailed characterization of the biochemical and morphological changes associated with constitutive and induced plant resistance may also facilitate the development of resistant varieties by traditional breeding methods. Induced resistance is often broad in its spectrum of activity, and thus may provide insights into those plant traits that confer broad-based resistance. In addition, detailed knowledge of the mechanisms of plant resistance may reveal phenotypic traits that can be used as proxies for the laborious and often destructive process of quantifying resistance during the breeding process.

Research on the elicitation of plant responses and on the signaling pathways underlying induced resistance has already led to the commercialization of several inducers of plant resistance (Leadbeater and Staub, 2007), and the strategic stimulation of broad-based plant resistance via application of elicitors may be a usable tactic in some future IPM programs (Stout et al., 2002).

Finally, a greater understanding of the mechanistic bases of plant resistance may suggest novel targets and novel uses of genetic engineering. The engineering of terpene emission by plants to make them more attractive to natural enemies has already been mentioned. The transfer of R genes from one variety to another (e.g., from a line with poor agronomic traits to an elite cultivar) and even from one plant species to another (e.g., among cereal species) will be a possibility in the near future as more resistance genes for insects are identified (Harris et al., 2003; see below). Detailed knowledge of the interactions of insects and their detoxicative systems with plant secondary metabolites will also reveal targets for genetic engineering. Mao et al. (2007), for example, transformed cotton to express double-stranded RNA specific to a cytochrome P450 gene from *Helicoverpa armigera* (Hubner) involved in detoxifying gossypol. *H. armigera* larvae fed the transgenic plants showed lower levels of P450 transcripts in their midguts (RNA interference) and reduced growth relative to controls. Another potentially useful approach is the "pyramiding" of natural plant resistance with transgenic resistance: expression of a cystatin gene in potato plants with low levels of natural resistance to nematodes resulted in full resistance (Urwin et al., 2003), and a similar strategy (combining natural resistance with transgenic resistance) has been suggested for management of lepidopteran pests in soybean (Zhu et al., 2008).

7.3.2 Increased Application of Modern Genetic Tools

The successful development of resistant varieties by breeding depends upon knowledge of the genetics of a crop plant, a fact that has been recognized since the inception of host-plant resistance as a discipline (Painter, 1951: "...the ease of incorporating genes for resistance into a commercial crop depends partly on the available knowledge of genetics in the crop..." [p. 111, paperback edition]). Thus, dramatic advances in plant genetics over the past two decades have transformed, and will continue to transform, the practice of breeding plants, and have made it increasingly possible to apply a mechanistic understanding of plant resistance (see above) toward the rapid and targeted development of resistant varieties. The sequencing of *Arabidopsis thaliana, Oryza sativa* (L.), and other plant genomes is advancing our understanding of plant-herbivore interactions at the molecular level. The locations, structures and functions of R genes and other genes involved in resistance can now be assessed. Resistance factors, previously uncharacterized, can now be defined through transcription profiling and functional genomics. New information on molecular aspects of plant-insect interactions is accumulating rapidly, and a full discussion of this topic is beyond the scope of this chapter. Here, we will restrict our brief comments to two subjects, the sequencing of R genes and marker-assisted selection.

Only two insect R genes have been sequenced: *Mi-1.2* and *Vat* (Smith, 2005). The *Mi* gene, identified in tomato, provides resistance to three species of root knot nematodes (Roberts and Thomason, 1986), *Macrosiphum euphorbiae* (Thomas) (Rossi et al., 1998), and *Bemisia tabaci* (Gennadius) (Nombela et al., 2003). The *Vat* gene confers resistance to *Aphis gossypii* Glover in melon (Pitrat and Lecoq, 1982). These resistance genes are of the nucleotide binding site-leucine rich repeat (NBS-LRR) class or class II plant resistance gene proteins. The other classes of genes conferring resistance to pathogens are I (*Pto*), III (TIR LZ), IV (*Cf*), and V (*Xa21*). Undoubtedly, insect genes of these classes will be identified in the future. Synteny among plant species has already allowed the comparison of resistance gene conserved motifs to identify resistance gene analogs (RGAs). Sequenced RGAs will lead to identifiable genes which can then be transferred through transgenic technologies into distantly related species and marketable cultivars. Attempts at transforming eggplant with *Mi-1.2* have conferred nematode resistance but not aphid resistance (Goggin et al., 2006).

Advances in plant genomics have increased the ease of incorporating insect resistance factors into commercial crops. Association of resistance(s) with molecular marker(s) allows breeders to directly track the introgression of genes responsible for resistance. By using marker assisted selection (MAS), it is possible to quickly screen large quantities of plant materials and remove progeny lacking the marker prior to testing for phenotypic response (Barone, 2004). As noted above, resistance to insects is typically a polygenic trait, with two or more quantitative trait loci (QTL) related to resistance against a given pest (Nunez-Farfan et al., 2007). MAS can greatly facilitate the transfer of such polygenic traits. In the past, QTLs for insect resistance have been hard to identify due to lack of discrete phenotypic segregation, leading to differences between laboratory and field identified host plant resistance. However, advances in plant genomics, marker technologies, and statistical analyses have made QTL MAS a reality. Accelerated selection and directed breeding made possible by use of MAS is expected to greatly shorten the time from initial selections and release of resistant crop cultivars. MAS has already been shown to be effective in breeding potato resistant to potato leafhopper (Bonierbale et al., 1994), soybean lines resistant to defoliating lepidopterans (Narvel et al., 2001; Zhu et al., 2008), and rice lines resistant to brown planthopper (Jena et al., 2006).

7.3.3 Quantitative Approach to Implementation of Host-Plant Resistance

A final key to increased and more effective use of host-plant resistance in IPM is the adoption of a more quantitative approach to the use of host-plant resistance in IPM. This includes, of course, more quantitative estimates of the economic, environmental, and societal benefits of host-plant resistance in the context of multi-tactic IPM programs, as a means of justifying continued public and private investment in plant resistance research. Another area of particular need is the development of variety-specific recommendations for the use of insecticides on resistant varieties (Teetes, 1994). Variety-specific recommendations can take several forms, including variety-specific thresholds for insecticide applications and variety-specific use rates for resistant varieties. A recent example of the former was provided by Posey et al. (2006), who showed that higher thresholds for initiating insecticide applications against *D. saccharalis* on resistant sugarcane varieties were as effective as lower thresholds on susceptible varieties. An example of variety-specific use rates in peanut was given by Campbell and Wynne (1985), who demonstrated that rates of insecticides could be reduced by as much as 80% on 'NC 6' (a peanut variety with multiple pest resistance) relative to a susceptible variety.

7.4 Conclusion: Prospects for Increasing the Adoption of Plant Resistance in IPM

All IPM programs have a plant-herbivore interaction at their center, and thus plant resistance has rightly been described as the "base from which all management strategies must arise." (Wiseman, 1994). The use of resistant crop varieties is desirable not only for the reductions in pest populations it engenders but also for the reduced dependence on insecticides it allows, with the attendant benefits of reduced environmental impact and reduced interference with biological controls. However, the development of resistant varieties and the use of resistant varieties in IPM programs face many challenges. The development of resistant varieties is hampered by the typically complex genetic and phenotypic nature of plant resistance, especially when resistance to multiple stresses is needed; furthermore, the efficient use of plant resistance in IPM is hindered by lack of past attention to the integration of plant resistance with other tactics. Although significant progress in the development and utilization of resistant varieties has been made in the past with little detailed knowledge of the mechanisms of plant resistance, further progress will depend on a highly detailed, mechanistic understanding of plant resistance at multiple levels of analysis. Fortunately, the availability of increasingly sophisticated tools for investigating the genetic and phenotypic basis of plant resistance is making it possible to achieve such an understanding and to apply that understanding to the development of resistant cultivars. At the same time, development of these varieties must be accompanied by a more quantitative approach to integrating plant resistance into IPM programs and to quantifying the impacts of plant resistance. The combination of a more detailed understanding of the mechanisms of plant resistance, the use of modern genetic tools to apply this understanding to the development of agronomically acceptable varieties, and a more quantitative approach to the implementation of host-plant resistance will allow the full economic and environmental benefits of host-plant resistance to be realized.

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Chapter 8
Biotechnological Interventions in Host Plant Resistance

Aditya Pratap and S.K. Gupta

Abstract Host plant resistance forms an integral part of integrated pest management. Conventional host plant resistance is slow and difficult to achieve due to the involvement of quantitative traits at several loci. However, recent biotechnological interventions have opened up new opportunities for pest control by providing an access to novel molecules, ability to change the level and pattern of expression of genes and development of transgenic varieties with insecticidal genes. Several transgenics have been developed in a number of crop plants including corn, rice, cotton, canola, soybean, tobacco, apple, potato and many others that have genes for δ-endotoxins from *Bacillus thuriengiensis* Berliner. The economic and environmental impact of adoption of such crops has been huge and it has led to a significant reduction in the global environmental impact of production agriculture. However, the reports on the development of insect resistance to the δ-endotoxins from Bt have raised questions on the sustainability of Bt-based pest management strategies. Gene-pyramiding, which comprises stacking of multiple genes and leads to simultaneous expression of more than one toxin in the transgenic variety, has been advocated as one of the solutions though it is also associated with problems such as development of cross- and multiple resistances. Further, possible environmental and ecological impacts, particularly gene-flow and effect on non-target organisms pose more serious questions and need to be addressed properly before the commercialization of a transgenic variety. This chapter focuses on the recent developments in insect-resistant transgenic varieties and their impact as well as the problems associated with them.

Keywords Host plant resistance · Bt · Transgenics · Insect-resistance · Resistance management · Gene-flow

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A. Pratap (✉)
Division of Plant Breeding and Genetics, Sher-e-Kashmir University of Agricultural Sciences and Technology of Jammu, Chatha, Jammu-180 009, India; now at: Crop Improvement Division, Indian Institute of Pulses Research (ICAR), Kanpur 208024, India
e-mail: adityapratapgarg@gmail.com

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8.1 Introduction

Currently, the insect-pest associated losses account to about 14 percent of the total agricultural production. Besides direct losses, indirect losses by pests as vectors of various plant pathogens leading to diseases and additional costs in the form of pesticides applied for pest control were valued at $32.66 billion annually (Allan Woodburn Associates, 2005). There has been a long co-existing relationship between plants and insects and chemical pesticide usage has been the most preferred way to control them. However, these pesticides, while incredibly efficient, are also associated with numerous problems including development of insecticide resistance leading to pest resurgence, emergence of secondary pests, loss of natural enemies, secondary outbreaks due to increased resistance and environmental contamination (Blackmer, 2007). The modern and most promising approach to reduce the damage by insects is by implementing integrated pest management (IPM) that uses the integrated host plant resistance (HPR) in combination with biological, cultural and chemical control methods. Among these, HPR is the most effective and eco-friendly tools for reducing insect damage. IPM relies to a great extent on HPR. Extensive efforts in the past have been done towards innovative techniques, which could develop inbuilt resistance in plants for prominent insect-pests and diseases. Amongst such techniques, the most fruitful has been the genetic transformation leading to the insertion of exotic genes into the plant genome that confers resistance to insects. Bacteria such a *Bacillus thuringiensis* Berliner (Bt) and *B. sphaericus* Neide (Bs) have been successfully exploited for the control of insect-pests in commercial varieties (Gill et al., 1992 and Charles et al., 1996). There are several insecticidal genes such as protease inhibitors, ribosome inactivity proteins, secondary plant metabolites, plant lectins and insecticidal proteins from Bt and several other related species and small viral RNAs which can be used alone or in combination with Bt genes for the development of insect resistant transgenic plants (Hilder and Boulter, 1999).

Insect resistance conferred via the expression of Cry proteins from *Bacillus thuringiensis* is by far the most common trait that has been engineered into the plants and these toxins represent the only insecticidal proteins expressed in the commercial genetically modified (GM) crops till now (James, 2005). Other insecticidal proteins such as protease inhibitors (PI) and lectins, despite having been engineered into different crops, have largely remained in the experimental stage.

The first Bt toxin gene was cloned in 1981 and since then concerted efforts have been undertaken in several crops and consequently, genes conferring resistance to different insects have been inserted into potato, cotton, maize, rice, tobacco, alfalfa, lettuce, soybean, tomato and walnuts etc. (Benet, 1994; Fedrici, 1998; Griffiths, 1998).

As far as the effects of transgenics are concerned on the population dynamics of target and non-target insects, it resembles with the plants with conventional HPR (Luginbill and Knipling, 1969). However, there is a need to understand the natural population regulation of the target pest, assess the field performance of insect resistant cultivars under diverse environmental conditions, determine the long-term effects of resistant cultivars on the insect populations, and determine the level of adoption of insect-resistant transgenic cultivars before their active deployment for HPR (Sharma and Ortiz, 2000).

8.2 Mechanisms of Development of HPR

Mechanisms of resistance were grouped into three main categories by Painter (1951) viz., non-preference, antibiosis and tolerance. Among these, antibiosis and tolerance are the properties of the host plant whereas, non-preference is the reaction of a particular insect towards a plant and not a property of host plant, which was later described as antixenosis by Kogan and Ortman (1978). Therefore, antixenosis is a mechanism, which includes physical, morphological and structural qualities that interfere with the behavior of the insect such as mating, oviposition, feeding and feeding ingestion. As a resistance mechanism, antixenosis acts as a structure barrier, which affects the insect behavior in selecting their host. Various plant organs such as trichomes and surface waxes, chemical constituents of plants such as sugars, amino acids and phospholipids and repellents and deterrents offer barriers which affect the insect behavior in selecting their hosts. Trichomes provide barrier that prevents small arthropods landing onto the plant surface and prevent their movement and feeding (Goertzen and Small, 1993). Trichome-based antixenosis has been reported in many cultivars in cotton which are resistant to the whitefly, *Bemicia tabaci* (Gennadius) and leafhopper of genus Empoasca (Butler et al., 1991). Similarly, leaf pubescence also contributes to the feeding antixenosis of some cultivars of soybean to the cabbage looper, *Trichoplusia ni* Hubner (Khan and Saxena, 1986). A layer of surface waxes over epicuticle protects plants against desiccation, insect predation and disease spread. Plant waxes, which are mainly constituted of alkanes, may physically prevent the movement of insects across leaf surface. Insects possess sensory apparatus that can detect primary and secondary plant compounds at the plant waxes (Panda and Khush, 1995). Stok (1980) reported that *Brassica oleracea* cultivars that don't have heavy wax bloom are more attacked by mustard beetle than those that have heavy bloom.

Other preformed plant defense compounds are repellents that hinder the contact between the insect and the substrate. Repellents of rapeseed have shown an avoidance response behavior by saw-toothed grain beetle-*Oryaephilus surinawensis* (Watson and Baron, 1995). At the same time, insect-pest deterrence by allelochemicals exists across a broad taxonomic range of plants. Allelochemical compounds which lead to deterrence are alkanoids, flavanoids, terpenes, lactones and phenols (Smith, 1989).

Tolerance on the other hand, is the ability of host plant to withstand an insect population sufficient to damage the susceptible plants and is generally attributed to plant growth and vigor, resistance to lodging and shattering, compensation by neighbouring plants, and regeneration of the damaged tissues. As such, tolerance does not have any adverse effect on the inset populations and it also does not provide a selection pressure. Therefore it is useful in preventing the development of new insect biotypes (Panda and Khush, 1995).

Antibiosis is the adverse effect of the host plant on the biology of the insects and their progeny and usually starts with the ingestion of a plant part by the insect. The insects feeding on resistant plants may infest antibiotic symptoms varying from acute or lethal to subchronic and chronic. These symptoms may appear due to various physiological processes, viz., presence of toxic substances, absence or insufficient amount of essential nutrients, presence of antimetabolites, nutrition imbalances and enzymes adversely affecting food digestion and utilization of nutrients (Kogan, 1982). The most common symptoms on insects due to antibiosis include adverse effects on the nutritional physiology of the insect including consumption, assimilation, utilization and subsequent allocation for reproduction (Ananthakrishnan et al., 1994).

8.3 Transgenics Versus Conventional HPR

HPR is an ecologically sound, economically practical, socially acceptable and environmentally sustainable strategy, which has been classified as genetic resistance and induced resistance. Information about genetic resistance to insects contributes to the development of plant varieties with a broad base for insect resistance, which may help in reducing the development of insect biotypes. On the other hand, induced resistance, which is the qualitative or quantitative enhancement of the defense mechanism of a plant against pests in response to external physical or chemical stimuli, is a non-heritable resistance, wherein the host plants are induced to impart resistance to overcome the pest infestation. In-built HPR to insects in crop plants is an attractive and practical concept in integrated pest management and historically, the target has been set on this strategy by the breeders globally. However, it can not be viewed as a stand-alone IPM strategy. In the past, HPR traits such as okra leaf (Thomson, 1994) have made significant contributions to reducing pesticide usages in cotton, but these have relied upon mainly reducing the preference for cotton as a host for insect-pests rather than killing the pests.

Conventional HPR involves quantitative traits at several loci leading to a slow progress, which is also difficult to achieve (Sharma et al., 2000). The situation is further complicated when desirable genes for resistance are not available in cultivated or related species and we have to search for such genes among distant relatives. In such cases, it is extremely difficult, rather sometimes impossible to accomplish gene transfer through conventional hybridization due to various genetic and crossability barriers. Even where the genes are available in it or related species in intense form, conventional breeding for pest resistance makes only small incremental improvements in the tolerance of new varieties to insect feeding or damage, and that too takes much time due to recurrent breeding cycles. Consequently, conventional HPR slows down the rate of increase of pest populations and exposes the pests for prolonged periods to natural enemies (Sharma, 1993). However, biotechnology has opened up new vistas for pest control by providing access to novel molecules, ability to change the level and pattern of gene expression and development of transgenics with insecticidal genes. Transgenics developed through the science of biotechnology have a potential to significantly increase the genetic component of IPM through the development on insect-resistant cultivars with very strong in-built insecticidal properties, comparable to those of chemical pesticides. With the development of genetic transformation techniques, it has become possible to bring about quick and dramatic improvements in the tolerance to many Lepidopteran and other insect-pests. As a result, much emphasis is now placed on the transgenic resistance to pests, particularly in crops like cotton, corn and rice where the Bt genes represent a major step in the direction of HPR. Any change to the plant that makes it less attractive to pests or more tolerant to the damage will only enhance the value of genetically engineered traits by providing a strong, more stable basis on which to manage these genes (Fitt et al., 2002). Insecticidal genes such as Bt, trypsin inhibitors, lectins, ribosome inactivating proteins (RIPs), secondary plant metabolites, vegetative insecticidal proteins and small RNA viruses can be used alone or in combination with Bt genes that have been exploited most till now for the development of transgenic insect resistant plants through biotechnological methods.

8.4 Mode of Action of Bt Crops

Bacillus thuringiensis is a gram positive bacterium, produces crystalline inclusions during sporulation, which consist of either one or a subset of related crystal (Cry) proteins (Maddox, 1994; Ferry et al., 2004). These Cry proteins are highly insecticidal in nature and are dissolved in the midgut of a susceptible insect species, which is alkaline in nature, releasing proteins known as δ-endotoxins. These crystalline prototoxins are inactive until they are solublized by the gut proteases (Tojo and Aizawa, 1983; Gill et al., 1992; Milne and Kaplan, 1993). Once activated, the toxin interacts with an appropriate midgut epithelial cell receptor and gets inserted into the midgut plasma membrane, leading to the lesion formulation and production of pores that disturb the osmotic balance leading the cells to swell, and eventually lyse and as a result, the larvae stop feeding and die (Hofte and Whiteley, 1989; Schnepf et al., 1998; de Maagd et al., 2001; Frey and Van Rie, 2002; Shelton et al., 2002). The lepidopteran insect midgut is alkaline in nature and the pores probably permit the leakage of K^+ ions leading to the disruption of membrane potentials (English and Slatin, 1992; Knowles and Dow, 1993). This consequently leads to the midgut necrosis, degeneration of pleiotropic membrane and epithelium, and finally to septicemia (Sneh and Schuster, 1981; Salama and Sharaby, 1985). The highly specific insecticidal activity exhibited by the Bt Cry proteins is influenced by the presence of high affinity toxin binding receptors in the guts of different insects and also the difference in solublization or processing efficiency of endotoxins in the midguts of insects (Maddox, 1994; Knight et al., 2004).The difference in the extant of solublization of the Bt toxins also explains the difference in toxicity of various proteins (Meenakshisundaram and Gujar, 1998) and a reduced solubility could lead to reduced insect resistance to Bt proteins (McGaughey and Whalon, 1992).

8.5 Transgenic Crops with Bt Gene

Considerable progress has been made in the development of transgenic crops with resistance to the target pests over the past one and a half decade. Undoubtedly it is the Bt gene that has been most exploited for the development of transgenic insecticidal plants and a number of vectors have been developed for the delivery of the gene of interest into the target crop plants. *B. thuringiensis* is an endospore forming soil bacterium characterized by the presence of insecticidal protein crystals (Cry protein) within the cytoplasm of the sporulating cell, each protein having selective toxicity against the different groups of arthropods. Bt genes have been engineered into a large number of plant species such as maize, cotton, potato, tomato, brinjal, rice and oilseed rape (Ely, 1993; Shelton et al., 2002; de Maagd, 2004). The first transgenic tobacco plants with Bt were produced in 1987 (Barton et al., 1987; Fischhoff et al., 1987; Vaeck et al., 1987), which led to 20 percent mortality of tobacco hornworm (*Manduca Sexta* Johannsen) larvae. These plants expressed full length or truncated Bt toxin genes (Cry 1A) under the control of constitutive promoters. This was closely followed by a series of other experiments with marginal success in the increased gene expression (Perlak et al., 1990; Carozzi et al., 1992). Successful control of pink bollworm [*Petinophora gossypiella* (Saunders)] was achieved in transgenic cotton (Wilson et al., 1992). Wong et al. (1992) produced transgenic tobacco plants by placing the FM Cry 1A gene under the control of *Aradopsis thaliana* small subunit promoter with its chloroplast transit peptide sequence and these plants recorded 10 to 20 fold increase in Cry1A(c) m RNA and proteins as compared to gene constructs with CaMV 35S promoter with duplicated enhancer region. Simultaneously, synthetic Cry III genes were expressed in tobacco and potato plants for the control of Colarado potato beetle (*Leptinotarsa decemlineata* Say) (Perlak et al., 1993).

Transgenic Bt-potato plants expressing Cry3Aa to control the Colorado potato beetle had been commercialized from 1996 to 2001. However, these had to be withdrawn from the market due to fewer acceptances among the consumers and also due to the introduction of a novel insecticide which was able to control the beetle as well as aphids (Shelton et al., 2002). Svab and Maliga (1993) were successful in expressing Cry 1A gene in tobacco chloroplasts using chloroplast transformation vectors and microprojectile bombardment. Similarly, insect resistant tobacco and tomato plants expressing Cry 1A(b) and Cry 1A(c) genes have also been developed (Van der Slam et al., 1994). Transgenic maize with Cry 9c, a protein from *B. thuriengiensis* ssp. *Tolworthi*, recorded an effective control of European corn borer (*Ostrinia nubilalis*) (Jansens et al., 1997). Arencibia et al. (1997) developed transgenic sugarcane plants using a truncated Cry1Ab gene under the control of CaMV 35S constitutive promoter. These plants exhibited significant larvicidal activity against the neonatal larvae of sugarcane borer (*D. saccharates*). Truncated Cry 1A(b) gene has also been introduced into several rice cultivars (Datta et al., 1998) leading to upto 100 percent mortality of the yellow stem borer (*Scirpophaga incertulas* Walker) in transgenic plants. Maqbool et al. (1998) transformed two rice cultivars, Basmati 370 and M7, by using Cry 2A gene against the yellow rice stem borer and leaf folder. Successful expression of Bt genes has also been obtained in tomato (Delannay et al., 1989). Selvapandian et al. (1998) transformed tobacco plants using Cry 1Ia5 insecticidal toxin from a Bt strain, which was effective against *H. armigera* (Hubner).

In China, several insect-resistant transgenic rice lines have been developed and field-tested (Li et al., 2005b). Some of these contain a single insecticidal Bt gene, the prominent among them being, Kemingdo (KMD) (Shu et al., 2000), Cry 1Ab/1 Ac fusion gene in hybrid line Bt Shanyou 63 (Tu et al., 2000) or Cry 2A (Chen et al., 2005a,b). Others are pyramided with dual insecticidal genes of modified CpTi (Cowpea Trypsin Inhibitor) and Cry 1Ac in MSA/MSB (Zhao et al., 2004), that have different binding sites and insecticidal mechanisms with increased potential to delay insect resistance development (Zhao et al., 2003). Similarly, some transgenic rice lines were stacked with other types of genes, including Bar for herbicide tolerance (Zhu et al., 1999; Yao et al., 2002) and Xa 21 for disease resistance (Wang et al., 2002a).

Bt-maize with Cry 1Ab gene to control the European corn borer was also developed, which has also shown to be effective against various other lepidopteran pests such as *Sesamia nonagrioides* Lefebvre, *Spodoptera littoralis* Biosduval and *Helicoverpa zea* Boddie (Pilcher et al., 1997; Gonzalez-Nunez et al., 2000; Dutton et al., 2005).

8.6 Strategies for Resistance Management Using Transgenics

The possibility of insects overcoming HPR poses a serious challenge. In any case, a breeder will imagine it to be the last thing to happen to his variety. Unfortunately, most of the genetically engineered Bt crop varieties express only one toxin gene and therefore are devoid of the complexity of Bt formulations available commercially. Further, the insect population is subject to a heavy and continuous selection pressure due to uninterrupted production of a specific type of toxin by the plants and exposure of the insects to the Bt toxins throughout their feeding cycle. Consequently resistance to Bt toxins is developed and it poses a grave risk to their sustainable use in agriculture (Frey and Van Rie, 2002; Ru et al., 2002; Gahan et al., 2005). With the development of resistance to Bt toxins, the value of microbial insecticides based on Bt proteins will diminish due to reduced sensitiveness of the target pests to Bt formulations (Sharma and Ortiz, 2000). For example, Diamondback moth (*Plutella xylostella* Linnaeus) has already developed field resistance to Bt and this is due to a reduction in toxin binding to gut receptors (Shelton et al., 2002; Kain et al., 2004). This will have a direct bearing on the way farmers use broad-spectrum herbicides and consequently upon environment and indirectly on human beings and other living organisms.

Incidentally, most of the transgenic plants have Bt genes under the control of cauliflower mosaic virus (CaMV 35S) constitutive promoter and since in this system toxins are expressed in whole plant, the target insects may develop resistance. At least at laboratory level, many insect species have been reported to develop resistance to Bt genes, particularly in Lepidoptera (Tabashnik, 1994). Therefore, there is an urgent need to develop strategies for the development and effective deployment of transgenic crops in a sustainable way with a special emphasis on minimizing the rate of development of resistance in the target insect populations to the target genes. This could be achieved through use of resistance management strategies since the beginning, gene pyramiding, gene deployment, synthetics, refugia, control of alternate hosts, use of planting window and above all, integrated pest management (Sharma and Ortiz, 2000). All these strategies are relevant to conventional HPR and hold equally good for the transgenic crops as well.

8.6.1 Gene Pyramiding

Gene pyramiding entails the simultaneous expression of more than one toxin in a transgenic plant (Shelton et al., 2002). The logic behind gene pyramiding in the transgenic crops is the same as the ancient practice of using a mixture of genotypes or spraying a mixture of insecticides on a single variety to control an array of insects. However, sometimes, this strategy has lead to a faster development of resistance in the insect species as a result of intense selection pressure. Also in transgenics, many of the Bt genes are either too specific or are mildly effective in pest control (Sharma and Ortiz, 2000). Further, some of the insect species are insensitive to some of these genes. In such a situation, gene pyramiding has been recognized as a lasting Bt resistance management strategy and operates on the principle of delaying the evolution of insect populations resistant to the target genes by the deployment of an array of genes that produce different types of toxins into the same plant at the same time.

Bt gene pyramiding strategy is based upon three assumptions. The first assumption is that the insects showing resistance to one toxin can be effectively controlled by another toxin produced in the same plant by other gene. The second one is that the strains resistant to two toxins with independent actions cannot emerge selection pressure with one toxin alone and the third assumption is that a single gene will not confer resistance to two toxins that are immunologically distinct and that have different binding targets (Gahan et al., 2005; Manyangarirwa et al., 2006). Considering the above three assumptions, gene pyramiding can be done to improve the durability of insect resistant transgenic crops through multigene resistance. For this, several genes such as trypsin inhibitors, vegetative insecticidal proteins, secondary plant metabolites, plant lectins, small RNA viruses and enzymes selectively toxic to insects can be deployed alongwith Bt genes. As a matter of fact, gene pyramiding offers effective control because an insect species can not simultaneously evolve resistance to number of toxins produced by different genes deployed in pyramiding since that would require simultaneous and independent mutational events in a gene encoding the receptors and practically therefore, the more is the number of genes deployed, the less is the possibility of development of resistance. For example, the cotton variety Bollgard®II has two toxins viz., Cry 1Ac controlling tobacco budworm and pink bollworm, and Cry 2Ac, controlling corn earworm (Jackson et al., 2003; Purcell et al., 2004). The second generation dual Bt gene cottons, Bollgard II® with Cry 1Ac together and Widestrike™ with Cry 1Ac and Cry 1F express two Bt endotoxins and were introduced to increase the control of

H. zea, which was not satisfactorily controlled by Cry 1A gene alone (Bates et al., 2005; Gahan et al., 2005). Similarly, Cry 1Ac and Cry 1F can be deployed together in transgenic plants for effective control of *H. armigera* (Chakrabarti et al., 1998). Activity of Bt in transgenic plants has been shown to be enhanced by serine protease inhibitors (MacIntosh et al., 1990) and also in combination with tannic acid (Gibson et al., 1997). It has also been demonstrated that potato transgenic lines with Cry V-Bt gene, which is specifically toxic to Coleoptera and Lepidoptera, and PVYocp gene, a potato Y potyvirus Yo coat protein gene (Li et al., 1999), exhibited increased resistance to potato tuber moth and PVY infection than non-transgenic line 'Spunta'.

While employing the gene pyramiding strategy, the fact that the insect populations have enormous genetic plasticity and dynamism must not be ignored. Further, in many insect populations, there may be a proportion of resistant alleles which may witness an increase in homozygous individuals over space and time (ffrench-Constant et al., 2000). Also since in most of the Bt genes, Bt toxin is driven by the same CaMV 35S constitutive promoter, there is a continuous production of toxins in all parts of the target plant, thereby conferring a continuous and intense selection pressure on the insects and therefore, there is always a potential for the development of resistance to at least some of the pyramided genes. Practically, one toxin can bind to several sites, and this can also lead to the development of cross-resistance or multiple resistance of an insect, particularly in cases where it was not previously exposed to the original toxin, which is especially effective against the insect. It has been reported that resistance can also develop in insects as a result of disruption of any of the steps in the mode of action of Bt toxins, viz., ingestion, solublization, proteolytic processing, membrane insertion, activation of protoxin to toxin, binding to receptors, crossing from peritropic membrane, pore formation and lysis of midgut cells (Karim et al., 2000, Manyangarirwa et al., 2006), besides alterations in other biochemical pathways in Bt toxin metabolism in insects.

8.7 Environmental and Ecological Impacts

There is an increasing concern that engineered insect-pest resistance genes or synthetic resistance genes could be passed to weed populations and present hazards. The environmental and ecological concerns of immediate attention through the use of transgenics include their effects on population dynamics of target and non-target insects; evolution of new insect biotypes; insect sensitivity, gene-escape into the environment, secondary pest problems, effects on non-target organisms and influence on natural enemies (Sharma and Ortiz, 2000).

8.7.1 Gene Flow

In GM crops, the plants may naturally hybridize with the sexually compatible species and have an impact on environment through the production of hybrids and their progeny. This could have a serious impact on the biological diversity available outside.

Escape of resistance genes into the wild relatives may lead to the faster development of resistances in insect populations. The gene-flow through hybridization between a GM and non-GM plant depends upon a host of factors viz., the distance travelled by the pollen of the GM crop and the distance of the GM crop from a non-GM crop; the synchrony of flowering between the GM crop and the recipient species; the sexual compatibility between both the species, and the ecology of the recipient species. For example, in cotton, it has been observed that the pollen dispersal from transgenic cotton is low, but it increases with an increase in the size of the source plot (Llewellyn and Fitt, 1996). Further, the consequences of transfer of the novel genes from GM crops to weeds or non-GM crop plants also depends upon the nature of the novel gene and biology and ecology of recipient species (Dale et al., 2002).

The transfer of characteristics such as resistance to particular pests and diseases or tolerance to stressful conditions like drought could offer the weed species a selective advantage (Dale et al., 2002). Ellstrand et al. (1999) reviewed the possibilities of hybridization between oilseed rape and the related species. Ramachandran et al. (2000) investigated the competitive ability of insect resistant transgenic oilseed rape varieties compared with non-transgenic oilseed rapeseed mixture. The GM variety was competitively superior when the two varieties were subjected to Diamondback moth selection pressure in greenhouse as well as in fields. Similarly, Stewart et al. (1997) reported the likelihood of increased fitness in oilseed rape varieties expressing Bt under certain conditions. Behavioral differences between the resistant and susceptible insects have also been reported to affect gene-flow between the transgenic and the adjacent non-transgenic crops. It is a general assumption that the escaped genes are likely to have an environmental impact only if the novel trait acquired through them confers greater environmental fitness on the crop plant or its sexually compatible relative. However, a gene that confers reduced fitness on a plant in a wild habitat could adversely affect wild sexually compatible natural populations through recurrent pollinations by a GM crop (Gidings, 2000).

8.7.2 Effect on Non-Target Organisms

Controversy about the benefits and ecological impacts of transgenic crops have existed since their advent and became still more controversial after commercialization of the Bt crops was started in 1996. However, on the basis of the field and restricted trials, the transgenic rice did not negatively impact the arthropods as determined by the guild dominance, family composition, diversity index, evenness index and species richness (Chen et al., 2003b,c; Liu et al., 2005). Also, no significant difference on the feeding and oviposition behavior of the non-target insects *Nilaparvata lugens* (Chen et al., 2003a,c), insect development (Wang et al., 2002b) or population dynamics (Zhou et al., 2004) was detected. Also, the Bt rice did not adversely affect predation and functional response of the predatory natural enemies compared with non-Bt rice (Bai et al., 2005).

Non-target organisms have to ingest the insecticide proteins expressed by insect-resistant GM crops in order to be affected directly. Ingestion could occur through several ways: by feeding on plant material, by feeding on insect or their larvae that have previously fed on insect-resistant (IR) GM crops, and via exposure through the environment eg. when toxins from residues persist in the soil (Groot and Dicke, 2002). As far as Bt toxins are concerned, most of them are specific to insects only as they are activated in the alkaline medium of the insect midgut (Sharma and Ortiz, 2000). However, Bt toxins can have harmful effects on insects though such effects are comparatively less severe than the broad-spectrum insecticides.

In case of honeybees, the main insect species known to act as pollinators in various crops, pollen feeding represents the most likely route of exposure to Bt toxins for adult honeybees (Malone and Pham-Delegue, 2001). Honeybees could collect pollen from large sources of plants including maize and rapeseed-mustard and the potential hazard of Bt will depend upon the amount of toxins expressed in the transgenic pollen. Picard Nizou (1997) assessed the impact of genetically modified oilseed rape on environment, expressing genes conferring resistance to insects and fungi [Cowpea trypsin inhibitor (CpTi) for insects, chitinase for fungi, and β-1,3-glucanase]. Chitinase did not affect the learning performance of honeybees, β-1,3-glucanase affected the level of conditioned responses, with the extinction process occurring more rapidly, increase in concentration and CpTi exhibited marked effects in both conditioning and testing phases at higher concentrations. In general, transgenic rapeseed does not appear to have harmful effects on the lifespan and behavior of honeybees, though it is required to be confirmed by further testing (Pham Delegue and Jouanin, 1997).

Since Cry 1Ab is selectively toxic to Lepidoptera, pollen flow from Bt fields could have adverse effects on moths and butterflies if their larvae feed on the host plant having Bt pollen on them. The much talked about story of Monarch butterfly (*Danas plexippus*) and Bt maize pollen (Losey et al., 1999) had led to public debate as to the potential risks and environmental effect of Bt maize. Though the immediate laboratory studies confirmed the doubts, the extensive field investigations suggested that the exposure was not to the dangerous levels in the field. An examination of an overlay map showing the distribution of endangered Lepidopteran species and maize production areas also revealed that the listed Lepidopteran species did not occur in agricultural areas where maize is grown besides the fact that maize is not considered a host plant for these species. Interestingly, the effects of Bt-maize on non-target herbivorous insects have been assessed less frequently than those on other non-target pests, possibly due to the fact that these are considered as potential pests, particularly those species that are found in the crops and are generally associated with yield losses. Cry 1Ab has been observed to be effective against various other lepidopteran species that are not the primary target (Pilcher et al., 1997; Dutton et al., 2005). However, there is a need for information on long-term effects of Bt genes on non-target organisms including birds, human beings and other animals.

8.7.3 Development of Resistance and Evolution of New Insect Biotypes

Though there is no direct relationship between the evolution of new insect biotypes and deployment of insect-resistant cultivars, it could happen in any case i.e. in varieties with conventional HPR as well as the GM varieties with insect-resistance genes. Farmers and researchers have been continuously struggling to compete with a pest's ability to adapt itself to the techniques used to control it. Several recent studies have shown that the pests can also develop resistance to Bt toxins produced by the pesticide sprays containing *B. thuriengiensis* under field and laboratory conditions (Gould, 2000). Though till date, pest resistance to GM Bt crop has not been reported in any crop under field conditions, it has definitely been observed under laboratory conditions (Tabashnik, 1994; Shelton et al., 2002). Several studies have reported the development of resistance to Bt in different insect species.

The first report of insect resistance on Bt was in the year 1985 (Harris et al., 1998). The Diamondback moth *P. xyllostella* developed high levels of resistance due to the repeated use of Bt (Schnepf et al., 1998; Frey and Van Rie, 2002). Bt resistant populations have been developed in laboratory screening in many lepidopteran and coleopteran insects. A strain of *H. virescens* selected for resistance to Cry1Ac under laboratory conditions was cross resistant to Cry 1Aa, Cry 1Ab, Cry 1Ba, Cry 1Ca and Cry 2Aa toxins (Karim et al., 2000). Similarly laboratory selected *Ostrinia nebularis* strains also developed resistance to several individual Bt protoxins after repeated exposure to Dipel (*B. thuriengiensis* var. Kurstaki) (Li et al., 2005a). Laboratory screening has resulted in the development of Bt resistant populatins in Lepidoptera (*Heliothis virescens* Fabricius, *Spodoptera exigua* Hubner, *S. littoralis* Boisdual, *Trochoplusia ni, P. xylosella, Ephestia kuahniella* Zeller, *Cadara cautella, Homoeosoma electellum, Plodia interpunctella* Hubner *and Christoneura fumiferana*), Coleoptera (*Chrysomella scripta* and *Leptinotarsa decemlineata* Say) and Diptera (*Aedes aegypti, Culex quinquefasciatus* Say, *Drosophila melanogaster* and *Musca domestica*) (Tabashnik, 1994; Sharma and Ortiz, 2000). However, in such cases, the gene pyramiding strategy is expected to delay the evolution of resistance much more effectively than the presence of a single insecticidal gene though cross-resistance among the toxins is a potential risk to the use of pyramids. Therefore, it has been suggested that 100 percent mortality of susceptible insects on the GM crop is more critical to delaying the onset of resistance (Roush, 1998).

Also there are many species of insects that are not susceptible to the already deployed Bt genes. Particularly those IR GM crops where only one Bt toxin gene is employed for resistance control of less sensitive or non-sensitive species pose major challenge. In such cases, there is a need to broaden the pool of genes which can be effective against the insects that are not sensitive to the currently available genes (Sharma and Ortiz, 2000).

8.8 Adoption and Impact

The transgenic crops for all traits are grown in 17 countries on a total area of 81 million ha (Zehr, 2006) (Table 8.1). Among these, the insect-resistant GM crops were first introduced commercially in 1996 in the US on an area of 730,000 ha (James and Krattiger, 1996). Since then, these crops have provided benefits to the growers and also reduced the use of insecticides (Shelton et al., 2002; James, 2005), thereby

Table 8.1 Global Area of Biotech Crops in 2007: by Country (Million Hectares)

Rank	Country	Area (m ha)	Biotech Crops
1*	USA*	57.7	Soybean, maize, cotton, canola, squash, papaya, alfalfa
2*	Argentina*	19.1	Soybean, maize, cotton
3*	Brazil*	15.0	Soybean, cotton
4*	Canada*	7.0	Canola, maize, soybean
5*	India*	6.2	Cotton
6*	China*	3.8	Cotton, tomato, poplar, petunia, papaya, sweet pepper
7*	Paraguay*	2.6	Soybean
8*	South Africa*	1.8	Maize, soybean, cotton
9*	Uruguay*	0.5	Soybean, maize
10*	Philippines*	0.3	Maize
11*	Australia*	0.1	Cotton
12*	Spain*	0.1	Maize
13*	Mexico*	0.1	Cotton, soybean
14	Colombia	< 0.1	Cotton, carnation
15	Chile	< 0.1	Maize, soybean, canola
16	France	< 0.1	Maize
17	Honduras	< 0.1	Maize
18	Czech Republic	< 0.1	Maize
19	Portugal	< 0.1	Maize
20	Germany	< 0.1	Maize
21	Slovakia	< 0.1	Maize
22	Romania	< 0.1	Maize
23	Poland	< 0.1	Maize

*13 biotech mega-countries growing 50,000 hectares, or more, of biotech crops;
Source: Clive James, 2007

having a positive impact on the environment. Since 1996, the use of pesticides was reduced by 172 million kg (a 6% reduction) and the overall environmental footprint from GM crops was reduced by 14 percent (Brookes and Barfoot, 2005).

Bt rice has a potential to eliminate yield losses caused by Lepidopteran pests of upto 2-20 percent of Asia's annual rice yield of 523 million tons (High et al., 2004). Deployment of Bt cotton, corn and rice together has resulted in significant decreases in insecticide use in the developed and developing countries and increases in yield and profitability (Shelton et al., 2002; Huang et al., 2002b, Qaim and Zilberman, 2003). However, debate about their commercial introduction has led to the questions about their potential impacts on economy, environment and the farmers (Fig. 8.1) though it is true that the adoption of GM crops has contributed to a significant reduction in the global environmental impact of production agriculture, besides significantly increasing farm income benefits across the globe (Table 8.2). As a result, the global adoption of Bt cotton had risen dramatically from 800,000 ha. in 1996 to 5.6 million hectares (alone and staked with herbicide tolerant canola) in 2003 (James, 2003). This further rose to 26.3 million ha. worldwide in 2005 (James, 2005). It suggests that the transgenic crops have been spreading more rapidly than any other commercial agricultural technology in history, obviously the farmers perceiving significant advantages in growing them. This becomes more important when 38 percent of the global transgenic area is accorded for by the

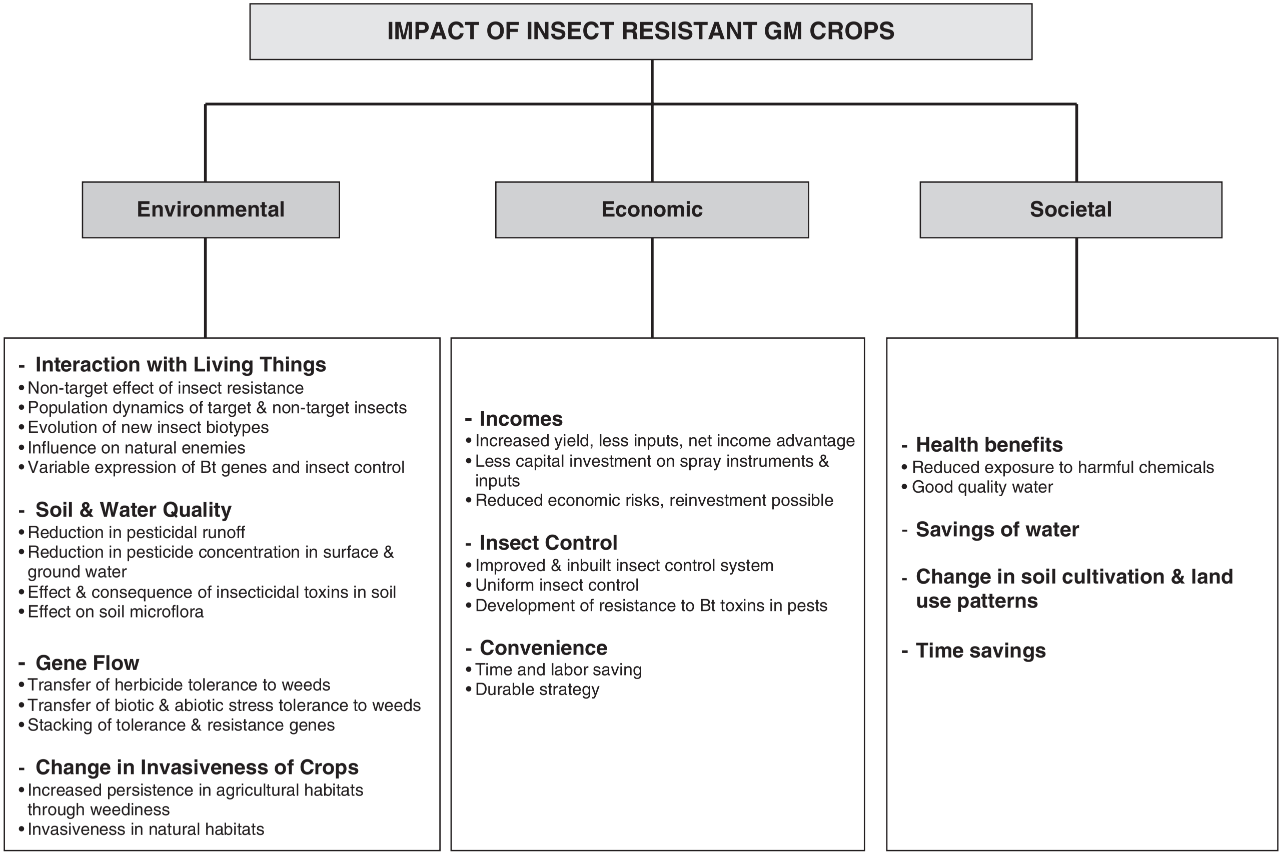

Fig. 8.1 Potential environmental, economic and societal impacts of insect resistant transgenic crops

Table 8.2 Farm income benefits from GM crops in selected countries, 1996–2004 (US$ million)

Country	GM HT Soybean	GM HT maize	GM HT cotton	GM HT canola	GM IR rice	GM IR cotton	Total
United States	6,371	564	746	96	1626	1,301	10,704
Argentina	9,965	NA	NA	NA	120	16	10,101
Brazil	829	NA	NA	NA	NA	NA	829
Paraguay	80	NA	NA	617	NA	NA	80
Canada	55	16	NA	NA	119	NA	807
South Africa	0.8	0.2	0.01	NA	44	11	56.01
China	NA	NA	NA	NA	NA	4,160	4,160
India	NA	NA	NA	NA	NA	124	124
Australia	NA	NA	NA	NA	NA	70	70
Mexico	NA	NA	NA	NA	NA	41	41

Adopted from: Brookes and Barfoot, 2005, NA: Not applicable

developing countries (James, 2005), despite continuing controversies surrounding them. In 2002, insect-resistant Bt cotton was being grown commercially in the United States, Argentina, Mexico, South Africa, Australia, Indonesia, India, Colombia and China. Although large acreages were there in United States and Australia deriving significant values from Bt cotton, but the majority of farmers who adopted Bt cotton are in the developing countries (Purcell and Perlak, 2004). A number of studies have examined the significant social, environmental and economic benefits derived from growing Bt cotton as well as other insect-resistant GM crops (Ismael et al., 2002a,b; James, 2002, 2003; Pray et al., 2002; Purcell et al., 2004; Peshin et al., 2007). James (2002) reported yield advantages from Bt cotton to the tune of 5–10 percent in China, more than 10 percent in the United States and more than 20 percent in other countries.

In India, Bt cotton was approved for cultivation in 2002. Since than, the Bt cotton acreage increased manifolds, the area being 3 million ha in 2006–07 (Peshin et al., 2007), which further soared to 6.2 million hectares grown by 3.8 million small and resource poor farmers in 2007 (James, 2007). As many as 20 insect-resistant cotton varieties had been approved by the biosafety authorities. At present, Bt cotton is grown in eight states in India including Madhya Pradesh, Gujarat, Maharashtra, Andhra Pradesh, Karnataka, Tamil Nadu, Punjab and Haryana (Peshin et al., 2007). Qaim (2003) and Qaim and Zilberman (2003) found that in field trials in India, average yields from Bt cotton hybrids were 80 percent greater than non-Bt hybrids, though the later farm level research found comparatively smaller but significant yield advantages (Bennet et al., 2004a). This was observed even for unofficial varieties (Morse et al., 2005). For Bt cotton, farmers in India have observed a reduction of upto 70 percent in the use of insecticides, thereby leading to substantial savings in the expenditure on insecticides. However, a subsequent study on farm level data across four states in India by Qaim et al. (2006) found large net gains from the adoption of Bt cotton at the national level, although significant variation was reported across the states. One state, Andhra Pradesh, experienced negative results.

In China, about 7.5 million small farmers are growing IR cotton and it is one of the most successful examples so far in terms of productivity, farmer incomes, equity and sustainability (Pray et al., 2002) using crop varieties. With the use of GM varieties, China has been able to significantly reduce the use of pesticides on cotton (Huang et al., 2003), thereby leading to environmental and farmer health benefits. The farmers cultivating Bt cotton have been able to reduce the number of insecticide sprays to one-third in comparison to the farmers growing conventional cotton (Huang et al., 2005). In total, the pesticide applications have been reduced by an average of 67 percent and the pesticide use (active ingredient) by 80 percent. While reporting the potential benefits and impacts of Bt cotton in China, Huang et al. 2002a highlighted that the actual use of pesticides in Bt cotton was much less, ranging from 11.8 Kg/ha in 1999 to 32.0 Kg/ha in 2001 as compared to that in non-Bt cotton, which varied from 48.5 kg/ha to 87.5 kg/ha over the same period. In general, cultivation of Bt cotton helped reduce the pesticide usage by 35.7 kg/ha. Also, the number of farmers in China reporting pesticide-poisoning symptoms in conjugation with cultivation of Bt cotton was reduced from 50,000 to less than 2,500.

Advances in insect-resistant transgenic rice in China and other countries in recent years also offers a promising alternative to chemical insecticides for the control of Lepidopteran pests in rice (Zhu, 2001; High et al., 2004). Although not yet commercialized, large scale productive testing of the different Bt lines were approved in 2002, both in the experimental station and farmers fields in at least 13 sites (Chen et al., 2006). Large-scale productive testing of different Bt rice lines in fields as well as under restricted conditions verified yield increases of approximately 6–9 percent with a reduction of about 80 percent in pesticide usage (Huang et al., 2005; Chen et al., 2006). Due to all these efforts, China has emerged as one of the most advanced countries for the research and development of insecticidal transgenic rice (James, 2005). The laboratory and field trials in this country since 1998 indicate that Bt rice has effectively controlled target pests, primarily stem borers (*Chilo suppressalis* Walker, *Scirpophaga incertulas* Walker, *Sesamia inferens* Walker) and leaf folder (*Cnaphalocrocis mendinalis* Guenee) (High et al., 2004; Li et al., 2004, 2005a; Han et al., 2006b).

Similarly, growers in the United States had also reduced insecticide use by 1,870,000 pounds of active ingredients per year in 2001 (Gianessi et al., 2002). In 1997, the farmers growing Bt cotton achieved greater productivity by $24.43 per acre ($9.77/ha) including insect control costs and the increase in returns rose to $39.86 per acre ($15.94/ha) (Boulter and Hilder, 2002). In South Africa, the farmers have been able to reduce sprays by 66 percent using Bt cotton (Ismael et al., 2002a), where IR cotton and yellow IR maize were introduced in 1998–99. A comparison of IR maize varieties and their non-IR counterparts in South Africa in 2001–02 reported that while the large commercial farmers experienced yield, pesticide and income advantages, the smallholder farmers experienced higher yields (Gouse et al., 2005). Positive economic impacts for smallholder farmers in South Africa have been observed in a couple of other studies also (Bennet et al., 2004b; Thirtle et al., 2003). In Mexico, though area under IR cotton is limited, Raney (2006) estimated that the farmers gained 83 percent of the total economic value created by the crop on an average for two years of study.

The environmental gains from the GM crops were the largest of any crop on a per hectare basis from the adoption of GM IR cotton (Brookes and Barfoot, 2005). Since 1996, farmers have used 77 million kg less insecticide in the GM cotton crops (15% reduction). Important environmental gains have also been witnessed in canola and maize. In maize, pesticide use decreased by 24 million kg due to a combination of reduced insecticide use and a switch to more environment friendly herbicides. Similarly, in canola also the pesticide and herbicide use decreased considerably. This had a significant role in the reduction of environmental footprint also.

8.9 Conclusion

Biotechnology has opened up new vistas for effective pest control through the transgenic technology and in just about 15 years, this technology has become popular among the farmers of the developed as well as developing countries. The use of transgenics for crop protection is expected to further expand in future and gene-stacking or gene-pyramiding will gain more popularity owing to researchers' concern towards development of transgenic cultivars having resistance to a wider range of insects. Gene pyramiding could be deployed in combination with Bt resistance management strategies such as crop refugia, biological pest control, spatial and temporal crop rotations among others. The concerns of general public regarding the safety of transgenic crops for consumption as well as their impact on environment needs to be addressed properly. For this, the economic and ecological advantages and disadvantages of the insect resistant transgenic varieties should be compared with their conventional counterparts in combination with conventional plant protection measures on a case-to-case basis. Also more stress should be laid on the development of methods for removal of selectable marker genes after the selection of the transgenics, which still remains the major concern of safety of transgenics for human consumption.

A resistance management strategy involving transgenics should be as broad as feasible and should be equally acceptable to all stakeholders including farmers, crop consultants and scientists, seed developers, extension workers and the policy makers. To increase the durability and acceptability of the transgenic varieties, the management strategy should reflect the biology of pest, insect-pest interactions and their effect on natural enemies. With a long-term objective in view, a strategy involving combination of conventional HPR and novel exotic genes as well as a combination of several genes conferring resistance to a wider array on insect-pests will definitely go a long way in the commercial success of transgenics. At the same time, the general public needs to be properly educated about the potential uses and limitations of transgenic plants not only in crop protection, but also in crop development, quality enhancement and their effect on environment. It is also important that the assessment of the resistance mechanisms should be done in ecologically relevant *in vivo* agricultural environments besides laboratory experiments, before their commercialization.

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Chapter 9
Biological Control and Integrated Pest Management

David Orr

Abstract The manipulation of beneficial organisms remains a very important tool in integrated pest management programs of insect pests worldwide. This chapter describes the approaches to using biological control and a historical perspective of each. Recent developments in genetics, systematics, population dynamics, pesticide chemistry, and public opinion have led to increased scrutiny and inclusion of beneficial insects into IPM programs. This chapter describes these developments and the variety of approaches that have been used to implement biological control as a useful tactic in IPM. It also describes how biological control interacts with other IPM tactics, and the potential for better integration into IPM programs.

Keywords Beneficial organisms · Importation biocontrol · Augmentation · Conservation biocontrol · Predators · Parasitoids

9.1 Introduction

Biological control has been a valuable tactic in pest management programs around the world for many years, but has undergone a resurgence in recent decades that parallels the development of IPM as an accepted practice for pest management. This chapter is not intended to be an exhaustive review of research involving biological control. Instead, it will try to focus on implementation of biological control practices in insect pest management programs. It will begin with an overview of the general concepts and challenges facing the use of beneficial organisms within each of the general approaches to biological control. A brief historical perspective of biological control follows. Next, the interaction of biological control with the various elements of integrated pest management programs is considered. Existing implementation, as well as potential uses of biological control in IPM are also considered.

D. Orr (✉)
Department of Entomology, North Carolina State University, Raleigh, North Carolina, 27695-7613, USA
e-mail: david_orr@ncsu.edu

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9.2 Approaches to Biological Control

Natural enemies have been utilized in the management of insect pests for centuries. However, this last 100 years has seen a dramatic increase in their use as well as our understanding of how they can better be manipulated as part of effective, safe, pest management systems. Recent advances in molecular systematics are shedding new light on classification of groups of beneficial insects such as the Hymenoptera (e.g. Sharkey, 2007), and delivery of this information on the internet makes it quickly and widely available (e.g. The Tree of Life Web Project at http://tolweb.org). Recent advances in the study of beneficial organism behavior (e.g. parasitoid foraging: Smid et al., 2007; van Nouhuys and Kaartinen, 2008) and reproductive biology (e.g. symbionts in parasitoids: Clark, 2007) are revealing surprising complexities in the life histories of these organisms. Understanding this complexity should lead to potential new methods for their manipulation.

Despite the long history of utilizing natural enemies, it wasn't until 1919 that the term biological control was apparently used for the first time by the late Harry Smith of the University of California (Smith, 1919). There has been debate regarding the scope and definition of biological control brought about by technological advances in the tools available for pest management. (see Nordlund, 1996). In this chapter I will follow the definition presented by DeBach (1964) as the "study, importation, augmentation, and conservation of beneficial organisms to regulate population densities of other organisms". Biological control efforts conducted with predators and parasitoids still can be organized under three general approaches: importation, augmentation and conservation of natural enemies (Debach, 1964; Bellows and Fisher, 1999). Each of these approaches has been used to varying degrees in integrated pest management programs (see Fig. 9.1).

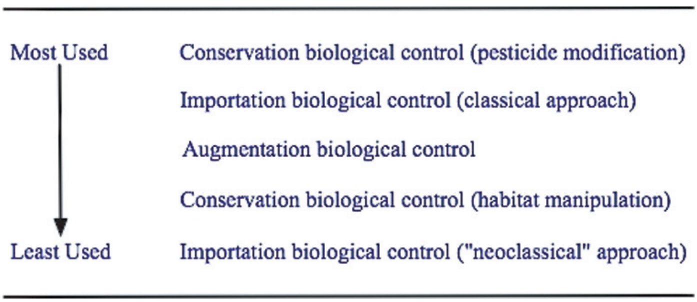

Fig. 9.1 Relative frequency of implementation of various biological control practices in IPM

9.2.1 Importation Biological Control

Importation biological control is often referred to as "classical biological control", which reflects the historical predominance of this approach to utilizing beneficial insects. It usually involves the re-uniting of natural enemies with pests that have escaped them into a new geographical area. Although the practice of introducing biocontrol agents from a related host species for the control of native arthropod pests has been used, in some cases effectively, this approach has been strongly criticized for its potential non-target impacts (see discussion below, this section).

9.2.1.1 Success Rates

From 1890 through 1960, approximately 2300 species of parasitoids and predators were introduced in approximately 600 different situations worldwide for suppression of arthropod pests (Hall et al., 1980). The overall level of establishment of these natural enemies was calculated to be 34%, with complete suppression of target pests occurring in 16% of situations, and some level of pest suppression achieved in an additional 42% of situations (Hall and Ehler, 1979; Hall et al., 1980). These rates have apparently not increased over the last 100 years (Hall and Ehler, 1979; Hall et al., 1980), although the percentage of successful projects that are complete successes has reportedly risen since the 1930's (Hokkanen, 1985). A more recent analysis has shown that the percentage of agents that establish is between 20 and 55%, and the percentage of introductions contributing to success falls within the range 5 ± 15% (Greathead and Greathead, 1992; Gurr and Wratten, 1999).

9.2.1.2 Economics

Economic assessments of the use of introduced natural enemies are not common, but have been made for several arthropod pests (Ervin et al., 1983; Voegele, 1989; Tisdell, 1990; Jetter et al., 1997; Zeddies et al., 2001; Kipkoech et al., 2006). The most common method of determining the economic benefits of biological control programs is cost-benefit analysis, which offers a systematic way of determining if the use of biological control results in a net gain (Headley, 1985; Tisdell, 1990). Classical biological control programs have produced some of the highest benefit-to-cost ratios of any pest management approach, exceeding billions of dollars in terms of total savings (Tisdell, 1990). Several highly successful individual projects have produced exceptional ratios. For example, a recent introduction program initiated against the ash whitefly in California resulted in a benefit: cost ratio ranging between $270:1 and $344:1 (Jetter et al., 1997). Zeddies et al. (2001) estimated the benefit to cost ratio of biological control targeting the cassava mealybug *Phenacoccus manihoti* Mat.-Ferr. (Homoptera: Pseudococcidae) in sub-Saharan Africa ranged from 200: to 740:1, depending on the market price used for cassava. Marsden et al. (1980) reported an average benefit-cost ratio (for the period 1960–2000) of 9.4:1 for three importation biological control programs conducted by CSIRO Division of Entomology against insect pests in Australia, compared to a 2.5:1 benefit-cost ratio for non-biological control projects conducted by the agency during the same time period. However, these numbers do not reflect the average of all projects that have been done, i.e. both successful and unsuccessful. Since the success rate of classical biological control has ranged between 5 and 15% for the last 100 years (Gurr and

Wratten, 1999), the average cost-benefit ratio of all importation programs combined is undoubtedly lower than for only the successful programs. Regardless, economic benefits that are provided by successful classical biological control are enhanced by the fact that programs are self-sustaining and permanent, so that benefits continue to accrue annually without additional cost.

9.2.1.3 Non-target impacts

Because importation biological control has historically been targeted primarily towards exotic pest species, it is particularly suited as a pest management tactic for exotic invasive pests. This approach continues to play an important role in this area. An example is the recent successful control of glassy-winged sharpshooter in the South Pacific (Grandgirard et al., 2008). However, because these agents are exotic, there is the possibility for non-target impacts.

Some controversy had developed over the last two decades regarding these potential non-target impacts (see reviews of this subject by Follett and Duan, 2000; Bigler et al., 2006; Van Lenteren et al., 2006). Simberloff and Stiling (1996) summarized the controversy and highlighted potential risks such as predation or parasitism of non-target species, competition with native species, community and ecosystem effects, and unexpected effects such as loss of species dependent on the target of biological control efforts. The significance and practical impacts of these potential non-target impacts has been thoroughly debated in the literature (Simberloff and Stiling, 1996, 1998; Frank, 1998; also see articles in Follett and Duan, 2000; Bigler et al., 2006), and conclusions vary depending on individual perspective. Many biological control scientists view these impacts as a real concern, but primarily as a problem of the past currently considered and dealt with by existing rules and regulations. They also feel that the benefits provided by importation biological control far outweigh the few negatives resulting from occasional cases of non-target impacts. Simberloff and Stiling (1996) argued that the few documented cases of non-target impacts, compared with the number of natural enemy introductions, may have been more the result of a lack of monitoring and documentation than a lack of actual impacts. This suggestion may be supported by the database on non-target effects of importation and augmentation compiled by Lynch and Thomas (2000). These authors found that from the relatively few cases where data had been collected in biocontrol projects, there appeared to be a number of non-target effects, although these were primarily from very early importation efforts and were mostly relatively minor.

There is one example of a biological control agent that became a widespread and well known pest following its release. The ladybeetle *Harmonia axyridis* Pallas (Coleoptera: Coccinellidae) was released in North America and Northwest Europe as a predator of aphid pests (Roy and Wajnberg, 2008; Koch and Galvan, 2008). However, it has become not only a threat to native biodiversity and possibly ecological services through intra-guild and inter-guild predation, but also a noxious household pest, and minor agricultural pest (Roy and Wajnberg, 2008; Koch and Galvan, 2008).

9.2.1.4 Pest Resistance

Although importation biocontrol has been practiced for more than 100 years, there has only been one documented case of a target pest developing resistance to a biological control agent. The introduced larch sawfly, Pristophora erichsonii (Hartig) (Hymenoptera: Tenthredinidae), improved its defenses against the parasitoid Mesoleius tenthredinis Morley (Hymenoptera: Ichneumonidae), after the parasitoid was introduced into Canada for suppression of the pest (Messenger and van den Bosch, 1971; Pschorn-Walcher, 1977). This suggests that importation biological control is a highly sustainable practice for management of insect pests.

9.2.2 Augmentation Biological Control

Augmentation biological control includes activities in which natural enemy populations are increased through mass culture, periodic release (either inoculative or inundative) and colonization, for suppression of native or non-native pests. Augmentation is a practice that has been widely recognized by the general public for some time in the United States mainly as a result of widespread availability of arthropod natural enemies such as lady beetles (especially *Hippodamia convergens* Guerin-Meneville) and mantids through garden catalogs and nurseries (Cranshaw et al., 1996). The expansion of the internet in recent years has only increased this awareness.

9.2.2.1 Scientific Basis of Augmentation

Augmentation biological control has recently been criticized (Collier and van Steenwyk, 2004) and debated (van Lenteren, 2006; Collier and van Steenwyk, 2004, 2006) in the literature regarding the scientific foundation, efficacy, and cost effectiveness of its use in pest management. Some of these issues have been discussed in the past. Several authors have called for development of predictive models to assist in implementation of augmentation biological control (Huffaker et al., 1977; Stinner, 1977; King et al., 1985; van Lenteren and Woets, 1988; Ehler, 1990), but this has only rarely been done (see for example Parrella et al., 1992). Because of the lack of supporting data for many augmentation approaches, (Parrella et al., 1992) stated that recommendations could not be made regarding rates and application methodologies that provide predictable results. Poor quality of released natural enemies or incorrect release rates can lead to unsatisfactory pest suppression and contribute to the unpredictability of augmentation biological control (Hoy et al., 1991). However great strides have been made recently to improve this situation (see articles in van Lenteren, 2003a).

Several explanations have been offered for the lack of experimental work supporting augmentation. One is certainly the tremendous logistical difficulties involved in conducting the large-scale, statistically valid, detailed studies that are required to effectively evaluate natural enemy augmentation (Luck et al., 1988). Another may be a perceived similarity between augmentative releases and the insecticide paradigm that has discouraged research interest in this area (Parrella et al., 1992). In this regard, augmentation could be considered the least sustainable of the three types of biological control, because it does require continued external inputs.

9.2.2.2 Implementation of Augmentation

Despite these concerns, as van Lenteren (2006) points out there are numerous examples of successful implementation of augmentation (Gurr and Wratten, 2000; van Lenteren and Bueno, 2003; Shipp et al., 2007). Van Lenteren (2003b) estimated that approximately 17.1 million hectares are under some form of augmentation. A significant industry has developed that supplies these organisms (van Lenteren, 2003b). Hunter (1997) reported 142 commercial suppliers and over 130 different species of beneficial organisms, of which 53 were arthropod predators and 46 were parasitoids. An annually updated list included in the "Directory of Least Toxic Pest Control Products" produced by the Bio-Integral Resource Center of Berkeley, California (www.birc.org) includes natural enemies and the companies that provide them. These products are focused on the greenhouse market, and only four pest groups (whiteflies, thrips, spider mites, and aphids) account for 84% of expenditures on augmentation (van Lenteren, 2003b). The augmentation biological control industry is supported by a sizeable scientific community (see for example articles in van Lenteren, 2003a; Enkegaard, 2005; Castañé and Sánchez, 2006).

In addition to larger scale commercial sales, there are a number of state and farmer operated insectaries (van Lenteren, 2003c). The bulk of these insectaries apparently rear *Trichogramma* spp. wasps for release against lepidopteran pests (Smith, 1996). An intriguing example of widespread use of augmentation comes from Cuba where trade embargos prevented other pest management tactics from being practicable (Dent, 2005).

9.2.2.3 Non-Target Impacts

Augmentation biological control often utilizes exotic natural enemy species that have broad host ranges, and undoubtedly have some effect on populations of non-target insects. However, augmentation does not face the same scrutiny as importation biocontrol over these potential non-target impacts. This is at least in part due to the temporary, non-persistent activity of released natural enemies (Lynch and Thomas, 2000; van Lenteren et al., 2006).

9.2.3 Conservation Biological Control

Conservation biological control seeks to understand human influences on resident natural enemies in a system, then manipulate those influences to enhance the ability of natural enemies to suppress pests. DeBach (1964) considered conservation biological control to be environmental modification to protect and enhance natural enemies. These activities range from modification of pesticide use practices to manipulation of beneficial insect habitat within an agroecosystem (for reviews, see Barbosa, 1998; articles prefaced by Pimentel, 2008).

9.2.3.1 Pesticide Use Modification

Probably the most common pest management activity that negatively impacts beneficial organisms in agroecosystems is pesticide application. As a result, modifications of pesticide use practices are the most commonly implemented form of conservation biological control (Ruberson et al., 1998), and have long been considered an important component of integrated pest management programs (Stern et al., 1959; DeBach, 1964; Newsom and Brazzel, 1968).

Pesticide use can be modified to favor natural enemies in a variety of ways, including treating only when economic thresholds dictate, use of active ingredients and formulations that are selectively less toxic to natural enemies, use of the lowest effective rates of pesticides, and temporal and spatial separation of natural enemies and pesticides (Hull and Beers, 1985; Poehling, 1989; Ruberson et al., 1998). Decisions regarding pesticide use for insect pests in IPM programs are typically based on sampling pest populations to determine if they have reached economic threshold levels (Pedigo, 1989), although some work has been done to incorporate natural enemy sampling into these pesticide use decisions.

9.2.3.2 Other Approaches to Conservation Biocontrol

A variety of other approaches to conservation biological control have been studied, and are comparatively complex. These include management of soil, water and crop residue; modification of cropping patterns; manipulation of non-crop vegetation; and direct provision of resources to natural enemies (see review by Barbosa, 1998; articles introduced by Pimentel, 2008). In general, these approaches are aimed at enhancing the density of resident natural enemy populations or communities to increase their effectiveness in pest suppression. As highlighted by Ehler (1998) and Jonsson et al. (2008) many of the management techniques developed for conservation biological control (other than pesticide use modification) have been of academic, rather than practical interest, and are not widely implemented in IPM programs. However, a considerable amount of research has been conducted in this area recently and there appears to be great potential for future applications in IPM programs (Jonsson et al., 2008).

One possible explanation for the low rate of success in importation biological control compared with establishment rates of introduced natural enemies is the lack of resources available for enemies in agroecosystems (Gurr and Wratten, 1999). Provision of these resources through conservation biological control methods has been suggested as one way to improve the success rate for both importation and augmentation, an approach referred to as integrated biocontrol (Gurr and Wratten, 1999).

9.2.3.3 Economics

Unlike importation and augmentation biological control, economic assessments of conservation biological control programs are not only rare, but uniquely difficult to conduct (Cullen et al., 2008). These authors, however, suggest an approach for conducting such an assessment.

9.3 Historical Perspective of Biological Control

The first accounts of predatory insects being used as insect management tools date back as early as 300 AD when Chinese citrus growers placed paper nests of ants (*Oecophylla smaragdina* F.) on trees to protect them from other insects (van Lenteren, 2005). These early augmentation efforts were apparently helped along by the conservation biological control practice of aiding inter-tree movement of the ants by placing bamboo rods as runways or bridges between trees (DeBach, 1974). These ants reportedly were still available for purchase up to at least the 1970's (DeBach, 1974).

While the predatory behavior of some insects was recognized long ago and taken advantage of for pest management, the recognition and utilization of the less obvious parasitic insects did not occur until much later. Parasitism by tachinid flies was first correctly interpreted in China in the 11th century, while ichneumonoid parasitism was correctly interpreted in Europe in the 17th century (Cai et al., 2005; van Lenteren and Godfray, 2005). The difference in time between these two events was likely the more complex life history of the latter group.

The first deliberate movement of parasitoids from one location to another was conducted by C.V. Riley, who distributed parasitoids of the weevil *Conotrachelus nenuphar* (Herbst) around the state of Missouri in 1870 (Doutt, 1964). The first parasitoid successfully moved and established from one continent to another, however, was *Cotesia (=Apanteles) glomeratus* (L.), which was shipped from England to the United States for suppression of *Pieris rapae* (L.) by the U.S. Dept. of Agriculture in 1883 (Riley, 1885; Riley, 1893). Transcontinental shipment of a predatory arthropod soon followed with the transport of the predatory mite, *Tyroglyphus phylloxerae* Riley &. Plancon, from the United States to France in 1873 for suppression of the grape phylloxera, *Daktulosphaira vitifoliae* (Fitch) which it did not suppress (Fleschner, 1960; Doutt, 1964). While a variety of international movements of insects for pest control occurred in the late 1800s, none of them achieved complete economic control (Fleschner, 1960).

It is generally accepted that the first case of complete and sustained economic control of an insect pest by another insect was control of the cottony cushion scale, *Icerya purchasi* Maskell, in California during the late 1800s (Fleschner, 1960; Doutt, 1964; Debach, 1974; van den Bosch et al., 1982). *Icerya* was introduced into Californiai in 1869, and by 1886 it threatened to destroy the entire southern California citrus industry (DeBach, 1974). Two insects, the vedalia beetle, *Rodolia cardinalis* Mulsant (Coleoptera: Coccinellidae), and a parasitic fly, *Cryptochetum* *iceryae* (Williston) (Diptera: Cryptochètidae), were imported to California from Australia in 1877 and 1888. Within two years, *I. purchasi* was under complete biological control throughout the state. Although the vedalia beetle is mostly credited for controlling the cottony cushion scale, once established, the parasitic fly became the major control factor of the pest in the coastal areas of the state (Van Driesche and Bellows, 1996). This classic example is presented in many books dealing with insect biological control (e.g. DeBach, 1964, 1974; van den Bosch et al., 1982; Van Driesche and Bellows, 1996), and set the stage for future biological control programs. Probably because *I. purchasi* provides suppression of *C. iceryae* only over a limited portion of the pests' range, Greathead (1986) considered the importation of *Encarsia berlesi* (Howard) into Italy from USA in 1906 for control of the mulberry scale, *Pseudaulacaspis pentagona* Targioni-Tozzetti to be the first successful introduction of a parasitoid from one country to another for insect pest control.

Following the success of the cottony cushion scale project, numerous biological control efforts ensued worldwide (Clausen, 1978; Luck, 1981; van den Bosch et al., 1982; Greathead, 1986; Greathead and Greathead, 1992) some of which were just as successful. Although the primary focus of early efforts in biological control was importation of natural enemies, other methods of manipulating parasitoids and predators were also considered. While the concept of mass rearing insects for future releases was proposed as early as 1826 by Hartig, the first practical attempt towards augmentation of natural enemies in western Europe was probably made in 1899 by Decaux who devised a complete management program for apple orchards, including releases of field-collected inchneumonid wasps (Biliotti, 1977). The first sustained, large-scale, and successful augmentation biological control project involved mass-production of the ladybeetle *Cryptolaemus montrouzieri* Mulsant, targeting the citrophilus mealybug, *Pseudococcus calceolariae* Fernald (= gahani Green), a pest of citrus in southern California (Luck and Forster, 2003). Large-scale releases began in the early 1920's, and continued for decades, with as many as 40 million beetles being produced annually. This beetle is still available through commercial insectaries in both the United States and Europe (van Lenteren, 2003b).

The history of conservation biological control has been one of mainly potential practices developed by researchers that do not appear to have become widely adopted (Ehler, 1998). However, organic and sustainable farming systems have tried to take advantage of these practices to some degree (Altieri et al., 2005).

9.4 Interaction of Biological Control with Other IPM Tactics

In integrated pest management programs, specific tactics often do not act independently of one another. This may be especially so for biological control since the agents of insect biological control such as parasitoids and predators are susceptible to environmental perturbations such as pesticide applications. This section will examine how biological control interacts with the various tactics employed in IPM programs.

9.4.1 Population Monitoring

Pest population monitoring is a cornerstone of many IPM programs. Pesticide use decisions for insect pests are typically based on sampling pest populations to determine if they have reached economic threshold levels (Pedigo, 1989), although some work has been done to incorporate natural enemy sampling into these pesticide use decisions. Sampling for natural enemy populations or their effect on pests can be used to revise economic thresholds to more accurately determine the need or timing for pesticide applications within a pest generation (Ostlie and Pedigo, 1987), or to predict the need for treatment of a future pest generation (Van Driesche et al., 1994). An example is a sequential sampling plan that takes into account parasitized *H. zea* eggs when estimating this pest's population levels in tomatoes (Hoffman et al., 1991). Formal revised economic thresholds incorporating natural enemy numbers are not common in IPM programs. However, consultants and other pest management professionals probably informally incorporate natural enemy numbers into decision making more frequently, such as with cotton aphid management in the mid-Atlantic region of the United States (Orr and Suh, 1999). However, the use of economic thresholds alone in IPM doesn't necessarily lead to natural enemy conservation, if for example a broad-spectrum pesticide is used for treating pest populations when they exceed threshold levels (Ruberson et al., 1998). Consideration of natural enemy numbers, as well as careful selection of pesticide use practices (discussed below) can lead to a more integrated approach to IPM.

9.4.2 Cultural Controls

A variety of cultural practices such as management of cropping patterns, soil, crop residue, and non-crop vegetation are used in management of insect pests. These practices in some cases can be manipulated to enhance natural enemies of insect pests. In general, these approaches are aimed at increasing the density of resident natural enemy populations or communities to increase their effectiveness in pest suppression.

9.4.2.1 Habitat Stability

It has long been recognized that perennial cropping systems such as orchards are more favorable to natural enemies and biological control because of the habitat stability they provide (DeBach, 1964). Habitat stability can also be provided in situations where crop cycles overlap throughout the year in a substantial portion of the landscape so that individual fields are not too far apart for enemies to move between them (e.g. Mogi and Mayagi, 1990). Although there are several examples of harvest modification to allow for conservation of beneficials such as alfalfa strip harvesting (Stern et al., 1976), hay strip-harvesting (Nentwig, 1988), alternate row pruning (Rose and DeBach, 1992), and relay cropping or intercropping (e.g. Bugg et al., 1991; Parajulee and Slosser, 1999), logistical concerns prevent widespread adoption of these practices (Hokkanen, 1991; Ehler, 1998; Jonsson et al., 2008).

9.4.2.2 Crop Rotation

Crop rotation is a foundation for pest management in some cropping systems, dissociating pest populations from continued food supply from one year to the next. Although not common, crop rotation can also affect populations of beneficials such as ground-dwelling rove beetles (Lubke-Al-Hussein and Al-Hussein, 2006). Placement of rotated crops in relation to prevailing wind direction and previous years crops may influence the ability of parasitoids to locate and colonize the new crop (Williams et al., 2007)

9.4.2.3 Intercropping

The increased vegetational diversity provided by intercropping was proposed by Root (1973) as a possible means to reduce pest discovery and retention in crops, and to enhance natural enemy populations and activity (Root, 1973). Andow (1986, 1988) reviewed intercropping studies in the literature and noted that pest densities were reduced in 56% of cases, increased in 16%, and not affected in 28%. Russell (1989) reviewed natural enemy activity in intercropping studies, and reported increased pest mortality due to natural enemies in 70% of cases, lowered mortality in 15%, and no effect in another 15%. The responses of both pest and beneficial insects to intercropping are not well understood, because the underlying mechanisms at the behavioral level have not been well studied (Bukovinszky, 2007). An understanding at this level is important to develop intercropping systems with more predictable outcomes.

9.4.2.4 Trap Cropping

Trap crops are deployed to intercept dispersing pests before they can enter the main crop, allowing control measures to take place in a smaller area (Hokkanen, 1991). Natural enemies invariably follow these pests, and may be affected as well. These effects may be positive, where natural enemy populations are able to build up on concentrated pest populations and then move into the main crop (Hokkanen, 1991), although this does not necessarily lead to increased pest reductions in the main crop (Tillman, 2006a). The trap crops may also act as a sink for insect pest populations as a result of increased natural enemy activity (Tillman, 2006b). However, control measures taken for pests in trap crops have the potential to negate these positive effects by eliminating natural enemies as well. (Hokkanen, 1991), although this is not necessarily the case. Barari et al. (2005) found that parasitism of the oilseed rape (*Brassica napus* L.) pest *Psylliodes chrysocephala* (L.) (Coleoptera: Chrysomelidae) by the ichneumon wasp *Tersilochus obscurator* Aub. was not affected by insecticide treatment of a bordering trap crop of turnip rape (*Brassica rapa* L.). This was at least in part due to temporal separation of insecticide treatment and peak parasitoid activity. Even if control measures are used in traps crops, the main impact of trap cropping on beneficial insects may be the reduction in pesticide usage in the main crop resulting in conservation of beneficial insect populations.

9.4.2.5 Cover Cropping

Cover crops are employed in crop production systems for a variety of reasons including soil fertility, erosion control, and in some cases, pest management (Mangan et al., 1995; Teasdale, 1996). In a number of agricultural systems, cover crops have been shown to disrupt behavior of pest insects and reduce their abundance (Bugg, 1992; Bugg and Waddington, 1994; Teasdale et al., 2004). It is less clear how cover crops influence natural enemies, and as a result the pest insects they attack. For example, clover cover crops have been shown in some studies to enhance natural enemy populations in cotton (Tillman et al., 2004), while other studies have found no effect (e.g. Ruberson et al., 1997). Buckwheat (*Fagopyrum escalentum* Moench) has been shown to enhance natural enemy activity in crops as diverse as cabbage and grapes (e.g. English-Loeb et al., 2003; Lee and Heimpel, 2005), but in very few cases have effects on pest densities been associated with this enhancement (e.g. Nicholls et al., 2000). When mulched, cover crops can provide microhabitats favorable to insect natural enemies and increase their numbers (Altieri et al., 1985; Stinner and House, 1990; Orr et al., 1997). There does not appear to be any study that links enhancement of natural enemy populations by cover crops with economic suppression of insect pests.

9.4.2.6 Manipulation of Non-Crop Vegetation

Because cultural control practices may include consideration of non-crop vegetation, it’s appropriate to outline some considerations of this vegetation by workers in biological control. Research examining the manipulation of vegetation, or habitat, within agroecosystems on a variety of scales has come to dominate studies of conservation biological control recently (see articles introduced by Jonsson et al., 2008). The goal is to build populations of beneficial insects to reduce pest populations, and increase crop yields. There are few studies where all three goals have been met, but this work appears to hold much promise. In addition to natural control, Gurr and Wratten (1999) argue that success levels of importation (classical) and augmentative releases of biological control agents could be increased through habitat manipulation. They suggest that little consideration is given to these enemies beyond their host range, host/prey consumption rates and climatic requirements. They point out that poor availability of key ecological resources such as nectar, pollen, moderated microclimate, or alternative hosts may constrain the ability of enemies to regulate host populations following their release.

While IPM practitioners have often focused on implementing biological control on a more local scale, such as an individual field, studies have indicated that landscape structure may be quite important in determining the levels of natural control provided by beneficial insects (Thies and Tscharntke, 1999; Tscharntke et al., 2007).

Fiedler et al. (2008) suggest that the goals of conservation biological control may be more easily met by combining multiple ecological service goals. This might be accomplished by looking for synergies in various activities such as biodiversity conservation, ecological restoration, human cultural values, tourism, biological control and other ecosystem services

The concept of agrobiodiversity (see series of 22 articles in van Rijn, 2007) has recently been promoted for not only the practical values provided by ecological services such as biological control and pollination, but also for preserving or enhancing biodiversity in agricultural landscapes for its own sake. Likewise, concepts such as farmscaping (Dufour, 2000) and permaculture (Mason, 2003) have tried to incorporate similar ideas to enhance ecological values such as natural controls in agricultural or residential settings.

While there is limited information on how fertilization affects natural enemies, parasitoid activity may be lowered under reduced nitrogen conditions (Fox et al., 1990; Loader and Damman, 1991; Bentz et al., 1996). However, Chen and Ruberson (2008) reported that increasing levels of nitrogen fertilization in cotton in field conditions decreased predation, but did not affect parasitism. Thomson and Hoffmann (2007) found that even though mulches increased populations of both soil dwelling predators as well as canopy dwelling predators and parasitoid, they had no effect on pest populations.

9.4.3 Mechanical or Physical Controls

9.4.3.1 Tillage

Tillage is the primary means of disturbance in agroecosystems, and is central to many agricultural practices such as preparation of seedbeds, incorporation of organic material and fertilizer, and suppression of weeds and some diseases and insect pests (Gebhardt et al., 1985). Tillage practices can have significant influences on arthropod populations, including natural enemies, and in turn pest management (Hammond and Stinner, 1999).

A significant amount of research has been directed toward understanding the influence of reduced tillage systems on arthropods, including natural enemies. In some cases, conservation tillage has been shown to increase natural enemy populations (e.g. Gaylor et al., 1984; McCutcheon et al., 1995; McCutcheon, 2000; Tillman et al., 2004), while in others they were either not affected (Ruberson et al., 1997; Gencsoylu and Yalcin, 2004), or reduced (Ruberson et al., 1995).

Much of the work dealing with soil-dwelling insect natural enemies has focused on carabid beetles (Coleoptera: Carabidae), which are significant generalist predators in annual row-crop agricultural systems (Thiele, 1977; Kromp, 1999; Menalled, 2007). Tillage affects carabid populations through direct mortality from tillage events, or indirectly through loss of prey resources and changes in microclimate (Hance et al., 1990; Thorbek and Bilde, 2004). Shearin et al. 2007 reported that entomophagous carabid beetles were more sensitive to tillage than herbivorous carabids. While diversity and abundance of carabids appears to be favored by reduced tillage (see review by Shearin et al., 2007), there are examples where entomophagous beetles are significantly more abundant in conventional tillage systems (e.g. Carcamo, 1995; Menalled, 2007).

Interpretation of results of these studies is complicated by the sampling method employed. Populations of carabids are usually sampled with pitfall traps with trap catches expressed as activity-density (Thomas et al., 1998). However, there are significant constraints to using this method, and care should be taken when designing studies and interpreting results (Thomas et al., 2006). In addition, dispersal of beetles between experimental plots may mask treatment effects (Thorbek and Bilde, 2004; Shearin et al., 2007). More work appears to be needed to gain a clearer understanding of the effects of tillage on ground-dwelling arthropod natural enemies. What is less clear, and needs even more work perhaps, is the link between population changes in enemies from tillage practices and suppression of target insect pest populations.

Tillage has also been found to affect foliage dwelling arthropod predators (House and Stinner, 1983; Troxclair and Boethel, 1984; Funderburk et al., 1988; Hammond and Stinner, 1999; Marti and Olson, 2007) as well as parasitoids (Nilsson, 1985; Ellis et al., 1988; Runyon et al., 2002; Weaver, 2004; Williams, 2006; Rodriguez et al., 2006) either directly from soil disturbance, or indirectly by altering weed communities. This is especially important where natural enemies pupate in soil. For example, an outbreak of cereal leaf beetle, *Oulema melanopus* (Coleoptera: Chrysomelidae), in Canada was linked to a change in tillage practices that killed parasitoids of the beetle overwintering in the soil (Ellis et al., 1988).

In addition to tillage, other practices used to manage crop residues can affect natural enemies. Several studies have shown that leaving crop residues behind, in cases where there is no good pest management (or other) reason to remove them through tillage or other means, can conserve populations of parasitoids and predators (Joshi and Sharma, 1989; Mohyuddin, 1991; Shepard et al., 1989).

9.4.3.2 Traps and Barriers

Traps and barriers are frequently employed in IPM programs to either reduce pest numbers directly or deny them access to crops (Pedigo, 1989). However, there are cases where they may have side effects on beneficial organisms that may interfere with pest management.

Semiochemicals, including pheromones and kairomones, are commonly utilized in host-finding by natural enemies such as parasitoids (see reviews by Vet and Dicke, 1992; Powell, 1999). They may have potential for manipulating populations of natural enemies to benefit pest management (e.g. Powell and Pickett, 2003; Quarles, 2007; Khan et al., 2008). These same semiochemicals in turn can have non-target impacts on natural enemies when traps employing them are used in IPM programs (e.g. Franco et al., 2008; Perez and Sierra, 2006).

In mass-trapping efforts or even monitoring with traps such as colored sticky traps, attraction and effect on natural enemy populations should be considered prior to implementation (e.g. Blackmer et al., 2008). Frick and Tallamy (1996) found that electric traps, using ultraviolet light as an attractant killed almost exclusively non-target insects, rather than the targeted biting flies, with approximately 13.5% of the catch predatory and parasitic insects.

Mesh size of insect barriers require testing to determine the size that excludes pest, but does not also exclude natural enemies that may be attacking other pests in a cropping system (Hanafi et al., 2007). The use of UV blocking films has potential for use in IPM programs against insect pests in greenhouse crop production, through interference with insect visual receptors and behavior (Doukas and Payne, 2007). However, these films also have the potential to interfere with biological control, and more studies examining effects on natural enemies should be undertaken (Doukas and Payne, 2007).

In the 1980's and 90's vacuum systems became popularized for management of insect pests organically, and a few systems are still available for this purpose (Kuepper and Thomas, 2002). Studies conducted to date have not demonstrated any negative impact on beneficial insects in crop field treated with the vacuums (Kuepper and Thomas, 2002).

9.4.4 Plant Breeding and Transgenic Crops

Both biological control and host plant resistance are important components of many IPM programs. However, these two methods do not necessarily act on target pests independently of one another, and IPM practitioners should consider their interactions when designing management programs (Bottrell et al., 1998). Pest resistant plants can have a variety of positive and negative influences on natural enemies (see reviews by Boethel and Eikenbary, 1986; Dicke, 1999; Ode, 2006). Likewise enemies can contribute to the sustainability of plant resistance by slowing pest adaptation to resistant plants (Gould et al., 1991; Gould, 1998).

9.4.4.1 Conventional Plant Breeding

Conventionally bred resistant plants affect natural enemies either directly through chemical or physical plant traits such as trichomes, or indirectly through plant mediated effects on host or prey characteristics such as quality (Godfray, 1994; Kennedy, 2003; Ode, 2006). These effects can be either constitutive, or inducible as a result of herbivore attack (Dicke et al., 2003; Kennedy, 2003; Pieterse and Dicke, 2007).

Although the interactions between natural enemies and pest-resistant plants have been studied for decades (see for example Boethel and Eikenbary, 1986), most attention in this field has been focused recently on genetically-modified or transgenic plants. This is especially timely now, given the expansion of transgenic crops into areas where they were previously excluded (Pollack, 2008).

9.4.4.2 Transgenic Plants

Transgenic plants currently deployed act on natural enemies directly, in a manner similar to antibiosis (Gould, 1998). The majority of studies done to date have not reported profoundly negative effects of transgenic plants on arthropod natural enemies (Callaghan et al., 2005). Lovei and Arpaia (2005) in reviewing the literature dealing with laboratory studies of the effects of transgenic plants on arthropod predators and parasitoids, reported that roughly one third of these studies indicated significantly negative effects of genetically modified plants on life history parameters of predators (30%) and parasitoid (39.8%). However, they note that there were inadequacies in the experimental methods used for these studies, including: artificial test conditions not at all related to those insects would experience under field conditions, small range of taxa tested, and variability in the types of measured parameters. Romeis et al. (2006) reviewed laboratory, greenhouse, and field studies that examined effects of transgenic crops expressing *B. thuringiensis* toxins on arthropod predators and parasitoids. They conclude that there were no direct toxic effects, and negative effects only occurred where Bt susceptible, sublethally damaged herbivores were used as prey or hosts. Several reviews have concluded that Bt cotton has a minimal impact on beneficial insect communities in cotton worldwide (Sisterson et al., 2004; Naranjo, 2005; Whitehouse et al., 2005).

Field studies reviewed by Romeis et al. (2006) indicated that abundance and activity of predators and parasitoids were similar in Bt and non-Bt crops. Romeis et al. (2006) suggest that Bt crops have fewer adverse effects on natural enemies than conventional insecticides, and can reduce insecticide use through incorporation into IPM programs with strong biological control components. A meta-analysis conducted by Marvier et al. (2007) reviewed 42 field experiments and found that non-target invertebrate populations generally were more abundant in Bt versus insecticide treated field crops, although some non-target invertebrate populations were less abundant in Bt versus non-Bt fields not treated with insecticides. A review of the economic, ecological, food safety and social consequences of transgenic Bt-expressing plants concluded that the risks of deploying transgenic Bt plants were lower than many current or alternative technologies, and the benefits greater (Shelton et al., 2002). The same pattern of results seen with Bt transgenic crops has also been reported for genetically modified crops based on insecticidal proteins other than the *B. thuringiensis* delta-endotoxin (Callaghan et al., 2005; Whitehouse et al., 2007).

Deployment of transgenic crops has resulted in lower insecticide use. Over the nine year period from 1996 through 2004, insecticide use on the genetically engineered corn and cotton grown in the US dropped by 5% (7.08 million kg) (Benbrook, 2004). Bt cotton has significantly reduced pesticide inputs wherever it has been commercially adopted, such as Australia where a 50% reduction was reported in comparison with conventionally sprayed cotton (Whitehouse et al., 2007). In contrast, from 1996 through 2004, herbicide use on genetically engineered corn, cotton, and soybeans grown in the US increased by 5% (Benbrook, 2004). However, the use of transgenic herbicide-tolerant soybeans does not appear to have any significant effect on arthropod communities (Buckelew et al., 2001).

A difficulty with making larger analyses of non-target effects of transgenic plants has been the variability in experimental approaches. To help make the evaluation process systematic, Romeis et al. (2008) propose a scientifically rigorous procedure to evaluate the risks of insect-resistant genetically modified crops to non-target arthropods that provide ecological services such as biological control, pollination, and decomposition.

The debate over the safety of genetically modified crops is likely to continue (Thies and Devare, 2007). Despite early concerns over sustainability (e.g. Gould 1998), insect pest management using transgenic crops appears to be working quite well. Concerns over impacts on non-target beneficial arthropods in transgenic crops are largely uncorroborated by the data collected to date. By reducing insecticide applications, the use of transgenic herbivore resistant crop plants likely outweighs any specific negative effects they may have on natural enemy biology. The primary means by which conservation biological control of arthropods is implemented is through the modification of insecticide applications (Ruberson et al., 1998). Rather than having anticipated negative effects, transgenic varieties appear to have resulted indirectly in the conservation of beneficial insects in crops in which they are used.

9.4.5 Pesticide Use

Probably the most common pest management activity that negatively impacts beneficial organisms in agroecosystems is pesticide application. Although herbicide use can influence both pest and natural enemy populations (see for example Shelton and Edwards, 1983; Taylor et al., 2006), this section will focus on insecticide effects since they are so much more significant.

Pesticide products used for pest management in agriculture have been changing so that use of the oldest and most toxic cyclodienes, carbamates and organophosphates is slowly decreasing worldwide (Devine and Furlong, 2007). For example, in the United States between 1992 and 2000, the use of these materials had declined by 14% (by weight of active ingredient), even though overall agricultural pesticide use had not declined in that same period (GAO, 2001). However, these materials still retain a 50% worldwide market share (Devine and Furlong, 2007; Singh and Walker, 2006). Synthetic pyrethroids, with their vastly improved mammalian and avian toxicity profiles, now account for 20% of global insecticide sales (Devine and Furlong, 2007).

9.4.5.1 Side Effects on Natural Enemies

Studies examining the side effect of pesticides on natural enemies have been reviewed several times (Haynes, 1988; Croft, 1990; articles in Vogt and Brown, 2006; Desneux et al., 2007). These side effects are manifested in several different ways. Indirect effects include habitat destruction, and damage to nesting, oviposition, resting, and mating sites (Desneux et al., 2007). Direct lethal effects of insecticides are the most well known and have typically been estimated by determining a median lethal dose (LD50) or median lethal concentration (LC50) that enemies are directly exposed to. Sublethal effects of insecticides on beneficial arthropods include deleterious side effects of direct pesticide exposure on physiology and behavior (Desneux et al., 2007). The physiological effects extend to general biochemistry and neurophysiology, development, adult longevity, fecundity, sex ratio and immunology, while behavioral effects extend to mobility, navigation/orientation, feeding behavior, oviposition behavior, and learning performance (Desneux et al., 2007). In addition to direct lethal and sublethal effects, insecticides may also lead to pest population resurgence, often attributed to the removal of a target pests natural enemies by the application of broad-spectrum insecticides (Hardin et al., 1995).

Taking sublethal effects of pesticides into consideration when choosing pesticides for an IPM program can result in great improvements in natural enemy performance (e.g. Desneux et al., 2005). In some cases, sublethal doses of pesticides have been shown to have favorable effects on arthropod physiology and/or behavior, a phenomenon known as hormoligosis (Luckey, 1968). Although hormoligosis has been reported in a beneficial arthropod, the predatory mite *Amblyseius victoriensis* (Womersley), this phenomenon appears very uncommon for natural enemies and likely of little widespread value in the integration of chemical and biological controls (James, 1997).

9.4.5.2 Modification of Pesticide Use Practices

Because of the widespread use of pesticides in agricultural systems, it follows that modifications of pesticide use practices are probably the most commonly implemented form of conservation biological control. This approach has long been considered an important component of integrated pest management programs (Stern et al., 1959; DeBach, 1964; Newsom and Brazzel, 1968). The use of pesticides can be modified in a variety of ways to minimize their impact on natural enemies. These include treating only when economic thresholds dictate, use of active ingredients and formulations that are selectively less toxic to natural enemies, use of the lowest effective rates of pesticides, and temporal and spatial separation of natural enemies and pesticides (Hull and Beers, 1985; Poehling, 1989; Ruberson et al., 1998). While the concepts behind modifying pesticide use are relatively straightforward, implementing these modifications is not necessarily straightforward. One obstacle is that the primary source of information regarding IPM is probably extension services, yet at least in the United States, there are a variety of competing sources from which growers can get information regarding pesticide use (Rajotte et al., 1987).

The practice of IPM has been shown under large-scale field conditions to be favorable to beneficial insects. Furlong et al. (2004) determined the impact of IPM practices at different farms on beneficial insects in *Brassica* crops in the Lockyer valley, Australia. Their study clearly demonstrated increased natural enemy abundance and diversity, as well as significantly greater predator and parasitoid efficacy at farms practicing IPM compared with farms that frequently treated with insecticide.

9.4.5.3 Reduced Risk Pesticides

Newer insecticide classes have been introduced over the last 15 years in response to increasing environmental concerns and more difficult registration processes. These "reduced-risk pesticides", including insect growth regulators, neonicotinoids, antibiotics, and oxadiazines are considered by the US Environmental Protection Agency (EPA) to be safer for human health and the environment than older pesticides. Their low mammalian toxicity allows for a shorter pre-harvest interval, and most are less likely to harm natural enemies and other non-targets making them more compatible with IPM programs. A definition has been provided for these materials and a procedure established to facilitate their registration in the United States (EPA, 1997). This definition includes the following characteristics: "not harmful to beneficial insects, highly selective pest impacts". Studies have demonstrated these compounds are less harmful to natural enemies than organophosphates, carbamate and pyrethroid insecticides (Balazs et al., 1997; Dhadialla et al., 1998; Pekar, 1999; Hewa-Kapuge et al., 2003; Hill and Foster, 2003; Studebaker and Kring, 2003; Williams et al., 2003a; Thomas and Mangan, 2005; Arthurs et al., 2007). However, some toxic effects on beneficial arthropods have been reported from exposure to reduced-risk insecticides such as imidacloprid and thiamethoxam (Williams et al., 2003a; Nasreen et al., 2004; Richter, 2006), indoxacarb (Haseeb et al., 2004; Galvan et al., 2006), and spinosad (Suh et al., 2000; Nowak et al., 2001; Cisneros et al., 2002; Schneider et al., 2003; Williams et al., 2003b; Wang et al., 2005). Although these reduced risk pesticides have a number of advantages over older pesticides, their use does not necessarily lead to natural enemy conservation. Sarvary et al. (2007) concluded that the use of reduced risk insecticides in individual crop fields within an agricultural landscape did not result in increased natural enemy activity in those fields, even when suitable natural habitat was interspersed with cropland.

9.4.5.4 Selectivity

The use of selective pesticides is perhaps the most powerful tool by which pesticide use decisions can be modified to favor natural enemies (Hull and Beers, 1985), and the one most readily available to growers (Ruberson et al., 1998). Selecting the best insecticides for pest management that have minimal impacts on beneficials can be challenging. To assist in this effort, a variety of databases and ranking systems have been developed which incorporate insecticide toxicities to non-target species and other information such as human toxicity and environmental contamination potential (van der Werf, 1996). These systems can be used to compare relative impacts of different pesticides on non-target organisms and to estimate probable effects on non-target environments (Reus and Leendertse, 2000). However, they have rarely been used to consider insecticide impacts on predators and parasitoids in the crop environment at a landscape level (Ferraro et al., 2003). In an effort to make this process more user friendly a beneficial disruption index (BDI) was developed by Hoque et al. (2002) to provide a generalized measure of insecticide impacts on beneficial arthropods in Australian cotton crops. This index was tested by Mansfield et al. (2006), who concluded that the BDI is an effective measure of insecticide impacts on beneficial insects in Australian cotton crops.

Pesticide exposure of natural enemies may also be reduced by applying materials only where they are needed within crop fields. Coll (2004) reviewed the future potential for reducing the negative impacts of pesticide use on natural enemies through the use of precision agriculture technologies.

9.4.5.5 Resistant Natural Enemies

Efforts have been made over the last several decades to develop natural enemies that are pesticide-resistant with the goal of better integration of chemical and biological control (Beckendorf, 1985; Croft, 1990). Genetically manipulated arthropod natural enemies have been used only a few times in IPM programs (Havron et al., 1995; Hoy, 1996). Only one transgenic arthropod natural enemy has been released on an experimental basis (i.e. with only a molecular marker), a transgenic strain of the predatory mite *Metaseiulus occidentalis* (Nesbitt) (Acarina: Phytoseiidae) (McDermott and Hoy, 1997). While this approach may have potential for improving resistance to pesticides, as well as other traits of natural enemies, a variety of scientific, regulatory, and political issues remain to be resolved before transgenic arthropod natural enemies can be used in practical pest management programs (Ashburner et al., 1998; Hoy, 2000, 2005). Meanwhile, traditional selective breeding programs attempting to develop pesticide resistant strains of beneficial insects continue to be explored (e.g. Devi et al., 2006; Ingle et al., 2007). While some authors have advocated the use of resistant beneficial insects in IPM programs (e.g. Graves et al., 1999), it could be argued that this approach is counterproductive to the goals of IPM because it could encourage more pesticide use as with herbicide resistant soybean cultivars.

9.4.5.6 Market Demands

Consumers are becoming a driving force in determining pest management practices, with retailers increasingly requesting horticultural or agricultural practice standards from farmers (Warner, 2006; Dent, 2005). Public opinions on pesticides have become polarized, with measures such as organic agricultural production gaining popularity. Global sales of organic produce are rising approximately 20% per year, with 97% of that market in North America and Europe (Davidson, 2005). However, approximately 70% of organic production occurs outside of North America and Europe, primarily in Oceania and Latin America (Davidson, 2005), meaning the effects of this organic demand will not be restricted to western countries. However, organic production still only represents a small fraction of total agricultural sales (Kiplinger, 2007; Willer and Yussefi, 2006), which means that synthetic pesticides can be used on the vast majority of agricultural production, and remain a critical component of IPM programs worldwide.

9.5 Conclusions

The use of biological control in pest management systems has had a long, rich history. While there are a variety of impediments, there also exist many opportunities for the continued use and expanded role of natural enemies in the management of insect pest problems. Changes in pest management tactics are resulting from a variety of factors, including environmental and human safety concerns, development of insecticide-resistance, increases in pesticide cost and availability, and market demand. However, pesticides will likely remain a major component of IPM programs into the foreseeable future. Modification of pesticide use practices will also probably remain the most commonly implemented form of biological control in agricultural IPM. The continual influx of alien arthropod species resulting from increased international trade presents new pests of agriculture annually (see review by Roll et al., 2007). This influx also ensures that importation biological control will continue to play an important role in IPM practices. As the scientific foundation of augmentation biological control develops, so too should its implementation. As IPM evolves to more ecologically based practices (Koul and Cuperus, 2007), the biological control practice that probably has the greatest opportunity for expanded use is conservation biological control involving agroecosystem modification.

Agriculture as a whole is facing a variety of challenging changes. Global climate change is beginning to affect agricultural systems worldwide, and biological control practices may have to altered to adapt to these changes (Stacey, 2003; Hance et al., 2007). Recent losses of conservation land and changing markets resulting from crop-based biofuels (Streitfeld, 2008), increased use of genetically modified crops (Pollack, 2008), and rising demand for organic produce (Davidson, 2005) make it clear that market forces are a major and sometimes unexpected driving force in agricultural production. Regardless of the production system, IPM will have an important role to play, and the use of biological controls can be an integral part of IPM.

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Chapter 10
Conventional and New Biological and Habitat Interventions for Integrated Pest Management Systems: Review and Case Studies using *Eldana saccharina* Walker (Lepidoptera: Pyralidae)

D.E. Conlong and R.S. Rutherford

Abstract Conventional Integrated Pest Management (IPM) systems have concentrated on controlling pests through informed use of cultural and biological control and host plant resistance characteristics to minimise pesticide interventions. The basic foundation of successful IPM systems is a thorough knowledge of the target pest's life cycle, and its ecological and behavioral interactions with the environment and natural controlling factors in both its indigenous and crop habitats. Through this basic knowledge, a number of new interventions can be added to the IPM arsenal. These include management of the habitat to make the crop less suitable for colonisation by potential pests, and to increase natural enemy foraging and abundance in the crop habitat, increasing the efficacy of conservation, inoculative and augmentative biological control. In addition, more is known about impact of plant and insect pathogens and symbionts on target pest populations by making potential host plants more or less suitable for colonisation, adding a fourth trophic level to agro-ecosystem dynamics. Furthermore, the impact of these on fertility and offspring sex ratios (e.g. *Wolbachia* isolates in pest and natural enemy populations) makes their exploitation, in combination with interventions such as Sterile Insect Technology (SIT), a real and practical possibility. This chapter evaluates the newer interventions, using examples from the literature and from local research to show the effectiveness of these, and how they can be incorporated into conventional IPM practices, to make them more effective.

Keywords Ecology · Agronomic · Cultural · Habitat management · Induced plant resistance · Endophytes · *Wolbachia* · Sterile insect technology

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D.E. Conlong (✉)
Department of Conservation Ecology and Entomology, Faculty of AgriSciences, Stellenbosch University, Private Bag X1, Matieland. 7602. South Africa; Crop Biology Resource Centre, South African Sugarcane Research Institute, Private Bag X02, Mount Edgecombe. 4300. South Africa
e-mail: Des.Conlong@sugar.org.za

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10.1 Introduction

Since its inception some 65 years ago (Herren, 2003), major advances in Integrated Pest Management (IPM) have been made (Kogan, 1998). These advances are documented in many textbooks, reviewing IPM across agricultural plant, animal and stored product disciplines (Delucchi, 1987), worldwide agriculture (Maredia et al., 2003), organic crops (Zehnder et al., 2007) and on different continents and subcontinents, for example Asia (Pontius et al., 2002), North America (Kogan, 1998) and Africa (Neuenschwander et al., 2003). The linking of specific management options, such as biological control, to IPM by Neuenschwander et al. (2003), has also been done with other components of the IPM arsenal, for example habitat management (Gurr et al., 2004), plant provided food to keep carnivorous insects in agro-ecosytems (Wäckers et al., 2005), soil health (Uphoff et al., 2006), biodiversity (Altieri and Nicholls, 2004) and plant resistance (Eigenbrode and Trumble, 1994; Thomas and Waage, 1996; Gatehouse, 2002; Sharma and Ortiz, 2002).

Electronic information sources are becoming key reference areas for IPM, and provide up to date reviews on all aspects of IPM, including other data base sources (Dufour, 2001; Anonymous, 2007). A concise discussion and summary of worldwide online resources for IPM information delivery and exchange, as well as a list of good IPM websites around the world is provided by Bajwa and Kogan (2003). In addition, regular newsletters on IPM aspects are available on line, for example IPMnet News[1].

Basically, IPM has frequently been described as a "knowledge intensive" approach to farming (Bartlett, 2002), with the basic building block of IPM still regarded as a sound knowledge of ecology (Dufour, 2001; Gurr et al., 2004; Kogan, 1998; Landis et al., 2000). The four phases of arthropod pest management and their interactions, as outlined by Zehnder et al. (2007), should form the basis of all IPM programs, from their planning through to their implementation phases.

The South African Sugarcane Research Institute (SASRI) has for many years been trying to control an indigenous stalk boring insect *Eldana saccharina* Walker (Lepidoptera: Pyralidae) (Carnegie, 1974). Since its first record in sugarcane in 1939 (Dick, 1945), many good cultural control measures have been developed for its control (Carnegie, 1981; Carnegie and Smaill, 1982), and resistant varieties of sugarcane have been developed against it (Keeping, 2006). However, it still remains a pest, and has spread throughout the sugar industry (Atkinson et al., 1981; Webster et al., 2006). This has necessitated a refocusing of control efforts into area-wide integrated pest management (AW-IPM) (Klassen, 2005), using the already developed and more conventional control options, but marrying them with sound, ecologically based, new technologies such as delineation of within species populations, chemical ecology, habitat management, sterile insect technology, and utilising what we call the "fourth trophic level"- plant endophytic pathogens and *Wolbachia*- to produce a workable IPM strategy.

[1] (Send the message "subscribe," or "unsubscribe" to: IPMnet@science.oregonstate.edu, being sure to state your e-mail address)

Following on from reviews of some conventional and also these new technologies, examples from the SASRI experience will be given to provide case studies of the relevance of these in developing an AW-IPM system along the lines proposed by Zehnder et al. (2007).

10.2 New Insights/Technologies for IPM

10.2.1 Ecology

Dufour (2001), Gurr et al. (2004), Kogan (1998) and Landis et al. (2000) all show beyond doubt why ecological knowledge is regarded as the basis of IPM. The study of ecology though is dynamic, and continually more information on ecological interactions becomes available as new techniques become known and more widely used, and more intra- and inter-continental studies on similar organisms take place. An example provided by studies on *E. saccharina* throughout its range in Africa showed behavioral, host plant and natural enemy differences in populations occurring between South and West Africa, with them seemingly coming together in Uganda (Conlong, 2001). These confusing factors between different populations of what is otherwise a morphologically similar species made it an ideal candidate for molecular systematic analyses, a relatively new and very useful technique (Evans et al., 2000; Scheffer, 2000). Assefa et al. (2006b) using the cytochrome c oxidase subunit 1 (CO1) region of the mitochondrial genome, separated the African species analysed into three distinct groups (west, south and Ethiopian). Two of these groups (west and south) were found in Uganda. The genetic diversity between these groups was as large, if not larger than that of related species of other lepidopterans (Assefa et al., 2006b). In IPM programs which use classical biocontrol of an exotic pest as one of their management options, and/or translocation of natural enemies of an indigenous pest from one local area to another (Schulthess et al., 1997), effectiveness of parasitoid searches for example can be enhanced by using such molecular techniques to identify cryptic species, or populations of species most closely related to each other over a wide geographical range, so that more informed decisions can be made regarding natural enemy selection for use against problem pest species. This applies not only to other pest species, (Sezonlin et al., 2006), but also to parasitoids (Dittrich et al., 2006).

10.2.2 Agronomic Control Options

IPM is especially suited to subsistence farming in developing countries (Charleston et al., 2003), and many of the cultural and agronomic control components have been developed from the knowledge of these small-scale farmers. Furthermore, in addition to a sound knowledge of the potential pests ecology, a sound knowledge of the agronomics of the crops under attack, and the ability to link the two knowledge bases to identify areas which could be exploited to minimise the pests impact has long been used as a basis for IPM (Bird, 2003). Examples from developing countries IPM programs (reviewed by Maredia et al., 2003) will be used to illustrate the importance of cultural and agronomic components that are now also used in commercial agriculture.

Agronomic or cultural practice IPM techniques can vary from the simple, such as physical removal and/or killing the rhinoceros beetle (*Oryctes monoceros* Oliv. [Coleoptera: Scarabaeidae]) *in situ* in young coconut plants in Tanzania (Nyambo et al., 2003), and hand picking of melon bug (*Aspongopus viduatus*) from watermelons and shifting planting dates in Sudan (Bashir et al., 2003). They can become more complicated too; such as using fluorescent lights around stone fruit orchards to repel nocturnal invasions of fruit piercing moths (Charleston et al., 2003). They can involve alternate crops. For example, nematodes attacking tomatoes grown in their dry season in Burkino-Faso were controlled using alternate crops planted in the rainy season that decreased nematode populations in the soils (Sawadogo et al., 1995). Ploughing before planting and after harvest has been used to control lepidopteran maize stem borers (Charleston et al., 2003) in South Africa, and white grub species (Coleoptera: Scarabaeidae) in Ugandan sugarcane (Mugalula et al., 2006).

Two major and essential tools for IPM, population monitoring and the use of damage and/or population thresholds, on which control interventions are based have been successfully used to plan conventional and botanical pesticide interventions against white flies, jassids, aphids and bollworm on cotton, and aphids on wheat in Sudan (Bashir et al., 2003), against lepidopteran stem borers in rice in Burkino-Faso (Dakouo et al., 1992) and sorghum in the same country (Dakouo and Ratnadass, 1999). These authors have also successfully combined plant resistance in their IPM programs. The South African deciduous fruit industry relies heavily on monitoring and pest threshold levels to implement mating disruption or low volume bait sprays against a number of key pests. In addition, pest phenology models are used to predict optimum periods for insecticidal applications (Charleston et al., 2003).

Often cultural control options can have contrasting impacts. Ants are problems in some agricultural industries, as they protect pest species against other natural enemies such as parasitoids. This situation has occurred in South African citrus and deciduous fruit industries, which have very good classical biological control programs against a number of pests using introduced parasitoids. The impact of ants was minimised by using ant barriers around the lower fruit tree trunks (Charleston et al., 2003) to prevent ant movement up them. In contrast, some ants are regarded as good biocontrol agents, and aerial "bridges" are erected in coconut plantations in Tanzania to encourage their foraging for the coreid bug, *Pseudotheraptus wayi* Brown (Nyambo et al., 2003). Increasing nitrogen fertilizer application to field soils has been useful for *Striga* control in maize (Snapp and Minja, 2003), but increases populations of *E. saccharina* in sugarcane (Carnegie, 1981) and is thus not recommended where this stem borer is a pest.

However, cultural and agronomic control methodologies have formed the basis of the IPM strategy of many commercial agricultural undertakings. Downy mildew and the parasitic plant *Striga hermonthica* in millet fields in Burkino-Faso have been controlled by the integrated use of hand weeding through to ploughing before planting, managed fertilizer usage, and planting patterns in time and space (Bonzi, 1996), as has *Striga asiatica* in Malawi (Snapp and Minja, 2003). Sound deciduous fruit orchard and vineyard management, which includes weed management, pruning, and field sanitation has reduced pest infestation pressures in South Africa (Charleston et al., 2003). In South African sugarcane, early cutting of the crop to reduce the period of exposure to the adults is recommended, as is applying reduced nitrogen fertilizer levels, good field hygiene is promoted, and pre-trashing to reduce oviposition sites is recommended in their IPM approach to control *E. saccharina* (Carnegie, 1981). Furthermore, insecticide applications are linked to moth trap catches, and resistant varieties are used on a large scale. In addition, habitat management options are used to manage *E. saccharina* populations between sugarcane and their indigenous host plants (Charleston et al., 2003).

10.2.3 Habitat Management

The concept of using trap crops, or other plant communities to attract insects from a more valuable crop, has been used for centuries (Hokkanen, 1991). It is very important to understand the role of the plant in managing insect populations, as the plant has many attributes that can either attract or repel insects (herbivores and natural enemies) to it (Cortesero et al., 2000; Wäckers et al., 2005). For many years it was puzzling why parasitoids of *E. saccharina*, abundant in its indigenous host plants (Conlong, 1990), were never found in sugarcane infested with *E. saccharina*, even when this crop was planted adjacent to the indigenous host plants, and was infested with *E. saccharina*. Recent work by Smith et al. (2006) eventually provided the answer. From Fig. 10.1, it is clearly evident that the crop and indigenous host plants emit different volatile profiles, and these profiles are even more different when the plants are attacked by *E. saccharina*. Even the volatiles emitted from the frass of *E. saccharina* feeding on the different host plants are different (Fig. 10.2). The response of one of its indigenous parasitoids, *Goniozus indicus* Ashmead (Hymenoptera: Bethylidae) (Fig. 10.3) to these volatiles in a 4-way olfactometer clearly showed that the parasitoid did not recognise plant volatiles from the crop host itself, nor in the frass of *E. saccharina* feeding on sugarcane. In contrast, it responded strongly to volatile cues from the indigenous host plant, and from frass of *E. saccharina* feeding on the indigenous host plant (Smith et al., 2006).

The response of *E. saccharina* itself to host plant volatiles is far less evident. Conlong et al. (2007) showed that ovipositing moths had a hierarchical preference for their indigenous host plants (Cyperaceae), over sugarcane, and choosing indigenous grasses least preferentially in cage trials. However, in all cage trials, in addition to eggs being found on the host plants themselves, many others were found in unnatural oviposition sites, i.e. under plant pots, on netting in cage corners etc. These observations supported the fact that *E. saccharina* adult females oviposit in cryptic “unnatural” sites (Atkinson, 1980), provided the sensory hairs

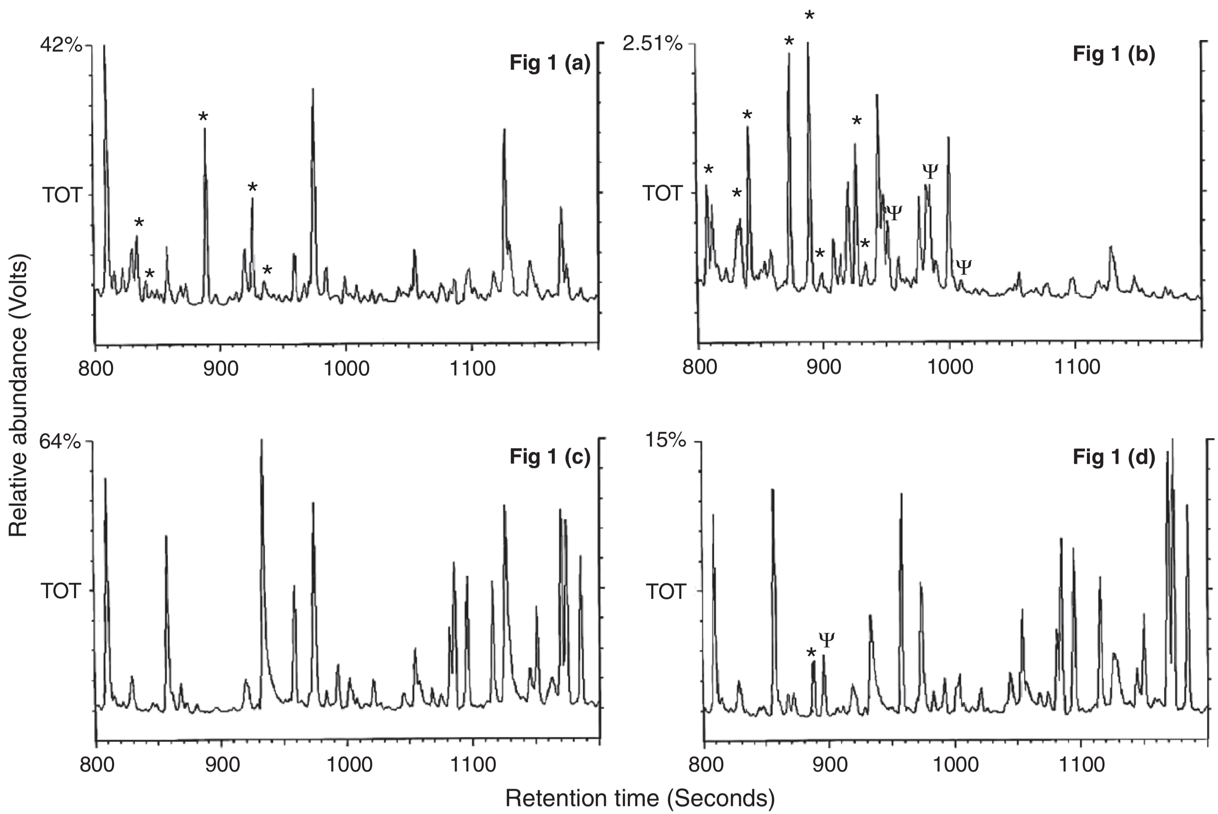

Fig. 10.1 Gas chromatograms of volatiles released by (**a**) uninfested *C. papyrus*, (**b**) infested *C. papyrus*, (**c**) uninfested sugarcane variety N11 and (**d**) infested sugarcane variety N11 (* = common compounds; Ψ = unique compounds) (From Smith et al., 2006)

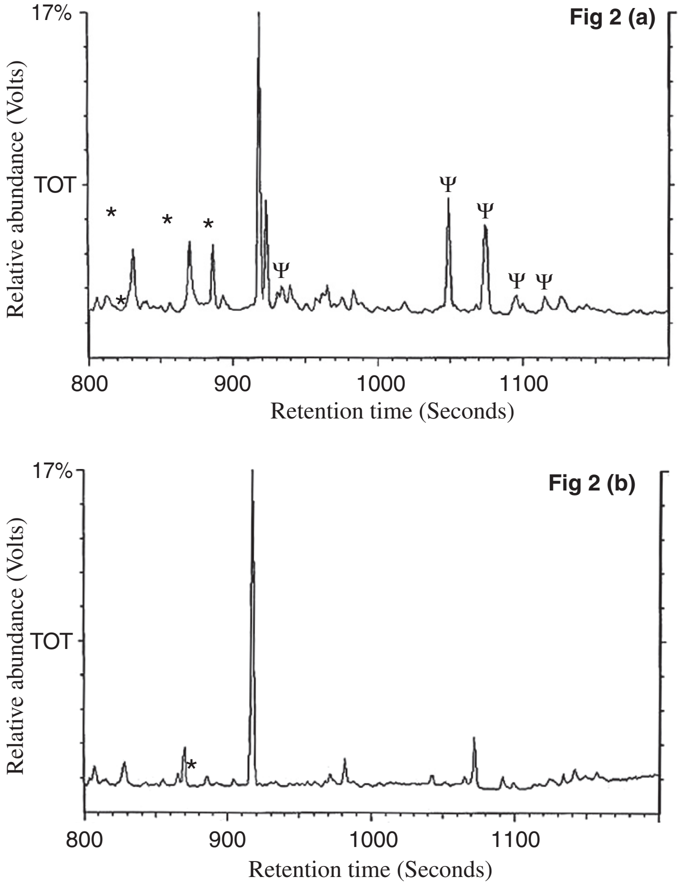

Fig. 10.2 Chromatograms of volatiles released by frass of *E. saccharina* feeding on (**a**) *C. papyrus* and (**b**) sugarcane variety N11 (* = common compounds; Ψ = unique compounds) (From Smith et al., 2006)

on the tip of their prehensile ovipositor (Wallade, 1982) are stimulated. This could have explained the early invasion of sugarcane, when the crop was planted in wetland areas amongst indigenous hosts of *E. saccharina* (Atkinson et al., 1981). The dead leaf material of mature sugarcane produces copious cryptic oviposition sites, which mated *E. saccharina* females would surely have exploited. The very soft sugarcane varieties planted at that time (Atkinson et al., 1981) would also have allowed the young neonate larvae to bore into the softer stalks, and feed to maturity on the stalk material. The large areas planted, at the expense of the natural hosts, would have meant that the insect would have emerged into a sugarcane "monoculture", with good oviposition sites, so the cycle would have thus continued, allowing *E. saccharina* to become habituated to the new host. However, if given the choice, neonate *E. saccharina* larvae still show a distinct preference for their indigenous

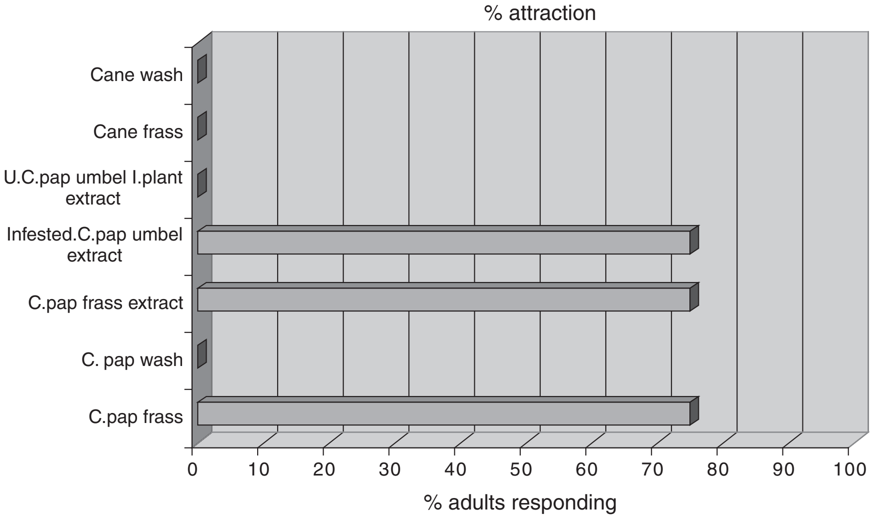

Fig. 10.3 Attraction of *Goniozus indicus* to different plant odours in a four-way olfactometer (U = uninfested; C. pap. = *Cyperus papyrus*)

Cyperaceous hosts over sugarcane over the indigenous grasses in petri dish bioassays (Conlong et al., 2007), indicating a distinct volatile response for the larvae. This is in keeping with the idea that oviposition strategies are linked to neonate larval mobility (Bergman, 1996), and has led to the hypothesis that *E. saccharina*, [because of its polyphagous nature in attacking species in the plant families Cyperaceae, Typhaceae, Juncaceae and Graminaceae (Atkinson, 1980; Conlong, 2001; Mazodze and Conlong, 2003)], would oviposit in the vicinity of host plants belonging to these families, leaving the more mobile and fastidious neonate larvae to search for a host plant that will supply its nutritional needs (Conlong et al., 2007). The overriding need to cryptically hide its eggs in mature host plant tissue (Girling, 1978; Kasl, 2004) was again demonstrated by Keeping et al. (2007), who showed that if given the choice between older sugarcane and maize, *E. saccharina* would oviposit on the older maize leaf tissue rather than on the equivalent on sugarcane, even if the maize was Bt maize, and larval survival on this was zero.

These results have provided evidence that habitat manipulation of *E. saccharina* is possible, and that *E saccharina* seems to have a hierarchical preference in choosing a host plant habitat to oviposit in i.e. Cyperaceae (Conlong et al., 2007) and maize (Keeping et al., 2007), and both have *E saccharina* population controls in place- natural enemies in the Cyperaceae (Conlong, 1990, 1997) and genetically engineered Bt toxins in maize (Keeping et al., 2007). Further evidence to promote habitat management as a control option was provided by Khan et al. (1997a, 2001) who showed and explained the repellent properties of the indigenous African grass *Melinis minutiflora* Beauv. to cereal stemborers, and also its attractant properties to cereal stem borer parasitoids (Khan et al., 1997b). Kasl (2004) in laboratory and cage trials showed that *E. saccharina* too was repelled by this grass, and that one of its parasitoids (*Xanthopimpla stemmator* (Thunberg) (Hymenoptera: Ichneumonidae) parasitised more *E. saccharina* pupae in sugarcane in the presence of this grass, then in pure sugarcane alone. The next phase in developing this habitat management approach for *E. saccharina* was to set up replicated field trials using the indigenous Cyperaceae as trap, or "pull" plants along the borders of selected sugarcane fields, and rows of *M. minutiflora* along either irrigation or drainage lines, as a repellent or "push" plant for *E. saccharina* (Fig. 10.4). Barker et al. (2006) showed that *E. saccharina* populations, and damage was halved in the "push/pull" plots compared to pure sugarcane control plots. In addition, he showed a dramatic reduction in weed abundance where *M. minutiflora* was planted, much the same as Khan et al. (2001) found in their trials with similar plants against *Striga hermonthica*. Based on the success of these trials, a farm based habitat management plan has been devised, incorporating the indigenous host plants and Bt maize as "pull" plants for *E. saccharina* and *M. minutiflora* as the "push" component. It has been expanded into an IPM plan, as it incorporated the use of sugarcane varieties known to be resistant to *E. saccharina*, and suited to the soil types and environmental conditions of the farm area. It is described diagrammatically in Figs. 10.5 and 10.6. An added aspect to the plan is to plant buckwheat at the time of sugarcane planting to attract adult parasitoids and predators into the sugarcane environment by providing a pollen and nectar source for them, much the same as advocated by Wäckers et al. (2005) and Zehnder et al. (2007) in their conservation biological control approach to enhance the activity of indigenous natural enemies.

Fig. 10.4 A habitat managed field of sugarcane. The grass with the flower heads bordering the mature sugarcane is *Melinis minutiflora*. Its closed sward outcompetes weeds as clearly shown. Creeping grass species such as *Cynodon dactylon*, are also outcompeted thereby preventing their invasion from field margins into sugarcane stands

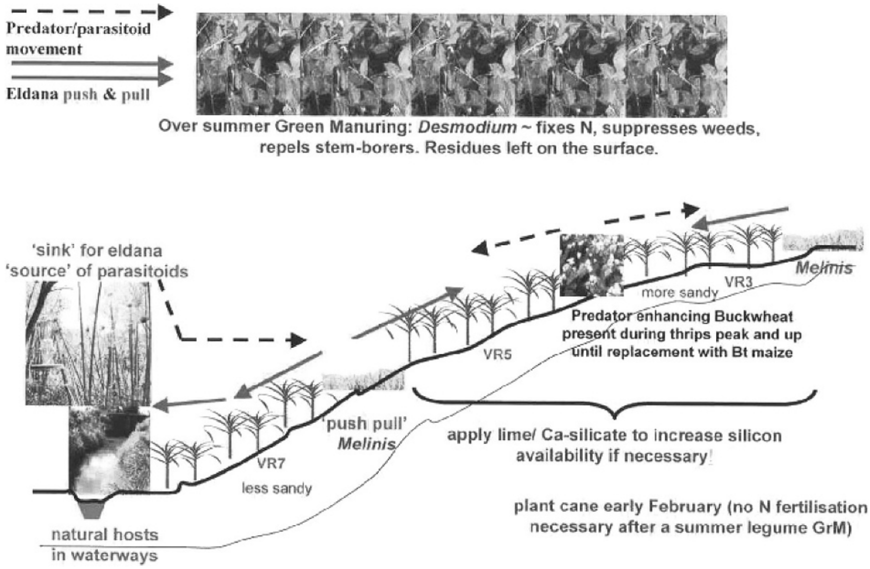

Fig. 10.5 Conceptual diagram for a habitat management based IPM approach to control thrips (Thysanoptera: Thripidae) at planting, and *Eldana saccharina* infestation in older sugarcane: Management just prior to planting and at planting (VR3, VR5, VR7 = sugarcane varieties recommended for the particular soil and environmental conditions of the planting site, and resistant to *E. saccharina*)

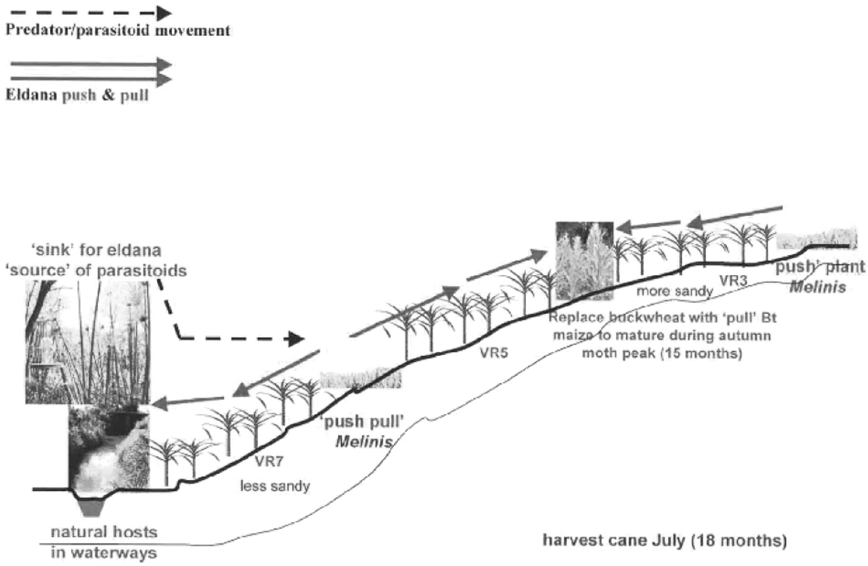

Fig. 10.6 Conceptual diagram for a habitat management based IPM approach to control thrips (Thysanoptera: Thripidae) at planting, and *Eldana saccharina* infestation in older sugarcane: Management from planting to harvest. (VR3, VR5, VR7 = sugarcane varieties recommended for the particular soil and environmental conditions of the planting site, and resistant to *E. saccharina*)

10.2.4 Induced Plant Resistance

In addition to knowledge of ecology, host plant resistance is regarded as another basic requisite for an IPM strategy (Maxwell, 1985). Many textbooks and papers have been written on this subject and are excellently reviewed by Zehnder et al. (2007), as is the concept of partial host plant resistance. There are many varieties of plants worldwide that have been developed for resistance to a variety of pests. The varieties produced by the different breeding programs differ in their resistance to particular insects. While one particular variety may be resistant to one species of insects, the same variety may be susceptible to another species. This anomaly was shown to occur with South African sugarcane varieties developed for resistance to *E. saccharina* (Keeping, 1999; Keeping and Govender, 2002). In Mozambique, where the South African varieties were exposed to an exotic stalk borer, *Chilo sacchariphagus* Bojer (Lepidoptera: Crambidae), the one most resistant to *E. saccharina* (variety N21) was susceptible to *C. sacchariphagus*, and others showing susceptibility to the former, were resistant to the latter (Conlong et al., 2004).

Keeping and Meyer (2002) have shown that this resistance can be enhanced by incorporation of silicon into the soil. In addition, the use of plant elicitors to induce resistance (Zehnder et al., 2007) shows much promise as an IPM tool. Stout et al. (2002) provide a good review of the concept of inducing resistance of plants to their insect herbivores. Many of these elicitors have a two-fold benefit. In addition to inducing resistance, they are also used to attract predators and parasitoids into crop fields, to increase their populations and foraging (James et al., 2005).

10.3 The Fourth Trophic Level

10.3.1 Fungal Endophytes

Azevedo et al. (2000), in their review showed that research into endophytic microorganisms in plants as control mechanisms for insect herbivores only commenced in the early 1980's. They defined endophytic micro-organisms as "mainly fungi and bacteria . . . inhabiting the interior of plants . . . doing no apparent harm to their plant host." They cite many examples of where an endophyte, mostly fungi of the genus *Acremonium*, associated with a plant host has led to insect pest reductions, and that as early as 1987 endophytic fungi had been isolated from at least 80 temperate grass species (Azevedo et al., 2000).

In most cases cited by Azevedo et al. (2000), pest reductions were associated with increased toxin production caused by the endophytes. Often these toxins are also toxic to mammals (Azevedo et al., 2000; Cardwell et al., 2000). However, Azevedo et al. (2000) cite work by Breen that shows that the opposite may occur, ie the pest may increase on a plant infected with a particular endophyte.

This was also demonstrated by Cardwell et al. (2000), who showed that maize infested with *Aspergillis flavus* Link:Fr. caused the production of aflotoxins. *Chilo partellus* Swinhoe (Lepidoptera: Crambidae) was killed and mummified by this fungal endophyte in maize, and *Heliothis zea* and *Spodoptera frugiperda* (both Lepidoptera: Noctuidae) had reduced survival when fed on diet containing this fungus. *Mussidia nigrivenella* Ragonot (Lepidoptera: Pyralidae) in contrast, was not sensitive to aflotoxins or *A. flavus*. However, they also showed that in maize infested with *Fusarium verticillioides* Sacc. (Nirenberg), which causes the toxin fumonisin, infestation by *E. saccharina* was higher than in *A. flavus* infested maize, and also higher than in the control. This was even evident in maize genotypes bred for resistance to *E. saccharina*- those containing *F. verticillioides* infestation, contained higher populations of *E. saccharina* and *M. nigrivenella* (Cardwell et al., 2000). This backs up other literature implicating this fungus in cereal crops as being an insect growth promoter. However, it has also been described as an entomopathogen [for example, of *Heliothis virescens* (Lepidoptera: Pyralidae)] (Cardwell et al., 2000). It is hypothesised that the use of maize infested with *F. verticellioides* would increase the maize attractancy to *E. saccharina* in the habitat manipulation studies to decrease infestation in sugarcane described above.

Fungi have many ways of entering plants to become endophytes. In maize they can enter by spores germinating on cob silks either just prior to or after pollination, or by spores being carried by insects infesting the plants (Cardwell et al., 2000). Akello et al. (2007) demonstrated that by dipping roots and rhizomes of banana plants in a conidial suspension of *Beauveria bassiana* (Balsamo) Vuillemin they could achieve an endophytic relationship between the fungus and the plant. This was also achieved by injecting the suspension into the rhizome and the plant, and by growing the plant in soil mixed with *B. bassiana* colonised rice grains, but not as effectively as the dipping technique (Akello et al., 2007). Cherry et al. (2004) achieved this endophytic association between maize and *B. bassiana*, by injecting the conidia into the maize stalk, and also by conidial seed dressing and topical application of the conidia to leaf axils. In this way they demonstrated reduced infestation of *Sesamia calamistis* Hampson (Lepidoptera: Noctuidae) in maize treated with *B. bassiana* compared to untreated maize.

Conlong (1990) showed that in *Cyperus papyrus* L., *B. bassiana* is one of the major mortality factors of *E. saccharina*. He did not, however, demonstrate that the fungus was endophytic in this host plant. In recent trials testing the efficacy of isolates of *B. bassiana* as sugarcane sett (or stalk) dip to kill *E. saccharina* in setts to be used for planting (seedcane), no colonisation of the borings by this fungus could be demonstrated (Conlong, unpublished). Generally, when *E. saccharina* bores in sugarcane, the tissue surrounding the boring becomes discoloured (Fig. 10.7), This reddish discoloration has been shown to be caused by *Fusarium* spp. Morris (pers. comm.) in petri-dish nutrient agar plates showed that this fungus was aggressive, and did not allow colonisation of the agar by *B. bassiana* that was plated with it. These observations and the work of Schulthess et al. (2002) led Mc Farlane and Rutherford (2005) to isolate numerous endophytic *Fusarium* spp. from sugarcane unbored

Fig. 10.7 Split sugarcane stalk showing *Eldana saccharina* boring, a cocoon covered *E. saccharina* pupa, and the discolouration always associated with *E. saccharina* caused by *Fusarium* spp

and sugarcane bored by *E. saccharina*. These species elicited different responses from *E. saccharina* exposed to them. Some were beneficial to the borer, with it showing similar growth response and attraction as demonstrated by Schulthess et al. (2002). Others were clearly antagonistic, with *E. saccharina* growth retarded (Mc Farlane and Rutherford, 2005), and individuals being repelled by these (Mc Farlane and Rutherford, 2006).

The most attractant and beneficial *Fusarium* isolate to *E. saccharina* found in sugarcane has been tentatively identified as *F. pseudonygamai* (Mc Farlane and Rutherford, 2005, 2006). In an integrated control approach against *E. saccharina*, seedcane hot water treatment or treatment with fungicides could reduce the infestation of the seedcane by this *Fusarium* isolate, thereby reducing the chance of *E. saccharina* infestation. Alternatively, the facilitation of endophytic colonisation of sugarcane stalks by the *Fusarium* species antagonistic to *E. saccharina* (Mc Farlane and Rutherford, 2005, 2006) could afford more sustainable and environmentally friendly protection from this stalk borer, as these isolates once established in sugarcane, could restrict colonisation of stalks by isolates beneficial to *E. saccharina*.

10.3.2 Wolbachia

These obligate intracellular bacteria (Phylum α-Proteobacteria: Family Rickettsaceae) are commonly found in diverse arthropod and nematode taxa and can profoundly alter their hosts' reproduction (Floate et al., 2006). They are maternally inherited, residing mostly in reproductive tissues of their invertebrate hosts and it has been suggested that they may infect over 20% of arthropod species worldwide (Bourtzis, 2007). In Canada, *Wolbachia* infections have been detected in 46% of the 105 arthropod species studied in biocontrol research programs (Floate, 2007). It was first described in the 1920's and 30's as a micro-organism infecting the ovaries of mosquitos belonging to the *Culex pipiens* L. complex and named *Wolbachia pipientis* Hertig (Werren, 1997).

In their reviews on the biology and uses of *Wolbachia*, Werren (1997), Floate et al. (2006) and Bourtzis (2007) all regard the symptoms of infection such as feminisation of genetic males, parthenogenesis induction, male embryo killing and cytoplasmic incompatibility of related strains of arthropods as useful characters for arthropod population regulation. This is because these properties alter the reproductive success of their hosts (Floate, 2007). As such, *Wolbachia* have potential as a new type of biological control agent (Bourtzis, 2007; Floate, 2007), because they could enhance the productivity of natural enemies (Werren, 1997). In addition, *Wolbachia*-induced cytoplasmic incompatibility (CI) for example can be used in three ways: to directly suppress populations of economic and public health importance; as a tool to spread genetically modified strains into wild populations and as an expression vector, once a genetic transformation system for this bacterium is developed (Bourtzis, 2007).

Reduced offspring numbers from matings of certain strains of arthropod species are a typical symptom of *Wolbachia*-induced CI (Werren, 1997). Assefa et al. (2006a) after mating adults of *E. saccharina* from the South African Sugarcane Research Institute's (SASRI) insect rearing unit, with adults of the opposite sex from a population collected at Lake Naivasha, Kenya (in the Great African Rift Valley), and then backcrossing the F1 offspring of the crosses back with the SASRI strain, revealed reduced fertility of eggs produced from F1 hybrid/SA parent population cross compared with fertility of the eggs from the true SA line cross, and also an F1/F1 hybrid cross. The F1 hybrid female/SA population male cross had particularly low fertility. This is consistent with Haldane's rule, which states that heterozygotic females are more infertile than heterozygotic males (Assefa et al., 2006a). The sequence divergence in his mitochondrial DNA (Mt DNA) study done at the same time, of these two populations showed them to be as equally divergent as sister species. These two facts led him to hypothesise that there are cryptic species in the African *E. saccharina* complex, as a broader phylogeographic study of *E. saccharina* showed similar large sequence divergences (Assefa et al., 2006b). This hypothesis was further supported by differences in behavior, host plant preferences and parasitoids species complexes found between *E. saccharina* populations of west, east and southern Africa (Conlong, 2001).

The reduced fertility of the hybrid female/SA male cross (Assefa et al., 2006a) was recognised as a possible *Wolbachia*-induced CI. On the strength of this, a study was initiated to screen all the specimens used for Assefa's studies for *Wolbachia* presence, using PCR techniques. Very recent results (Rutherford, unpublished) have confirmed the presence of *Wolbachia* in *E. saccharina* from two localities in Kenya: Lake Naivasha, and from Mbita Point on Lake Victoria, as well as from wild host populations in Uganda. Results from further populations are eagerly awaited. This now opens the use of *Wolbachia* in an IPM strategy. Werren (1997) cites clear evidence that cytoplasmically inherited *Wolbachia* infections can readily spread through uninfected populations due to CI. Could this be achieved in the South African population, which at this stage is uninfected with *Wolbachia*? Should this be the case, and *Wolbachia* can be introduced, then a female biased population can be expected, rather than the 1:1 male to female population currently found in sugarcane and wild hosts in South Africa (Conlong, unpublished). This would complement, for example, the use of sterile insect technology, especially F1 sterility (see next section), as it would mean that sterile males produced would have fewer "wild" males to compete with, thereby reducing the numbers of sterilised males needed for release into the environment.

10.4 Links with Sterile Insect Technology (SIT)

The concept of area wide integrated pest management was introduced when humans had to control locust plagues and vector borne diseases (Klassen, 2005). This concept makes sense, as insects do not consider international, provincial, or even farm boundaries. Their distributions are more constrained by biotic and abiotic factors. Klassen (2005) reviews the development of Area-Wide Integrated Pest Management (AW-IPM) and shows its links with SIT. He lists the benefits of AW-IPM as (a) "requiring multiyear planning, and an organisation dedicated exclusively to its implementation, whereas conventional pest management involves minimal forward planning, tends to be re-active, and is implemented independently by individual producers, businesses or households"; and (b) "it utilises advanced technologies, whereas the conventional strategy tend to rely on traditional tactics and tools". He further regards SIT as "a species-specific form of birth control imposed on a pest population", which is "a powerful tool for "mopping-up" sparse pest populations". He regards it as being "most efficient when applied as a tactic in a system deployed on an area-wide basis. On environmental, economic and biological grounds, the case for SIT is compelling".

SIT and its link with AW-IPM is comprehensively dealt with by numerous authors in the books edited by Dyck et al. (2005) and Vreysen et al. (2007). The many approaches to, and successes using this combined approach are clearly outlined in these books. For some groups of insects such as the Lepidoptera, however, doses of radiation are too high if full sterility is the desired outcome (Carpenter et al., 2005). These doses affect other life functions of the sterilised insects, making them less fit than their wild counterparts, thereby giving the latter a competitive advantage over them. This does not make them unsuitable for SIT, as inherited sterility is another SIT option (Carpenter et al., 2005). This option allows the radiation dose to be adjusted lower to produce partially sterile but more fit males, who, when mated with wild females, have the radiation induced deleterious effects passed on to the F1 generation. This results in reduced egg hatch, with the F1 offspring sterile, and male biased (Carpenter et al., 2005). These attributes, however, considered with the more conventional IPM interventions such as host plant resistance, insecticides, entomopathogens and other natural enemies could potentially interfere with the effectiveness of F1 sterility if the controlling factor killed a higher proportion of treated than wild individuals (Carpenter et al., 2005). In the case of *E. saccharina*, this is not a problem, as the above more conventional control interventions have not provided a solution to its control. In addition, many laboratory and field studies have investigated these interactions, and none so far have shown incompatibility between the control options and F1 sterility (Carpenter et al., 2005).

Furthermore, models cited by Carpenter et al. (2005) have shown that inundative releases of natural enemies and sterile insects should complement each other. This is because SIT increases the ratio of natural enemies to adult hosts, which is particularly important when considering parasitoids, who work better when the host to parasitoid ratio is reduced. Surely this would also apply in the case where an effective indigenous egg parasitoid is already present in a habitat where F1 sterility is to be applied? The abundance of sterile eggs which could be parasitized by an indigenous egg parasitoid, for example, thereby building up numbers of the natural enemy, and increasing the natural enemy to host ratio, would lead to substantial control of the pest population. An ideal model to be tested is provided by the recent invasion of African sugarcane in Mozambique by *C. sacchariphagus* (Way and Turner, 1999). Already resistant host plants can be planted in the estates affected by this borer (Conlong et al., 2004), and a very effective indigenous egg parasitoid, *Trichogramma bournieri* Pintureau & Babault (Hymenoptera: Trichogrammatidae) is present on the affected estates (Conlong and Goebel, 2006). Should this model prove effective, F1 sterility of *C. sacchariphagus* in the Mascarene Islands and Madagascar, where it also occurs, and where other egg and larval parasitoids occur (Williams, 1983; Goebel et al., 2001), should become an effective reality.

10.5 Conclusion

Hopefully this chapter has shown, with practical examples that modern IPM is not only about insect/plant interactions, it is about holistic agro-ecosystem interactions, in which increased knowledge about the environment, plants, pathogens, endophytes, symbionts and insects are all combined to provide effective crop protection in an environmentally friendly manner. As knowledge about, and interactions between, chemistry of induced plant resistance, chemical ecology, micro-organisms such as endophytic fungi and *Wolbachia*, SIT and phylogenetics and phylogeography of arthropods becomes more easily available, it is hypothesized that these will become important components of AW-IPM, thereby minimising the impacts of synthetic pesticides even more. IPM practitioners are encouraged to consider the complete ecology of the perceived pest, and try to use ecological concepts and theory in its management, to provide sustainable, environmentally friendly control rather than the knee-jerk reaction of pesticide spraying.

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Chapter 11
Behavior-Modifying Strategies in IPM: Theory and Practice

Cesar R. Rodriguez-Saona and Lukasz L. Stelinski

Abstract The possibilities of using strategies to manipulate insect behavior in agricultural systems have increased due to strict regulations imposed on the use of insecticides worldwide. Here we discuss the potential of semiochemicals, specifically sex pheromones and host-plant volatiles, as tools to manipulate insect behaviors in integrated pest management (IPM) programs. Sex pheromones are widely used in agriculture for monitoring abundance and distribution of insect pest populations and predicting timing of insecticide applications. They have also been used, to a lesser extent, in insect pest control. One of the most promising concepts is the deployment of synthetic sex pheromones into a crop to disrupt insect mating. Three mechanisms of mating disruption: sensory desensitization, competitive attraction, and non-competitive mechanisms, are described. In addition to mating disruption, sex pheromones can be employed in mass trapping and attract-and-kill approaches for pest control. An area of increased interest among entomologists and chemical ecologists is the use of host-plant volatiles to manipulate insect behavior. Host-plant volatiles can be a source of attractants and repellents, and can be implemented into monitoring and pest management practices. These volatiles can be used alone or in combination with other stimuli in control strategies such as mass trapping, attract-and-kill, push-pull, and disruption of host finding. Plant volatiles in most cases synergize with sex pheromones and biological control. To be adopted by farmers, strategies to modify insect behavior will need to be comparable to newer insecticides in efficacy and costs. Increased adoption will also require extensive educational programs for farmers.

Keywords Semiochemicals · Sex pheromones · Mating disruption · Host-plant volatiles · Behavioral manipulation · Crop protection

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C.R. Rodriguez-Saona (✉)
Department of Entomology, Rutgers University, USA,
PE Marucci Center for Blueberry & Cranberry Research & Extension, 125A Lake Osweg. Rd., Chatsworth NJ 08019, USA
e-mail: crodriguez@aesop.rutgers.edu

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11.1 Introduction

Most control strategies against insect pests involve some sort of change to their behavior (Gould, 1991; Foster and Harris, 1997), whether it is through chemical (i.e., volatiles and non-volatile compounds, feeding deterrents), visual, or auditory signals. The concept of manipulating pest behavior for insect control has been known for centuries through the practice of trap cropping (Hokkanen, 1991). Food lures and baits treated with a poison have also been used for more than a century to control household pests (Pedigo, 1996). Historically, however, the adoption of technologies to manipulate insect behavior in agricultural systems has been slow largely due to the arrival of cheaper chemical controls with broad insecticidal activity. This situation is likely to change with the increasing public awareness of the negative effects of broad-spectrum insecticides on humans and non-target organisms. More stringent regulations have been imposed on the use of insecticides worldwide. In the United States, the Environmental Protection Agency (EPA) implemented the Food Protection Act (FQPA) in 1996 (U.S.E.P.A., 2008). Since then, several broad-spectrum insecticides have been either banned, scheduled for elimination, or their use has been restricted in several agricultural crops. These regulatory restrictions are expected to help the adoption of alternative pest management practices, including manipulation of pest behavior, and promote a transition from insecticide-based to more ecologically, integrated pest management (IPM)-based programs.

Manipulation of pest behavior is defined as “the use of stimuli that either stimulate or inhibit a behavior and thereby change its expression” (Foster and Harris, 1997). Manipulation of insect behavior involves detection of signal chemicals known as semiochemicals (Nordlund and Lewis, 1976), also referred to as infochemicals (Dicke and Sabelis, 1988). Pheromones are semiochemicals used in intraspecific communication, and can be classified according to their function, such as sexual attraction, aggregation, alarm, marking, etc. Allelochemicals are semiochemicals that facilitate interspecific communication. Allelochemicals include a greater number of chemicals than pheromones, and can be grouped into: allomones that benefit the emitter and are detrimental to the receiver; kairomones that benefit the receiver and are detrimental to the emitted; and synomones that benefit both the emitter and the receiver. Although other groups of allelochemicals have been added to this list (e.g., Dicke and Sabelis, 1988), they will not be discussed in this chapter and thus were omitted. Depending on the context, plant volatiles are allomones if they repel herbivores, kairomones if they attract herbivores, or synomones if they attract the herbivores’ natural enemies. In many instances, a single plant chemical has more than one function which may in turn limit their application for pest management, as will be discussed in this chapter.

Our main intent here is to provide a basic synopsis of our current knowledge of insect sex-attractant pheromones and host-plant volatiles (Fig. 11.1), including their chemistry, activity on insect pests and their natural enemies, applications to manipulate insect behavior in agricultural systems, and adoption. Although manipulation of insect behavior can be achieved through changes in chemical, visual, and/or auditory

Attributes	Sex Pheromones	Host-Plant Volatiles
A) Physical		
Specificity	High	Low
Complexity	Low-High	Mostly low
Volatility	Variable	Mostly high
Stability	Often high	Often low
Toxicity	Low (?)	Low (?)
B) IPM		
Target gender	Only one sex	Both sexes
Insect stage	Adults only	Adults and larvae
Background odors	Unimportant	Very important
Compatibility with other control strategies	High	High
Non-target effects	Low	High
Adoption	Wide	Limited

Fig. 11.1 Differences and similarities between sex pheromones and host-plant volatiles used for behavioral manipulation of insect pests. Graphic designed by Robert Holdcraft

stimuli, this review will focus only on the manipulation of chemical stimuli for insect pest management. Furthermore, we will only discuss volatile chemicals used by insects as long-range cues, as opposed to non-volatile compounds that only function as contact chemicals. This review will focus on examples where the chemicals that elicit a change in the insect's behavior have been isolated, identified, and used for pest management purposes. First, we will discuss general aspects of insect sex pheromones focusing mainly on mating disruption. We will discuss the proposed mechanisms underlying mating disruption, and provide two case studies in apples and blueberries from our own research. The second part of this review will focus on the responses of insects to host-plant volatiles and their potential for pest management. The final section provides an overview of farmer attitudes towards these technologies and the needs for increasing their adoption.

Although insect pheromones have been, and most likely will continue to be, the basis of insect behavior manipulation, the extent to which plant volatiles influence host-plant location in insects and their potential use in crop protection has become increasingly apparent in light of recent findings. This is most evident from the increasing numbers of studies on the chemistry, activity, and application of host-plant volatiles over the last five years (Table 11.1).

Table 11.1 Numbers of publications in selected journals that investigated sex phermones or plant volatiles as tools for insect control[1]

	Sex Phermones[2]		Plant Volatiles[3]	
	1994–2002	2003–2008	1994–2002	2003–2008
Journal of Economic Entomology	88 (9.8)	83 (16.6)	21 (2.3)	16 (3.20)
Environmental Entomology	57 (6.3)	26 (5.2)	25 (2.8)	23 (4.5)
Journal of Chemical Ecology	100 (11.1)	33 (6.6)	68 (7.6)	27 (5.4)
Chemoecology[4]	3 (3.0)	4 (0.8)	2 (2.0)	5 (1.0)
Entomologia Experimentalis et Applicata	45 (5.0)	25 (5.0)	26 (2.8)	23 (4.6)
Totals	122 (13.5)	171 (34.2)	40 (5.3)	94 (18.8)

[1] Based on records from Web of Science. In parenthesis are average numbers of records per year
[2] Keywords = Sex pheromones AND insect AND pest AND management
[3] Keywords = Plant volatiles AND insect AND pest AND management
[4] Records starting in 2002

11.2 Sex Pheromones and IPM

Insect sex-attractant pheromones are chemical signals emitted into air by one of the sexes and guide the opposite sex to the source of the resultant aerial plume for mating. In most insect species, especially in moth pests, it is the females that emit the sex pheromone to attract males. In many cases, stationary females can call responsive males from distances of 40 m or more, depending upon the degree to which vegetation breaks up and dilutes the pheromone plume. When in close proximity, both sexes may emit and receive short-range signals (chemical, visual, and acoustical) that reciprocally elicit the courtship sequence leading to copulation. One successful mating of a female moth, for example, can yield 100 or more fertilized eggs. The first chemical identifications and syntheses of sex-attractant pheromones of moths were published over 40 years ago (Butenandt et al., 1959; Berger, 1966). Realization that normal long-distance mate finding is elicited by minute quantities of sex pheromones gave rise to several decades of applied research toward development of insect control tactics with synthetic pheromones. One promising idea was that deployment of synthetic pheromone into the crop could confuse males encountering it such that they fail to find authentic calling females (Wright, 1965). The desired end-result is reduction in fertilized eggs and resultant damaging larvae because females failed to mate. Today, mating disruption, as the technique is commonly referred to, is practiced worldwide for control of moth pests in fruits, vegetables, and forestry (Cardé, 2007). Mating disruption reduces the need for chemical insecticide applications, and in some cases it is practiced as a stand-alone tactic. In addition, the use of pheromones for pest monitoring and as a tool for accurately timing insecticide sprays has become a cornerstone feature of many prominent IPM programs. Finally, other applications of pheromone-based technologies for direct pest control such as mass trapping and attract-and-kill have shown promise in specific instances.

11.2.1 Applications

11.2.1.1 Monitoring

The identification and synthesis of thousands of insect sex pheromones (El-Sayed, 2007) has allowed widespread and reliable use of synthetic attractants for pest monitoring. These synthetic copies of insect attractants are formulated in controlled-release devices and deployed in association with a wide variety of trapping surfaces (Cardé and Elkinton, 1984; Wall, 1989; Jones, 1998). Traps are often characterized by a sticky surface or liquid mote for capturing attracted insects. Synthetic semiochemicals attached to such traps are typically released from rubber septa, sleeves, or reservoirs made of polyethylene or polyvinyl chloride. Traps baited with pheromones or plant-derived kairomones are simple and inexpensive tools for detecting pest presence. Semiochemical-baited traps are effective means of monitoring for introductions of exotic pests, maintaining quarantine guidelines such as the "fruit fly free zone" in Florida citrus production (Simpson, 1993), and for determining the effectiveness of pest management techniques such as mating disruption. Furthermore, degree-day models have been developed using synthetic attractants; these models effectively predict insect egg hatch allowing for targeted applications of insecticides rather than prophylactic calendar-based sprays (Welch et al., 1981; Riedl et al., 1986; Knight and Croft, 1991). In certain cases, good correlations between adult insect captures in monitoring traps and larval damage has led to the development of predictive models for effective timing of management sprays (Van Steenwyk et al., 1983; McBrien et al., 1994; Bradley et al., 1998; Morewood et al., 2000). For example, severe outbreaks of the eastern spruce budworm, *Choristoneura fumiferana* (Clemens), can be predicted years in advance based on annual trapping data of adult moths (Sanders, 1988). One example where this has been effectively implemented is the apple maggot fly, *Rhagoletis pomonella* (Walsh), in North America (Stanley et al., 1987; Agnello et al., 1990). Using sticky traps baited with a potent apple maggot kairomone, an action threshold of 8 flies per trap was developed, which reduced annual sprays by 70% while maintaining acceptable levels of control. Similarly, treatment thresholds for tortricid pest of tree fruit have been developed using pheromone traps as the predictive tool (Riedl et al., 1986; Wall, 1989).

11.2.1.2 Mass Trapping

Mass trapping is the application of semiochemical-baited traps for capturing a sufficient proportion of a pest population prior to mating, oviposition or feeding so as to prevent crop damage. The utility of mass trapping as a practical application in IPM programs has been very limited given that the technique is density dependent (Knipling, 1979). Mass trapping is only viable at low pest densities, since male attractant traps are competing directly with females. In those cases where only males are targeted, they must be removed from the population prior to mating to impact population growth. Given that most male insects mate more than once, nearly 99% male removal is required to prevent sufficient female mating for effective crop protection (Roelofs et al., 1970). The effectiveness of the technique is likely greater in those rare instances in which a mating system is characterized by a male-produced sex attractant. Under such circumstances, the reproductive females would be trapped out and the impact on population growth would be much larger with fewer traps than in the typical case where a mating system is characterized by a female-produced sex attractant. Other drawbacks exist including the need for frequent trap maintenance given that traps can quickly become saturated with insects. The efficacy of mass trapping is also dependent on the development of highly effective lure and trap combinations that can attract insect from large distances and efficiently capture the majority of attracted individuals. Ultimately, the cost of deploying a sufficient number of attractive traps to effectively compete with typically high insect population densities renders the technique impractical. In situations where the tolerance for crop damage is relatively high or the pest population extremely low, the technique may prove effective (Zhang et al., 2002). However, attempts to control insects such as the Japanese beetle, which typically occur at high population densities, have generally failed (Klein, 1981; Gordon, and Potter, 1985, 1986).

One of the most prominent examples of success with mass trapping is with certain species of forest bark beetles, given their use of aggregation pheromones for mass colonization of host resources. Trapping out the conifer bark beetle, *Ips typographus* (L.), with a synthetic aggregation pheromone has proven highly effective in reducing populations and preventing damage (Dimitri et al., 1992). Also, mass trapping has proven highly effective for controlling ambrosia beetles in timber processing facilities (Borden, 1990). Furthermore, combining the use of both anti-aggregation and aggregation pheromones to manipulate bark beetle behavior has proven effective in mass trapping protocols (Lingren and Borden, 1993; Borden, 1997).

11.2.1.3 Attract-and-Kill

This approach is also known as “attract-annihilate” (Foster and Harris, 1997). In principal, attract-and-kill and mass trapping are variations of the same tactic and like mass trapping, the efficacy of attract-and-kill systems is highly dependent on pest density. The major difference between the two tactics is that in attract-and-kill a semiochemical-based lure is combined with a toxic substrate rather than a sticky surface or liquid receptacle. This difference can overcome the logistic constraint of trap saturation reducing the cost of trap maintenance.

Tephritid fruit fly pests have been the target of several attempts to develop effective attract-and-kill tactics. For example, protein or pheromone (1,7 dioxaspiro)-based bait sprays laced with either malathion or dimethoate have proven highly effective in controlling the olive fly, *Bactrocera oleae* (Gmelin) (Howse et al., 1998). In addition, biodegradable or wooden spheres with a low dose of imidacloprid have shown promise for control of *R. pomonella* in apple and *R. mendax* in blueberry (Hu et al., 1998; Liburd et al., 1999; Ayyappath et al., 2000; Prokopy et al., 2000; Stelinski et al., 2001, Stelinski and Liburd, 2001). Such devices have been termed “pesticide-treated spheres” and rely on both visual and olfactory attractants to lure the target pest as well as a surface-borne feeding stimulant that causes the insect to ingest the toxicant present on the surface of the device. Deploying such devices on perimeter trees or bushes of commercial apple or blueberry blocks, respectively, resulted in control of apple maggot (Prokopy et al., 2000) and blueberry maggot flies (Stelinski and Liburd, 2001) equivalent to that achieved with conventional insecticides.

11.2.1.4 Mating Disruption

One of the most successful applications of insect sex pheromones for direct pest control has been mating disruption. Table 11.2 provides a list of successful cases of mating disruption for insect pest management. Mating disruption is a biorational method of controlling insect pests by saturating the environment with synthetic copies of natural insect pheromones to interfere with normal mating behavior. Currently, hand-applied, Isomate-style dispensers (Fig. 11.2A) deployed at ca. 1–4 per tree are the dominant method of dispensing pheromone for mating disruption of moth pests in orchards (Nagata, 1989; Agnello et al., 1996; Knight et al., 1998; Knight and Turner, 1999). The exposure concentration of moths treated with this technology can vary widely. Male moths may be exposed: to a ‘cloud’ of pheromone resulting from a coalescence of plumes emanating from many dispensers; a localized plume down-wind of a single dispenser; or, at the highest level of exposure, a moth could directly contact a dispenser following attraction. Use of low-density, high-release dispensers like puffers (Shorey and Gerber, 1996) or Microsprayers

Table 11.2 Successful cases of mating disruption in IPM

Insect pest	Crop	Sex pheromone	Reference
Codling Moth (*Cydia pomonella*)	Pome fruit	(*E,E*)-8, 10-dodecadien-1-ol (major component)	Charmillot (1990) Brunner et al. (2002) Knight (2004) Stelinski et al. (2005d)
Oriental Fruit Moth (*Grapholita molesta*)	Pome fruit Stone fruit	(*Z*)-8-dodecenyl acetate and (*E*)-8-dodecenyl acetate (95:5 ratio), and (Z)-8-dodecen-1-ol	Charlton and Cardé (1981) Rice and Kirsch (1990) Il'lchev et al. (2006) Stelinski et al. (2007c)
Leafrollers (various species)	Pome fruit	Δ11-tetradecenyl acetate Δ11-tetradecenyl alcohol (common components)	Pfeiffer et al. (1993) Stelinski et al. (2007b)
Grapevine Moth (*Lobesia botrana*)	Grape	(*E,Z*)-7,9-dodecadienyl acetate (*E,Z*)-7,9,-dodecadienol (*Z*)-9- dodecanyl acetate	Schmitz et al. (1997) Torres-Villa et al. (2002)
Pink Bollworm (*Pectinophora gossypiella*)	Cotton	(*Z,Z*)- and (*Z,E*)-7,11-hexadecadienyl acetate (1:1 ratio)	Doane et al. (1983) Flint and Merkle (1984) Cardé et al. (1998)
Tomato Pinworm (*Kaiferia lycopersicella*)	Tomoto	(*E*)-4-tridecenyl acetate	Trumble and Alvarado-Rodriguez (1993)

(Isaacs et al., 1999) likely increases the probability of exposure to extraordinarily high concentrations of pheromone. Pheromone solution sprayed from these dispensers adheres onto foliage and droplets of pure pheromone accumulate over time on the source tree. This may result in large and highly concentrated plumes that should waft great distances downwind of the source trees. Although the average airborne concentration of pheromone achieved in orchards treated with pheromone dispensers is unlikely to desensitize males flying or resting meters away from the source of emanating pheromone, anemotactic orientation of attracted male moths to within close proximity of dispensers likely does induce habituation (Stelinski et al., 2006a). Moths may be capable of making these close (within 1 m) approaches to high-dosage dispensers by orienting along the edge of the pheromone plume, modulating their exposure dosage (Kennedy et al., 1981; Stelinski et al., 2005b). Thus, the combination of initial orientation by tortricid male moths along plumes of synthetic pheromone followed by habituation due to over-exposure, likely explains disruption by Isomate dispensers and related technologies. This potential explanation for mating disruption of moths, in general, was proposed almost a decade ago (Cardé et al., 1998), and current evidence is consistent with this hypothesis.

Pheromone baited traps are often used to monitor the effectiveness of a mating disruption treatment (Fig. 11.2B). Acting as a female-proxy, if male catch in such traps is reduced by the mating disruption treatment, it is inferred that the

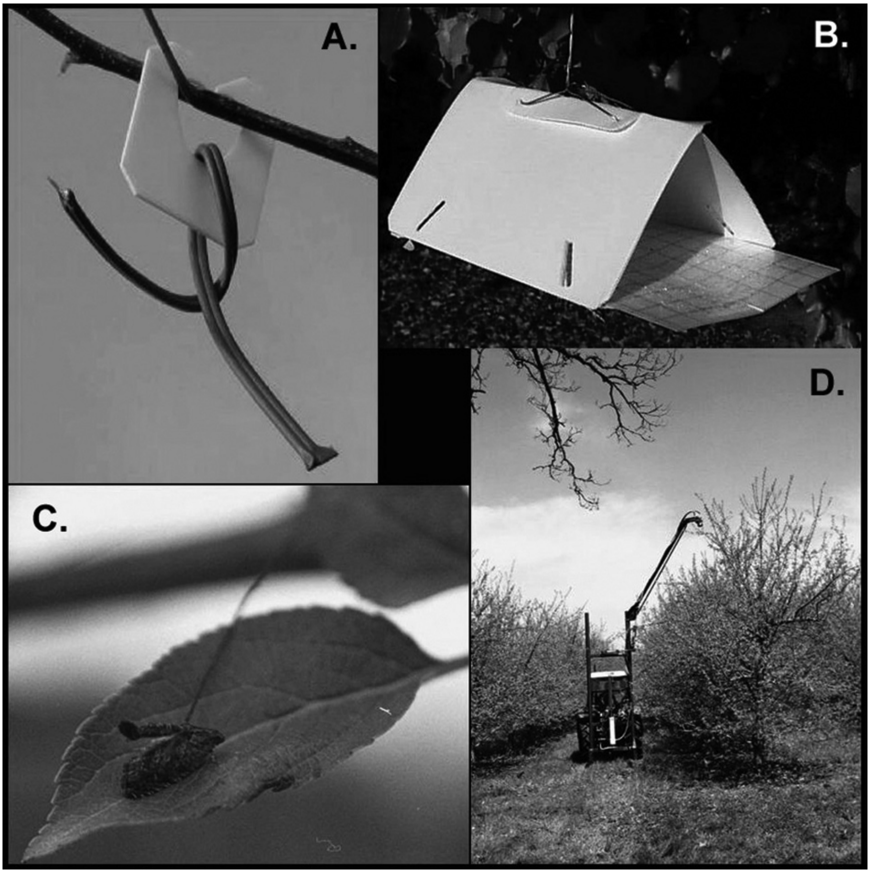

Fig. 11.2 Isomate (Shin-Etsu Chemical Co. Ltd.) polyethylene-tube dispenser of pheromone; this is the most commonly used dispenser type for releasing tortricid moth pheromones in tree fruit; depending on moth species and formulation type, each dispenser is typically loaded with 80–200 mg of pheromone and the treatment is deployed at 500–1000 units per hectare (**A**). Plastic delta trap with removable sticky insert card used for monitoring Lepidoptera with pheromone or kairomone lures placed inside (**B**). Tethered virgin female oriental fruit moth (*Grapholita molesta*) used to assess the effectiveness of mating disruption treatments; females are deployed for 24–48 h periods in pheromone treated and companion untreated control blocks; subsequently, females are harvested and dissected to determine mating status and thus effectiveness of the pheromone disruption treatment (**C**). Custom mechanized applicator (Proptec) for deployment of female-equivalent point source dispensers of pheromone (**D**). Photo Credit for A and B: Peter McGhee, Michigan State University

males' capability of finding authentic females was also impeded. A good correlation between disruption of male capture in traps, commonly referred to as "trap shut-down", and reduction of mating of tethered virgin females (Fig. 11.2C) has been observed (Stelinski et al., 2007a). However, there have been recorded cases in which a high level of trap shut-down due to the pheromone treatment have not correlated with adequate crop protection (Ridgeway et al., 1990; Rice and

Kirsch, 1990; Atanassov et al., 2002) or suppression of mating of females (Suckling and Shaw, 1992). In order to monitor for the presence of male moths under mating disruption, higher dosage lures have been developed and shown to be effective in catching moths in disrupted crops, particularly for *C. pomonella* (Charmillot, 1990; Barrett, 1995).

Mechanisms

Several hypotheses have been proposed to explain how sexual communication of insects is disrupted by deploying formulations of synthetic pheromones to prevent mating. These "mechanisms of disruption" have been formally defined in reviews by Bartell (1982) and Cardé (1990). A recent series of articles re-analyzed these mechanisms (Miller et al., 2006a,b) using mathematical models to "deconstruct the results of mating disruption trials with the goal of determining which possible mechanisms of mating disruption were operative" (Millar, 2006). Of these hypotheses, perhaps the most commonly cited mechanisms are: false-plume following, camouflage, desensitization, and sensory imbalance. False-plume following, also called competitive attraction, is the decrease in visitation rate of calling females by available males due to preoccupation with false plumes sent out by competing synthetic pheromone sources. For camouflage, it is believed that the boundaries of a calling female's plume are obscured by a background concentration of synthetic pheromone; this mechanism assumes that the male's sensitivity to pheromone is unaffected by continual exposure to high concentrations of background pheromone. Desensitization is defined as decreased sensitivity to pheromone due to continuous exposure to high background concentrations of pheromone. This mechanism is comprised of two possible sensory changes: (1) adaptation is defined as decreased sensitivity of the peripheral nervous system, while (2) habituation is defined as decreased sensitivity of the central nervous system. Finally, for sensory imbalance, it is believed that the natural pheromone component ratio released by females and required by males for normal orientation is adulterated by dispensing large amounts of one or more synthetic components of the pheromone into the atmosphere. Elevating the background concentration with a partial blend of synthetic pheromone component(s) may alter this required balanced ratio of sensory input perceived by males and thus disrupt the oriented response.

Sensory Desensitization

Investigations of the mechanisms of mating disruption were initiated over three decades ago. Attempts have been made, both in laboratory and in the field, to determine the dosage of pheromone required for disrupting normal behavioral responses and mating. In early laboratory studies, moths were caged in static or moving air with dosages of pheromone known to attract males to sticky traps in the field. Caging males and females in static-air 1.2 L containers with 1.0 mg of (*E*,*E*)-8,10-dodecadien-1-ol (codlemone) resulted in a 65% reduction of mating for the codling moth, *Cydia pomonella* (L.) (Fluri et al., 1974). Exposing caged males and females to air moving over 1 or 3 rubber septa loaded with 1.0 mg of codlemone resulted in a maximum of only 38% mating reduction (Charmillot et al., 1976). These initial studies with codling moth established that high-dosage exposure to pheromone in small cages reduced but did not eliminate mating. Pioneering laboratory studies with other tortricid species produced similar results in that exposure of males to high dosages of pheromone reduced subsequent behavioral responses for prolonged intervals (Bartell and Roelofs, 1973; Bartell and Lawrence, 1976; Bartell, 1977a,b). Although these early laboratory investigations showed that pheromone exposure affects mating behavior, they did not definitively establish the operative mechanism(s) (desensitization versus camouflage, for example) or the airborne concentration of pheromone mediating the effects.

A recent investigation of codling moth disruption quantified the airborne concentration of codlemone required for both adapting male antennal sensitivity and reducing subsequent behavioral response (Judd et al., 2005). Exposure to ca. 35 μg of codlemone / L of air in static-air chambers for 10–30 min reduced electroantennogram (EAG) responses and nearly eliminated subsequent male orientation in a flight tunnel. The effect was reversible and behavioral responses were subnormal for a much longer interval (ca. 4 h) than antennal sensitivity (ca. 1 h). This result suggested that habituation rather than adaptation was the more important and longer-lasting component of desensitization mediating disruption following high-dosage exposure to pheromone in the codling moth. Stelinski et al. (2005a) confirmed that the duration of peripheral adaptation in male codling moth following prolonged exposure at μg/L dosages of airborne pheromone lasts ca. 1 h. The duration of peripheral adaptation in codling moth males is substantially longer than that recorded for several other tortricids [*Choristoneura rosaceana* (Harris), *Argyrotaenia velutinana* (Walker), *Grapholita molesta* (Busck), and *Pandemis pyrusana* (Kearfott)] after exposure to their pheromone components at the same dosages; these durations of reduced antennal sensitivity range between < 1 min and ca. 15 min (Stelinski et al., 2003, 2005a). Regarding the extraordinary duration of adaptation in codling moth males, Judd et al. (2005) postulated that the codlemone diene alcohol might adsorb into the insect's waxy cuticle to a greater degree than the acetate and aldehyde pheromones of the other above-mentioned tortricids in which antennal adaptation has been investigated.

Despite the presence of a 60–75 min long duration of peripheral adaptation in male codling moth following exposure to pheromone, Stelinski et al. (2005a) questioned its potential importance as a contributor to mating disruption. Caging male codling moths for 30–34 h in an orchard treated with 1,000 Isomate C dispensers/ha did not impact the males' capability of subsequently orienting to pheromone sources in a flight tunnel (Judd et al., 2005). Thus, male sensitivity to pheromone was not affected under the standard Isomate dispenser pheromone treatment, which is known to disrupt male orientation to traps and virgin females and reduce crop damage (Gut et al., 2004; Epstein et al., 2006). The findings of Judd et al. (2005) for codling moth were similar to those reported by Schmitz et al. (1997) and Rumbo and Vickers (1997) for the European grape moth, *Lobesia botrana* (Denis and Schiffermüller) and the oriental fruit moth, *G. molesta*, respectively. For *L. botrana*, males were captured in attractive sticky traps in the field directly after 8 h of exposure in vineyards treated with polyethylene-tube dispensers (1 dispenser/5 m^2; each dispenser contained 500 mg of *E*7,*Z*9-dodecadienyl acetate; Schmitz et al., 1997). Reduction in male moth response to traps in the field occurred only after males were exposed in the laboratory at an airborne pheromone concentration of 4 μg/L of air. For *G. molesta*, reduction of male captures in attractive sticky traps occurred only after one hr of laboratory exposure to pheromone at 65 $\mu g/m^3$ (3,200 female equivalents) (Rumbo and Vickers, 1997). Collectively, current data suggest that desensitization of tortricid moth species is not induced after field exposures at rates of synthetic pheromone dispensers per area of crop known to result in effective disruption.

In addition, studies quantifying the airborne concentrations of pheromone achieved in the field by mating disruption dispensers suggest that laboratory experiments investigating desensitization have exposed moths to dosages of pheromone far greater than what is actually achievable in the field. Specifically, the average airborne concentration of pheromone achieved in crop treated with mating disruption dispensers has been quantified as ca. 1-2 ng/m^3 (Koch et al., 1997; Koch et al., 2002). Thus, the airborne concentrations of pheromone shown to desensitize moths in most laboratory investigations to date far exceed (by ca. 1,000-fold) the actual concentration of pheromone achieved in the field by application of commercially available dispensers such as Isomate polyethylene tubes.

Judd et al., (2005) postulated that desensitization of male codling moths might occur following prolonged or repeated visits in close proximity to Isomate C Plus dispensers. For example, moths exposed minutes-long might receive a sufficiently high dose of pheromone exposure to reduce behavioral responses as seen in laboratory experiments. However, in cases where male codling moth behavior has been directly observed in orchards treated with polyethylene-tube dispensers, including Isomate C Plus, males rarely directly contacted dispensers following oriented approach (Witzgall et al., 1997,1999; Stelinski et al., 2004a,b). Furthermore, the majority of approaching males remained visible in the vicinity of dispensers for approximately 10–120 s. This duration of exposure was likely insufficient to induce peripheral adaptation in the field (Judd et al., 2005; Stelinski et al., 2005a); however, subsequent behavioral response could have been affected due to habituation. Stelinski et al. (2006a) investigated the effect of brief exposure to Isomate C Plus dispensers and rubber septa loaded with codlemone at dosages ranging from 0.1 to 10 mg on subsequent behavioral responses of male codling moth in the wind tunnel and associated antennal changes as measured by EAGs. This series of experiments was designed to mimic the types of exposures males were observed receiving in the field while orienting within plumes emanating from Isomate C Plus dispensers (Stelinski et al., 2004a, 2004b). Specifically, males were allowed to dose themselves while orienting in or flying through plumes generated by the pheromone dispenser placed ca. 2 m upwind. Exposure durations were brief, lasting ca. 35 s on average (range 3–180 s) and male moth response was assayed 15 min or 24 h after exposure. These brief exposure treatments to Isomate C Plus dispensers nearly eliminated subsequent male moth responses to otherwise highly-attractive codlemone or 3-component (codlemone:14OH:12OH) lures in the flight tunnel.

This effect was much more drastic than that observed for *C. rosaceana*, *A. velutinana* (Stelinski et al., 2004a), and *G. molesta* (Stelinski et al., 2005b) in similar investigations. Also, it was dosage-dependent given that identical exposure to 0.1 mg lures with codlemone only or a 3-component blend mimicking that found in C Plus did not reduce behavioral responses of males to the same degree. Concurrent antennal (EAG) recordings revealed that the behavioral effect was likely explained by habituation, given that antennal sensitivity to codlemone was not different in pheromone-exposed moths compared with air-exposed controls. Given that long-lasting adaptation was not recorded in this investigation (Stelinski et al., 2006a), the exposure dosage was likely below the $\approx 355\ \mu g \times$ min/L of air required to induce the effect (Judd et al., 2005). The observed habituation was also consistent with an elevation in response threshold (Mafra-Neto and Baker, 1996). Specifically, more pre-exposed males oriented to elevated and normally unattractive dosages of codlemone (1.0 and 10 mg) than did air-exposed control moths (Stelinski et al., 2006a). In contrast, Isomate-exposed males did not orient to normally attractive dosages of codlemone (0.1 mg). The results of this study suggested that brief but high-dosage exposure to pheromone while orienting in plumes generated by Isomate C Plus dispensers raises the response threshold of codling moth males. This result is consistent with greater captures of males in traps baited with 10 mg codlemone lures in pheromone-treated orchards, which elicit little or no moth catch in traps when placed in untreated orchards (Vickers and Rothschild, 1991). Finally, as in Judd et al.'s (2005) report, the effect of brief exposure to Isomate C Plus was reversible; normal behavioral responsiveness was resumed after 24 h of recovery in clean air. Nevertheless, the results of this study suggested that habituation of male response following brief oriented flight to reservoir dispensers may be an important contributing mechanism to mating disruption of codling moth.

Competitive Attraction

Field observations have revealed that male codling moth orient to and approach mating disruption dispensers such as Isomate C Plus and "female equivalent" paraffin-wax dispensers (Barrett, 1995; Witzgall et al., 1999; Stelinski et al., 2004b; Epstein et al., 2006). Similar results have been observed with several other tortricid species (Stelinski et al., 2004a, 2005c). Far more males may actually orient to these dispensers than what has been actually observed given that oriented progress is likely terminated downwind at a certain distance at which the pheromone concentration is above the upper threshold for response (Cardé et al., 1975; Baker and Roelofs, 1981). These results suggest that competitive attraction between calling females and synthetic point sources of pheromone may be an important contributing mechanism to mating disruption.

If competitive attraction is an important contributor to mating disruption, then efficacy should be highly dependent on moth population density and the density of synthetic point sources that are deployed (Knipling, 1979; Miller et al., 2006a,b). One contested issue among investigators has been whether efficacy of mating disruption can be maintained while decreasing point source density per ha of crop and proportionally increasing the amount of pheromone released per point source. Some researchers (Shorey and Gerber, 1996; Knight, 2004) have suggested that this is indeed possible, postulating an economic advantage by deploying fewer dispensers of higher potency rather than many evenly distributed dispensers of lower potency throughout the crop. In fact, Shorey and Gerber (1996) demonstrated 95–98% disruption of codling moth in walnuts by deploying only 2.3 pheromone puffers/ha (each puffer releasing ca. 240 mg of pheromone/day). However, this was under comparatively low moth population densities (mean of 20 and 10 males/trap/week for lures and virgin females, respectively).

There is mounting corroborating evidence that disruption of various moth species is superior via higher rather than lower densities of pheromone release sites (Charlton and Cardé 1981; Palaniswamy et al., 1982; Suckling et al., 1994; Stelinski et al., 2005c; Miller et al., 2006a,b). This has also been recently confirmed by Epstein et al. (2006) for codling moth. In that recent study, the investigators varied Isomate C Plus density from 0 to 1,000 dispensers / ha. Male moth abundance in pheromone-baited traps decreased as a function of increasing dispenser density. Correspondingly, fruit injury decreased as the density of Isomate dispensers was increased and was lowest in plots treated with 1,000 evenly-distributed dispensers/ha. In a companion study, the density of 0.1 ml paraffin-wax drops containing 5% codlemone was manipulated. Disruption likewise increased with increasing density of wax drops deployed. In addition, the data with wax drops were analyzed according to recently proposed mathematical models developed to differentiate between competitive versus non-competitive mechanisms of disruption (Miller et al., 2006a). Under the scenario of competitive attraction, plotting 1/male visitation rate to a given attractant source on the y-axis against dispenser density on the x-axis yields a straight line with positive slope. Furthermore, plotting "male visitation rate" to a given attractant source on the y-axis against "dispenser density x visitation rate" on the x-axis yields a straight line with negative slope; disruption by a non-competitive mechanism was found not to share this set of properties (Miller et al., 2006a). The resultant analyses were consistent with the hypothesis that competitive attraction mediated disruption of codling moth with high densities of 0.1 ml wax drops (Miller et al., 2006b). Finally, the most compelling evidence in favor of competitive attraction was that male moths of several tortricid species were observed readily orienting to pheromone-releasing wax drops in the field (Stelinski et al., 2004a; Epstein et al., 2006). Collectively, these results suggest that false-plume following by male moths to dispensers contributes to disruption and that point source density and distribution may be critically important factors to achieving effective disruption, particularly under high moth densities.

Non-Competitive Mechanisms

Unfortunately, there are few manipulative studies on the impacts of non-competitive mating disruption mechanisms of moths. In fact, there is a paucity of studies investigating sensory imbalance in general, as a potential contributor to mating disruption (reviewed in Bartell, 1982; see also Flint and Merkle, 1984). Codling moth is a unique species in that the full repertoire of male sexual behaviors is elicited by the major pheromone component alone, codlemone, despite evidence of additive contribution of certain minor components (Einhorn et al., 1984; Arn et al., 1985; El-Sayed et al., 1999). Given that a complex multi-component and ratio-specific blend is not required for male orientation in this species, sensory imbalance may not be an important factor contributing to disruption of this species. However, in cases where antagonists are added to the blend (e.g. El-Sayed et al., 1999), there may be a greater impact of this mechanism. More research on sensory imbalance is needed to determine how it may contribute to disruption of codling moth. However, in most moth species, the pheromone is a blend of several chemicals released in a specific blend ratio. In these cases, the contribution of sensory imbalance to disruption is more likely.

The role of camouflage in mating disruption has also not been directly investigated, although this mechanism is often implicated in published studies on mating disruption. Indirectly, the role of camouflage has been falsified in a number of studies reporting male attraction to pheromone dispensers, including polyethylene reservoirs, in treated plots of various sizes (Barrett, 1995; Witzgall et al., 1996a, 1999; Stelinski et al., 2004b; Epstein et al., 2006). By definition, if plumes of attractant and/or female-equivalent pheromone sources were obscured by a sufficiently high background concentration of pheromone in treated plots, males should not be capable of orienting to point sources of synthetic pheromone in these plots. However, males have been directly observed orienting along plumes from pheromone dispensers or captured in sticky traps baited with these dispensers in pheromone-treated plots where disruption of lures or females was recorded (references above in this paragraph). This suggests that boundaries of discrete plumes are not camouflaged by background pheromone in plots treated with current commercial formulations of synthetic pheromone point sources.

Completeness of Pheromone Blend and Antagonists

The importance of pheromone blend components as well as antagonists and their impact on moth disruption has received considerable attention. The codling moth is an interesting example for which the importance of pheromone blend for disruption has received considerable attention. A total of thirteen minor compounds have been identified in addition to codlemone from the sex pheromone gland of female codling moths (Witzgall et al., 2001); dodecanol (12OH) and tetradecanol (14OH) were quantitatively most significant, enhancing behavioral responses of males to codlemone (Einhorn et al., 1984; Arn et al., 1985). Also, addition of the *Z*,*E* isomer to codlemone slightly increases male orientation in the wind tunnel, but does not increase capture of males in traps (El-Sayed et al., 1999). Conversely, *E*,*Z* isomer antagonizes male response to codlemone both in the wind tunnel and in the field (El-Sayed et al., 1999). In addition to the *E*,*Z* isomer of codlemone, *E*8,*E*10-12Ac (codlemone acetate) inhibits male attraction to codlemone in the field (Hathaway et al., 1974) and in the wind tunnel (El-Sayed, 2004). Given that attractiveness of synthetic codlemone is not greatly improved by the addition of synthetic minor components compared with codlemone alone, competitive attraction will likely not be enhanced by the addition of minor components to pheromone dispensers. Furthermore, exposure of male codling moths to a 3-component blend of codlemone, 12OH, and 14OH does not habituate males more than exposure to codlemone alone (Stelinski et al., 2006a). Thus, there is no published evidence that formulating dispensers with additional minor components such as 12OH and 14OH, as in the industry standard Isomate C Plus, should improve disruption over that achieved with codlemone alone. More laboratory and field research is warranted to determine whether any of the other behaviorally-active minor components may contribute to improved disruption over codlemone alone. However, addition of codlemone antagonists has shown some promise for improving disruption of codling moth. Witzgall et al. (1996b) investigated the potential of releasing a combination of codlemone and codlemone acetate from polyethylene-tube reservoir dispensers for improved disruption compared with treating plots with dispensers releasing codlemone alone. In 300 m^2 plots, disruption with codlemone dispensers alone was superior to that in plots treated with both codlemone and codlemone acetate dispensers; field observations confirmed that competitive attraction was the operating mechanism for the former treatment (Witzgall et al., 1996b). In smaller 100 m^2 plots, disruption of traps was highest in plots treated with a combination of codlemone and codlemone acetate. In a related follow-up study, Witzgall et al. (1999) conducted further observations in plots treated with codlemone dispensers with and without additional codlemone acetate dispensers (4.2 ha orchard) versus a 0.4 ha untreated control orchard. The dispensers used were either resin-treated cellulose flakes or polyethylene-tubes, similar to Isomate C Plus, containing codlemone, codlemone acetate or a blend of these two components. The investigators observed more male codling moths flying within codlemone-treated plots compared with untreated controls, implying that males were attracted into these plots. Also, male codling moths approached dispensers releasing codlemone and those releasing both codlemone and codlemone acetate in approximately equal frequencies. However, the major difference between attractant and attractant + antagonist treatments was that fewer males were observed taking long-range flights from nearby untreated orchards into those treated with codlemone and codlemone acetate compared with those treated with codlemone alone. The authors of that study postulated that deploying a combination of attractive codlemone dispensers with antagonistic codlemone acetate dispensers may improve disruption because long-range attraction into treated orchards may be reduced while close-range plume following and desensitization may be enhanced. Follow-up studies in large-scale replicated plots are warranted to fully test this hypothesis.

11.2.1.5 Case Studies

Mating Disruption of Tortricid Moths in Tree Fruit

Isomate polyethylene-tube reservoir dispensers have been the industry standard for mating disruption of tortricid moths for over a decade and have remained largely unchanged during this time; therefore, this section will discuss this technology in more detail. Disruption with this technology is practiced with success in many locations, especially under low population densities and with the application of companion insecticides to keep potential population outbreaks in check (Witzgall et al., 2008). With our current understanding of mating disruption, a greater emphasis has been placed on the importance of competitive attraction (Miller et al., 2006a,b) and the requirement for high-density pheromone point sources per area of crop, particularly under high population densities (Epstein et al., 2006). The idea of a "threshold concentration" for achieving effective disruption of tortricid moths (Vickers et al., 1985; Vickers and Rothschild, 1991) should be de-emphasized. Operating under the assumption that disruption is mediated mainly by a non-competitive mechanism, this hypothesis suggested that a minimum threshold concentration of pheromone release per hour exists for various moth species, above which mating disruption is completely effective. If this were true of current mating disruption technologies, then mating disruption should be density independent. Of course, this is not the case.

The Isomate polyethylene tube formulation and deployment protocol has remained unchanged as the industry leader for a decade because it effectively exploits the key combination of false-plume following and habituation. This is the case probably by happenstance rather than by intentional design given that the dispenser was not developed with these mechanisms in mind. Moths orient to such dispensers in the field, and such orientations habituate subsequent response, rendering males less capable of further oriented flight. The disruptive effects of competitive attraction and habituation are likely compounded in this case by other factors such as diminished fecundity with age (Knight, 1997; Jones and Aihara-Sasaki, 2001; Torres-Villa et al., 2002). At low to moderate population densities (1–2 moths per tree) and with the application of companion insecticides to keep these densities low, 1,000 Isomate dispensers/ha is likely an effective deployment rate to fully exploit the combination of these mechanisms. If Isomate C Plus functioned purely by competitive attraction without associated habituation, it is unlikely that only 1,000 units/ha would effectively disrupt even low population densities of codling moth. However, under high population densities, even as many as ca. 5,000 dispensers/ha fail to disrupt male codling moth orientation to traps (Stelinski et al., 2006a). This suggests that the desensitizing effect of this technology does not fully compensate for the density dependence of mating disruption. This is because a "threshold for disruption" does not exist with current mating disruption formulations and false-plume following to the dispenser is a prerequisite of habituation. Thus, at moderate to high moth densities, 1,000 dispenser/ha is insufficient. Simple mathematical modeling suggested that for densities of 2, 20, and 200 moths per tree, 1.3, 12.5, and 125 dispensers per tree are required for 98% disruption, if that disruption functions by pure competitive attraction (Miller et al., 2006a). The need for such high densities of dispensers per tree is likely realistically moderated by the beneficial impact of habituation. The density dependent nature of tortricid moth disruption by Isomate dispensers is highly consistent with the hypothesis that competitive attraction is an important contributing mechanism (Miller et al.,, 2006a,b).

Development of an ideal pheromone formulation or tactic for disrupting mating of moth pests will likely be governed more by economics and environmental considerations than by an understanding of the underlying biological mechanisms of disruption. Perhaps the most effective disruption formulation would be one that exploited a non-competitive mechanism such as camouflage or desensitization (without false-plume following). If this type of formulation could fully exploit the "threshold for disruption" hypothesis with 100% efficiency, mating disruption would be rendered density independent and perfect control could be achieved without the need of companion insecticides. However, this would likely require deploying an astonishingly high and economically (and perhaps environmentally) prohibitive amount of pheromone per area of crop. Remaining within the boundaries of economics, the second most effective direction is likely the exploitation of false-plume following to an attractive point source resulting in sufficient pheromone exposure so as to habituate males. As mentioned above, the Isomate hand applied formulation exploits this combination of mechanisms at low population densities. However, considerable improvement is needed given that habituation is likely a prerequisite of plume following and the degree of elicited plume following is a key component to achieving efficacy. Pheromones are susceptible to chemical degradation in the field (Millar, 1995), which affects their attractiveness. The breakdown products accumulating on the surface of certain Isomate formulations, commonly seen as a white film, likely decrease the attractiveness of these dispensers (El-Sayed el al., 1998). Thus, one area that to this day requires improvement is increasing the chemical stability of pheromones in release devices. This challenge is technological and thus economical in nature rather than biological. For example, the chemicals that stabilize codlemone and impede isomerization identified by Millar (1995) add to the cost of an already expensive pheromonal active ingredient. Identifying more effective and less expensive means of stabilizing codlemone from both isomerization and free radical formation will likely improve the efficacy of codling moth disruption.

A second component that requires improvement over today's commercial standard is increasing point source density per area of crop. A density of 500–1,000 units/ha has become the standard protocol based on economic limitations and not based on efficacy requirements. A reservoir dispenser that is applied by hand requires labor investment and this is why a single application of dispensers that stay effective season-long has remained an attractive idea among the applied pheromone industry. A single early-season application limits the total number of units that can be deployed per ha given the cost of materials and active ingredients. In order to improve upon this and develop a technology that deploys more than 1,000 point sources/ha, less active ingredient must be loaded per unit. This necessitates the development of a mechanized applicator to economically deploy many thousands of sources per ha of crop and it requires multiple (likely 2–4) applications per season given that dispensers with lower pheromone loading would likely not last season-long. Such technologies and pheromone formulations do exist, but are still ineffective due to technological flaws. These include Hercon Disrupt CM flakes (Hercon, Emigsville, PA) and Scentry NoMate CM Fibers (Scentry, Billings, MT)

(Swenson and Weatherston, 1989; Stelinski et al., 2008), and mechanically applied wax drops (Fig. 11.2D; Stelinski et al., 2006b). The first problem with these current so-called "high-density" or "female-equivalent" formulations is insufficient adherence of deployed material onto trees resulting in a waste of more than half of deployed dispensers, which do not contribute to disruption from the orchard floor (Stelinski et al., 2008). Second, in cases where the disruption formulations are phytotoxic, fruit can be damaged at mid-season applications (LLS, personal observation). In addition to chemical instability, a second challenge to overcome is the phytotoxicity of certain pheromone active ingredients (Giroux and Miller, 2001). Given that high-density formulations will likely require multiple applications per season onto fruit-bearing trees, these dispensers will need to be formulated so as to prevent pheromone from damaging fruit. This may be impossible to achieve and thus a single early-season application of a dispensers before fruit set remains a potential necessity.

One potential simple solution to the problem of developing a high-density reservoir formulation that is applied only once per season is decreasing the loading rate of active ingredients and their release rate per hour while proportionally increasing the deployment density of dispensers. For example, a reservoir dispenser that contains 1/3rd of the loading of Isomate polyethylene tube dispenser and that releases the pheromone at 1/3rd of the rate, but is applied at 3,000 units/ha will likely exploit competitive attraction better than Isomate C Plus while still inducing habituation in attracted males. This type of dispenser should be more effective than Isomate at higher moth densities. Such a formulation could be mechanically-applied (as a wax-based matrix for example, Stelinski et al., 2006b, 2007a) prior to fruit set, thus preventing the possibility of fruit damage due to phytotoxicity. The remaining technological challenge to overcome is that a high proportion of such mechanically-deployed dispensers would need to successfully adhere to tree foliage and hold out season-long.

The pursuit of sprayable microencapsulated formulations of pheromone (Knight and Larsen, 2004; Knight et al., 2004; Stelinski et al., 2007b) is likely not a productive direction for effective and economical disruption of tortricid moths because these formulations do not exploit the main operating mechanisms at dosages of pheromone that can be feasibly maintained in the field. This likely explains why such formulations have been either completely ineffective (Knight and Larsen, 2004; Stelinski et al., 2007b) or slightly effective for brief periods following application (Stelinski et al., 2007b). The concentration of airborne pheromone achieved by such formulations might affect disruption by a non-competitive mechanism for a brief period soon after application; but in the long run, pheromone is over-dispersed and lack of discrete point sources does not produce plume-following or habituation. Searching behavior of males and calling behavior of females (Weissling and Knight, 1995) may be affected by microcapsules adhering to foliage, but this requires further investigation. Knight and Larsen (2004) were able to improve the effectiveness of a sprayable microencapsulated formulation by modifying the deployment procedure. By applying microcapsules in a highly-concentrated, 'ultra-low volume', method using approximately 10 times less water in the spray tank as compared with standard formulations, efficacy was improved. The authors of that study found clumps of microcapsules adhering to leaves that were attractive to males and perhaps contributed to disruption as point sources. Stelinski et al. (2005d) confirmed that such clumps of microcapsules are highly competitive with optimally-attractive lures and likely attract males in the field disrupting moths by false plume-following. Also, Stelinski et al. (2007b) improved efficacy of sprayable pheromones by deploying lower rates of AI more frequently (ca. 10 times per season) than previous standard applications of more AI per application, but applied fewer (3–4) times per season. Excluding these cases where the application protocol has been manipulated to improve efficacy, microencapsulated formulations has shown limited effectiveness. The technological challenges that must be further improved, despite past progress (Knight and Larsen, 2004; Knight et al., 2004), remain protection of pheromone from degradation and rainfastness (Waldstein and Gut, 2004; Stelinski et al., 2007b). Rather than spending considerable effort toward modifying this technology and its associated application protocols to exploit the operating mechanisms of mating disruption, it might be more efficient to pursue other technologies that, by their existing design, exploit these key mechanisms.

Additional research with low-density dispensers such as puffers is also warranted. Given the savings associated with reduced labor cost compared with applying many hundreds of reservoir dispensers per ha, this technology is desired by the commercial industry and growers. Shorey and Gerber (1996) demonstrated a high degree of disruption efficacy (95–98%) with puffers (2.3/ha) when deployed over large acreages of walnut with low codling moth population densities. However, in Michigan apple orchards with moderate to high codling moth population densities, disruption efficacy using puffers has been very poor (50–80%) (Stelinski et al., 2007c). Shorey and Gerber (1996) estimated that their puffer treatment achieved an airborne concentration of pheromone of approximately 6.3 ng/m^3 air. This is below the concentration required to desensitize male codling moth antennal response (Judd et al., 2005; Stelinski et al., 2005a). Other interesting research questions regarding disruption of tortricid moths in tree-fruit are: by what mechanism(s) do low-density aerosol devices, such as puffers, affect disruption? Are moths attracted to the large plumes generated by these devices and the buildup of pheromone adhering to nearby tree surfaces? If so, following anemotactic orientations of males along these giant plumes is their behavior desensitized to a greater degree than that achieved by other commercial formulations? Or, do puffers disrupt males by a non-competitive mechanism such as camouflage? Answering these questions could potentially improve this tactic and make it more effective in higher moth density orchards. One potential avenue to explore is an intermediate device between puffers and reservoir devices such as Isomate C Plus (Stelinski et al., 2007c). Such devices could potentially better exploit competitive attraction under higher moth densities than the 2–3 currently designed puffers per ha, if plume-following is a mechanism of disruption by these devices. Such dispenser formulations would still reduce the total application cost relative to those requiring application of many hundreds of units per ha. Investigating whether fewer more-potent dispensers or more less-potent dispensers per area of crop achieve better disruption (Byers, 2007) will likely remain a productive area of research among investigators of mating disruption in the future. Although the balance will likely shift towards higher density point-source treatments under elevated moth densities given what we understand about competitive attraction. A compromise between the two density extremes will likely remain the leader of commercial market share given the need to balance economics and efficacy.

Oriental Beetle Mating Disruption in Blueberries

Almost all examples of successful tests for pheromone-based mating disruption involve moth pests (Cardé, 2007). One exception is the use of the sex pheromone to disrupt mating in the oriental beetle, *Anomala orientalis* (Waterhouse) (Coleoptera: Scarabaeidae). The oriental beetle became a problematic pest in the Northeast USA after its introduction sometime before 1920 (Vittum et al., 1999), and it is currently considered one of the most important turfgrass, ornamental, and blueberry insect pest in New Jersey, southeastern New York, Connecticut, and Rhode Island (Polavarapu, 1996; Alm et al., 1999). In blueberries, the root feeding damage caused by grubs can result in complete destruction of the root system and the death of host plants, especially when larval populations are high. Infested blueberry bushes show reduced vigor and support fewer berries compared to non-infested bushes.

Even though few options are currently available for management of oriental beetle in blueberries, the development of mating disruption for its control has been a very slow process. Currently, the neonicotinoid insecticide imidaclopid is the only treatment option available for grub control. Having a single control method not only raises the potential for resistance development, but also magnifies other constraints of using this active ingredient: imidaclopid is expensive, requires precise timing of application, it has limited efficacy against late-instar grubs (Koppenhöfer et al., 2002), is highly leachable (González-Pradas et al., 2002), and may disrupt pollination and biological control (Rogers, and Potter, 2003). Insecticides do not target the adults because they cause limited damage, the emergence period is long and coincides with harvest, and they are difficult to target with insecticide applications due to their cryptic behavior. The limited options available for oriental beetle control in blueberries makes the development of new environmentally safe alternatives, such as mating disruption, necessary for implementing in IPM programs.

The sex pheromone of the oriental beetle consists of (*Z*)-7-tetradecen-2-one and (*E*)-7- tetradecen-2-one (9:1 blend) (Zhang et al., 1994; Facundo et al., 1994). Previous field studies by Polavarapu et al. (2002) evaluated microencapsulated sprayable formulations of (*Z*)- and (*E*)-7-tetradecen-2-one for oriental beetle mating disruption. Adult male trap captures in blueberry plots treated with the pheromone formulation were reduced by over 90% compared to untreated controls. Mating rates were also lower in treated plots compared to untreated plots. However, the use of sprayable microencapsulated formulations is not feasible in fruit crops, such as blueberries, because the oriental beetle pheromone is a ketone. According to current EPA regulations, ketones do not qualify for tolerance exemptions allowed

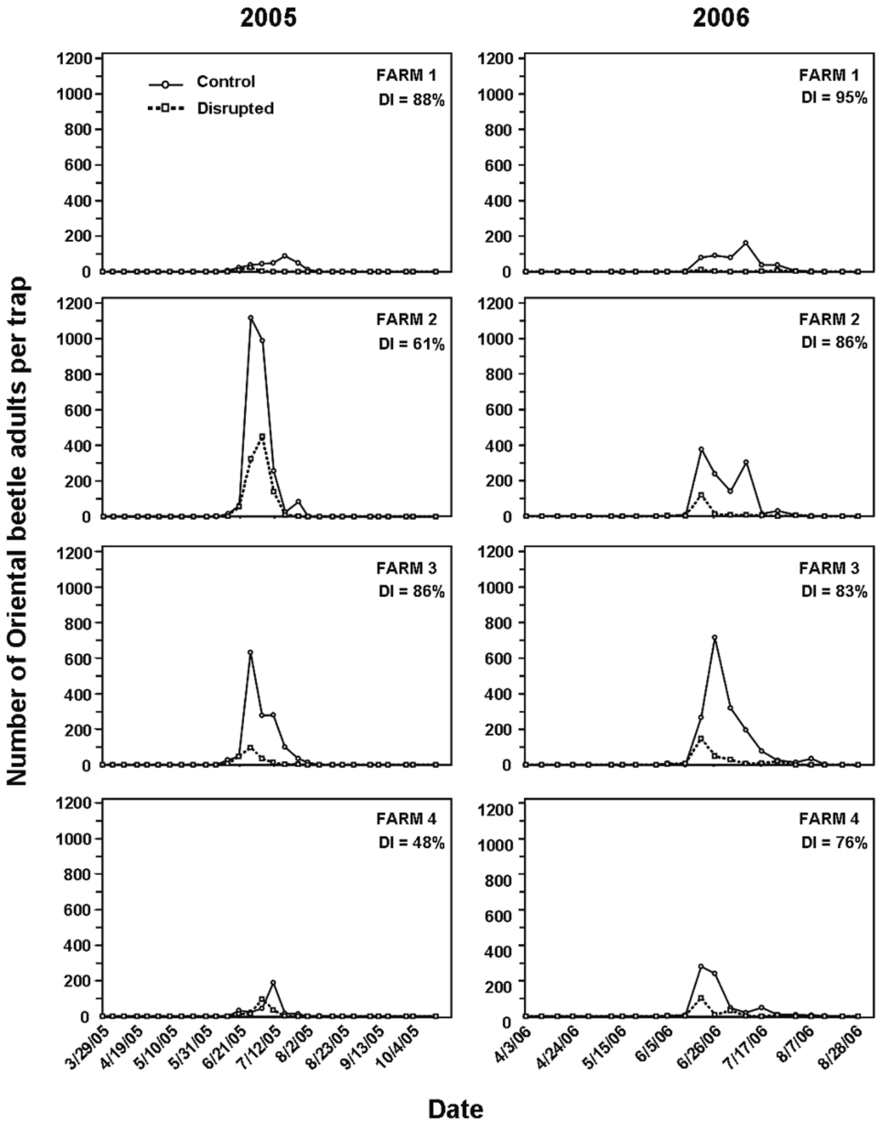

Fig. 11.3 Mating disruption for oriental beetle (*Anomala orientalis*) in blueberries: a field demonstration. The data are season-total male oriental beetle catches in pheromone-baited traps in control plots (control) and plots treated with 50 per ha dispensers loaded with 1 g of the sex pheromone (disrupted). Each plot was 1.6–2.0 ha. The study was conducted in four New Jersey (USA) blueberry farms in 2005 and 2006. DI = disruptive index

for alcohols, acetates, or aldehydes; this has been a key obstacle for the development of mating disruption in oriental beetle. An alternative formulation is the use of point-source dispensers, which are exempt from tolerance restrictions (Weatherston and Minks, 1995). Sciarappa et al. (2005) evaluated mating disruption for oriental beetle with 50–75 dispensers/ha with (*Z*)-7-tetradecen-2-one at 1 g active ingredient (AI) per dispenser. Pheromone treatment reduced beetle captures in traps, mating rates, and grub densities compared with those found in untreated control plots. Mating disruption for oriental beetle has also been used successfully in ornamentals (Polavarapu et al., 2002), turf (Koppenhöfer et al., 2005), and cranberries (Wenninger and Averill, 2006).

In a 2-year experiment (2005–2006), we evaluated the potential of mating disruption for oriental beetle in commercial highbush blueberry fields in New Jersey (USA). The experiment was conducted at four farms, each with two 1.6–2.0 ha experimental plots. One of the plots received 50 dispensers per ha at 1 g AI per dispenser (total of 50 g AI/ha; disrupted plots), while the other plot received no pheromone (control plots). One Japanese beetle trap baited with 300 mg of oriental beetle sex pheromone was placed in the interior of each plot and monitored weekly to determine adult male abundance. Successful mating disruption of oriental beetle is inferred by trap shut-down in disrupted plots, i.e., a decrease in number of male beetles captured in traps in treated plots compared with paired untreated controls. In both years, the disrupted plots had lower numbers of male beetles in traps compared to control plots (Fig. 11.3). The disruptive index ($(C - T)/C \times 100$ where $C =$ average beetle captures per trap in control plots and $T =$ average beetle captures per trap in disrupted plots), varied between 48–95%. These results indicate that oriental beetle mating disruption was effective in some farms but not in others. One of the potential reasons for this variability is the potential difference in oriental beetle pressure among farms. Mating disruption for oriental beetle might work best under low-to-medium population pressure. Similar to that observed with the codling moth, it is also likely that more point sources are required in areas of high oriental beetle populations (see Miller et al., 2006a,b). The size of fields might also limit efficacy of mating disruption because it often works best when used in larger areas (Cardé, 2007). Ongoing work is underway to address these and other factors, including obtaining a commercial product for oriental beetle mating disruption so that it can be tested on a large scale (i.e., an entire blueberry farm), testing new pheromone formulations that can be applied as multiple point sources, evaluating long-term effects of mating disruption on oriental beetle populations, and reducing pheromone rates to make the technology more cost effective.

11.3 Host-Plant Volatiles and IPM

Host-plant volatiles play a critical role in the life of insects (Miller and Strickler, 1984; Visser, 1986; Bernays and Chapman, 1994). Herbivorous insects may use host-plant volatiles to locate food, mates, and/or oviposition and hibernation sites

(Visser, 1986). Plant volatiles may also aid insects to remain in a suitable habitat (e.g. Eigenbrode et al., 2002), avoid a dangerous habitat (e.g. Choh and Takabayashi, 2007), and aggregate (e.g. Loughrin et al., 1996a; Dickens, 2006). The behavioral response of insects to plant volatiles may have important implications related to crop injury. Adult females need to locate suitable hosts for the successful development of their offspring (Thompson, 1988). Host-plant volatiles may play an important role in decision-making by females and thus affect the success and distribution of their offspring within a habitat (Courtney and Kibota, 1989; Mayhew, 1997). For mobile pests, such as alate aphids and thrips, plant volatiles may attract and arrest them in certain areas (e.g. Eigenbrode et al., 2002). This can be a disadvantage to farmers if aphids and thrips transmit viruses, such that plant volatiles may lead to increases in virus transmission (Kennedy et al., 1959).

Taking into consideration all the signals used by insects in host location and mate finding, and the potential synergistic interactions between them, studying the behavioral response of insect pests to host-plant volatiles can become a challenging task. Here we provide a sequence of steps for conducting such studies. The first step when considering the use of host-plant volatiles for IPM is to understand the behavior of the insect. This is the most critical, and possibly most time consuming, of all steps. The initial questions to answer are: Is the insect attracted to intact host plants? Is the insect attracted to host plants that are damaged by conspecifics or other herbivores? And, what specific part of the plant is attractive? To answer these questions researchers will require the use of behavioral arenas such as wind tunnels or Y-tube olfactometers.

Management of an insect pest using plant volatiles to manipulate host-finding behavior will also require knowledge of the insect's life history. For instance, results from studies on host finding behavior most likely will differ when comparing insect herbivores adapted to a crop versus non-adapted herbivores. On one hand a plant volatile can be attractive to an adapted herbivore, while it might be repellent to a non-adapted herbivore (i.e., non-host volatiles). The results may also differ when studying adapted herbivores that differ in their degree of specialization (Bernays and Chapman, 1994). For example, different responses to plant volatiles might be expected when comparing a specialist herbivore that feeds on one or few plant species to a generalist herbivore that feeds on a wide range of plant species in different families. This degree of specialization should be considered when developing behavioral-based strategies using host-plant volatiles for pest management. In fact, specialists might use specific signals from their host-plant while generalists might use more generalized plant signals. This specialization may be due to a greater degree of sensitivity to host-plant volatiles mediated by more sophisticated detection mechanisms (but see Bruce et al., 2005). On the other hand, specialists may use more complex signals than generalists by obtaining more information from blends of host-plant volatiles in specific ratios. Even within a species there can be differences between sympatric or allopatric populations. One of the most well-known studies of host race formation on alternative hosts is that of the apple maggot fly, *R. pomonella* (Linn et al., 2003). In this species there are differences among populations in preference for different host plants, such that flies of apple origin chose apples significantly more often than flies of hawthorn origin and vice-versa.

It is also important to consider the insect's physiological state and gender differences in their response to host-plant volatiles. The integration of external stimuli and internal physiological state will determine the threshold and ultimate outcome of the response of insects to plant volatiles (Miller and Strickler, 1984). For example, males and virgin females are often less responsive than gravid females to host-plant volatiles (e.g. Hern and Dorn, 1999; Yan et al., 1999; Mechaber et al., 2002; Masante-Roca et al., 2007). However, altering the internal state of an insect is often not feasible and therefore most efforts to manipulate insect behavior focus on altering the insect's response to an external stimulus. In addition, plant phenology often has an effect on volatile emissions. Different plant parts may emit distinct volatile blends (e.g. Bengtsson et al., 2001; Vallat and Dorn, 2005). Volatile emission can also vary among cultivars (Loughrin et al., 1996b). All of these factors add to the complexity of studying insect behavioral response to plant volatiles.

Once researchers have an understanding of the behavioral responses of the target pest to its host plant and have identified the source of attractive volatile emissions from plants, the next step is similar to the identification of insect pheromones. It involves the detection and analysis of behaviorally-active compound(s) through the use of EAG, gas chromatography (GC), and coupled GC-EAD. The identified compounds can then be tested individually or as a blend(s) in the laboratory to determine if they act as attractants or repellents. The third step is to test the active compound(s) under field conditions. Most of the research on the effects of host-plant volatiles has been limited to the first two steps, i.e., to controlled laboratory conditions. Only few studies have been able to make the transition from the laboratory to the field successfully and they are discussed below. The final step is to incorporate the active volatile blend into an IPM-based program and achieve adoption.

11.3.1 Manipulation of Host Finding

According to their effects on insect behavior, plant volatiles can be classified as attractants or repellents (Dethier et al., 1960; Bernays and Chapman, 1994). This classification is not always clear because a plant volatile can act as an attractant or a repellent depending on its concentration. For instance, many attractants will repel herbivores at high concentration (e.g. Finch, 1978; Hern and Dorn, 1999; Mewis et al., 2002). In addition, host-plant volatiles are often induced by different environmental factors (Karban and Baldwin, 1997). For example, herbivore feeding increases emission of volatiles in plants; these volatiles are referred to as herbivore-induced plant volatiles (HIPVs; e.g. Arimura et al., 2005) (Fig. 11.4). Examples of host-plant attractants and repellents and of the effects of HIPVs on insect behavior are presented below.

11.3.1.1 Attractants

Plant attractants are those volatiles that cause an insect to orient its movement towards the emitting source (Dethier et al., 1960; Bernays and Chapman, 1994). Most research on host-plant volatile effects on herbivore behavior has focused on the

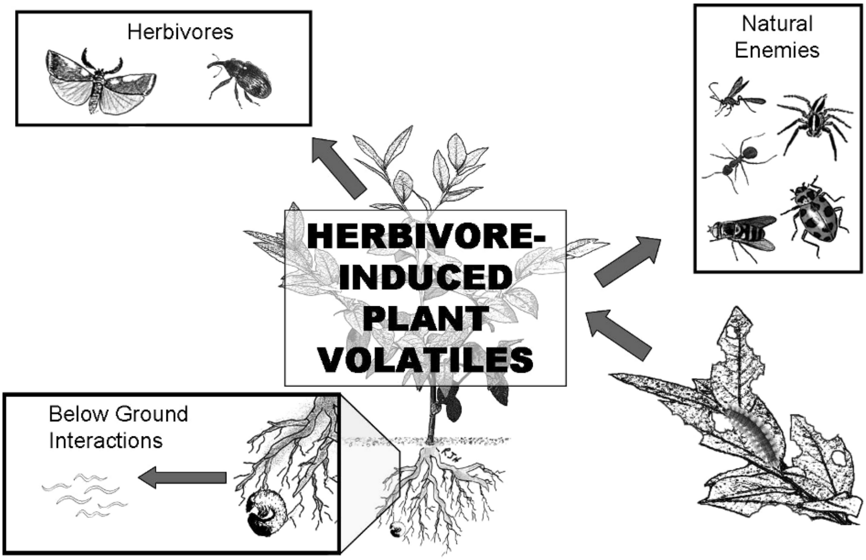

Fig. 11.4 Herbivore-induced plant volatiles (HIPVs) effects on herbivores and their natural enemies. Herbivory often induces a volatile response in plants than can attract or repel herbivores. HIPVs also can serve as long-distance cues for natural enemies during host/prey searching. These effects are not only found aboveground, but also belowground. Herbivore feeding on roots releases HIPVs that attract entomopathogenic nematodes. Graphic designed by Robert Holdcraft

discovery of new insect attractants. Here we discuss four general examples where an individual chemical or blend of host-plant volatiles has been isolated, identified, and shown to attract agricultural pests. We include examples of attractants derived exclusively from plant odors. These examples are summarized in Table 11.3. We do

Table 11.3 Examples of insect attractants derived from host plant volatiles

Insect pest	Host	Plant volatiles	References
Coding Moth (*Cydia pomonella*)	Apple	Butyl hexanoate *E,E*-α-farnesene	Hern and Dorn (2004) Hern and Dorn (1999)
	Pear	Ethyl(*E,Z*)-2,4 decadienoate (pear aster)	Light et al. (2001)
Grapevine Moth (*Lobesia botrana*)	Grape	(*E*)-β-caryophyllene (*E*)-β-farnesene (*E*)-4,8-dimethyl-1,3,7-nonatriene	Tasin et al. (2006)
Colorado Potato Beetle (*Leptinotarsa decemlineata*)	Potato	(*Z*)-3-hexenyl acetate Linalool Methyl salicylate	Martel et al. (2005)
Plum curcuiio (*Conotrachelus nenuphar*)	Plum Apple	Benzaldehyde	Piñero and Prokopy (2003)

not include examples of volatiles from other food sources such as protein baits (e.g. NuLure or Mazoferm), that attract and stimulate feeding in fruit flies and are widely used in IPM programs worldwide (e.g. McQuate and Peck, 2001).

Codling Moth

As indicated previously, sex pheromones have been used for monitoring and in various formulations to disrupt mating. The codling moth, *C. pomonella*, is a major pest in pome fruits and walnuts. The sex pheromone, however, only attracts males; finding a plant volatile that is attractive to both sexes and especially to females is an important research goal. Wearing et al., (1973) and Yan et al., (1999) found that females are attracted to the odor of apples. Sutherland (1972) and Hern and Dorn (1999) found that larvae and adults of codling moth, respectively, respond to the plant volatile *E*,*E*-α-farnesene. This terpene attracted female codling moth at low doses and repelled them at high doses (Hern and Dorn, 1999). Because of its low environmental stability, *E*,*E*-α-farnesene has limited value in the field. A recent breakthrough in the development of an effective kairomonal lure was the identification of the pear ester, ethyl (*E*,*Z*)-2,4-decadienoate, a volatile present in the odor of ripe Bartlett pears (Light et al., 2001). Field tests showed that pear ester lure-baited traps capture more codling moths than pheromone baited traps in orchards treated with mating disruption. This kairomone attracts both males and females. The pear ester also attracted codling moth neonates in laboratory studies (Knight and Light, 2001). This chemical is stable, inexpensive to synthesize, and readily released from dispensers such as rubber septa. The use of kairomone-baited traps for codling moth has recently been developed to establish accurate action thresholds (Knight and Light, 2005a), and for monitoring females (Knight and Light, 2005b). However, the pear ester is found only from the odor of ripe pears but not in other host plants of the codling moth. Therefore, it is likely that codling moth females use other volatiles from non-pear hosts to recognize suitable oviposition sites (Witzgall et al., 2005). An apple-derived ester, butyl hexanoate, attracts mated codling moth females in laboratory studies (Hern and Dorn, 2004); however, it has not been proven to attract adults in the field.

Grapevine Moth

The European grapevine moth, *L. botrana* (Lepidoptera: Tortricidae), is a polyphagous insect and one of the most serious pests of vineyards. Females oviposit on flower buds, green berries, and mature grapevine berries. Adults are attracted to odors from grapevine berries (Tasin et al., 2005). Headspace volatile collections from green berries elicited antennal responses of mated *L. botrana* females. Masante-Roca et al. (2005) showed that plant volatiles are processed in the moth's antennal lobe. In wind tunnel assays, females responded to volatiles from grapevine branches and green berries (Tasin et al., 2005). Masante-Roca et al. (2007) also showed attraction to flower buds and ripe berries (both infested and uninfested with the pathogenic fungus *Botrytis cinerea*) but not to flowers. A recent breakthrough was the development of a complex attractive kairomonal lure for the grapevine moth (Tasin et al., 2006). They identified a blend of volatiles that attracts mated females consisting of (*E*)-β-caryophyllene, (*E*)-β-farnesene, and (*E*)-4,8-dimethyl-1,3,7-nonatriene. Attraction to the blend in the wind tunnel was achieved only when the individual compounds were mixed at a 100:78:9 ratio.

Colorado Potato Beetle

McIndoo (1926) first determined the attraction of the Colorado potato beetle, *Leptinotarsa decemlineata* (Say) (Coleoptera: Chrysomelidae), an important pest of solanaceous crops, to potato foliage in the laboratory. Recently, Dickens (1999) identified a synthetic blend of volatiles released by potatoes that attract Colorado potato beetle. Using GC-EAD analyses, nine volatiles contained in the potato blend elicited an antennal response in adult Colorado potato beetle (Dickens, 1999). Seven of these nine compounds were also detected by antennal receptors of two of its predators, the generalist *Podisus maculiventris* (Say) and the specialist *Perillus bioculatus* (F) (Dickens, 1999). Behavioral studies showed that adult Colorado potato beetles and the generalist predator are attracted to a blend of five compounds: (*E*)-2-hexenol, (*Z*)-3-hexenol, nonanal, linalool, and methyl salicylate. Further studies showed that Colorado potato beetle adults and larvae were attracted to blends comprised of (*Z*)-3-hexenyl acetate, linalool, and methyl salicylate (Dickens, 2000; Dickens, 2002). Recent field experiments by Martel et al. (2005) showed that pitfall traps baited with this blend captured more Colorado potato beetle adults than unbaited pitfall traps.

Plum Curculio

The plum curculio, *Conotrachelus nenuphar* (Herbst) (Coleoptera: Curculionidae), is a serious pest of stone and pone fruit in eastern North America. Behavioral studies showed that adult plum curculio use olfactory cues to locate its host fruit trees (Butkewich and Prokopy, 1993; Leskey and Prokopy, 2001). Further studies revealed that apple and plum odors released during bloom and 2 weeks after bloom attract adults (Leskey and Prokopy, 2000). Adults were attracted to fruit volatiles, particularly (*E*)-2-hexenal, hexyl acetate, ethyl isovalerate, limonene, benzaldehyde, benzyl alcohol, decanal, and geranyl propionate (Leskey et al., 2001; Prokopy et al., 2001). In field experiments, only benzaldehyde synergized the response of plum curculio to its aggregation pheromone grandisoic acid (GA) (Piñero and Prokopy, 2003). Although the combination of benzaldehyde and GA has yielded higher adult trap captures in baited traps than in non-baited traps, baited traps have failed to reliably monitor plum curculio activity in apple and peach orchards because captures decline rapidly after fruit set suggesting that traps were out-competed by fruit volatiles (Prokopy et al., 2003; Leskey and Wright, 2004).

11.3.1.2 Repellents

Plant repellents are volatiles that cause an insect to orient their movement away from the emitting source (Dethier et al., 1960; Bernays and Chapman, 1994). Compared to attractants, fewer plant-derived insect repellents have been studied, and as a result the use of repellents for exogenous applications to prevent pest infestations in agriculture has not been widely practiced. The role of non-host volatiles as repellents has been tested mainly in forest systems (e.g. Byers et al., 2004). Among agricultural pests, host-plant repellents have been mostly studied in aphids. (*E*)-(β)-Farnesene, a common sesquiterpene host-plant volatile and the major component of the alarm pheromone of several aphid species, repels some aphid species (Pickett et al., 1992; Bernasconi et al., 1998). Methyl salicylate and (-)-(1*R*,5*S*)-myrtenal were repellent to the black bean aphid, *Aphis fabae* Scop, and inhibited attraction to its host, the broad bean (Hardie et al., 1994). *A. fabae* and *Brevicoryne brassicae* (L.) were repelled by volatiles from tansy and summer savory (Nottingham et al., 1991). The authors found that *A. fabae* was repelled by 4-pentenyl isothiocyanate. Isothiocyanates are catabolites of glucosinolates and characteristic of the Brassicaceae, and most likely repellent to non-adapted insects. Limonene, a common monoterpene volatile from plants, has also been shown to repel some insects (e.g. Ibrahim et al., 2001). Other plant monoterpenes such as (*E*)-ocimene and sesquiterpenes such as (-)-germacrene D repel herbivores (Bruce et al., 2005).

11.3.1.3 Herbivore-Induced Plant Volatiles

Herbivory often increases volatile emissions from plants (Karban and Baldwin, 1997). Studies on the effects of HIPVs on insect behavior have been viewed mainly in a tritrophic context (Vet and Dicke, 1992). Natural enemies of herbivores may use volatiles from herbivore-damaged plants to locate their host or prey (see discussion below). Recently, however, HIPVs have been shown to also influence the behavior of phytophagous insects (Dicke and van Loon, 2000) (Fig. 11.4). For example, grape volatiles induced by insect feeding (conspecifics) attracted Japanese beetles in the field (Loughrin et al., 1996a). Similarly, Colorado potato beetles are attracted to potato plants damaged by conspecific larvae (Schutz et al., 1997; Landolt et al., 1999). HIPVs can also repel insect herbivores. For example, undamaged wheat seedlings arrested, and damaged wheat seedlings repelled, the bird cherry-oat aphid, *Rhopalosiphum padi* (L.) (Quiroz et al., 1997). Four compounds, 6-methyl-5-hepten-2-one, (–)- and (+)-6-methyl-5-hepten-2-ol, and 2-tridecanone, were present in volatile blends from aphid-infested but not from un-infested wheat seedlings. De Moraes et al. (2001) showed that caterpillars induce volatiles at night from tobacco plants that are repellent to female *Heliothis virescens* (Fabricius) moths.

HIPVs can also affect the behavioral response of immature insects towards plants. For example, neonate larvae of the codling moth are attracted to larval-infested apple fruit (Landolt et al., 2000). (*E*,*E*)-α-Farnesene was emitted in greater amounts from infested compared to un-infested apples. Previous studies had shown that neonate codling moth is attracted to α-farnesene, as previously discussed. Similarly, *Spodoptera frugiperda* (J.E. Smith) larvae were attracted to volatiles from herbivore-damaged maize seedlings (Carroll et al., 2006).

11.3.2 Applications

To a large extent, plant volatiles can be used in a similar manner to sex pheromones. Plant volatiles can be used to bait traps for monitoring, or in pest control strategies such as in mass trapping and attract-and-kill approaches, or to disrupt host-finding behavior.

Figure 11.1 provides a comparison of different attributes of insect sex pheromones and host-plant volatiles. The development of plant-based kairomones in IPM offers several advantages over sex pheromones, which typically attract only one sex or only males in the majority of cases. This is important because most efforts in pest management are directed towards attraction and control of females. For example, monitoring for the presence of females, which mate and lay eggs offers a distinct advantage in terms of predicting crop damage. Plant volatiles are also advantageous because they may attract both immature and adult stages. A third advantage of plant volatiles over pheromones is that they are often simple, commercially available, and cheap chemicals. Plant-based kairomones can serve as an alternative to sex pheromones when the pheromone is absent or produced at amounts undetectable by GC, has low volatility, or is difficult and/or expensive to synthesize.

A major disadvantage of host-plant volatiles is their limited specificity, or lack thereof, compared to sex pheromones. Plant volatiles are ubiquitous and plant species often share similar biosynthetic pathways in volatile production; the most prominent being the lipoxygenase, leading to the production of green leaf volatiles, and the isoprenoid pathways, leading to the production of terpenes (Paré and Tumlinson, 1999). Thus, plant-derived attractants will often attract several species of non-target insects. This might be problematic if the blend attracts beneficial insects, such as bees and predators; thus potentially disrupting pollination or biological control. Also, host-plant volatiles may be less effective than sex pheromones because they have to compete with abundant surrounding odor sources for attraction. This might be more problematic in agriculture than in forest systems because most crops are grown as monocultures. Under these crop conditions, a good understanding of the pest's behavior will be important when testing plant-based kairomones in the field. For example, if the pest migrates from the forest into the crop, attractants could be placed near the forest edge to avoid competition with the host plant.

11.3.2.1 Monitoring

Host-plant volatiles can be deployed in the same manner as described for sex pheromones, and may provide a natural source for the development of attractants for monitoring insect pests that are safe to the environment. Attraction to kairomone-baited traps by insect pests will require the detection of a specific blend of host-plant volatiles or specific ratios of these volatiles. However, finding the right combination of plant volatiles at the correct ratio is often a challenging task. As indicated previously, attractants from plant volatiles are currently under development for various species of moths and beetles (Table 11.3). Yet, the best-known success case is the use of food-derived attractant traps to monitor and control fruit flies (e.g., Morton and Bateman, 1981; Prokopy et al., 1992; Prutuele et al., 1993; Cornelius et al., 1999). The use of kairomone-based lures for pest monitoring may feature more prominently in future pest management as our understanding of plant-based attractants for both generalist and specialist herbivores increases. Currently, the number of potent pheromone-based insect attractants vastly outnumbers the number of effective known kairomones.

11.3.2.2 Mass Trapping

The host-plant volatiles used for monitoring insect pests can be used in a mass trapping approach. Only few studies have investigated this approach to protect plants in an agricultural system. For example, Ruther and Mayer (2005) tested synthetic plant volatiles in a mass trapping experiment to control the garden chafer, *Phyllopertha horticola* L., in an apple orchard. They found that orchards treated with attractant traps had about 7% less disfigured fruit by adult feeding compared to control orchards.

11.3.2.3 Attract-and-Kill

Although attract-and-kill strategies have mainly used sex pheromones and food lures (see Section 11.2.1.3), host-plant volatile attractants can also be employed with an insecticide to increase its efficacy in crop protection. An attract-and-kill tactic that uses a kairomone-based attractant to target females would have a much greater effect on pest population growth compared with those that target males only. Some important chemicals, including methyl eugenol, 1-(p-acetoxyphenyl)-butan-3-one (cue-lure), and t-butyl 4 (or 5)-chloro-2-methyl-cyclohexanoate (trimedlure), have been used as attractants for fruit flies. For example, methyl eugenol was used in the eradication program for the oriental fruit fly, *Dacus dorsalis* (Hendel), on the island of Rota in the Marianas (Steiner et al., 1965). Other volatiles used for monitoring fruit flies are derived from food sources (food baits), such as from the protein hydrolysates of corn, soybeans, or yeast. Fermentation of these baits results in volatile emissions attractive to fruit flies. Several attractants (baits) for fruit flies are commercially available (e.g., Nu Lure, GF-120, Naturalure).

The attract-and-kill concept has also been tested in trap crops, where more attractive plants are used to lure insects away from the economic crop, and then reduce the pest populations by either killing the insects in the trap crop with an insecticide or destroying the trap crop (Hokkanen, 1991). The attractiveness of trap crops to insect pests can be enhanced by the use of host-plant volatiles. This approach has been called "semiochemically assisted trap cropping" (Shelton and Badenes-Perez, 2006). For example, Martel et al. (2005) evaluated the potential of a synthetic host-plant attractant blend for the Colorado potato beetle to enhance efficacy of trap cropping. More colonizing adults, eggs, and larvae were found in attractant-treated trap crops than in untreated trap crops. This resulted in reduced amounts of insecticides applied to plots bordering the attractant-treated trap crops.

11.3.2.4 Push-Pull Strategy

Push-pull (Pyke et al., 1987), or stimulo-deterrent diversion (Miller and Cowles, 1990), is a strategy where a host-plant attractant(s) and a repellent(s) are used in combination. This concept has been tested using a repellent intercrop and an attractant "trap" plant. Here insects are repelled by volatiles emitted from the intercrop (push) and simultaneously attracted by volatiles from the trap plant (pull). The most successful work on push-pull to date has been conducted in Africa to control stem borers in maize and sorghum (Cook et al., 2007). This work has lead to the adoption of push-pull strategies among thousands of small and medium scale farmers in eastern Africa (Khan and Pickett, 2004). The strategy works not only by decreasing stem borer damage to maize, but also by enhancing the efficacy of natural enemies (Khan et al., 1997a,b). Here, the two most successful trap crops are Napier and Sudan grasses; they receive greater stem borer oviposition than maize. Six volatiles found in Napier grass attractive to female stem borers are octanal, nonanal, naphthalene, 4-allylanisole, eugenol, and linalool (Khan et al., 2000). Napier grass also produces larger amounts of green leaf volatiles hexanal, (*E*)-2-hexenal, (*Z*)-3-hexenol, and (*Z*)-3-hexenyl acetate than maize and sorghum (Chamberlain et al., 2006). These green leaf volatiles might be responsible for female stem borer attraction to trap plants because they are emitted at the beginning of the scotophase, when females seek plants for oviposition (Khan et al., 2008). The intercrops with greatest repellent effects are molasses grass and two legumes: siverleaf and greenleaf desmodium. Six volatiles are emitted from molasses grass but not in the trap plants; these are (*E*)-ocimene, (*E*)-4,8-dimethyl-1,3,7-nonatriene, β-caryophyllene, humulene, and α-terpinolene (Khan et al., 2000; Pickett et al., 2006). The ocimene and nonatriene were found repellent to stem borer (Khan et al., 1997a). These compounds were also found in the desmodium intercrops (Khan et al., 2000). Volatile chemicals from molasses grass that repelled female stem borers attracted females of its parasitoid *Cotesia sesamiae* (Cameron) (Khan et al., 1997a).

11.3.2.5 Disruption of Host Finding

Host-plant volatiles can be sprayed on a crop to disrupt the pest's host finding behavior. For example, an attractant crude oil was used to disrupt the host-finding behavior of the navel orangeworm, *Amyelois transitella* (Walker), a pest of almonds in California (Van Steenwyk and Barnett, 1987). Spraying a formulation of 5% crude almond oil on trees suppressed egg deposition in egg traps and reduced the infestation of nuts. An approach recently employed is to apply an elicitor of plant defenses that can activate the production of volatiles in plants. For example, Thaler (2001) showed that application of jasmonic acid (JA), a hormone known to induce plant resistance and HIPVs, reduces the number of caterpillars, aphids, flea beetles, and thrips on tomato plants. Whether the negative effects of JA treatment on herbivores were due to an increase in HIPVs was not investigated. Disruption of host finding by spraying a synthetic volatile attractant or repellent has rarely been tested to control an agricultural pest, possibly because it might unintentionally attract other pests into the crop.

11.3.3 Synergism with Other Stimuli and Control Strategies

11.3.3.1 Visual Cues

As indicated above, host-plant selection by insects usually requires visual (color, shape, or size) and chemical (pheromones or host-plant volatiles) signals. Therefore, combinations of these signals might work better in attracting insects than a single stimulus. Several examples exist where visual stimuli enhance insect responses to host-plant volatiles (Prokopy, 1986; Blackmer and Cañas, 2005; Kendrick and Raffa, 2006). Colored traps have historically been used to monitor insect pests. Yellow sticky traps have been used to monitor whiteflies (e.g. Gillespie and Quiring, 1987), plant bugs (e.g. Prokopy et al., 1979), and leafhoppers (e.g. Meyerdirk and Oldfield, 1985). Red spheres attract female apple maggots, *R. pomonella*, by mimicking ripe fruit (Prokopy, 1968). Sticky red spheres have been used to protect apples against this fruit fly species (Prokopy, 1975); however, a combination of visual and chemical cues proved to be more attractive (Prokopy et al., 1990; Aluja and Prokopy, 1993). Prokopy et al. (1990) found that sticky spheres baited with butyl hexanoate placed in the perimeter of orchards provide protection similar to unbaited spheres on every tree. Adding an insecticide and/or a food stimulant can further enhance the efficacy of sphere traps (see Sections 11.2.1.3 and 11.3.2.3).

11.3.3.2 Pheromones

Probably the most effective method for using host-plant volatiles is in combination with insect pheromones. Host-plant volatiles, particularly green leaf volatiles, can enhance the insect's response to their sex pheromone. For example, male corn earworm, *Helicoverpa zea* (Boddie) response to the sex pheromone is enhanced when combined with (Z)-3-hexenyl acetate (Light et al., 1993). Males were not attracted to this green leaf volatile when presented alone, indicating that it acted synergistically with the sex pheromone. (Z)-3-hexenyl acetate also acts synergistically with the sex pheromones of the codling moth, *C. pomonella*, the diamondback moth, *Plutella xylostella* (L.), and the tobacco budworm, *H. virescens* (Reddy and Guerrero, 2004).

Host-plant volatiles can also enhance the insects' response to their aggregation pheromone. Reddy and Guerrero (2004) provide a list of examples where synergistic effects of plant volatiles and aggregation pheromones have been reported. For example, the response of the boll weevil, *Anthonomus grandis* Boh., to their aggregation pheromone (grandlure) is enhanced when combined with the green leaf volatiles (*E*)-2-hexenol, (*Z*)-3-hexenol, or 1-hexanol (Dickens, 1989).

Host-plant volatiles can also inhibit the insect's response to their pheromone. This concept has been investigated for forest pests but not for agricultural pests. Non-host, green leaf volatiles have been shown to inhibit the response of several species of bark beetles to their pheromone (e.g. Dickens, 1992; De Groot and MacDonald, 1999; Poland and Haack, 2000). Whether non-host volatiles can be used to protect plants in agricultural systems requires further investigation.

11.3.3.3 Biological Control

Plant volatiles are critical in host finding not only for insect pests but also for their natural enemies, i.e., insect predators and parasitoids (Price et al., 1980) (Fig.11.4). Natural enemies may use plant volatiles to find a habitat where their host or prey can be found. However, more reliable cues for natural enemies are herbivore-induced plant volatiles (HIPVs). The role of HIPVs on natural enemy host finding behavior has been studied extensively in the past few decades and several reviews have been written on the subject (e.g. Dicke et al., 1990; Lewis and Martin, 1990; Vet and Dicke, 1992; Tumlinson et al., 1993). Here we will only discuss examples where synthetic HIPVs have been used to manipulate natural enemy behavior. These chemicals may increase biological control success in agriculture by "enhancing the searching efficacy of natural enemies, bringing the natural enemies into a searching mode, and making novel or artificial host-prey species acceptable in a mass rearing program" (Khan et al., 2008). In contrast, when applied to agricultural crops, HIPVs may reduce searching efficacy of natural enemies by attracting them to areas where the prey or host are absent. Thus, it might be important to consider the abundance and distribution of the pest when using HIPVs to enhance biological control.

To date, field demonstrations on the use of HIPVs to manipulate the behavior of the natural enemies of herbivores remain limited. James (2003a) was the first to demonstrate attraction of predators to synthetic HIPVs in an agricultural system. In hop, sticky traps baited with synthetic methyl salicylate (MeSA) caught greater numbers of lacewings than unbaited traps (James, 2003a). In another study, traps baited with (*Z*)-3-hexenyl acetate caught more predatory mirids, *Deraocoris brevis* (Uhler), and anthocorids, *Orius tristicolor* (White), than unbaited traps; whereas traps baited with MeSA attracted more geocorids, *Geocoris pallens* Stal., and hover flies (James, 2003b). Subsequently, James and Price (2004) showed similar results in juice grape vineyards, with sticky traps in MeSA-baited blocks attracting greater numbers of predatory insects than traps in unbaited blocks. Significantly greater numbers of the parasitoid *Anagrus* spp. were also found in MeSA-baited blocks

(James and Grasswitz, 2005). (*Z*)-Jasmone is another HIPV that attracts natural enemies of aphids (Powell and Pickett, 2003; Pickett et al., 2006). Another approach is to spray specific plant hormones, such as JA, to induced HIPV emissions and orient predators and parasitoids to plants (e.g. Thaler, 1999).

The mode of action of HIPVs on natural enemies remains unknown. However, two mechanisms have been proposed; HIPVs may influence the natural enemies' behavior directly by attracting them and increasing their searching behavior, or indirectly by making plants more responsive to insect damage for increased volatile emissions (Khan et al., 2008). The later mode of action has been referred to as "priming" (Engelberth et al., 2004), and is expected to be less disruptive to biological control because plant volatile emissions are activated only when under attack by herbivores, thus increasing the detectability of volatiles to natural enemies. Predalure (AgBio Inc.) is a commercially available lure to attract multiple species of insect predators.

HIPVs are not only important in attracting natural enemies aboveground but also belowground (Fig. 11.4). Recently, Rasmann et al. (2005) reported the first identification of an insect-induced belowground plant signal. (*E*)-β-caryophyllene was released from maize roots in response to feeding by the beetle *Diabrotica virgifera virgifera* LeConte, and shown to strongly attract an entomopathogenic nematode.

Biological control agents can enhance the efficacy of strategies for the manipulation of pest behavior, such as in trap crops and push-pull approaches. For instance, trap plants often serve as reservoirs for beneficial insects (van Emden and Dabrowski, 1994). Molasses plants, when intercropped with maize, increased parasitoids and predators of stem borers (Khan et al., 1997a, 1997b, 2008). Furthermore, the use of insect pheromones with host-plant volatiles can reduce pest populations by increasing natural enemy populations, a research area that needs further investigation. On the other hand, some approaches may reduce the abundance of beneficial arthropods such as the use of attract-and-kill strategies that attract natural enemies.

11.4 Farmer Education and Adoption

A list of technical, socio-economic, and policy-related constraints for the development and adoption of behavior-modifying strategies is provided in Table 11.4. For many growers, farming is a family affair, with the older generation teaching the younger about the practice. Educating farmers on a new strategy for pest management, such as manipulation of a pest's behavior, can be challenging because it requires changes in the farmers' current management practices. Here communication between researchers and farmers is key and can be achieved through an extensive education/demonstration program showing the benefits of new strategies. These educational programs should focus on subjects that provide farmers with a better understanding on general aspects of the pest, such as pest identification, biology, and behaviors, as well as aspects on pest-monitoring such as trap efficacy,

Table 11.4 Constraints hindering development and adoption of behavior-modifying strategies in IPM

Technical	• Specificity. Sex pheromones are highly specific, and thus their use in strategies such as mating disruption might be limited when there is need to control several pests. • Complete control is rarely achieved. This is most critical when controlling a pest with "O" or very low tolerance. • For some pest species, these strategies are not sufficient for control as a stand alone treatment. • Often low efficacy under high pest pressure. • Need for large-scale (area-wide) implementation (i.e., for mating disruption programs).
Socio-economic	• High input costs. • High competition with pesticides. Pesticides are often cheaper and have broader spectrum activity. • Need for multi-grower implementation. • Require intense education and on-farm demonstrations. Need for change in farmer perception of benefits compared to other strategies.
Policy related	• Regulatory: certain chemicals of natural origin may not have tolerance exemptions. • Registration: market volume will dictate the interest from industry to pursue registration. In most cases, interest will be biased towards highly valuable, widely cultivated, and vastly consumed crops.

assemblage, timing, and position. Educational programs also need to focus on the type of field data to be recorded by farmers, which will provide information on the occurrence and possibly the distribution of pests depending on the number and location of traps within farms. Trap information can be combined with geographic information systems (GIS) for an area-wide approach to manage insect pests (e.g. Carrière et al., 2006). Geographical information can be used to target insecticide applications to specific areas of infestation, and thus may result in reduced pesticide use.

Ultimately, the adoption of semiochemicals for control of insect pests will depend on the farmers' perception of these strategies, i.e., costs, compared to their current practices. Current pest management is dominated by the use of broad-spectrum insecticides. However, due to increased restrictions on the use of broad-spectrum insecticides in agricultural crops worldwide (e.g. Matteson, 1995), there is a growing demand for the study of alternative pest management methods. These new regulatory measures will likely increase adoption of new technologies including the use of semiochemical-based strategies for monitoring and management of insect pests. Manipulation of insect behavior through the use of semiochemicals may provide farmers with a highly specific, minimally or non-toxic, and environmentally friendly alternative to insecticides. Although semiochemicals are expected to be less toxic than broad-spectrum insecticides, their toxicity has not always been thoroughly tested.

The trend towards restricting the use of broad-spectrum insecticides in the 1990s was one of the motivating factors that led to the large-scale adoption of mating disruption in regions such as the U.S. Pacific Northwest (Brunner et al., 2002). Today, the majority of apple orchards in Washington State (USA) rely on mating disruption as part of an integrated strategy for managing pests such as codling moth. In this state, farmer adoption of mating disruption has been due to the concerted team effort between industry, academia, and U.S. government researchers, who worked together to demonstrate the effectiveness of the technology and spread awareness of its benefits. In addition to producing clean fruit, farmers have become keenly aware of the other benefits mating disruption provides, such as increased worker safety, greater positive impact of unaffected natural enemies, and reduced environmental pollution. However, large-scale adoption of mating disruption remains an economically-driven decision, and has been slower in tree fruit growing regions where a complex of multiple Lepidopteran pests affects production such as in Michigan (USA). One of the main impediments is that the most effective mating disruption technology available today still requires hand application. Cost of labor for such formulations remains an economic limitation even though these technologies are applied only once a year. The species specificity of pheromones as tools for monitoring pests is unfortunately one of their greatest drawbacks as tools for direct pest suppression or control. In regions where a complex of pests concurrently affects fruit production, use of species-specific control technologies is an economic burden that many growers cannot afford. Fortunately, multi-species formulations of pheromones have been developed, which simultaneously disrupt the communication of several moth species (e.g., Stelinski et al., 2007c). Such formulations may feature prominently in farmer management programs in tree fruit areas affected by multiple pests. The codling moth is a potent example of the broad-scale adoption of mating disruption with over 160,000 ha of pome fruit treated with pheromone for control of this pest annually (Witzgall et al., 2008). The development of effective new generation insecticides for use in tree fruit such as neonicotinoid insecticides and spinosad (Thompson et al., 2000; Tomizawa and Casida, 2003) may slow the adoption of mating disruption, as broad-spectrum insecticides are phased out, because these new generation pesticides are often less expensive than pheromone active ingredients and often target multiple pests simultaneously. However, as the deployment of mating disruption technology is further mechanized and as more effective technologies are developed based on knowledge of the actual mating disruption mechanisms, adoption of this biorational management tactic will likely increase. Pheromone or kairomone-based monitoring of Lepidopteran and Dipteran pests to determine action thresholds has become a commonplace component of many tree fruit management programs throughout the world and will likely only increase as the available number of effective semiochemicals continues to increase.

Furthermore, adoption of semiochemical-based strategies is most likely when farmers have limited alternative options for controlling a pest. For example, in highbush blueberries in New Jersey (USA) the only control for oriental beetle is soil treatment with the neonicotinoid insecticide imidacloprid. However, several blueberry farmers refuse to use this insecticide because of unsupported beliefs that imidacloprid applications reduce blueberry yield through decreased pollination. Several other growers have used imidacloprid for many years without any reductions in pollination or yield. Under this condition, the use of an alternative strategy, such as mating disruption, is likely to be adopted, not only by those farmers who do not want to use imidacloprid, but also by organic farmers. Making the cost of mating disruption more comparable to imidacloprid will also help increase its adoption among farmers. Adoption of mating disruption will reduce the use of imidacloprid, and in turn reduce the amount of pesticide in the environment and serve as a good practice for managing resistance.

Another limitation is the difficulty in obtaining registration for certain semiochemicals, such as the pheromone of the oriental beetle, which can cause delays in the commercial application of a product for several years. The oriental beetle pheromone is a ketone and this chemistry does not have a tolerance exemption for fruit crops. This has delayed the registration of the pheromone for mating disruption. In addition, the cost of registration of semiochemicals can be high, and thus interest from companies to register a product will depend on the size of the market. In fact, there is low interest from companies to register a product that is species-specific and that controls a regional pest. This is the case for oriental beetle mating disruption because blueberries are a minor crop and oriental beetle is a pest only in the Northeast USA. Oriental beetle is also a pest in ornamentals, turf, and cranberries, and mating disruption has been effective in controlling this pest in these crops (Polavarapu et al., 2002; Koppenhöfer et al., 2005; Wenninger and Averill, 2006). However, several other Scarab pests also attack them, making it unlikely that mating disruption for oriental beetle will replace the use of insecticides, which target all soil species in these systems.

A few other concerns that farmers have expressed in relation to using attractants for insect control are that deploying sex pheromones for mating disruption may inadvertently attract more pests into treated fields, thus potentially increasing the pest population, and that natural enemies attracted to the crop can unintentionally end up in the harvested fruit, especially during machine harvest, and thus be a source of contamination. These are examples where farmer education on the mechanism of these technologies is most crucial. Therefore, successful communication between industry, academia, extension personnel, members of the agri-business, and farmers is imperative when developing technologies to manipulate insect behavior.

11.5 Future Directions

Sex pheromones will likely continue to be an integral part of IPM programs in agriculture, particularly for monitoring insect pest populations. Research on mating disruption will continue to focus on understanding underlying mechanisms and developing more effective and economical release technologies. Fundamental research directions should include testing the recently formulated predictions of Miller et al. (2006a) by developing moth catch versus dispenser density profiles for various pest species. These analyses, combined with direct observations of insect behavior in the field, will determine the possible mechanism(s) of disruption. Generating such data will allow development of optimal formulations as well as facilitate determining optimal dispenser density for maximum efficacy against a particular pest. Practical research should focus on development of multi-species formulations that can be applied mechanically to large areas. Finally, although mating disruption exploits insect behaviors that are under intense selection pressure to maintain species isolation, development of resistance following prolonged use remains a possibility (Mochizuki, 2002; Roelofs et al., 2002), and should not be ignored.

More research is needed to better understand insect behaviors towards host-plant volatiles. Comparative studies should be conducted to determine the role of plant volatiles in host finding by insects with different life histories, i.e., specialists versus generalists. Although some plant-based attractants have proven successful in IPM, the use of plant repellents to control insect pests has yet to be exploited in agriculture. The best chance for implementing host-plant volatiles in IPM programs is in combination with other strategies. For instance, host-plant volatiles may enhance the efficacy of sex pheromones and biological control. Given that plant volatiles often synergize the insect's response to pheromones, the efficacy of mating disruption formulations that co-release pheromones and key behaviorally active plant volatiles requires prompt investigation. Whether a combination of host-plant volatiles and sex pheromones increases attraction of natural enemies also requires evaluation. Advances in molecular technology will lead to new ways of exploiting host-plant volatiles in IPM. Plants could be genetically-engineered to be more or less attractive to herbivores, or to be more attractive to natural enemies.

To increase farmer adoption, future research should focus on making these strategies more effective and less costly.

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Chapter 12
Botanicals in Pest Management: Current Status and Future Perspectives

Sanjay Guleria and A.K. Tiku

Abstract The problems caused by synthetic pesticides and their residues have increased the need for effective biodegradable pesticides with greater selectivity. Alternative strategies have included the search for new types of pesticides which are often effective against a limited number of specific target species, are biodegradable into nontoxic products and are suitable for use in integrated pest management programs. The natural plant products derived from plants effectively meet this criterion and have enormous potential to influence modern agrochemical research. When extracted from plants, these chemicals are referred to as botanicals. The use of botanical pesticides is now emerging as one of the prime means to protect crops and their products and the environment from pesticide pollution. Botanicals degrade more rapidly than most chemical pesticides, and are, therefore, considered relatively environment friendly and less likely to kill beneficial pests than synthetic pesticides with longer environmental retention. Most of the botanical pesticides generally degrade with in few days and some times with in a few hours, these pesticides needs to be applied more frequently. More frequent application coupled with higher costs of production makes botanicals more expensive to use than conventional pesticides. Moreover, in spite of wide recognition that many plants possess pesticidal properties, only a handful of pest control products obtained from plants (pyrethrum, neem, rotenone) are in use because commercialization of botanicals is hindered by several issues discussed in this chapter.

Keywords Botanicals · Pest management · Neem · Essential oils · Plant extracts · Commercialization

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S. Guleria (✉)
Division of Biochemistry and Plant Physiology, Sher-e-Kashmir University of Agricultural Sciences and Technology of Jammu, Chatha-180 009, Jammu, India
e-mail: guleria71@rediffmail.com

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12.1 Introduction

Pests are one of the serious problems faced by agriculture today. Although there are many ways to reduce or kill pests, every pest management method has certain drawbacks. Synthetic pesticides that have been commercialized are halogenated hydrocarbons or organophosphates which have long environmental half lives and are suspected to possess toxicological properties than most of natural compounds. Considering above and several other factors there is growing need for alternative, environmentally benign, toxicologically safe, more selective and efficacious pesticides. Botanicals being plant secondary metabolites, thus offer an attractive and favourable alternative for pest management (McLaren, 1986). Documented scientific literature also support the fact that plant secondary metabolites are involved in the interaction of plant with other species- primarily in the defence response of plant against pests. Thus the secondary compounds called botanicals represent a large reservoir of chemical structures with pesticidal activity (Klocke, 1987). This resource is largely untapped for use as pesticides. There are several advantages of botanical pesticides like fast degradation by sun light and moisture or by detoxifying enzymes, target specific nature and less phytotoxicity which provokes researcher to use botanicals in pest management. Higher plants produce diverse array of secondary metabolites which include phenolics, terpenes, alkaloids, lignans and their glycosides. These play significant role in plant defence system and offer an array of structural prototypes for development of lead molecules which can serve as new pest control agents (Lydon and Duke, 1989).

The knowledge of pest to which particular plant is resistant may provide useful information for predicting what pests may be controlled by secondary metabolites derived from a particular plant species. This approach has led to the discovery of several commercial pesticides such as pyrethroid insecticides. Botanicals have been classified into herbicides, insecticides, fungicides, nematicides, molluscides, and rodenticides. These pesticides have variable mode of action. Some act as direct toxicant, sterilant where as others act as antifeedant/repellant or behavior modifiers. The discovery process for botanical pesticides is more cumbersome as compared to synthetic counterparts but less environmental load caused by botanical pesticides makes them an attractive alternative. In spite of relatively small previous efforts in the development of botanical pesticides they have made large impact in the area of insecticides. Minor success has been achieved in herbicides, nematicides, rodenticides, fungicides and molluscides (Duke, 1990).

The number of options that must be considered in discovery and development of a natural product as pesticide is larger than for a synthetic pesticide. Further more complexity, limited environmental stability and low activity of many biocides from plants, compared to synthetic pesticides are discouraging. However, advances in chemistry and biotechnology are increasing the speed and ease with which man can discover and develop secondary compounds of plants as pesticides. All these advances combined with increasing need and environmental pressures are greatly increasing the interest for production of botanical pesticides.

12.2 Botanicals vs. Synthetic Chemicals

For self-defense purposes, many plants generate chemicals that are toxic to insects. Because these naturally occurring insecticides are derived from plants, they are called botanical insecticides or botanicals. Before World War II, botanical insecticides were commonly used throughout the world to defend against insect pests. However, just before the war, a highly effective "synthetic" (man-made) insecticide called DDT was introduced which changed the nature of pest control worldwide. Because these chemicals were cheaper, easier to apply and longer lasting, other synthetic insecticides soon followed, which quickly displaced botanicals in the marketplace and greatly slowed the research and development of natural, botanical compounds. Unfortunately, these synthetic insecticides target a nervous system common to people and animals, and can be toxic to fish and the environment. In addition, many of the chemicals persist for long periods and cause residual problems (Coats, 1994). Insect pests have also developed resistance to many of the synthetic chemicals over time (Roush, 1989). As awareness of the potential health and environmental hazards of many residual synthetic pesticides increases, and as pests become resistant to more and more synthetic compounds, interest in plant-derived pesticides is increasing (Isman, 2006).

Botanicals degrade rapidly in sunlight, air and moisture and by detoxification enzymes. Rapid breakdown means less persistence and reduced risk to non target organisms. However precise timing and/or more frequent applications may be necessary. Botanical insecticides are fast acting. Although death may not occur for several hours or days, insect may be immediately paralyzed or stop feeding. Most botanicals have low to moderate mammalian toxicity. Some botanicals quickly breakdown or are metabolized by enzymes inside bodies of their target pests. Breakdown may occur rapidly, so that the insecticide only temporarily stuns the insect but does not kill it (Rice, 1983). A synergist may be added to a compound to inhibit certain detoxification enzymes in insects. This enhances the insecticidal action of the product. Synergists are low in toxicity, have low or no inherent insecticidal properties, and have very short residual activity. Pyrethrins are often mixed with a synergist such as piperonyl butoxide (PBO) to increase their effectiveness. Rapid breakdown and fast action make botanicals more selective to certain plant feeding pests and less harmful to beneficial insects.

Most botanicals are not phytotoxic (toxic to plants). However nicotine sulfate may be toxic to some vegetables and ornamentals. Botanicals tend to be more expensive than synthetics and some are no longer commercially available (e.g. Nicotine). The potency of some botanicals may vary from one source or batch to the next. Data on effectiveness and long term (chronic) toxicity to mammals are unavailable for some botanicals. Tolerance for residues of some botanicals on food crops has not been established. Botanical insecticides include nicotine from tobacco, pyrethrum from chrysanthemums, derris from cabbage, rotenone from beans, sabadilla from lilies, ryania from ryania shrub, limonene from citrus peel, and neem from the tropical neem tree. Most, other than nicotine have low levels of toxicity in mammals and birds and create few adverse environmental effects (Prakash and Rao, 1997).

Major classes of synthetic insecticides are chlorinated hydrocarbons, organophosphates, carbamates and pyrethroids. Although, synthetic insecticides (e.g., chlorinated hydrocarbons, organophosphates and pyrethroids) have been an important part of pest management for many years, the disadvantages and risks of using them have become apparent. Some synthetic insecticides leave unwanted residues in food, water and environment. Some are suspected carcinogens and low doses of many synthetic insecticides are toxic to mammals. As a result, many people are looking for less hazardous alternatives to conventional synthetic insecticides. Organochlorines act by blocking an insect's nervous system, causing malfunction tremors, and death. All organochlorines are relatively insoluble, persist in soils and aquatic sediments, can bio- concentrate in the tissues of invertebrates and vertebrates from their food, move up trophic chains, and affect top predators (Brooks, 1974). These properties of persistence and bioaccumulation led eventually to the withdrawal of registration and use of organochlorine insecticides, from the late 1990s, in industrialized nations, although they continued to be used in developing countries. Organophosphate insecticides originated from compounds developed as nerve gases by Germany during World War II. Thus those developed as insecticides, such as tetra ethyl pyrophosphate (TEPP) and parathion, had high mammalian toxicities. In insects, as in mammals they act by inhibiting the enzyme cholinesterase (ChE) that breaks down the neurotransmitter acetylcholine (Ach) at the nerve synapse, blocking impulses and causing hyperactivity and titanic paralysis of the insect, then death. Some are systemic in plants and animals, but most are not persistent and do not bioaccumulate in animals or have significant environmental impacts. Carbamyl, the first carbamate insecticide, acts on nervous transmission in insects also through effects on cholinesterase by blocking acetyl choline receptors. Carbamates are broad spectrum insecticides, of moderate toxicity and persistence, they rarely bioaccumulate or cause major environmental impacts (Kuhr and Dorough, 1976).

Synthetic pyrethroid insecticides, with structures based on natural compound pyrethrum, were introduced in the 1960s and include tetramethrin, resmethrin, fenvalerate, permethrin and delta methrin, all used extensively in agriculture. They have very low mammalian toxicities and potent insecticidal action, and are photostable with low volatilities and persistence. They are broad-spectrum insecticides and may kill some natural enemies of pests. They do not bioaccumulate and have few effects on mammals, but are very toxic to aquatic invertebrates and fish (Elliot et al., 1978).

12.3 Botanicals as Fungicides and Insecticides

Pre-harvest losses due to fungal diseases in world crop production can amount to 11.8% or even higher in developing countries (Agrios, 1997). Most of the efforts in the past few years for the effective control of plant diseases have been focused on effective eradication or prevention through the development of synthetic chemical fungicides (Bajpai et al., 2004). However, increasing concern over the environmental load caused by the currently used synthetic fungicides has necessitated the search for fungicides of biological origin with the germane assumption that bio-products are more specific in their action and mechanisms, do exist in nature for their disposition and are thus less hazardous. Therefore, recently there is an upsurge of interest in natural plant products to be used as fungicides. Although it is difficult to define the ecological significance of most synthetic fungicides, there is good reason to suppose that a secondary plant metabolism has evolved to protect plants against attack of microbial pathogens (Benner, 1993).

Plant extracts or phytochemicals provide attractive alternative to currently used synthetic fungicides as regards controlling phytopathogenic fungi, since they constitute a rich source of bioactive molecules (Wink, 1993). They are often active against a limited number of specific target pests, are biodegradable into non-toxic products, and are, therefore, potentially useful in integrated pest management programs. Therefore, recent efforts have been directed towards the development of secondary metabolites as potentially useful products for commercial fungicides or lead compounds (Kim et al., 2003; Yoo et al., 1998).

Biologically active natural products have the potential to replace synthetic fungicides. Biologically active natural products such as flavour compounds, glucosinolates, chitosan, essential oils and plant extracts have been exploited for the management of fungal rotting of fruits and vegetables (Tripathy and Dubey, 2004). Botanical fungitoxicants are used for the protection of stored food commodities from fungal infestation (Kumar et al., 2007). Monoterpene isolated from essential oil of *Carum carvi* exhibited fungicidal activity in protecting the potato tubers from rotting (Anonymous, 1994). The essential oil and methanol extract and derived fractions of *Metasequoia glyptostroboides* showed great potential of antifungal activity against *Fusarium oxysporum, Fusarium solani* and *Sclerotinia sclerotiorum* (Bajpai et al., 2007). α-cedrol isolated from essential oil of *Thuja orientalis* possess antifungal activity against *Alternaria alternata* (Guleria et al., 2008a). Volatile oils from *Eucalyptus citriodora* showed complete inhibition of *Rhizoctonia solani* and *Helminthosporium oryzae* at 10 and 20 ppm respectively (Ramezani et al., 2002). Guleria et al., (2008b) reported toxicity of *Solanum xanthocarpum* leaf extract against *Alternaria brassicae*. Neem formulations have been used for controlling the damping off in brinjal and chilli (Bohra et al., 2006). Aqueous leaf extracts of *Datura metel* and *Lawsonia inermis*, known for their high antifungal activity against *Phaeoisariopsis personata*, completely inhibited the germination of urediniospores of *Puccinia arachidis* in vitro. In the greenhouse, extracts of *D. metel* (25 g/L) and *L. inermis* (50 g/L) applied as a prophylactic spray reduced the frequency of late leaf spot lesions and rust pustules by 65–74% compared with controls (Kishore and Pande, 2005). Saponin rich extracts (SREs) can also play an important role in controlling phyto-pathogenic fungi, especially under organic management (Chapagain et al., 2007; Guleria and Kumar, 2007).

The use of natural products as insecticides against crop pests is gaining importance in recent years. The organic synthetic insecticides are more hazardous, leave toxic residues in food products, and are not easily biodegradable; besides their influence on the environment and public health is deleterious. Unlike synthetic chemicals that kill both pests and predators outright, the natural insecticides are relatively inactive against the later. Most of the botanical insecticides are easily biodegradable and their supply can be made at cheaper rate by regular cultivation.

Though, botanical insecticides may not match synthetic insecticides in efficacy, but the natural insecticides extracted from plants in their semi purified form have slow releasing action and are prophylactic. Among the natural insecticides rotenone from *Derris elliptica*, nicotine from tobacco leaf, pyrethrins from pyrethrum flowers (*Chrysanthemum cinerariaefolium*) and azadirachtin from neem (*Azadirachta indica*) have attained commercial importance. Intensive chemical investigation on neem seeds reveal that azadirachtin, a complex and highly oxygenated compound belonging to tetranortriterpenoid class is the most potent antifeedant and growth disruptant to many insects. Antifeedant chemicals do not kill insects straightway but when sprayed on crops or applied to stored grains, the insect rather prefer to die of starvation than consume the treated food. Among the well represented plant insecticides is "Pyrethrums" obtained from *C. cinerariaefolium* which is mainly used as a domestic insecticide because it is non toxic to man and warm blooded animals and is highly sensitive to light. There are four main principal ingredients in *Chrysanthemum* viz., pyrethrum I and II and cinerin I and II (Verma and Dubey, 1999). Photostable pyrethroids synthetically prepared from pyrethrins are chemically similar to pyrethrins but are more stable outdoors to heat and light. Pyrethroids are neuroexcitatory, producing heightened repetitive nerve activity especially in the sensory nervous system (Vijverberg and Bercken, 1990). Pyrethrum is a predominant botanical in use, accounting for 80% of the world botanical insecticide market (Isman, 2005).

Terpenes isolated from Rutales have been shown as effective against stored grain pests (Omar et al., 2007). Essential oils of cumin (*Cuminum syminum*), anise (*Pimpinella ansium*), oregano (*Origanum syriacum* var. *bevanii*) and eucalyptus (*Eucalyptus camaldulensis*) were effective as fumigants against the cotton aphid (*Aphis gossypii*) and carmine spider mite (*Tetranychus cinnabarinus*) (Tuni and Sahinkaya, 1998). Contact, fumigant and antifeedant effects of a range of essential oil constituents (cinnamaldehyde, and α-pinene) against the maize weevil (*Sitophilus zeamais*) and the red flour beetle (*Tribolium castaneum*) have been demonstrated (Huang and Ho, 1998; Huang et al., 1998). In the United States, exemption from registration of some insecticides based on plant essential oils has greatly facilitated their commercial development (Quarles, 1996).

In search of botanical pesticides, toosendanin, an antifeedant limonoid from the bark of the trees *Melia toosendan* and *Melia azedarach* (Meliaceae) has gained a considerable attention as potential botanical pesticide (Chiu, 1989; Chen et al., 1995; Koul et al., 2002). Production of toosendanin based botanical insecticide containing approximately 3% toosendanin (recemic mixture) as the active ingredient has already commenced in the P.R. China (Koul, 2008).

12.4 Botanical Insecticides in Use and their Mode of Action

Pyrethrins (Pyrethrum/Pyrenone) – Pyrethrum is an extract from *Chrysanthemum cinerariaefolium* daisies. Pyrethrins act on insects by rapidly causing paralysis, and they are widely used in fast knockdown aerosol sprays. Pyrethrins affect the insect's central nervous system by moving through the insect's skin or through its gut after ingestion. They do not inhibit the choline esterase enzyme. Pyrethrins (Fig. 12.1) change the permeability of sodium channels in the nerve axon. This typically results in excitation, lack of coordination and paralysis.

In order to improve their killing ability, they are generally mixed with synergist (s) (e.g., piperonyl butoxide or PBO or n-octyl bicyclotheptone dicarboximide). PBO protects the pyrethrins from enzymatic degradation by insect's enzyme system. They have an oral LD_{50} of approximately 1,500 mg/kg (Casida and Quistad, 1995).

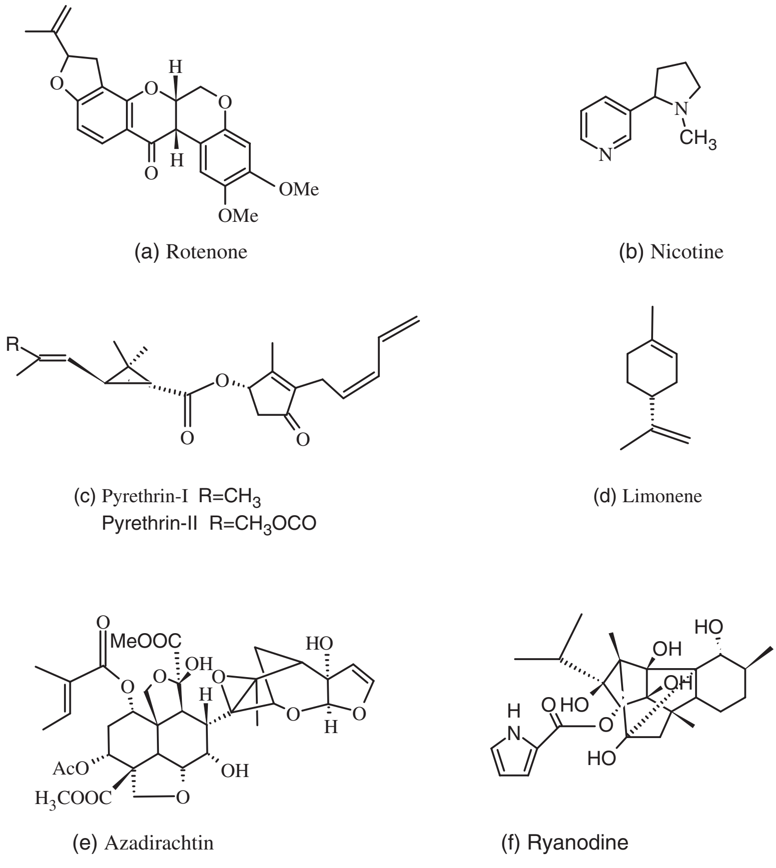

Fig. 12.1 Active constituent of some botanical insecticides from different plant sources discussed in this chapter. (**a**) Rotenone, (**b**) Nicotine, (**c**) Pyrethrin I and II, (**d**) Limonine, (**e**) Azadirachtin and (**f**) Ryanodine

As the pyrethrum mammalian toxicity is very low, it can be applied to food crops close to harvest. Pyrethrins knockdown, "flush out" or kill most insects, beneficial or otherwise. This can leave the plants to re-infestation in a milieu devoid of natural predators. It is toxic to bees and fish.

Rotenone – Rotenone is one of the most toxic of the commonly used botanical insecticides. It is extracted from the roots of two tropical legumes *Lonchocarpus* and *Derris*. Rotenone is a cell respiratory enzyme inhibitor and acts as a stomach poison in insects (Fields et al., 1991). Its mode of action involves disruption of cellular metabolism, acting between NAD^+ (a co-enzyme involved in oxidation and reduction in metabolic pathways) and Co-enzyme Q (a respiratory enzyme responsible for carrying electrons in electron transport chains), resulting in failure of respiratory function (Ware, 2000). Essentially, rotenone (Fig. 12.1) inhibits a biochemical process at the cellular level making it impossible for the target organism to use oxygen in the release of energy needed for body processes and hence conduction of nerve impulses (Hollingworth et al., 1994). Rotenone is extremely toxic to fish and other aquatic life and is commonly used as fish poison. It has an oral LD_{50} of approximately 350 mg/kg.

Rotenone basically slows nerve transmission to the point where the insect's body does not function. Rotenone degrades rapidly when exposed to air and sunlight (1–3 days). As rotenone is not absorbed through skin or gut, making it relatively "safe" for human. Rotenone is more toxic to mammals by inhalation than by ingestion, skin irritation and inflammation of mucous membranes may result from skin contact.

Nicotine – Nicotine is a natural insecticide from *Nicotiana spp*. (tobacco) stems and leaves and is most commonly available as nicotine sulfate. It is a fast acting nerve toxin and is highly toxic to mammals. It is generally absorbed through the eyes, skin and mucous membranes. Nicotine (Fig. 12.1) affects insects by decreasing the heart beat at high doses but increases the heart beat at low doses by interfering with the nervous system. It is highly toxic to all warm blooded animals as well as insects. It is having an oral LD_{50} of 50 mg/kg (Isman, 2006). Nicotine sulfate is also easily absorbed through the gut but not the skin. Generally the death is due to respiratory failure due to the chest muscles not functioning. Neither nicotine alkaloid nor nicotine sulfate affects choline esterase.

Sabadilla – Sabadilla comes from the ripe seeds of the tropical lily *Schoenocaulon officinale*. The alkaloids in sabadilla affect nerve cells, causing loss of nerve function, paralysis and death. Pure extracts are very toxic if swallowed or absorbed through skin and mucous membranes. It breaks down rapidly in sunlight and air, leaving no harmful residues. Sabadilla is a broad spectrum contact poison, but has some activity as a stomach poison. It has an oral LD_{50} of 5,000 mg/kg and acts as both a contact and stomach poison on insects. To humans, sabadilla is very irritating to the upper respiratory tract, causing sneezing. It is also irritating to the skin, and it is absorbed through the skin and the gut if ingested. Sabadilla is photosensitive and breaks down rapidly in sunlight. It contains alkaloids (primarily cevadine and veratridine) that act as nerve poisons.

Ryania – Ryania is an extract from the roots of *Ryania speciosa*. It has relatively low toxicity to mammals. It breaks down fairly slowly. It has an oral LD_{50} of approximately 750 mg/kg and affects insect's nervous system but it is not a choline esterase inhibitor. Ryanodine (Fig. 12.1) acts as a muscular poison by blocking the conversion of ADP to ATP in striated muscles (NRC, 2000).

Limonene – An extract from citrus oils. The oral LD_{50} is reported to be greater than 5,000 mg/kg. Linalool is a closely related material that is also an extract from orange and other citrus fruit peels. Citrus oil extracts have been combined with insecticidal soap for use as contact poisons against aphids and mites. Limonene (Fig. 12.1) and linalool are contact poisons (nerve toxins). They have low oral and dermal toxicities. Both the compounds evaporate readily from treated sufaces and have no residual effect.

Neem – The primary active ingredient in most neem based pesticides is a compound called azadirachtin (Isman, 2005). Azadirachtin (Fig. 12.1) a liminoid or more specifically as tretranor triterpenoid possess considerable insecticidal activity. Azadirachtin being chemically complicated has not been synthesized. Its major modes of action are that of powerful insect growth regulator (IGR), a feeding and an oviposition deterrent. It is structurally similar to the natural insect hormone ecdysone. Azadirachtin interferes with the production and reception of this insect hormone during insect's growth and molting. Thus azadirachtin blocks the molting cycle causing the insect to die (Mordue and Blackwell, 1993).

12.5 Factors Affecting Use of Botanical Pesticides

12.5.1 Raw Material Availability

Plants represent a vast store house of potentially useful chemical molecules. Many laboratories around the world are engaged in screening of plants not only for therapeutic purposes but also for useful natural products which have wider implications in the development of pest control agents for use in agriculture. These studies speak volume about the plant species possessing potential pest controlling activity under laboratory conditions but the step from the laboratory to field eliminates many contenders.

For commercial scale production of botanical pesticides there should be continuous supply of raw material and more importantly the source plant should be amenable to cultivation. Efforts for production of botanicals through tissue culture are yet to bear fruit. This further call for the selective production of certain novel molecules endowed with biological activity through genetic engineering of potential candidate plants.

12.5.2 Standardization of Botanical Extracts Containing a Complex Mixture of Active Constituents

The crude plant extract contains a mixture of chemical molecules belonging to different chemical class of compounds and all may not possess biological activity. Therefore, for a botanical pesticide to be effective, there should be chemical standardization in order to concentrate the chemical molecules possessing biological activity. This can be achieved through the use of standard procedures meant for particular class of chemical molecules followed by an appropriate analysis to ensure the desired level of biological activity. Complex mixtures of active ingredients in botanicals may help in mitigating the problem of resistance development. In a laboratory experiment green peach aphid, *Myzus persicae* was shown to evolve nine fold resistance to azadirachtin over 35 generation when selected agent was pure azadirachtin applied to plants at LC_{50} level; whereas, a parallel aphid line selected with neem seed extract, containing the same amount of azadirachtin but as a part of complex mixture did not evolve resistance to azadirachtin over the same period (Feng and Isman, 1995).

The exorbitant costs and cumbersome procedures involved in the isolation of bioactive constituents make it a difficult venture. The only exception to this statement is pyrethrum, where not only the bioactive molecule was isolated in pure form but also served as lead for the development of photo stable pyrethroids. There are certain disadvantages associated with complex mixtures, as it is difficult to standardize a product containing a mixture of active constituent of differing preparation and bioactivity.

12.5.3 Market Opportunities for Botanical Pesticides

Low market share of botanical pesticides in industrialized countries as compared to multimillion dollar regulatory costs prevent many botanical pesticides from reaching the market place. The registration of new active ingredient in the USA can be to the tune of US$ 250,000 or more. Further more, regulatory procedures presently in place are tailored specifically for synthetic chemicals. On the other hand complex mixtures of bioactive constituents in botanicals make their registration difficult. Hence, registration requirement needs to be modified in order to accommodate the environmentally benign botanical pesticides (Isman, 2006). In India for instance applicants are allowed to market new products up to a period of five years before final registration.

12.6 Future Perspective

Application of synthetic pesticides is a regular practice to ward off infestation of insect pests and diseases from field crops. However, as these conventional chemicals are reported to cause environmental load and threat to public health, the world trends in pesticide research now a day calls for discovery of safer and eco-friendly chemicals for pest control. Plants are rich resource of chemicals that are toxic to pests. When extracted from plants these chemicals are called botanicals. Botanicals are endowed with a spectrum of properties such as insecticidal activities, repellence to pest, insect behavior modifier, antifeedent activity, toxicity to mites, snails, slugs, nematodes and other agricultural pests (Duke, 1990). Apart from this, they also possess antifungal, antiviral and antibacterial properties. They have variable toxicity to non target organisms, although as a group they tend to be less toxic to mammals (with + ve exception to nicotine), than non botanicals.

The use of botanicals is now emerging as one of the prime means to protect crops and their products and the environment from pesticide pollution, which is a global problem. Since most of them generally degrade within few days, and some times within a few hours, these insecticides must be applied more often. More frequent application coupled with exorbitant cost of production usually makes botanicals more expensive to use than their synthetic counterparts.

In spite of the wide recognition that many plants possess insecticidal properties, only a handful of pest control products directly obtained from plants including pyrethrum (pyrethrin), neem (*Azadirachta indica*), rotenone, quassia and tomato leaf extract are in use because the commercialization of new botanicals can be hindered by a number of issues. Further more, regulatory protocols being designed, keeping in view the synthetic chemicals, constitute a barrier to the commercialization of potentially useful botanicals, mainly due to the presence of complex mixtures of active ingredients in them. However, in view of the negative effects of the synthetic chemicals on human health, environment and ecosystem the regulatory authorities are likely to look more favourably on the alternative products so that these new products can be mobilized into the market with less hurdles (Isman, 2006).

Insects have developed widespread insecticide resistance to many synthetic insecticides, and the industry may not have enough resources to continually develop and supply the market with new products precisely when needed to replace the old ones. Therefore, there is a growing need to develop insecticides with newer modes of action not leading to the development of resistance. In this regard, botanicals consisting of mixtures of active principles have an advantage over conventional synthetic insecticides.

The benefits of botanical insecticides can be best translated into practice in developing countries where farmers may not afford synthetic insecticides, due to their exorbitant costs and where the traditional use of plants for protection of stored products is long established (Kumar et al., 2007). Also thousands of pesticide related accidents occur, where farmers can afford synthetic insecticides, due to lack of protective equipment and limited literacy.

Future research efforts, therefore, should be directed not only towards the development and application of known botanicals but also on screening more plants and isolate new and novel bioactive molecules which have pest controlling properties or can serve as leads for the development of eco-friendly pesticides.

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Chapter 13
Insect Outbreaks and Their Management

T.V.K. Singh and J. Satyanarayana

Abstract Insect populations like all animal populations are governed by their innate capacity to increase as influenced by various abiotic and biotic factors. The intensification of agriculture and interference in forests have resulted in increasing incidence and outbreaks of a number of insect pests in agro ecosystems and forest ecosystems. In this chapter the historical perspective, reasons of outbreak of pests, theories of outbreaks, insect outbreaks in forest and agro ecosystem and management of outbreaks are covered, citing examples.

Keywords Insect outbreak · Theories · Factors · Management

13.1 Introduction

From the ecological point of view an outbreak can be defined as ‘an explosive increase in the abundance of a particular species that occurs over a relatively short period of time’. From this perspective, the most serious outbreak on the planet earth is that of the species *Homosapiens* from more narrow perspective of Homo, however, an outbreak is increase in the population of an organism that has a deleterious influence on human survival and well-being, such an organism is called a ‘pest’.

Outbreaks of pestiferous organisms have plagued humans from the times immemorial. Locusts and mice have periodically destroyed crops. Bacteria and protozoan have decimated their populations, mosquitoes and black flies have provided relentless annoyance. Experts assessment reveal that around 22 percent of yield losses in major crops like rice, cotton, groundnut, sugarcane, sorghum, tomato, chillies, mango, grapes, etc., can be attributed to insect pests (Barbosa and Schultz, 1987).

T.V.K. Singh (✉)
Department of Entomology, College of Agriculture, Acharya N G Ranga Agricultural University, Rajendranagar, Hyderabad-500 030, India
e-mail: tvksingh@yahoo.com

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13.1.1 Characteristics of Outbreaks

A study was conducted to examine the spatio temporal characteristics of two regional outbreaks of range land grasshopper, in Montana during the periods 1959–1966 and 1984–1992 (Cigilano et al., 1995) and characterized as follows:

1. Outbreaks are periodic and short-lived.
2. Over the long-term, the extent of the areas exhibiting high densities fluctuates to the extremes.
3. Areas of high densities are present every year, although they may be geographically restricted.
4. Areas of high densities can remain stable, decline, expand, or collapse from one generation to the next.
5. High densities can arise or fall simultaneously over a period of time.
6. Densities generally vary inversely with distance away from the edge of high density areas.
7. New regional outbreaks do not appear to be the result of insects influence from active infestations areas, although migration may occur.
8. If areas exhibiting high densities expand, the extension of the boundaries or the appearance of separate new high density areas beyond those boundaries does not follow any specific pattern.
9. Although no chronically high density areas could be detected. Some vegetation types appeared to be more inclined to high densities.
10. Outbreaks appeared not to be self-perpetuating.

13.2 Historical Perspective

The gains of the Green Revolution reflected in the shape of production of 200 million tonnes of food grains, 25 million tonnes of oilseeds and 15 million tonnes of fibres per annum in India. But, these steady gains in agricultural production over past four decades have not fully overcome the problem of rising demand caused by soaring population growth. Adding to the population explosion, there were frequent set backs to crop production experienced in the shape of abiotic and biotic stresses. Among the stresses on major crops, pest outbreaks leading to the stage of collapse of economy, at times make the planners and executors feel helpless. In the past, one and half decades, the periodical unabated explosions of aphids, whiteflies, bollworms, pod borers, defoliators, coccids, cutworms, etc., have made agriculture less remunerative and highly risk prone.

Historical records show all over the world that every time the oak leaftier (*Croesia semipurpurana* (Kerafott)) is mentioned, the oak leafroller (*Archips semiferana* (Walker)) is associated with it. In 1964–1965 Pennsylvania,USA reported about 50,000 acres of red oak being severely defoliated, and in 1978, Pennsylvania, New York, West Virginia, New Jersey, Massachusetts and Connecticut reported more than 100000 acres defoliated. Many races died as the result of the outbreak.

Some highlights of recorded infestations of pine beetle in British Columbia were reported by Wood and Unger (1996) and Taylor and Carroll (2003).

1. Significant outbreaks in the 1920s were recorded around Aspen Grove and in the Kettle valley in Lodgepole and Ponderosa pine (*Pinus ponderosa*).
2. In the 1930s and 40s, large areas of mountain pine beetle (*Dendroctonus ponderosae* Hopkins) causing mortality were recorded in Kootenav and Banff National parts. Smaller infestations were recorded in western white pine in the Shuswap region and in coastal British Columbia.
3. During the 1950s and 60s one of the longest duration outbreaks ever recorded was observed around Babine Lake and Stuart Lake in north-central British Columbia.
4. Major infestations developed in the 1970s and 1980s on the Chileotin plateau and in South eastern British Columbia.
5. During the 1990s the present outbreak began to develop in North Central British Columbia and is the largest recorded outbreak to date.
6. Spruce beetle outbreak in the 1940s killed spruce trees over much of the white river plateau in western Colorado. Historic photos and tree-ring evidence also document extensive insect outbreaks prior to the 20th century (Baker and Veblen, 1990; Veblen and Donnegan, 2006). Thus, insect outbreaks are a natural occurrence in almost all of the different kinds of forests in Colorado. Outbreaks do not occur very frequently, the time interval between successive outbreaks in any given area is usually measured in decades. Nevertheless, outbreaks can be expected periodically in almost any place in the United States where forests are found.

13.3 Reasons of Outbreaks of Pests

A number of hypotheses have been formulated in the past in an attempt to explain the causes of pest outbreaks. These hypotheses have usually resulted from research on particular kinds of organisms (rodents, insect herbivores, viruses, etc.), or on particular kinds of ecological processes (predator-prey or herbivore-plant interactions, genetic adaptation, etc.). The main weakness of these hypotheses is that they attempt to explain all outbreak phenomena (ultimate causation) from experience with particular kinds of outbreaks (proximate causation). If a general theory is to be developed, however, it should explain proximal hypotheses within a general frame work. Therefore, the major hypotheses of proximate causation are summarized below.

- Outbreaks are caused by dramatic change in the physical environment. Included in this group would be those explained by sun-spot theory (Elton, 1924). The Theory of Climatic Release (Green bank, 1956), and the Theory of Environment (Andrewartha and Birch, 1984).

- Outbreaks are caused by changes in intrinsic genetic (Chitty, 1971) or physiological (Weelington, 1960; Christian and Davis, 1971) properties of individual organisms in the population.
- Outbreaks result from trophic interactions between plants and herbivores or prey and predators. This hypothesis arises from the mathematical analysis of trophic interactions that produce large-amplitude population cycles under certain conditions (Lotka, 1925; Volterra, 1926; Nicholson and Bailey, 1935).
- Herbivore outbreaks are due to qualitative or quantitative changes in host plants, which are usually caused by environment stresses (White, 1978; Mattson and Addy, 1975).
- Outbreaks are the result of particular life history strategies being more common among pest species for example, 'r' strategies or opportunistic species (Southwood and Comins, 1976; Rhoades, 1985).
- Outbreaks result when pest populations escape from the regulating influence of their natural enemies (Holling, 1965; Morris, 1963; Isaew and Khlebopros, 1977).
- Outbreaks occur when populations cooperatively overwhelm the defensive systems of their hosts (Thalenhorst, 1958; Berryman, 1986a,b).

The causes of insect outbreaks given by Michigan University Ecologists are also outlined below:

i) The unnatural conditions in the man-made environment induce unusually high and destructive insect populations.
ii) Despite quarantine regulations, many foreign insect pests have been accidentally introduced, without proper consideration of their suitability for a particular site.
iii) Strains of insects can quickly develop and adopt to such genetically homogenous cultivars. For example sunburst honey locust clone is more susceptible to attack by the mimosa webworm (*Homadaule anisocentra* Meyrick), than other commonly planted clones of the some species.
iv) Drought stress or nutrient stress may also weaken the plants and make them more susceptible to insect attack.
v) Applications of insecticides may stimulate a rapid outbreak or a delayed resurgence of mites and aphids. Outbreaks of scale insects, leaf miners and other insects protected inside galls or under waxy secretions are frequently associated with pesticide application because the pests are physically protected from insecticides but their natural enemies are not.

13.4 Theory of Outbreaks

The appropriate model to consider is one of the dynamics of a single species. We can formulate such a model as follows. Let 'N' be the density of the populations, 'G' its genetic composition and the favourability of its environment; i.e. 'F' represents all the physical and biotic components of the environment that affect the reproduction, survival and dispersal of the species. We can write the gene single species population model as:

$$r = dN/Ndt = f(N, G, F) \tag{13.1}$$

Where, r, the specific grown rate of the population is expressed a function of population density, genetics and environments favourability. If we assume for the present that genetic and environmental factors remain constant overtime, one can examine the simple relationship between the specific growth rate and population density, that is, the density-dependent growth characteristics.

Under these assumptions, we can expand the Taylor's theorm to yield:

$$r = a_0 + a_1N + a_2N^2 + a_3N^3 + \ldots\ldots\ldots\ldots\ldots + a_iN^i \tag{13.2}$$

Where, a_0 is the specific growth rate of the population at the limit N – and a_1 . . ...a_i are coefficients describing the interactions among members of the population. In order to have abiologically reasonable population model, however, we need to place certain constraints. (C_1) dN/dt = 0 when N = 0, or populations do not grow when organisms are present.

(C_2)dN/dt = 0 when N>0, or populations can not grow for ever and therefore the specific growth rate must approach zero at same relatively large population size. Say K. In this case dN/dt and 'r' became zero when N = K.

The simplest form of Equation (13.2) that satisfies these constraints is:

$$r = a_0 + a, N \ldots\ldots\ldots\ldots\ldots\ldots\ldots.. \tag{13.3}$$

Provided that $a_0 > 0$ and $a_1 < 0$ Knowing that an equilibrium population density K occurs when r = 0 (C2), we can solve. Equation (13.3) for K,

$$O = a_0 + a_1K \tag{13.4}$$

$$K = \_a_0/a_1 \tag{13.5}$$

Where, K is, a positive number because $a_1 < 0$ Equation (13.3) is equivalent to the familiar Verhulst 'Logistic' (Verhulst, 1838) One can observe that the specific growth rate of the population is positive when N<K and negative when N>K. The starting population density N0 is below or above K. The population will grow or decline toward the equilibrium density K.

In other words both the maximum rate of increase of the population in the absence of density-dependent effects a_0 and the negative density dependent interaction coefficient a_1 are assumed to be functions of population genetics and environmental favourability. Under these assumptions, K can increase under the following conditions:

1. The environment becomes more favourable for the reproduction and/or survival of the species. This explanation is in line with hypothesis (H_1).
2. An increase occurs in the frequency of genes for high reproductive rates, reduced resource utilization, better defense or escape from natural enemies,

resistance to harsh physical conditions, and so on. This explanation is in line with hypothesis (H_2).

In general, then, when the dynamics of a population are governed by the elemental logistic equation, outbreaks can be caused only by large and rapid alterations in the environment or the genetic composition of the populations.

13.4.1 Positive Density Dependence

In more general terms, outbreaks can be set in motion by the following changes:

1. Increasing environmental favourability (more or better food, fewer enemies, etc.), larger a_0, smaller a_1 and/or a_3.
2. More fecund genotypes – larger
3. Genotypes less susceptible to natural enemies – smaller a_1
4. Genotypes with better cooperative interactions or adaptations – larger a_2.

13.5 Classification of Outbreak

If we accept the preceding theoretical arguments, we can identify three important features that determine the space-time dynamics of outbreaks.

1. Some outbreaks are self-perpetuating in that once initiated they tend to continue in both time and space. These outbreaks are driven by positive feedback processes that are operative at relatively high population densities and that gives rise to bimodal 'r' functions. Because of their expansive nature, such outbreaks are often termed 'eruptive' (Berryman, 1986, Berryman and Stark, 1985).
2. Other outbreaks are not self-driven but are entirely dependent on external environmental or internal genetic conditions. These outbreaks arise and subside as their driving forces change in time and space. These do not spread autonomously from their points of origin, and have unimodal 'r' functions with little evidence of cooperative effects at relatively high densities. Because these outbreaks merely track environmental gradients in time and space, they can be termed as 'gradient' outbreaks (Berryman, 1986; Berryman and Stark, 1985).
3. Irrespective of whether the outbreak is of the gradient or eruptive type, its temporal behavior, at any one locality, is determined largely by time lags in negative feedback processes regulating population growth, larger delay giving rise to greater oscillations around equilibrium. Time lags are usually due to time dependent response of natural enemy or host populations. It can be observed that population cycles can be maintained, amplified or suppressed by alterations in the physical environment and possibly by changes in gene frequencies.

These theoretical conclusions lead logically to the proposition that all pest outbreaks can be classified according to certain behavioral features, particularly their tendency to spread from epicenters (the gradient – eruptive dichotomy) and their tendency to cycle around equilibrium (the short-long negative feedback delay dichotomy). Further, more environmental variations play an important role in triggering all types of outbreaks but the eruptive kinds, being self-perpetuating are often insensitive to subservient environmental variations. The consideration of these dichotomies and sensitivities leads to the recognition of seven classes of outbreaks as illustrated below with particular reference to phytophagous forest insects.

Classification of insect outbreaks was independently developed by Berryman et al. (1987) and Isaev and Khlebopras (1984).

13.5.1 Sustained Gradient Outbreaks

Persistent high density pest populations often associated with stressed unhealthy hosts. For example, plants growing on suboptimal sites. These pests have little impact on the survival of their hosts and are not strongly affected by density dependent parasitism and/or predation. Examples are particularly evident among shoot and fruit infesting forest insects.

13.5.2 Pulse Gradient Outbreaks

Irregular short-lived pest outbreaks associated with changes in the abundance or quality of food (or other resources) brought about by external environmental disturbances (warm dry weather, gales, infestations of other insects or pathogens, etc.). Many cane and seed insects, nonaggressive bark beetles and some cyclical forest defoliators exhibit pulse gradient out breaks. In addition, outbreaks of this type are characteristic of many insect pests of annual agricultural crops e.g. red-headed hairy caterpillar *Amsacta albistriga* on various crops in India. In these cases the environment experiences drastic temporal alterations, being very unfavourable at certain times (after the crop is harvested) and very favourable at others and monocultures of susceptible host plants.

13.5.3 Cyclical Gradient Outbreaks

Outbreaks of short duration (usually 2–3 generations) that occur at regular intervals, are often associated with certain site conditions (e.g. soil type, elevation, slope, latitude). Numerical responses of natural enemies or delayed defensive responses of the hosts are usually the major factors involved in population regulation. Most forest insects exhibiting cyclical gradients seem to be defoliators that do not cause excessive mortality among their host populations during outbreaks. Host mortality is often prevented by virus epizootics or dramatic increases in other natural enemy populations, which prevents repetitive host defoliation.

13.5.4 Sustained Eruptive Outbreaks

Outbreaks that spread from local epicenters to cover large areas and that persist at outbreak levels in any one place for several to many years. Outbreaks of these pests rarely cause extensive mortality among their hosts, except after many years of attack. Natural enemies are often important at sparse densities, or the pest may have strong cooperative behavior. Most forest insects exhibiting sustained eruptions seem to be defoliators that do not cause extensive host mortality.

13.5.5 Pulse Eruptive Outbreaks

Outbreaks that spread from epicenters and go through a pulse like cycle at any one locality. These outbreaks often cause extensive mortality among the hosts. Natural enemies or cooperative behavior are usually important in population regulation. Examples can be found in forest defoliators that cause extensive host mortality. Aggressive bark beetles and insects that transmit plant pathogens, gypsy moth (*Lymantria dispar* (Linn.)), pine saw flies, etc cause extensive damage to their hosts.

13.5.6 Permanent Eruptive Outbreaks

Outbreaks that spread from local epicenters but remain at outbreak level thereafter. This behavior seems possible only if the pest has no impact on the reproduction and survival of its host.

13.5.7 Cyclical Eruptive Outbreaks

Short-lived outbreaks (2–3 generations) that occur at regular intervals (8–11 generations) and spread out from epicenters. Outbreaks do not have a severe impact on the survival of their hosts and are often terminated by populations explosions of natural enemies particularly viruses. For example, Psyllid, *Cardiospina albitextura, Zeiraphers diniana*.

13.6 Insect Outbreaks in Forest Ecosystem

In most communities some species are generally common, while others are usually rare. Although fluctuations in density must occur in all populations from generation to generation, some species exhibit changes in density that are extreme compared with those of related species, even in the same habitat.

Most North American tree-feeding, defoliating Lepidoptera species exhibit narrow density fluctuations (Watt, 1965). However, a few of these species exhibit strongly bimodal population trends in any one year or place, they may be either so rare as to be undetectable or so abundant as to defoliate their hosts completely (Campbell and Sloan, 1978). Because of their characteristically rapid increase and decline, they are referred to as irruptive or cyclic pests, depending on the temporal regularity of their irruptive pests or outbreaks.

Insect outbreaks are a major disturbance factor in Canadian forests (Fleming et al. 2004). If global warming occurs, the disturbance patterns caused by insects may change substantially, especially for those insects whose distributions depends largely on climate. The global warming already seems to be affecting the life cycles of some insects. The value of process-level understanding and high resolution, long-term monitoring in attacking such problems is emphasized. It is argued that a species-level, preservationist approach may have unwanted side-effects, may be cost-ineffective and ecologically unsustainable.

The round headed pine beetle (RPB), *Dendroctonus adjunctus* Blandfordis one of the most important bark beetle is associated with ponderosa pine, *Pinus ponderosa* in the South West. Outbreaks of this insect have caused extensive mortality in the Lincoln National Forest, USA in 1970s and in 1990s. During mid-1990s, a network of plots was established in infested and uninfested stands to develop models. In 2001, these plots were loaded with beetle outbreak. The bark beetle outbreaks can cause significant increases in fuel loads, influence fire behavior and perhaps increase the severity of the fires.

The first outbreaks of three species of large web-spinning sawflies (*Cephalcia larcciphila japonica* Shinohara, *C. kocbelei* (Rohwer), and *Acantholyda nipponica* Yano and Sato) occurred in 1993 in non-native larch plantations in Hokkaido. Defoliation in central Hokkaida increased to 2600 ha in the next year after initiation of the outbreak, continued at this level for 4 years and diminished in 1999. Outbreaks began in local epicenters and expanded to surrounding areas. Neither larch density, tree size (height and diameters at breast height) nor proportion of larch stems correlate with the prepupal densities although these factors varied considerably (Ozaki et al. 2003).

The Siberian Southern taiga, Russia Federation is characterized by so called 'dark-needle' species, spruce, and fir. In reality deciduous and mixed stands dominate in this area. Siberian silk moth (*Dendrolimus superans sibiricus* Tschetw) plays an important role in the formation of the current forest patterns in these forests. Siberian silk moth affects stands composed of fir, Siberian pine, spruce and larch. Catastrophic outbreaks of this insect are induced by a combination of favourable weather conditions (optimal temperature and low levels of precipitation and humidity). These outbreaks occur with a periodicity of 15–25 years (Kharuk et al., 2003).

13.7 Population Outbreaks in Agro-Ecosystems

Environmental and biological factors that allow insect population outbreaks in natural ecosystems are unique to agroecosystems. In agricultural systems, soil, plant and animal interactions are rarely persistent enough, in time and space, to provide the ecological stability or equilibrium characteristic of non-agricultural systems. Nevertheless, if these interactions are understood and properly managed, it may be possible to reduce insect pest outbreaks.

13.7.1 Colonization

The rate of colonization of a crop within an agroecosystem determines the initial phase leading to pest population outbreaks. The rate of colonization is dependent on the ability of the insect to locate a suitable host, cultural practices, natural enemies, reproductive potential and environmental limitations.

13.7.2 Location of a Suitable Host

A series of steps are completed as an insect colonizes a crop, and the amount of time devoted to this is influenced by the characteristics of the habitat of neighbouring crops and species diversity of this habitat.

13.7.2.1 Host Habitat Location

The habitat of the crop is generally located through phototactic, anemotactic and geotactic responses by the insect. Many aphid species that colonize cultivated plants are attracted to objects that have a peak reflectance of wave lengths of about 550 nm and 530–570 nm, which is the same as far many cultivated plants, weeds and herbaceous plants (Johnson, 1969).

13.7.2.2 Host Location

It does so by using several sensorial mechanisms; color, shape and odour are important cues for the cabbage maggot (*Delia radicum* (Linn.) in orienting to its host. Tuttle (1985) showed that when allyl isothiocyanate and some other mustard oils, found in cruciferous plants, were used with yellow stakes, the number of adult cabbage maggots trapped was higher. Further more, in addition to color and odour, cabbage maggot adults used shape as a cue for host orientation. Once on the plant, the insect uses olfactory (kairomone) and tactile (pubescence, texture) cues to assess the quality of its host.

13.7.2.3 Host Recognition

Plant chemicals may be detected by olfaction through gustatory activity or palpation of the plant surface. The onion maggot, *Delia antique* (Meigen) was attracted to n-dipropyl sulfide and other volatiles. Tactile cues are used by codling moth, *Cydia pomonella*(Walsh) adults which prefer to oviposit on the waxy surface of leaves and apples and avoid the bark and stems.

13.7.2.4 Host Acceptance

Tactile cues, odour and ingestion of plant material are all important for finding acceptable hosts. Aphids generally must probe tissue and ingest protoplasm before accepting the host (Garrett, 1973).

13.7.2.5 Host Suitability

Nutritionally, the plant may lack essential amino acids, it may have low concentrations of carbohydrates, or there may be an imbalance of these nutrients. The plants may contain an antibiotic that kills the colonizer or prevents the normal development of the offspring. If the host is suitable for sustained population growth and reproduction though the pest has successfully colonized the crop.

13.7.3 Reproductive Potentials and Environmental Limitations

Life history parameters determine, to a large extent, how rapidly an insect colonizes a crop and how quickly the population builds up. A migratory pest that is incapable of overwintering must have a high reproductive potential, colonize in large numbers, or have a short life cycle if it is to reach outbreak numbers. Death due to climate or natural enemies can regulate the size of the colonization population. *Pediobius foveolatus* a parasite of the Mexican bean beetle, *Epilachna varivestis* Mulsant, when released in innundative manner, caused high mortality to last-generation Mexican bean beetle in the fall. The parasites, caused sufficient mortality to reduce the colonizing population to a level that prevented it from reaching outbreak levels the following season (Forrester 1982). In addition low winter temperatures can inflict high mortality on overwintering populations, effectively reducing the number of colonizers.

13.8 Role of Climatic Variation and Weather in Forest Insect Outbreaks

In the 40 years since the Theory of Climatic Release was first postulated, important advances have been made in understanding of the atmosphere as a dynamic system. The theory is consistent with modern climatology and is testable. Prior to a critical examination of the theory, a historical review summarizes the place that weather and climate have had in the development of insect population dynamics theory.

Meteorology textbooks define ‘weather’ as short-term variation of the atmosphere or as the state of the atmosphere at a given time with respect to temperature, pressure, wind moisture, cloudiness, and precipitation, ‘Climate’ is usually defined as the statistical collective of the weather of a specified area during a specific interval of time or as the prevailing or average weather conditions of an area over a long period.

‘Infestation’ refers to the sudden appearance of visible damage (i.e., defoliation or dead timber) in a small continuous area caused by a high population of a forest or agroecosystem insect herbivore, 'Outbreak' refers to the simultaneous appearance of two or more disjunct infestations.

The role of weather and climate in the control of insect abundance entered the 'density-dependent', versus 'density-independent' debate at an early stage, Uvarov (1931), the first to undertake a comprehensive review of the subject, rejected the theory that insect populations fluctuate around a stable equilibrium. He also rejected the idea that the principal controlling factors of a population are density-dependent natural enemies and competition for limited resources. Instead, he believed that 'the key to the problem of balance in nature is to be looked for in the influence of climatic factors. . . which cause a regular elimination of an enormous percentage of individuals (even) under so-called normal conditions which are such that . . . survive them not because they are perfectly adapted to them, but only owing to their often fantastically high reproductive abilities,' Andrewartha and Birch (1954) hypothesized that insects are limited by shortage of time during which the weather is favourable enough to allow for population increase, and therefore the carrying capacity of the environment is never reached.

13.8.1 Mechanisms by Which Weather Causes Changes in Forest Insect Abundance

Weather has both direct and indirect effects on phytophagous forest insect populations. Direct effects of weather on behavior and physiology are well documented, and by now there exists a vast literature. Most population studies examining direct effects are restricted to a single stage or generation in the life history of the insect. Few attempt to relate weather conditions to changes in density between generations. It is nevertheless generally believed that atypical or anomalous weather is directly responsible for widespread changes in the abundance to many forest insects, although the mechanisms are rarely understood in detail.

White (1969) found that outbreaks of Psyllid *Cardiaspina densitexta* and other psyllids in Australia were correlated with moisture-induced stress in host plants. Similarly, outbreaks of several species of loopers in New Zealand, South Africa, the Netherlands, and North America (White, 1974) and of desert locusts (White, 1976) seemed to be related to a pattern of rainfall that could have stressed that attacked plants. White hypothesized that defoliator populations may typically suffer high mortality or poor fecundity due to an insufficiency of nitrogen in their food. However, when plants are physiologically stressed due to an insufficiency or excess of water, there may be a drop in protein synthesis, which in turn may lead to an increase of available nitrogen in their aerial parts.

13.8.2 Temperature

All life survives within a certain narrow range of temperature. Departure from this optimum range on both sides is tolerated to some extent, depending upon the physiological adaptations of the concerned species or populations. Temperatures above or below these limits prove lethal. Exposure to lethal high or low temperature may result in instant killing or failure to grow and reproduce normally. Harmful effects of exposure to sub-lethal temperatures may be manifested at some later critical stage like ecdysis and pupation. Some of the insect species have developed dormancy mechanisms like diapause, hibernation and aestivation to tide over periods of unfavourable temperature in their life cycle (Atwal and Singh, 1990).

13.8.3 Moisture

Most terrestrial insects live in an environment, which is dry. The only source of water for phytophagous insects is the water obtained with food material from their host plants. These insects have, therefore, developed a variety of mechanisms to conserve water. Inspite of these mechanisms, exceptionally dry air may prove lethal to most insects. Likewise, excessive moisture may also adversely affect many insects by encouraging disease outbreaks, affecting normal development and by lowering their capacity to withstand low temperatures. The reproductive capacity of most insects is also affected by moisture but there are great differences in the capacity of different insects to tolerate conditions ranging from extreme dryness to near saturated environments. Besides temperature and moisture, a number of other environmental factors like light, atmospheric pressure, air currents and carbon dioxide concentration also influence insect abundance to a lesser extent.

13.9 Biotic Factors

As early as 1863, Herbert Spencer in his book First Principles observed that every species of plant and animal is perpetually undergoing rhythmical variations in number in response to the availability of food and presence/absence of natural enemies.

13.9.1 Food

Phytophagous insects compete with man for food supply from our agroecosystem and are, therefore, labeled as pests. Survival, development rate and multiplication capacity of insect pests are all determined by the quantity and quality of food. An insect population would increase in number and attain the status of a pest in case sufficient supply of a suitable host is available. The differences in varieties/species as regards their suitability for a particular insect population are governed by their recognition and acceptability as host, nutritional adequacy and absence of inhibitors/toxicants to that pest species (Atwal and Singh, 1990). The modern agriculture utilizing large scale monocultures of a few high yielding varieties of important crops provides an almost inexhaustible source of food supply for insect pests feeding on these crops and has, therefore greatly contributed to increasing outbreaks of insect pests (Pimental, 1977; Jayraj, 1988).

13.9.2 Pathogen

Before the 1970s if one opened an ecology text to the section on population dynamics, one encountered analyses of the roles of predation, the physical environment, and perhaps parasites (Ricklefs, 1979; Krebs, 1978; Hutchinons, 1978) but little if any reference to the role of pathogens (i.e., microbial parasites). It is not clear why the potential importance of pathogens was overlooked.

The first steps in this direction were taken from the mid-1970s. They involved theoretical analyses of population-level effects of changes in population parameters and in characteristics associated with hosts and pathogen. Thus, characteristics of host-pathogen relationships at the organisma level, such as pathogenicity, are used to estimate population parameters such as mortality, which in turn, are used to predict how populations change over time.

13.9.2.1 Cyclic Versus Stable Regulation

General Model

Anderson and May (1981) studied the effects of several modifications of a model described by differential equations that compartmentalize the host population into infected individuals Y and uninfected susceptibles X. In the general model they described the rates of change of these two subpopulation as:

$$dX/dt = a(X + Y) + \gamma Y - bX - \beta XY \tag{13.6}$$

$$dY/dt = \beta XY - (\alpha + b + \gamma)Y \tag{13.7}$$

The entrance of susceptible individuals into the populations is assumed to depend on a per capita birth rate α, which is the same for infected and uninfected individuals and the per capita rate γ at which infected individuals recover from infections. Susceptible individuals are eliminated from the population based on a per capita rate of death due to causes other than infection b and the rate at which an infected individual will transmit its infections per susceptible individual (i.e., the transmission coefficient β) times both the number of infected and the number of susceptible individuals.

This model, however, is unrealistic in several respects: for example, it does not incorporate an incubation period. Anderson and May (1981) incorporated an incubation period into the model by defining a third subgroup of the population. *M,* which represents the number of hosts infected but not the one which represents the number of hosts infected but not yet infectious. In this case,

$$dX/dt = a(X + Y) + \gamma Y - bX - \beta XY + \gamma Y \tag{13.8}$$

$$dM/dt = \beta XY - (b + \nu)M \tag{13.9}$$

$$dY/dt = \nu M - (\alpha + b + \gamma)Y \tag{13.10}$$

$$dN/dt = rN - \alpha Y \tag{13.11}$$

where, v is the rate at which an infected but not yet infectious individual becomes infectious, which this modification, stable limit cycles can occur if α is similar in magnitude to ν and large relative to *a, b* and *r* (Anderson and May, 1981).

13.9.2.2 Pathogens, Multicellular Consumers, and Environmental Heterogeneity

Among multicellular parasites, parasitoids, herbivores, and predators, substantial lags generally occur between the time when a individual first exists (i.e., in the form of a fertilized egg) and when it makes extensive use of resources (i.e., usually in the adult or late juvenile stages). Such lags are destabilizing factors. In multicellular predators, parasitoids, and herbivores, lags tend to favor oscillations by causing the creation of greater numbers of consumers than can be supported on available resources (Nicholson, 1958; May, 1974).

In these respects such lethal sit-and-wait pathogens (e.g., the nuclear polyhedrosis virus of the Douglas fir tussock moth, *Orygia pseudotsuga* McDun.; Thompson and Scott, 1979) differ substantially from parasitoids and predators, for whom environmental heterogeneity should often stabilize interactions. The differences result in parts from the greater relative mobility, lethality, and the developmental time lags associated with these multicellular consumers.

The economic damage caused by episodic outbreaks of forest-defoliating insects has spurred much research, yet why such outbreaks occur remains unclear. Theoretical biologists argue that outbreaks are driven by specialist pathogens or parasitoids, because host-pathogen and host-parasitoid models show large-amplitude, long-period cycles resembling time series of outbreaks. Field biologists counter that outbreaks occur when generalist predators fail, because predation in low-density defoliator populations is usually high enough to prevent outbreaks. Neither explanation is sufficient, however, because the time between outbreaks in the data is far more variable than in host-pathogen and host-parasitoid models, and far shorter than in generalist predator models. Here we show that insect outbreaks can be explained by a model that includes both a generalist predator and a specialist pathogen. In this host-pathogen-predator model, stochasticity causes defoliator densities to fluctuate erratically between an equilibrium maintained by the predator, and cycles driven by the pathogen. Outbreaks in this model occur at long but irregular intervals, matching the data. Our results suggest that explanations of insect outbreaks must go beyond classical models to consider interactions among multiple species.

13.9.3 The Role of Natural Enemies

Our views on the role of natural enemies in insect population outbreaks are colored by the history of our science of ecology. Therefore, a historial perspectrive is important in evaluating how well our conventional wisdom matches the evidence for and against the proposition that natural enemies are a significant part of the regulation of insect populations.

13.9.3.1 Natural Enemies as Agents in Natural Selection

Early naturalists were impressed by the array of insect defenses against visually hunting predators. Modern science has strengthened the view that predators act as potent selective agents on the evolution of insect populations and species. Crypsis, catalepsies, aposematic coloration, Mullerian and Batesian mimicry, chemical defense, polymorphism, protean displays, and cellular defense against internal parasitoids illustrate the diverse evolutionary responses to enemies. Their commonness in nature demonstrates the pervasive effects that enemies have had, and still have, on insect populations.

13.9.3.2 Evidence in Biological Control

The history of applied biological control has been covered effectively by Doutt (1964), DeBach (1974), and Van den Bosch and Messenger (1973). The spectacular early successes of biological control helped to establish the important role of natural enemies in the population regulation of epidemic insect and plant populations; cottony-cushion scale(*Icerya purchasi* (Maskell)) in California, 1888–1889; sugarcane leafhopper(*Pyrilla purpusilla*) in Hawaii, 1904–1920; sugar-cane beetle borer(*Euetheola rugiceps*(Leconte)) in Hawaii, 1904–1910; citrus whitefly (*Dialeurodes citri* (Ashmead)) in Florida, 1910–1911; prickly pear cactus (*Opuntia littoralis)* in Australia, 1920–1925; coconut moth(*Ceromasia sphenophori*) in Fiji, 1925 (Examples and dates from DeBach, 1974).

Several important lessons have been learned from these experiments:

1. Populations of insects can erupt when introduced into new geographic areas without their natural enemies, the strong implication being that indigenous populations are regulated by enemies.

2. Populations of weeds can become exceedingly large when the weeds are released in new geographic areas without their naturally occurring herbivorous insects. Since such population eruption of weeds does not occur in native regions, the implication is that herbivores may be important in regulating populations and that their natural enemies do not suppress this ability.
3. When herbivores are introduced to regulate weedy plant populations where herbivore outbreaks are desirable, failure of biological control frequently results from natural-enemy regulation of the herbivore population.
4. Many attempts of biological control have failed. Even when natural enemies have become established they have remained at low levels, implying that, at least in exotic situations, the regulatory role of natural enemies is unlikely to be ubiquitous e.g., *Cryptochaetum iceryae* (Will.) introduced for the control of cottony-cushion scale.

13.10 Management

13.10.1 Spraying with Insecticide

This can be an effective means of saving high-value trees in localized areas, but is not feasible over large landscapes.

13.10.2 Preventing or Controlling Outbreaks Through Forest Management

Removing stressed or unhealthy trees and thinning to prevent crowding and competition among trees, can effectively reduce the risk of an insect outbreak getting started in a forest stand. Forest Management is unlikely to prevent all outbreaks, because (i) it will never be feasible to intensively manage all of the forests of Colorado, and (ii) drought and warm temperatures are also important causes of outbreaks. Once an outbreak has begun, management generally cannot stop it, because the insects are numerous enough to overcome even healthy trees.

13.10.3 Harvesting Insect-killed Trees to Reduce Wildfire Risk

Removing dead trees and other fuels can effectively reduce the risk of fire damage at a local scale, e.g. in the immediate vicinity of a home or community. However, the effectiveness of harvest in reducing fire risk over larger areas. e.g. a forest landscape, is less clear. Conventional timber harvest may do little to reduce fire risk at any scale if it removes primarily large trees, because smaller trees, brush and dead fuels often are the major carriers of a spreading fire. Harvesting smaller trees and removing small fuels may more effectively reduce the risk.

13.10.4 Salvaging Insect-killed Trees to Improve Overall Forest Health

From a purely ecological standpoint there usually is little or no need to remove insect-killed trees. However, many people do not like to see great numbers of dead trees surrounding their communities or places they like to visit. If the dead trees have a negative impact on aesthetic preferences or local economics, then it may be desirable to remove them.

13.10.5 Salvaging Insect-killed Trees for Economically Valuable Products

Salvage of insect killed trees may be a preferred option in some areas because of the economic value of the timber product that can be obtained. In these situations, the trees usually must be harvested as soon as possible, because the wood deteriorates rapidly after the trees die.

13.10.6 No Treatment

Natural ecological processes generally lead to the development of new forests after insect outbreaks, so a 'no treatment' option can be a form of responsible forest management.

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Chapter 14
Plant Disease Epidemiology and Disease Management – Has Science Had an Impact on Practice?

Gregory A. Forbes, Eduardo S.G. Mizubuti and Dani Shtienberg

Abstract Plant disease epidemiology as a sub discipline of plant pathology is concerned with the factors that cause plant epidemics. As such, the association between theoretical or experimental epidemiology and management of plant disease in the field is logical. A large body of literature has demonstrated that epidemiology has served a descriptive and predictive role by identifying and quantifying factors that lead to disease outbreak or cause spatial or temporal increase in disease intensity. However, as several authors have noted, the influence that epidemiology has had on disease management is not always clear, highlighting the need for a better appreciation of the link between theory (and experimentation) and practice. In this chapter, several case studies have been reviewed in which there has been a clear association between epidemiology and disease management. For epidemiological knowledge to influence disease management in practice there must be an effective information flow between researcher and practitioner. In the industrialized countries, this occurs through effective governmental and private institutions, and is increasingly dependent on modern communications technology, including Internet. In developing countries, where institutions are weak or don't exist, and where communication technology is limited, epidemiologists must seek novel mechanisms for interacting with farmers.

Keywords Farmer field schools · Plant disease epidemiology · Plant pathology

14.1 Introduction

The history of plant disease epidemiology has been described in a number of reviews, and was recently covered in detail by Madden et al. (2007). We make only a few comments about general trends relevant to this chapter. Plant disease epidemiology has been defined as the study of factors that affect the spread of disease

G.A. Forbes (✉)
International Potato Center, Apartado 1558, Lima 12, Peru
e-mail: g.forbes@cgiar.org

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in time and space (see for discussion Madden et al., 2007), and there is an implicit understanding that most research ascribed to this sub-discipline of plant pathology is quantitative in nature and frequently characterized by models of varying complexity (Fleming and Bruhn, 1983; Berger, 1989; Jeger, 2004). Nonetheless, some aspects of theoretical epidemiology are conceptual in nature (Jeger, 2000), and some authors consider epidemiology to have an early origin in efforts made long ago to control disease in populations of plants (Zadoks, 2001).

The birth of modern quantitative plant epidemiology is generally attributed to the early work of J. E. Vanderplank (Vanderplank, 1963) who popularized the concept of modeling disease change (epidemics) in time. However, as Madden et al. (2007) point out, the assessment of disease in populations and the mathematical description of temporal changes of disease intensity had begun prior to that. Nevertheless, it was Vanderplank who gave impetus to the science and initiated a stream of publications on the quantification of plant disease that has cascaded through the last five decades.

In spite of the steady outpouring of information in the area of plant disease epidemiology, several authors have questioned the impact this information has had on plant disease management, or at least highlighted a lack of evidence demonstrating a clear link between theory (or experimentation) and practice. Drenth (2004) described the importance of spatial structure in epidemic development, but noted that theory has been widely ignored in disease management. Jeger (2004) commented that, "Surprisingly, there has been little empirical evaluation of the extent to which improved disease management results directly from improved understanding other than in specific areas such as seed health management, the alignment of epidemiology with population genetics, or where climate is a critical influence on disease epidemics". Similarly, Scherm et al. (2006) argued that, "the image of theoretical epidemiology within the larger field of plant pathology could benefit from a clearer documentation of its impact on practical disease management."

Recently, epidemiology has also been used for predicting the effects of climate change on plant disease (Coakley et al., 1999; Bourgeois et al., 2004; Garrett et al., 2006; Jeger and Pautasso, 2008). Weather data generated from climate change models have been used to predict change in geographic range and/or severity of several diseases including rice leaf blast caused by *Pyricularia oryzea*[1] (Luo et al., 1998), oak disease caused by *Phytophthora cinimomi* (Bergot et al., 2004), grape downy mildew caused by *Plasmopara viticola* (Salinari et al., 2006) and several forest diseases in France (Desprez-Loustau et al., 2007). Garrett et al. (2006) reviewed the subject and developed a framework for studying the effects of climate change on disease. While these tools are clearly of potential use to planners and policy makers, we are not aware that their impact has been documented.

This paper attempts to further explore the influence that epidemiology has had on plant disease management. We employ a broad operational definition of

[1] This organism is now called Magnaporthe grisea, however it was called Pyricularia oryzea in the paper cited.

epidemiology that includes both theoretical and experimental (Scherm et al., 2006), and one in which theory may be demonstrated both mathematically and/or conceptually. With this general viewpoint, we may at times refer to incidents predating the seminal work of Vanderplank mentioned above, as do other authors (Zadoks, 2001). By using selected case studies, we try to identify factors that may enhance implementation of epidemiological principles in the field, with specific comments on disease management in developing countries.

14.2 Case Studies

14.2.1 Managing Disease Through Health of Planting Material

As noted above in the quote by Jeger (2004), one area where epidemiology has had impact on disease management is in production of seed with reduced or no pathogen incidence. For many crops, standards of seed health have been developed and are regulated with the aim of selling a healthy product and limiting spread of inoculum (McGee, 1995). Specialized production of vegetatively propagated planting material of ornamentals, fruits and vegetables from very clean or even disease-free sources has also led to effective disease management (Asjes, 2000; Haque et al., 2007).

The use of healthy seed may appear of limited importance within a discussion of epidemiology, since it generally involves only one strategy for managing disease in the subsequent plant generation, that of limiting initial inoculum. However, conceptual models have been developed for managing seed health and improved knowledge of factors causing seed infection has led to improved seed health (McGee, 1995). Furthermore, inoculum thresholds have been established based epidemiological studies and models predicting disease transmission based on critical factors such as weather and cultural practices (Gitaitis and Walcott, 2007). This is apparently not always the case, as many thresholds are based on simple correlation studies (McGee, 1995). Most epidemiology work in seed health has focused on specialized seed production systems and it would appear that very little epidemiology, theoretical or experimental, has been done for strategic or tactical management of seed borne diseases where seed is produced on the farm, which is particularly the case in developing countries.

Disease free planting material is also important for subsistence crops. This was evidenced by the introduction of a system for virus-free cuttings of sweet potato in China. The technology is now used by about 80% of the farmers and this has resulted in average yield increases of about 30% (Fuglie, 1999; Gao et al., 2000). Use of virus-free sweet potato cuttings is also common among commercial farmers in Egypt (Carey et al., 1999) and South Africa (Meynhardt and Joubert, 1982), however, we did not find evidence of its use in lesser developed countries, and farmers rely on selection of cuttings from healthy-looking plants in most of Africa (Gibson and Aritua, 2002). There is a long history of using virus-free planting material to control Cassava mosaic virus disease in Africa. However, most of the information dates back to the colonial era and there is a need to document the extent to which disease free material is being supplied presently (Thresh and Cooter, 2005). Unlike the case of (sexual) seedborne diseases, significant efforts in theoretical epidemiology have been applied to the problem of disease spread within multi-seasonal production units of vegetatively propagated crops, including the effects of management tactics, such as roguing (Jeger et al., 2004; van den Bosch et al., 2007).

14.2.2 Managing Virus Diseases

Many of the diseases affecting planting material (mentioned above) are caused by viruses, but the epidemiology and management of virus diseases *per se* has often been viewed separately within plant pathology (Jeger, 2000; Wisler and Duffus, 2000; Jones, 2004), and regular symposia on plant virus epidemiology are organized by the Plant Virus Epidemiology Committee of the International Society of Plant Pathology. Plant virus diseases provide some very interesting case studies for linking epidemiology (in a broad sense and predating the use of the term) and disease management. Management of beet curly top virus using knowledge of the virus and vector predates the emergence of theoretical disease epidemiology by decades. This disease virtually wiped out beet production in the Salinas valley of California at the end of the 19th century, and was eventually managed by applying knowledge about host resistance and vector biology. Subsequently, a complex of Beet yellows virus and Beet western yellows virus were controlled by several tactics including a beet-free period in the Salinas valley (Wisler & Duffus, 2000).

Plant virus epidemiology has also been a subject of some of the most intense work in theoretical epidemiology in recent years, including the refinement of the concept of evolutionary epidemiology in plant disease (van den Bosch et al., 2007). This work has demonstrated that different control measures may pose different selection pressures on viruses. Very practical implications have arisen from this work, which could directly improve sustainability of subsistence crops (e.g., relative value roguing in control of virus disease in vegetatively propagated crops). However, it remains to be seen how this new knowledge will be implemented, particularly where it has implications for management in subsistence crops in developing countries.

14.2.3 Managing Disease Based on Knowledge of Spatial Structure of Disease

Diseases intensity can increase over time due to the spread of pathogen propagules at different geographical scales. When inoculum is spread over large areas, this process is generally considered as inoculum dispersal. Local dispersal of inoculum usually results in a disease gradient. Knowledge about these processes can contribute to better understanding of the epidemics and ultimately to better disease management, although this is one area where a particularly poor linkage between generation of knowledge and subsequent field implementation has been documented (Jeger, 1999). Nonetheless, below are some examples of how knowledge of pathogen dispersal has been applied, with special emphasis on the management of citrus canker in Brazil.

Citrus production is an important sector in the Brazilian economy; exportation of pulp and juice totaled US$1.5 billion in 2007. However, Asiatic citrus canker, a bacterial disease caused by *Xanthomonas axonopodis* pv. *citri* has been a major problem to citrus growers, not only because of direct crop losses but also because of quarantine restrictions imposed by importing countries. The bacterium is readily dispersed by wind-driven rain (Bock et al., 2005) and enters host plants through stomatal openings and wounds caused by leaf abrasion, cultural practices or insects. Citrus canker has been present in Brazil since 1957 and disease control is based on a legally enforced eradication program (Rossetti, 1977). Fields are inspected monthly and if symptomatic plants are detected, the focus plant and all plants in the surrounding area must be eradicated.

Before the mid 1990s, the eradication program was derived from information on Asiatic citrus canker in Argentina and all trees in 30 m-radius from the infected focus plant were removed (Gottwald et al., 2007). In 1996 the Asian leafminer, *Phyllocnistis citrella* (Lepidoptera: Gracillariidae), was reported in Brazil and since then Asiatic citrus canker has worsened. The leafminer is not a direct vector of the bacterium, but the galleries opened by the insect facilitate pathogen penetration in the host. The spatial pattern of the diseased trees, earlier characterized as strongly aggregated, changed to an intermediate aggregation and even random pattern (Bergamin Filho et al., 2001). New sets of experiments were conducted to determine the eradication radius. Based on both disease progress (temporal dynamics) and spread in the field (spatial patterns), a more drastic action was implemented. The eradication was changed to include distance from the diseased tree and disease incidence: if incidence of diseased trees in an inspected area is less than or equal to 0.005%, the 30-m eradication strategy is used. However, if disease incidence is greater than 0.005%, all trees within the infected block are eradicated.

Gradient studies have also been used for a number of other applications including: (1) detection of sources of inoculum (e.g., cull piles) of *Phytophthora infestans* in potato in the Netherlands (Zwankhuizen et al., 1998); (2) definition of isolation distances for peach trees and roses to avoid spread of powdery mildew (Kable et al., 1980); (3) to generate hypotheses about the mechanism of dispersal of a pathogen (Fitt et al., 1987); (4) to make inferences about the etiological agent of a unknown disease, as for example in the case of Citrus Sudden Death (CSD) where a biological agent was proposed based on the disease gradient (Bassanezi et al., 2003); and (5) to assess the efficacy of disease control measures, as in the case of witches broom of cacao, where a flat disease gradient was indicative of ineffective disease control (Alves et al., 2006).

14.2.4 Managing Disease Based on Pathogen Phenology – Ascochyta Blight in Chickpea

Ascochyta blight, caused by *Ascochyta rabiei* (teleomorph *Didymella rabiei*) is the most important foliar disease of chickpea, and has been reported in most growing areas worldwide. *A. rabiei* survives on infected crop residues lying on the soil surface. Asexual reproduction on residues gives rise to pycnidia, which exude pycnidiospores, whereas sexual reproduction proceeds via pseudothecia. Pycnidiospores are spread by rain splash; ascospores by both rain and wind. Symptoms develop on all aerial parts of the plant and in some circumstances yield losses of susceptible cultivars may reach 100% (Pande et al., 2005) and suppression of Acochyta blight is essential to ensure profitable and sustainable chickpea production.

Epidemiological studies on pathogen biology were used to develop reliable and cost-effective management strategies. Pseudothecia maturation typically peaks at the beginning of spring in line with the emergence of new crops; ascospore release decreases drastically or stops altogether by the beginning of summer. After exhaustion of the pseudothecia, no more ascospores are produced, and the pseudothecial walls degenerate. The ascospores are dispersed over long distances by the wind and, as a considerable number of pseudothecia may be formed on infested debris, a great number of ascospores may be discharged into the air. Under environmental conditions conducive to the pathogen, a healthy field may become severely diseased over a short period of time following ascospore discharge. Adequate disease management can be achieved by application of prophylactic sprays, or by initiating spraying when the disease is still at a low level. Thus, combating the primary infections originating from airborne ascospores was found to be the key to acceptable, season-long disease suppression wherever the teleomorph stage plays a significant role in *D. rabiei* epidemiology. As the time of disease onset varies from year to year and in different environments, a tool for predicting the time of pseudothecia maturation and ascospore discharge was needed (Shtienberg et al., 2005).

Studies conducted under controlled environments indicated that temperature and moisture (wetness) are the key factors leading to pseudothecia formation and maturation in *D. rabiei*. This information was used to develop empirical models aimed at predicting the influence of temperature and interrupted wetness on maturation of *D. rabiei* pseudothecia (Shtienberg et al., 2005). The models were then validated with field data recorded in Israel and the following model provided the best predictions: starting at the beginning of the rainy season (October to December), the predictor of the model was assigned one severity value unit when there was a rain event (1 day or more) with $\geq$ 10 mm of rain, with a daily average temperature (during the rainy days) of $\leq$ 15 C. According to the model, pseudothecia mature after accumulation of six severity units, and ascospores will be discharged during the following rain event ($>$ 2 mm). The model provided accurate negative predictions (i.e., that pseudothecia would not mature and ascospores would not be discharged) in all four cases that were tested, and accurate positive prediction (i.e., that pseudothecia would mature and ascospores would be discharged at a particular time) in six out of eight tested cases (Shtienberg et al., 2005). In light of these results, chickpea growers in Israel are advised to initiate fungicidal spraying of susceptible cultivars after the accumulation of six rain events, in accordance with the empirical criteria listed above. The model has been used commercially since 2001, with appreciable success.

14.2.5 Managing Disease Based on Modeling the Time of Infection – Fire Blight in Pears

Fire blight, caused by the bacterium *Erwinia amylovora*, is the most destructive pathogen of pears and other pome-fruit trees worldwide (van der Zwet and Beer, 1995). The pathogen infects all plant parts including blossoms, shoots, leaves, fruits, limbs and trunks. Effects of the disease are devastating and severely infected trees may eventually die. Because of the erratic nature of fire blight, coupled with its destructive potential, management of the disease is difficult. Prevention of blossom infection by *E. amylovora* is the key to fire blight management. Prior to infection, populations of *E. amylovora* can increase greatly through an epiphytic phase that occurs on floral surfaces. During this phase, the ultimate size of the pathogen population is influenced by temperature, which regulates the generation time of the pathogen (Thomson, 2000). Stigmas have been shown to be the primary site of epiphytic colonization by *E. amylovora*. Most recent studies support the hypothesis that blossom blight is the result of *E. amylovora* first colonizing stigmatic surfaces, followed by the external washing of cells from the stigma to the hypanthium where infection occurs. On the hypanthium, *E. amylovora* gains entry into the plant through nectarthodes located on the hypanthial surface. Therefore, rain or heavy dew at the end of a warm period promotes infection (Thomson, 2000). Bactericide sprays may prevent blossom infections but blossoms that open after spraying are not protected. Consequently, for optimal chemical protection, sprays should be applied frequently, with short intervals between sprays to protect newly opened blossoms. This is not practical due to the cost of spraying and because of environmental considerations. Moreover, to lower the probability of resistance development in the pathogen population, spraying should be minimized. The solution was to apply the bactericides only when needed according to a warning system.

Investigations into the climatic factors influencing fire blight infections, with a view to possibly predicting of epidemics, were initiated in the 1920s and warning systems were developed by numerous workers from different countries. All models attempted to predict the occurrence of infection events based on empirical analyses of temperature and wetness duration. Some of the models were extensively examined and proved accurate in their country of origin, for example, MARYBLYT in northeastern USA (Steiner and Lightner, 1996), BIS in England (Billing, 1996), Cougarblight in northwestern USA (Smith, 1993) and FBCA in Israel. Occasionally the models performed adequately in alternate locations. Use of these systems assisted in timing the application of bactericides and early pruning of newly infected tissues (Shtienberg et al., 2003). In Israel, use of the local system, FBCA, greatly reduced risk imposed by the pathogen on the pear industry. The system is extensively used by Israeli growers and after its introduction, severe fire blight outbreaks were not recorded and there was a steady increase in the area of pear plantation in the country.

14.3 Transferring Epidemiological Knowledge to End Users

14.3.1 Industrialized Countries: Use of Decision Support Systems

As demonstrated in the descriptions above, and also evident in many other pathosystems, the factors governing the occurrence of epidemics are known or nearly so. However, as the biological systems are complex, interpreting this knowledge and employing it in disease management programs is difficult. Growers need assistance in incorporating existing knowledge into their decision-making procedures. Decision support systems (DSS) are the tools by which complex knowledge can be formulated in a "user-friendly" way. Numerous DSS have been developed to help farmers improve their use of fungicides and make other disease management decisions (Lynch et al., 2000; Magarey et al., 2002; Schepers, 2004; Bouma, 2007). The University of California at Davis maintains a Web page[2] with disease forecasting models for 12 diseases, many of which have more than one model. Potato late blight, for example, has 16 models.

DSS for fungicide use in control of potato late blight (*P. infestans*) has been the focus of much activity by both government and private organizations in Europe where the disease has become more difficult to manage in the last two decades (Hannukkala et al., 2007; Cooke et al., 2008). Computer-based DSS that require weather information and regular late blight scouting inputs have been developed and validated in a number of European countries (Cooke et al., 2008). Several European institutions have been formed to enhance research on potato late blight and these have created a critical mass for developing and improving DSS. Two EU concerted actions were funded to improve late blight management: the "European Network for development of an integrated control strategy of potato late blight (EU.NET.ICP)" and the EU Concerted Action on Potato Late Blight (EUCABLIGHT). Within these, at least six different DSS have been validated. Although much effort in the development of these DSS has focused on optimizing fungicide use, other management decisions are also involved. For example, reducing sources of initial inoculum for potato late blight is widely applied; farmers in the Netherlands who do not cover or destroy piles of culled tubers can be fined (Huub Schepers, personal communication). In spite of these intense efforts, utilization of DSS by European farmers is highly variable among European countries (Cooke et al., 2008).

There are other examples of DSS that have enjoyed wide adoption. Apple scab is a fungal disease caused by *Venturia inaequalis* that affects apples in several parts of the world. In Brazil, for example, a DSS based on meteorological variables was developed to predict periods favorable to the establishment of infection in apple trees. Whenever these periods are identified, fungicides should be sprayed to protect plants. A network of 8 meteorological weather stations was established in Santa Catarina state, Brazil, and daily issues of "infection risk" are broadcast by the media (TV, radio, e-mail, fax and telephone). The system was implemented in 1981 and

[2] http://www.ipm.ucdavis.edu/DISEASE/DATABASE/diseasemodeldatabase.html#DISEASEMODEL

is widely used in the apple growing regions of Santa Catarina for improved use of fungicides (Caramori et al., 2002).

A number of DSS related to the management of vector transmitted viruses have also been successful. The British Potato Council and the Central Science Laboratory of Britain offer an aphid monitoring system to potato growers that has had wide and growing acceptance.[3] In this system, farmers send aphids trapped in the field to a central location where they are identified, and very quickly receive a vector pressure index that they use in virus management decisions. Researchers in Australia have developed a DSS to forecast aphid outbreaks and epidemics of Cucumber mosaic virus in lupine crops that has also been widely adopted (Thackray et al., 2004).

This list of successful DSS is not intended to be exhaustive, but rather provide examples of clear impact of epidemiology on disease management. Nonetheless, not all DSS have been successful. Mackenzie (1984) noted that BLITECAST, one of the early forecasting systems for potato late blight, was not widely used by farmers in the US. Possible low use of and interest in DSS for potato late blight in the US may reflect the concentration of potato production in the western part of the country where the disease is not always important. Many of the earlier models based on humidity and temperature of periods of several days or weeks are inappropriate for the dry western US where late blight is sporadic. Recently, models for the western part of the US have been developed to use longer periods of general historical weather trends to predict years when the disease will be present (Henderson et al., 2007).

Overall, the degree of adoption of forecasting or DSS for late blight management in the US is still unclear as formal adoption studies were not available in the literature. However, serious investment in the development of DSS by academic services in many parts of the US has undoubtedly had positive effects on crop production. Many state services now offer on-line DSS for a number of crops, and the concept of DSS has become common knowledge among farmers. For example, potato farmers in Wisconsin now talk about blight units (for late blight) with full understanding of their meaning (W. Stevenson, personal communication). Thus, DSS may not only have immediate disease management benefits but may also lead to general transfer of epidemiological knowledge.

Magarey et al. (2002) noted that for every successful DSS, there are many that have had no impact, and the authors analyze factors that may influence success (i.e., adoption). In a more general view, Lynch et al. (2000) evaluated intelligent support systems in agriculture and found that the failure of many could have been predicted; as emphasis was put on model validity and not on the social issues that would affect adoption. A similar need for taking the end user into consideration in the design of DSS was highlighted by Bouma (2007).

Consistent with the end-user focus, there is a trend now for DSS to rely more on innovative information technology (IT), such as fax, Internet, telephone and SMS to make DSS more available and user-friendly (Schepers, 2004). With increasing

[3] We found no references on this program but much information is available at their Web site http://aphmon.csl.gov.uk/.

capabilities to measure, estimate and predict weather variables at high resolution, there are potentially powerful applications for pest management modeling. It was estimated that an integrated scouting, modeling, interpretation and dissemination program implemented by the United Stated Department of Agriculture saved US soybean farmers between 11 and 299 m US dollars in 2005 (Isard et al., 2006). The success of this project stimulated the development of a national Pest Information Platform for Extension and Education (PIPE), that will provide services for a number of pest problems at a national level and is eventually intended to be funded by users (Isard et al., 2006).

Integrated IT approaches will undoubtedly provide opportunities for scientists to improve the utility of models, as these programs are also designed as feedback mechanisms for research (Isard et al., 2006). For example, the DSS late blight community in Europe (described above) is striving to update the models to incorporate changes in pathogen population structure (Cooke et al., 2008; Hadders, 2008). One of the objectives of the EUCABLIGHT project was to standardize and collate data on pathogen and host for use in model parameterization within DSS (Hansen et al., 2007).

The DSS structure allows for identification of indirect effects of epidemiology on disease management via different impact pathways. For example, studies on relative importance of different inoculum sources of *Phytophthora infestans* (Zwankhuizen et al., 2000) have been used in the development of regulations on the amount of disease allowed in fields and on management of potato cull piles (Cooke et al., 2008).

14.3.2 Developing Countries: Farmer Field Schools

The examples given thus far in which epidemiology has led to improved disease management have all been in the industrialized countries or in the emerging economies, such as Brazil and China. For small-scale farmers in developing countries, indication of transfer of plant epidemiological knowledge that could enhance disease management is rare in the literature (Sherwood, 1997). Furthermore, some approaches that have worked in the industrialized world have not given similar benefits in developing countries. For example, almost all potato seed tubers in most developing countries, and particularly the poorer countries, are produced on-farm as a by-product of the ware potato harvest. Frequently “seed” potatoes are basically the tubers too small to sell as ware potatoes, but still large enough to produce a plant. This is the current situation in most developing countries in spite of numerous programs aimed at developing specialized potato seed systems based on distribution of seed with a low incidence of diseases and patterned after those in the industrialized countries (Thiele, 1999). The reasons for the lack of adoption of specialized seed programs in developing countries are undoubtedly many and complex (Thiele, 1999), and arguably not related to epidemiological theory but rather the myriad of factors affecting the adoption of any technology (Lee, 2005).

However, there is another aspect of the potato seed story that is salient for this discussion; the problem is not only that there has been lack of adoption but also a lack of research into alternative approaches. One can easily argue that the high disease-control efficacy of specialized potato seed production in the industrialized countries has diminished interest in other approaches to reducing the incidence of seed borne diseases in the potato crop. While studies have been done on potato seed degeneration, these have generally been designed to fine tune the formal seed system by measuring the rate of degeneration of clean seed assuming farmers will do nothing to maintain quality (Devaux et al., 2001). Nonetheless, Fankhauser (1999) and Gildemacher et al. (2007) demonstrated that farmers in developing countries could get significant yield gains by employing simple selection procedures in the process of producing their own seed on-farm.

Unfortunately, these empirical studies on the efficacy of selection have little theoretical underpinning for orientation. Although some generalized models for virus epidemics in vegetatively propagated plants include the effects of removal of diseased plants (Chan and Jeger, 1994; Jeger et al., 2004; van den Bosch et al., 2007), there are no specific applications for potato that we know of. One modeling study aimed at deciphering the complexity of potato seed degeneration in developing countries was done by Bertschinger et al. (1995) working in Peru in the 1980s. These workers developed EPIVIT, a PC-based model that predicts degeneration by major virus diseases utilizing heat (related to altitude) as a driving variable. They were able to quantify what farmers and potato workers qualitatively understood; potato degenerates slower at higher altitudes. Although this model was an excellent potential tool, it was never fully validated and to our knowledge has not been incorporated in any seed project.

There are some cases, however, when epidemiological knowledge has reached resource-poor farmers in developing countries. Generally, these have relied heavily on principles of knowledge management theory and adult pedagogy to enhance knowledge exchange, and have involved simple epidemiological principles rather than sophisticated modeling. One knowledge exchange mechanism that has been widely used with apparent success is the farmer field school (FFS). The FFS uses discovery based learning methods to improve the farmers' agro-ecological knowledge, and their capacity to make decisions (van de Fliert et al., 2002). Usually, a group of 20–25 farmers form a FFS, participating in weekly meetings during a whole cropping cycle. In the 1980's the FAO organized a concerted action in Southeast Asia to improve rice production with FFS as a component. It is estimated that in Asia, FFS were implemented in more than a dozen countries, such as Thailand, Indonesia, Bangladesh, Laos, Malaysia, Nepal, Philippines, Sri Lanka, Vietnam and others, where the goal was to transfer knowledge regarding the development of plant disease epidemics in rice (Bartlett, 2005).

As of 2007, reviewers estimated that FFS had been developed in 78 countries with a total of around 4 million graduates (Berg and Jiggins, 2007). Not all of these FFS necessarily involve disease management, but many do focus on production of one or more crops and include some information on disease management. Some of the more spectacular results relate to cacao farmers who have learned epidemiologically based management of several diseases including witches broom (*Crinipellis perniciosa)* and pod rots (*Phytophthora* spp). FFS for cacao production have been done in a number of countries in Africa, Asia and South America as part of a multi-national public/private collaboration involving the cacao industry (Hebbar, 2007). Undoubtedly, the large number of FFS done to date is a consequence of the high economic value of cacao and of the resources that this industry can generate. Regardless, recent studies demonstrate that famers who participate in the FFS improve their capacity to manage cacao diseases (Baah and Garforth, 2006).

FFS have also been successful for helping low resource farmers manage potato constraints, including potato late blight (Ortiz, 2006). FFS for potato producing farmers have not reached an implementation scale like those of cacao, but improvement in disease management capacity has nonetheless taken place for farmers who have graduated (Ortiz et al., 2004; Chettri et al., 2005).

14.3.3 The Role of Market

In the preparation of this review it became apparent that a major factor in the adoption of sustainable agricultural practices, many presumably based on epidemiological knowledge, is ultimately the pressure exerted by consumers. For quite some time this pressure has been evident through the growing, although demographically restricted, movement of organic products. However, this phenomenon has become more generalized, as evidenced by a large supermarket sector adopting strict pesticide use practices for their providers (Dolan and Humphrey, 2000).

The influence of the consumer on farmer practice relative to pest and disease management use is also affecting farmers in developing countries. Ironically, however, this has occurred primarily through the export market, such that it is consumers in the industrialized countries affecting producers in the developing countries. This occurs via exported organic products and also through global trade regulations, which are exerting pressure on growers of exporting countries to adopt standards of good agricultural practices (GAP). Consequently, for these sectors, epidemiologically-based information has become more important and there are incentives to build mechanisms for effective farmer capacity building. For instance, in order to be a certified GAP exporter, restrictions on the number of fungicide sprays may apply. Bar-codes allow tracking the product back to its origin and to all records of cultural practices that were used. In Brazil, this has been implemented in citrus, mango, papaya, banana, and apple orchards, as well as in strawberry, grapes, processing tomatoes, and melon fields, among other crops (www.agricultura.gov.br). Unfortunately, the complicated requirements for GAP certification often leave small-size famers out of the picture (Ogambi, 2006).

14.4 Conclusion

This brief review follows others that have, to a greater or lesser degree, explored links between plant disease epidemiology and disease management in practice

(Magarey et al., 2002; Scherm et al., 2006; Shtienberg, 2007). We have given several examples where greater knowledge of the processes causing disease spread in time and space has been used by farmers or other practitioners to improve management of plant disease. The impact of epidemiology has developed from several types of theoretical or empirical research, including disease dispersal gradients, the pathogen life cycle, and the driving factors of weather on disease development (e.g., DSS for fungicide sprays).

Overall, it would appear that one's appreciation of the link between epidemiology and disease management is in part dependent on the definition of the science. A broad definition of epidemiology as we have taken here and is apparent elsewhere (Zadoks, 2001), leads to a conclusion that epidemiological knowledge has been frequently and successfully applied to improve disease management. If one focuses more on theoretical epidemiology, particularly mathematical modeling, the link is less clear, as some modeling in the area of temporal or spatial dynamics would appear to have limited application. However, as Scherm et al. (2006) noted, theoretical problems are legitimate without immediate practical applications. As computing and IT capacities increase, sophisticated modeling may become more accessible to end users for the solution of practical problems.

A common element in all field applications of epidemiological principles would appear to be a strong information exchange network, involving state, private or non-governmental organizations, that enables knowledge to flow between scientist and practitioner. Magarey et al. (2002), used a water supply system analogy to assess factors that are needed for a DSS to be successful. In that analysis a distribution network was a critical component. In addition to information supply, the needs of the end user are critical for development of any new technology (Magarey et al., 2002; Bouma, 2007), and in a broader sense one can imagine that any new knowledge will only be considered if it provides effective solutions to real problem.

The situation in developing countries differs greatly for many reasons, an important one being the lack of strong extension institutions (Hart and Burgess, 2006). To this, one can add the disarticulation among existing extension efforts and research (Snapp et al., 2003). The discussion above regarding the use of FFS in developing countries highlights the difficult yet essential task of developing effective information exchange mechanisms that can bring farmer and scientist together (Snapp et al., 2003; Hart and Burgess, 2006; Bentley, 2006). FFS would appear to be one effective way of doing this, although undoubtedly there are many creative ways of providing effective knowledge exchange.

Policy clearly plays a role in adoption of many new technologies or approaches including those related to epidemiologically based disease management. For example, mandatory reduction of pesticide impacts imposed by governments can induce farmers to adopt IPM (Cooke et al., 2008). Nonetheless, policy is often weak in developing countries and has little effect even when intended to make pest and disease management more sustainable. A recent study in Peru and Ecuador found that implementation of the FAO Code of Conduct for pesticide usage is minimal (Orozco et al.). Beyond official policy, it appears that market forces may be more effective in providing a stimulus for adoption of sustainable disease management practices. This is now extending to developing countries, but the future role of small-scale farmers in highly specialized markets is an area of much concern (Brown, 2005).

Scherm et al. (2006) stressed the need for more formal studies of the impact of theoretical plant epidemiology. We would endorse that observation and generalize to a need for more clear understanding of the impact of plant pathology on disease management. The social impact of plant disease has at times been documented (Large, 1940; Schumann, 1991), but attempts to establish the social and economic impact of plant pathology, much less epidemiology, are rare and focus generally on scholarly interpretation of past events (Stakman, 1958; Yoneyama, 2004). The recent assessment of returns from investment in an integrated forecasting system based on state-of-art IT technology for soybean rust is a rare example of analyses that could be done (Isard et al., 2006).

Plant disease epidemics are dynamic processes and changes in any of the determinant factors can compromise the efficacy of management practice. A classical example is the variation in populations of plant pathogens, as variants resistant to chemicals or capable of overcoming disease resistance genes constantly represent a major threat to disease management. The host plant population can also change and interfere with control actions, as for example the introduction of new varieties in a given region. Different crop systems (organic, conventional, hydroponics, etc.) in new agricultural frontiers can also introduce variation in established practices. Additionally, regulatory and/or market actions can change the portfolio of chemical compounds available to growers in a country. Thus, lack of constancy in factors affecting disease management requires continuous exchange between epidemiologist and practitioner.

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Chapter 15
Integrated Disease Management: Concepts and Practices

V.K. Razdan and Sachin Gupta

Abstract The term Integrated Pest Management was first based on the concept of 'integrated control' given by the entomologists from University of California, who defined it as "applied pest control which combines and integrates biological and chemical control. Chemical control was used only if necessary and in a way which was least disruptive to biological control". Entomologists initiated the work on the concept of IPM following the problems faced with pest resistance to insecticides and the ecological damage identified with the widespread use of insecticides in the late 1950s and early 1960s. The concept got further importance due to the programs emphasizing sustainable agriculture, growing public concern regarding pesticides and food safety, greater difficulty in registering new pesticides and mounting pressure from growers and practitioners for IPM tactics. IPM does not seek to eliminate the use of pesticides, but aims to utilize the least disruptive options and to reduce the use of pesticides for pest control to the lowest practical levels. Food and Agriculture Organisation (FAO) survey showed that over 50% of the developing countries neither had legal means to limit pesticide use nor any code of practice. Whereas, countries like the Netherlands, which have adopted pesticide reduction programs, over 60% reduction in the amount of applied pesticides was achieved, in some seasons. Inclusion of the term 'IPM' in plant pathology was only after the formal involvement of plant pathologists with entomologists, nematologists and weed scientists in IPM programs under Huffaker Project, in the USA. Plant pathologists embraced integrated disease management by applying fundamental information on loss potential and pathogen biology, ecology and epidemiology, and applying the basic concepts of plant disease management. The principles of plant disease management should always be based on the integration of basic concepts such as avoidance, exclusion, eradication, protection, resistance and therapy. Adoption of Integrated Pest (Disease) Management against the diseases encountered in vegetable crops is of paramount importance as most of the vegetable crops are not harvested at the end of the crop season but it is spread over a long duration by way of several pickings, as

V.K. Razdan (✉)
Division of Plant Pathology, Sher-e-Kashmir University of Agricultural Sciences and Technology of Jammu, Chatha, Jammu, 180009, India
e-mail: vijayrazdan@rediffmail.com

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in case of tomato, okra, cucurbits, pea, beans, etc. Moreover, many of the vegetables are eaten raw, therefore, dependence on chemicals for the management of various diseases is a great health hazard to the consumer. This assumes greater importance in the developing countries where the farmers are not educated enough to follow some cut off date for application of chemicals to the standing crops. The present WTO scenario warrants the high quality disease free vegetable produce for ensuring competitive selling in the international market. All these factors along with the growing awareness among the users regarding pesticide residues, pollution to the environment and sub-soil water and increased problem of pathogen resistance towards the pesticides, have been the compelling reasons for moving away from the total dependence up on the pesticides and to adopt IPM strategies that would involve one or more than one concepts of plant disease management.

Keywords IPM · IDM · Concepts · Vegetable diseases

15.1 Introduction

Integrated pest management (IPM) is an approach which maximizes natural controls of pest populations, based upon knowledge of each pest, in its environment and its natural enemies, farming practices modified such as changes in the planting or sowing schedules, to affect the potential pests adversely and to aid natural enemies of the pests. It should be supplemented with the plantation of the resistant varieties. Once these preventive measures are taken, the fields should be regularly scouting to determine the levels of pests and the environmental factors. When the disease is above the threshold level then only the suppressive measures should be taken with most suitable technique or combinations of techniques, such as biological control, genetically resistant hosts, environmental modifications and when necessary and appropriate, selective use of pesticides, while causing minimum disruption of natural enemies (Bottrell, 1979). This approach is markedly different from the traditional application of pesticides on a fixed schedule. IPM strategies generally rely first upon all other concepts of disease management before chemically altering the environment. Thus IPM is the optimization of pest control in an economically and ecologically sound manner. This is accompanied by the use of multiple tactics in a compatible manner to maintain pest damage below the economic injury level while providing protection against hazards to humans, animals, plants and the environment.

Prior to the concept of IPM the major thrust for disease management remained focused on near total dependence on the use of chemical pesticides. Of the total agrochemical market, global fungicides sales constitute 1/3rd of the total sale. A survey of the global fungicide sales reflects that major consumption of fungicides is in Europe and Japan which comprise over half of the total sales value, whereas, in Asia and the New World fungicide sales are restricted either due to low crop values or to the presence of yield limiting factors other then diseases such as water deficiency (Hewitt, 1998). Of all the different modes of fungicide application, seed treatments are highly attractive and effective disease control methods, especially when the fungicides comprise of systemic, xylem mobile chemicals. However, among the potential disadvantage associated with systemic fungicides used for seed treatment is development of resistance through an increase in selection pressure especially if such treatments are followed later in the season with application of products having the same mode of action. In general, pesticides seed treatments are made to about 90% of all food crops and of there 99% receive a fungicide treatment (Martin, 1994). Of the total, about 40% of seed treatment market is in Europe.

Integrated pest management strategy is widely adopted by all the pest management disciplines but its early definitions and philosophies belonged to entomologists. While the term IPM has been used only sparingly in the phytopathology literature, the integrated disease management strategies were considered to be at the forefront of ecological based or biointensive pest management. The term Integrated Pest Management was first given by Smith and van den Bosch (1967), based on the 'integrated control' concept given by Stern, et al. (1959), entomologists from University of California, who defined it as "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". The concept of IPM was initially grasped by the entomologists following problems with pest resistance to insecticides and the ecological damage identified with the widespread use of insecticides in the late 1950s and early 1960s. It got further importance due to the factors such as the programs emphasizing sustainable agriculture, growing public concern regarding pesticides and food safety, greater difficulty in registering new pesticides and mounting pressure from growers and practitioners for IPM tactics. Since 1940s to the mid of 1960s plant pathologists have emphasized on non-pesticide control strategies such as genetic host resistance to pathogens, cultural controls such as rotation and tillage and use of disease free seed and planting materials. Therefore, it is imperative to discourage the use of high-risk pesticides, provide incentives for the development and commercialization of safer products and encourage use of alternative management modules that reduce reliance on toxic and persistent chemicals.

Of the many definitions of IPM the one adopted by the USA National Coalition on Integrated Pest Management is used is, "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 has established as the desirable pest control strategy from the perspective of both national policy and science based pest control. Broadly IPM can be defined as "the careful consideration of all available pest control techniques and subsequent integration of appropriate measures that discourage the development of pest populations and keep pesticides and other interventions to levels that are economically justified and reduce or minimize risks to human health and the environment. IPM emphasizes the growth of a healthy crop with the least possible disruption to agro-ecosystems and encourages natural pest control mechanisms." (FAO, 2002).

Growers and consultants need to understand and accept the basic concepts on which IPM is built. These mainly emphasize that mere presence of a pest species does not justify action for control; IPM is about containment or management of a pathogen, not its eradication. Hence some level of damage or loss to the crop should be tolerated. Moreover, no single control measure can be applied to all pest complexes. Therefore, IPM utilizes a diverse array of control options to minimize pest abundance or damage, with pesticides used as the last resort. IPM does not seek to eliminate the use of pesticides, but aims to utilize the least disruptive options and to reduce the use of pesticides for pest control to the lowest practical levels.

Inclusion of IPM in the plant pathology vernacular was only after the formal involvement of plant pathologists with entomologists, nematologists and weed scientists in IPM programs under Huffaker Project, named after Carl Huffakar, Entomologist from University of California (Jacobsen, 1997). Plant pathologists embraced integrated disease management by applying fundamental information on loss potential and pathogen biology, ecology and epidemiology, and applying the basic concepts of plant disease management.

15.2 Concepts and Principles of Plant Disease Management

The principles of plant disease management should always be based on the integration of basic concepts such as avoidance, exclusion, eradication, protection, resistance and therapy, as described by Singh (1987). The principle of avoidance involves tactics that prevent contact between the host and the pathogen. Under avoidance, strategies such as choice of geographic area, selection of field, choice of planting time, planting of disease escaping varieties and selection of disease free seed and planting material are considered. Selection of geographic area for any crop is made on the basis of suitability of climate for the crop, but the same climate may be suitable for the activities of the pathogen also. For example bean anthracnose is common in wet areas thus its plantation may be preferred in the dry areas. Similarly, diseases like smut and ergot are serious in areas where frequent rains occur during flowering of the crop, therefore, such areas should be avoided. Successful cultivation of a crop also depends on the selection of a proper field particularly if the field has the history of soil borne disease it should be avoided for the susceptible crop. In such diseases as bacterial wilt of potato, wilt of pigeon pea, ergot and smut of pearl millet, ear cockles of wheat and rot knot nematodes, the infested field can be avoided. In selection of fields drainage is also important, poor drainage aggravates many diseases. In fruit orchards the choice of land is most important because the trees are perennial, if proper selection of land is not done and it has a hard pan beneath it the trees may show signs of degeneration after few years. The coincidence of having the susceptible stage of the plant growth and favourable conditions for the pathogen at the same time can be avoided by alteration in date of planting. Late sown winter crops escape incidence of root rot and wilt favoured by high temperature and moisture that usually occur after the summer rainy season. In different crops, certain varieties escape damage by disease because of their growth characters, not due to their genetic resistance to the disease. In India, varieties of pea that mature early (by January) generally escape much damage from powdery mildew which becomes serious in January or later. Groundnut varieties with erect habit suffer less from damage of leaf spots. Proper selection of seed and planting material is important for such diseases which are carried by seed or vegetative planting material. Planting of disease-free seed in pathogen free soil is often the most effective method of control of certain diseases.

The principle of exclusion aims to prevent the entry of a pathogen in a field or area (state, country) supposedly free from that pathogen, this can be achieved by the adaptation of quarantine, inspection and certification, seed treatment, and eradication of vectors. For implementation of plant quarantine regulations proper check is maintained at the points of entry (airports, seaports, etc.). Suspected material is kept under quarantine for a specific period and if found contaminated it is either destroyed or effectively treated. Quarantine regulations are justified only when the inoculum cannot be disseminated by natural agencies. One of the best examples demonstrating loopholes in quarantine regulations is that of citrus canker. The disease had been introduced into USA (in 1910), South Africa and many other countries through planting material from south and Southeast Asian countries. Crops grown exclusively for seed are regularly inspected for presence of diseases that are disseminated by seed and the seed is then certified. The badly affected plots and seed lots are rejected. The method prevents regional and inter-regional spread of seed-borne pathogens. The seed tubers, grafts, bulbs and other propagative materials can be given heat, gas or chemical treatments to exclude the pathogens present in or on them. For effective exclusion of pathogens a check on vectors particularly insects having long flight range is necessary, therefore, the crop should be given insecticidal cover before arrival of the vectors on the plant surface.

The principle of eradication aims at removal of the inoculum already present in the field or the crop, the aim is to reduce the inoculum density to a level where it cannot cause significant damage. This is attempted through biological means, crop rotation, eradication of diseased plants or plant organs and physical and chemical treatments. The biological control aims at eradication and reduction of inoculum and protection of plant surfaces through the activity of other microorganisms. When the same crop is raised year after year on the same land the soil becomes heavily infested with the soil-borne pathogens of that crop and it becomes unfit for cultivation of that crop. Crop rotation is one of the oldest methods of fighting soil sickness and root diseases. The method is more effective against pathogens which have limited host range and restricted survival ability in soil. The presence of diseased plants, plant parts, alternate and collateral hosts in the field or orchard is a source of continuous release of inoculum and their removal from the field, thereby maintaining field sanitation and clean cultivation helps in removal and destruction of initial inoculum. This practice can be very effective in diseases such as loose smut of wheat, loose and covered smut of barley, red rot of sugarcane and many wilt diseases. Burying the crop debris deep in the soil by deep ploughing also inactivates inoculum of many pathogens and helps in maintaining field sanitation. Heat therapy and chemical treatments help in eradicating and inactivating viruses in fruit tree seedlings and grafts and destroys the exposed fungal and bacterial propagules. Similarly, soil treatments are carried out to inactivate or eradicate the pathogens present in the soil, it involves the use of chemicals, heat and cultural practices such as flooding and fallowing. Soil solarization is a novel method of soil treatment to destroy most of the fungal, bacterial and nematode propagules as well as weed seeds. It is a system of raising temperature of wet soil covered with polyethylene sheet thereby trapping the solar heat. The system is highly useful for sanitizing the nurseries and small field plots. Flooding of the field is also a method of eradicating fungal and nematodes pathogens from the field.

The inoculum of many infectious diseases is brought by wind from neighbouring fields or distant places of survival, hence the concepts of exclusion, avoidance and eradication are generally ineffective or insufficient to prevent development of such diseases. Plant has therefore to be provided some protective cover to create a toxic barrier between the host surface and the propagules of the pathogen to protect from such pathogens. Chemical sprays, dusts and seed treatment are recommended to form a protective toxic layer on the host surface so that when the pathogen comes in contact with the surface it is killed or prevented from growth. Many species of insects are important vectors of viral and other diseases, timely and effective destruction of these vectors is the most important approach to control such diseases, for which a protective coverage of insecticide is very effective.

Cultural practices by which there is some modification of the environment, like improvement of aeration under crop canopy thereby reducing humidity checks growth of many fungi. Reducing the number of irrigations also helps in modification of environment against certain diseases like some root diseases.

Host nutrition often influences development of disease in the plant. Many leaf diseases are favoured by high level of nitrogen in the soil. In rice application of 100 kg N/ha instead of 120 kg is recommended to prevent losses from leaf spots, blasts and sheath blight. Deficiency of potash in plants renders the tissue susceptible to many diseases. High calcium increase resistance to wilt and soft rot diseases through strengthening of pectic substances in the cell walls and obstructing the activity of pectic enzymes of the pathogen. Intensity of several diseases is decreased by such micronutrients as zinc, boron, manganese, etc.

Development of resistant varieties through hybridization is a cheap method of disease management for the farmers. With the development in biotechnology it is possible to introduce distant resistance genes in the plant by manipulation, genetic modification and multiplication of plants through techniques such as tissue culture and genetic engineering. Creation of transgenic plants, in which resistance genes from sources other than that particular plant species or incorporation of avirulence genes of the pathogen to impart resistance, is now possible. Induction of Acquired resistance, in which the plant acquires localized or systemic resistance through the effect of chemicals or microorganisms, using phosphates and carbonates as foliar therapy has been found to "turn on" the resistance genes. Rhizobacteria are also known to induce systemic acquired resistance in the foliar parts against many diseases simultaneously. Even biochemical resistance of non-genetic nature can be developed in plants by chemotherapy or host nutrition, but this type of resistance is temporary. Temporary physiological resistance in plants can be developed through chemotherapy, when systemic fungicides and antibiotics applied to the foliage or through the roots persist in the plants and while their toxic level is maintained the pathogen cannot invade the tissue. Nutrition cannot change a susceptible variety to a resistant variety, but making major- and micro-nutrients available there is strengthening of the tissue that can ward off invasion of the pathogen.

Cure of the diseased plant or its organ is not possible, but in many crops and fruits trees chemical and physical therapy has been applied to cure the plant by eradicating the pathogen, which can be achieved by chemotherapy, heat or thermotherapy and tree surgery. Chemotherapeutants such as systemic fungicides and antibiotics, when applied, eradicate the pathogen from the tissue of the diseased plant and thus curing it. Such chemicals are absorbed by leaves and roots and on reaching the site where the pathogen is present they either kill or incapacitate it by preventing sporulaltion, growth or both and even detoxifying the toxins produced by the pathogen.

Heat or thermotherapy are used for seed, tubers, bulbs and grafts which can tolerate the thermal inactivation or death points of the pathogen. Ratoon stunting disease bacterium and many viruses of sugarcane are eradicated by hot water, air or moist hot air treatment of the seed canes. Large size fruit trees are cleaned of infection by cutting/surgery or scrapping of the diseased part and covering the wound with a fungicidal paste.

15.3 Integrated Disease Management with Special Reference to Vegetable Diseases

In vegetable cultivation, one of the most serious constraints is the occurrence of diseases, whose magnification can be assessed by the socio-economic changes that it caused after the epidemics of potato late blight in 1840s in Ireland. Due to their tender and supple nature, vegetables are more prone to disease and pest attack, and at a conservative estimate cause about 20–25% losses. The management strategy for the insect pests and diseases remains largely confined to pesticides. About 13–14% of the total pesticides used in India are consumed in vegetable crops though only 2–3% of the area is covered by them (Sardana et al., 2004). Most of the vegetable crops are not harvested at the end of the crop season but harvesting is spread over a long duration by way of several pickings, for example in case of tomato, okra, cucurbits, pea, beans, etc. Moreover, many of the vegetables are eaten raw, therefore, dependence on chemicals for the management of various diseases is a great health hazard to the consumer. This assumes greater importance in the developing countries of Asia, Africa and Latin America, where the farmers are not educated enough to follow some cut off date for application of chemicals to the standing crops. Introduction of high yielding cultivars and adoption of highly intensive cultivation has created conditions favourable for growth of plant pathogens, thus further giving an impetus to the problems of diseases in vegetables. The present WTO scenario warrants the high quality disease free vegetable produce for ensuring competitive selling in the international market. Furthermore, the crop should be free from pesticide residue and pathogens. All these factors along with the growing awareness among the users regarding pesticide residues, pollution to the environment and sub-soil water and increased problem of pathogen resistance towards the pesticides, have been the compelling reasons for moving away from the total dependence up on the pesticides and to adopt IPM strategies that would involve one or more than one concepts of plant disease management discussed above. For timely management of diseases, an in depth knowledge of perpetuation and spread of the pathogens is essential. To elaborate and stress up on the use of IPM strategies in vegetable diseases examples of some commonly occurring important diseases in vegetable crops is given below.

15.3.1 Fungal Diseases

Damping off is an important disease in vegetable nurseries and is fairly common in poorly managed nursery beds. A number of species of soil-dwelling fungi, including *Fusarium, Rhizoctonia, Sclerotium, Pythium* and *Phytophthora* are responsible for the disease (Dixon, 1981; Shyam and Gupta, 2001). The disease is responsible for poor seed germination and stand of seedlings, manifested as pre- and post-emergence damping off. The disease usually radiates from initial infection points thus giving the appearance of islands wherein almost all the seedlings are killed. The disease is also carried over to the field where the transplanted seedlings are grown (Hendrix and Campbell, 1973). Integration of cultural practices, chemical and biological control methods can be useful for management of damping off. Cultural practices include avoidance of nursery sowing in the same bed repeatedly year after year and frequent heavy irrigations. Soil solarization with transparent polyethylene mulch has been found effective for control of the disease. Application of captan as seed dresser and for soil drenching 15 days after planting has been recommended for healthy plant stand in chilli, cabbage and onion crops (Champawat and Sharma, 2003). Seed coating with conidial suspension of several biocontrol agents like *Trichoderma koningii, T. harzianum, T. viride and T. virens* have been found more effective than soil application in protecting the tomato seedlings from damping off (Hazarika et al., 2000). An integrated management module comprising of change of nursery site every year along with pre-sowing soil sterilization with formalin (5%), seed treatment with captan or thiram and drenching of beds after emergence with captan (0.3%) or mixture of mancozeb (0.25%) and carbendazim (0.1%) at 8–10 days interval coupled with avoidance of heavy irrigations have been suggested by Shyam (1991) for management of damping off.

Potato and tomato are the two important solansceous vegetable crops and their cultivation suffers due to various diseases caused by fungi, bacteria, virus, nematodes etc. (Khurana et al., 1998). Late blight caused by *Phytophthora infestans* (Mont.) de Bary, is the most destructive disease of these crops throughout the world, but it can be effectively managed by various measures which aim to reduce the primary inoculum and spread of the disease. Although in potato sanitary measures and use of healthy tubers can ensure healthy and disease free crop, but use of resistant varieties is regarded to be the best means of late blight management

(Bhattacharya and Singh, 1990). In India, Central Potato Research Institute (CPRI), Shimla has developed and released several blight resistant varieties of potato like Kufri Jyoti, Kufri Sherpa, Khufri Jeevan, Kufri Jawahar, Kufri Badshah, etc. Some resistant cultivars have also been identified by (Erinle and Quinn, 1980) against the disease. Louwes et al. (1992) reported *Solanum circaefolium* to be a good resistance source against late blight. In tomato, cultural practices like avoiding tomatoes in succession to solanaceous crops, subterranean irrigation, wider spacing, avoiding direct contact of the fruit and foliage with soil, staking with bamboo sticks or bushes available in forest to avoid direct contact of fruits with soil and mulching with pine needles and dried grass can be helpful in reducing the disease. Collection and dumping of diseased fruits in pits and afterwards spraying them is also effective. Some resistant cultivars have also been identified against the disease (Erinle and Quinn, 1980). The introduction of systemic fungicides, like metalaxyl (acylalanines), with specific activity against the members of oomycetes has been a big success against *Phytophtora infestans* (Schwinn and Staub, 1987). In India, pre-prepared mixture products *viz.* Ridomil MZ (8% metalaxyl + 64% mancozeb), Galben M8-65 (8% benalaxyl + 65% mancozeb), Ridomil 45 (5% metalaxyl + 40% copper oxychloride), Curzate M-8 (8% cymoxanil + 64% mancozeb), etc. are available (Thind and Chahal, 2002). Disease forecasting based fungicide applications has been useful in reducing the number of applications and therefore the cost of disease management. Blite cast, a forecasting model is being used in North Eastern USA for timing fungicide application against potato blight (Krause et al., 1975). Singh et al. (2000) have also developed a foresting system called Julsa cast for plains of Western Uttar Pradesh (India) and the system is primarily based on temperature, relative humidity and rainfall. A mixture composed of 5 parts of activator BABA (DL-3-amino butyric acid) and 1 part of mancozeb was found highly effective in the management of late blight of tomato and potato (Baider and Cohen, 2003). Tomato seedling from *Fusarium oxysporum* MT0062 pre-treated soil showed reduced development of *P. infestans* on the aerial parts (Yamaguchi et al., 1992). Besides biological control agents, prophylactic sprays of aqueous and ethanolic leaf extracts of *Reynoutria sachalinensis* provides 40–50% control of the disease (Herger et al., 1988). Similarly, pre-inflectional treatment (2–14 days before inoculation) with ethanol extracts of *Hedera helix* and *Paeonia suffmficosa* extract suppresses late blight development (Rohner et al., 2004).

Early blight caused by *Alternaria solani* (Ellis & Mart.) Jones & Grout, another common disease of potato and tomato, is prevalent throughout the world. Integration of different methods such as adoption of field sanitation and cultural practices can be used for managing the disease. Maintaining field sanitation by removing and destruction of diseased haulms from the infected fields after harvest reduces the primary source of inoculum for the next crop. Moreover, various *Solanum* species such as *S. phureja* and *S. chacoense* have been exploited for breeding early blight resistant cultivars of potato (Stewart et al., 1994). Antagonistic organisms like *Trichoderma* spp. and *Pseudomonas* spp. can also be integrated with other disease control measures to manage the disease (Casido and Lukezic, 1992; Martinez and Solano, 1995). Fungicides like captafol, chlorothalonil, and fentin hydroxide are reported to have good efficacy in management of the disease. Carbamate fungicides have been found to be more effective than Bordeaux mixture or insoluble copper (Thind and Jhooty, 1982).

Black scurf caused by *Rhizoctonia solani* Kuhn is both soil and seed borne, therefore successful management of the disease can be achieved by following proper cultural practices and chemical treatment of the seed. Two to four years crop rotation with cereals, brassicas and legumes is helpful for the management of the disease. Green manuring with *Sesbania cannabina* has been reported to reduce the disease on tubers by 40% (Bhattacharya et al., 1977). Thind et al. (2002) reported almost complete control of black scurf by dipping infected seed tubers for 10 min, before sowing, in 0.25% solution of Monceren (pencycuron), a phenyl urea based fungicide. Good efficacy of carbendazim to control the disease has also been reported (Khanna et al., 1991).

Potato wart (*Synchytrium endobiotichum*) is known to cause serious losses in temperate countries of the world. In India this diseases, after being reported by Ganguly and Paul (1953) from Darjeeling hills, has been successfully restricted to that area only due to strict domestic quarantine on this disease. The disease mainly being soil borne in nature is difficult to manage, however, pathogen population in soil can be considerably reduced by 8–10 years crop rotation with non-host crops. In India varieties released by CPRI *viz.* Kufri Jyoti, Kufri Sherpa, Kufri Jeevan and Kufri Mithun have proved resistant to potato wart.

Buckeye rot caused by *Phytophthora nicotianae* (Breda deHaan) var. *parasitica* (Dastur) Whaterhouse, is an important disease of tomato in those areas where fruiting time coincides with high relative humidity coupled with warm temperature. Staking of plants in the field or maintaining wider spacing in un-staked planting is commonly practiced for the control of the disease (Sherbakoff, 1917; Wager, 1935). Various systemic and non-systemic fungicides have been recommended to manage the disease, however, due to continuous rains during the cropping season, routine application of fungicides is sometimes delayed which often results in heavy disease outbreak and poor disease control, therefore, proper timing of initial sprays is important for disease management. Integrated disease management of buckeye rot can be achieved through cultural practices like staking, periodical clipping of lower leaves (15–20 cm), weeding, mulching with white polythene sheet and regular removal of affected fruits and spraying of mancozeb, captafol, metalaxyl+mancozeb or cymoxanil+mancozeb (Sharma, 1992; Dodan et al., 1994; Shyam and Gupta, 1996).

Fusarium wilt is also an important disease of tomato particularly in those areas where soil temperature remains high during the period of plant growth in field. The disease can be efficiently controlled by careful crop rotation and use of healthy seed. Combined application of inorganic fertilizers and organic manures is considered effective in reducing disease incidence. Application of leguminous foliage like groundnut and *Sesbania grandiflora* has been reported to reduce the disease (Nirwanto et al., 1994). Soil solarization shows greater efficiency in reducing the wilt than fumigation with methyl bromide (El Shami et al., 1990). Hot water treatment of tomato roots at 48–49°C for 30 s delays the symptoms (Archisi et al., 1985). Soil fumigation with chloropicrin is an effective management strategy for control of tomato wilt. Benomyl, iprodione + carbendazim and carbendazim alone or a single pre-plant drench of benomyl or thiophanate-methyl shows good efficacy against tomato wilt (Atkinson and Adamson, 1977; Etebarian, 1992). Root dip treatment in spore suspension of non-pathogenic species like *Fusarium oxysporum* f. sp. *melongenae, F. oxysporum* f. sp. *cucumerinum* and *F. oxysporum* f. sp. *dianthi* suppresses the severity of wilt symptoms and induces resistance against the disease (Amemiya et al., 1986; Kroon et al., 1991). Sulfhydryl proteinases such as papain, bromelian, ficin and shoot extract of *Inula viscosa* have also shown potential as biopesticides against Fusarium wilt of tomato (Qusan et al., 1995).

Cruciferous vegetables are important *kharif* vegetable crops, grown both for table and seed purposes. Among the various diseases encountered in this group of vegetables are downy mildew, Alternaria leaf spots, rots and white rust. Downy mildew on crucifers has world wide distribution. Besides the damage that is caused by downy mildew itself, the affected tissues become susceptible to secondary fungal and bacterial invasions. The fungus responsible for this disease is *Peronospora parasitica* (Pers. ex. Fr.) which is an obligate parasite. Since the fungus survives in the form of oospores on perennial hosts, the management can be done through integration of cultural practices with fungicides and planting of resistant varieties. Destruction of crop debris and perennial weed hosts, crop rotation with non cruciferous crops and use of clean seeds are some of the cultural practices for the control of the disease. Seed dressing with metalaxyl before sowing helps in minimizing the initial inoculum (White et al., 1984). Fungicidal (35% metalaxyl) seed treatment followed by foliar spray is a common practice to control the disease (Crute, 1984).

Alternaria leaf spots are generally caused by *Alternaria brassicae, A. brassicola* and *A. raphani*. The infection reduces both quality and quantity of the produce and in nurseries, it even causes damping off. Cultural practices like use of clean and healthy seed, long crop rotations, proper plant density and proper drainage of fields have been suggested by various workers from time to time (Dixon, 1981; Singh, 1987). Ellis (1968) reported complete elimination of *Alternaria* infection from cruciferous seeds by hot water treatment for 25 min at 50°C. Various fungicides like mancozeb, zineb, captafol, thiram and carboxin have been found effective as seed dresser for the control of seed borne inoculum of *Alternaria* spp. (Ellis, 1968; Chahal, 1981; Maude and Suett, 1986; Valkonen and Koponen, 1990). Various systemic and non-systemic fungicides like Baycor, Benlate, Blitox-50 and Prochloraz have been reported effective against *Alternaria* spp. both under *in vitro* and *in vivo* conditions (Maude and Dudley, 1972; Verma and Saharan, 1994).

Stalk rot is another important disease of cauliflower seed crop and is caused by *Sclerotinia sclerotiorum* (Lib.) de Bary, which is a persistent soil inhabitant. No single disease management strategy effectively prevents the infection, however, various cultural, biological and fungicidal control measures can reduce disease severity and minimize yield losses. Among the cultural methods crop rotations such as cauliflower-paddy-cauliflower is highly effective in controlling the disease, as it helps in reducing the number of sclerotia in the soil. Mulching with pine needles, removal of diseased leaves and soil amendments with sunflower and rapeseed cakes reduces the incidence of stalk rot. Among the chemicals, maximum reduction in disease incidence was caused by carbendazim followed by metalaxyl+mancozeb, mancozeb and thiophanate methyl (Zewain et al., 2005).

White rust is another common disease of crucifers through out the world and can cause considerable loss when it occurs along with downy mildew. In India, among vegetables it is more serious on radish than any other vegetable. The fungus responsible for the disease is *Albugo cruciferum* S.F. Gray (*A. candida* (Lev.) Kunez, or *Cystopus candidus* Lev.). Practices like collection and burning of diseased plant materials, application of phosphorus and potassium, avoidance of excess application of nitrogen and maintenance of weed free cultivation reduces the disease severity and incidence. Application of chlorothalonil at the time of flowering proved quite effective to eradicate the white rust (Verma and Petrie, 1979). Other fungicides like captafol, mancozeb, metalaxyl, and copper oxychloride are also effective against the disease (Gupta and Sharma, 1978).

Yellows disease caused by *Fusarium oxysporum* f. sp. c*onglutinans* (Wr.) Snyder and Hansen which causes heavy losses, can be kept under check by following crop rotation, deep ploughing during summer months, use of disease free soil for raising the nursery and addition of vermicompost in the bed before sowing (Szezech and Brzeski, 1994). However, the best method to manage the disease is through resistant varieties (Pesti et al., 1987). Several biocontrol agents like *Pencillium* spp., *Bacillius subtilis* and actinomycetes have been reported effective in reducing the incidence of disease in heavily infested fields (Kobayashi, 1991).

Downy mildew is an important disease of cucurbitaceous vegetable crops particularly in areas having adequate moisture. Fungus responsible for causing the disease is *Pseudoperonospora cubensis* (Berk. & Curt.) Rostow. The disease can be kept under check by integration of various management methods, such as cultural methods like destruction of plant debris of previous crop and cucurbitaceous weeds and avoiding high crop population densities for preventing the build up of moist microclimates within leaf canopy. Irrigation should be used in such a way that relative humidity and leaf wetness is reduced thereby minimizing the chances for disease development and its further spread. Ridomil MZ, Galben M8-65 and fosetyl-Al have exhibited good protective and eradicative properties (Thind et al., 1991). The disease can also be kept under check by spraying or dusting of chemicals like copper in the form of Bordeaux mixture and mancozeb but copper fungicides should be used with care as some of the cultivars exhibit copper phytotoxicity (Dixon, 1981).

Powdery mildew of cucurbits too is a widespread disease and is reported to be caused by two pathogens *viz. Sphaerotheca fuliginea* (Schlect.) Poll. and *Erysiphe cichoracearum* DC. Initially sulphur fungicides were generally recommended for the control of the disease but some of the cucurbits like cucumber have been reported to be sensitive to these fungicides. Although systemic fungicides like benzimidazoles and EBIs have been able to provide excellent control of powdery mildew of cucurbits but the pathogen has developed resistance to some of them. Dinocap which was initially developed as acaricide also controls powdery mildew on cucurbits effectively, with no phytotoxicity. Among systemic fungicides carbendazim, benomyl and thiophanate-methyl are highly effective. *Ampelomyces quisqualis* is a commonly occurring hyperparasite of powdery mildew fungi, and use of this as biocontrol agent can be exploited as an ecofriendly approach to manage the disease (Singh and Thind, 2001).

Adoption of IPM strategies is very effective for all the soil borne diseases as the pathogens responsible for such diseases have the capacity to inhabit the field for long durations and inflict economic damage on most of the crops. Pathogens such as *Sclerotium rolfsii* and *Rhizoctonia solani* produce highly resistant sclerotia, therefore depending only on the chemical pesticides is hardly effective in combating the diseases. However, a number of cultural practices such as, avoidance of heavily infested fields, burial of infected plant residues, long rotations, soil solarization for 4–6 weeks, deep ploughing just before planting and weed control may help to control the soil borne diseases (Jenkins and Averre, 1986). Combination of solarization with the introduction of the disease-suppressing organisms like *Trichoderma* spp. in the solarized soils is even more effective than any of these two control measures alone (Ristaino et al., 1991). Similarly, *Sclerotinia sclerotiorum* is another important soil borne pathogen causing white mould on beans, cottony soft rot of carrot, watery soft rot of cole crops, root rot of pea and timber rot of tomato. Sclerotia, the overwintering structures produced by the fungus, can survive for 3–4 years in soil. Thus the disease is not easily controlled by incorporating residues. However, the pathogen can be managed by adopting rotation to resistant crops (beets, onion, spinach, peanuts, corn and grasses) and flooding of the field for 23–45 days. Furthermore, growing vegetables with an upright rather than a sprawling growth habit, wide plant spacing and low plant density also reduces disease development (Anas and Reedleder, 1987). In case of Verticillium wilt of tomatoes, potatoes and melons 3–4 year rotation is usually sufficient to reduce the disease incidence although microsclerotia persist in the soil for 10 years or more. Reducing root lesion nematode populations helps control the wilt because fungus often infects nematode-damaged root systems. Selection of resistant cultivars, soil solarization and rotation to non-host crops is usually recommended for the management of the disease (Scholte, 1992).

15.3.2 Bacterial Diseases

Common scab of potato is worldwide in distribution and disease incidence as high as 100% has been reported in hilly areas (Shekhawat, 1990). Although, the main pathogen associated with the disease is *Streptomyces scabies*, but *S. griseus, S. collinus, S. aureofaciens, S. longisporoflavus, S. flaveolus* have also been reported to cause common scab (Dey and Singh, 1983). The disease is both tuber and soil borne, hence, healthy seed tubers should be selected for sowing in order to reduce the primary source of inoculum. Successful control of potato scab has been achieved by frequent irrigations of the field at weekly intervals from tuberization until maturity (Singh and Singh, 1981). Application of gypsum is reported effective to reduce common scab (Singh and Soni, 1987). Tubers can also be treated with 3% boric acid and certain antibiotics like Streptocycline and Plantamycin for disease control.

Bacterial wilt is the most devastating bacterial disease of solanaceous plants and is also known as solanaceous wilt or southern bacterial wilt. The bacterium responsible for the disease was named as *Bacillus solanacearum* which was changed to *Pseudomonas solanacearum* and has finally been changed to *Ralstonia solanacearum* (Yabuuchi et al., 1992, 1995). Control of the disease in infested soil is very difficult, attempts have been made to combat this disease through cultural, chemical, biological and host resistance mechanism either alone or in combination. Reduction of the initial inoculum by cultural practices is of great importance. Use of disease free seed avoids introduction of the wilt pathogen in the new fields, and crop rotation is most generally used control measure employed world wide to check bacterial wilt. Destruction of weeds, collateral and other off season hosts help in minimizing the inoculum potential of the pathogen. Certain bacteria like *Pseudomonas fluorescens, Bacillus polymyxa* and actinomycetes have been found to delay the development of *R. solanacearum* and reduce the incidence of bacterial wilt (Sivamani et al., 1987). Various soil amendments also decrease wilt incidence. Suppression of pathogen in amended soil was observed by stimulating the growth of saprophytic microorganisms especially actinomycetes and *Bacillus* species or by the release of toxins during the decomposition by soil microorganisms (Yao et al., 1994). Application of bleaching powder (15 kg/ha) has also been found effective against this disease (Yamada et al., 1997). Yamazaki et al., (2000) suggested that calcium concentration in soil should be increased to have better control of the wilt. El-Shanshoury et al. (1996) have reported the possibility of using biocontrol agent along with herbicides like Pendimethalin and Metribuzin for the control of bacterial wilt in tomato. Plantomycin alone or in combination with copper oxychloride have been effective in controlling the disease upon 95% (Ojha et al., 1986).

Cultural control measures such as use of healthy and certified whole tubers as seed, avoiding injury to tubers at harvest, harvesting tubers during dry weather, sorting out and destroying tubers showing signs of soft rot, planting at less depth and use of adequate nitrogen fertilizers are the main approaches to reduce Black leg and soft rot of potato caused by *Erwinia* spp. Hot water treatment of tubers has also been reported to be successful in controlling tuber rot (Wale et al., 1986).

Bacterial spot is a devastating disease of tomato through out the world which is caused by *Xanthomonas vesicatoria*. The disease can be managed effectively through integration of various management strategies such as crop rotation, field sanitation, production of disease free plants and use of disease free seeds (Jones, 1991; Jindal, 1992). Soaking the seeds in sodium hypochlorite either alone or in combination with chlorohydric acid for 20 min or application of BF-3 (dimethyle-(2 oxy-4-phenylbutone-3y1-2) as root dip for tomato plants at a concentration of 0.05% for 30 min before planting eliminates the seed borne inoculum and reduces the disease (Hernandez and Medina, 1991). Efficacy of various chemicals *viz.* streptomycin, streptomycin+terramycin, Agrimycin −100, etc., have been reported against bacterial spot of tomato (Maringoni et al., 1986). Ahn and Cho (1996) found glycinecin, a bacteriocin produced by *Xanthomonas campestris* pv. *glycine* to inhibit the growth of *X. vesicatoria*.

Among the bacterial diseases, black rot (*Xanthomonas campestris*) is one of the most destructive vascular diseases of crucifers and occurs in all parts of the temperate and subtropical zones of the world where temperature remains between 25 and 30°C and dews are plentiful. Integration of cultural, chemical and biological methods can save the crop from the disease. Crop rotations with non cruciferous crops for at least two years and application of various forms of mulches which reduce the extent of splashing of infested soils and hence secondary spread of the disease can be helpful in the management of this disease (Onsando, 1988). Since the bacterium is seed borne in nature, seed dip in hot water (50°C for 25–30 min) virtually eliminates the pathogen without affecting seed vigour. Several antibiotics like streptomycin, aueromycin and terramycin also eradicate or greatly reduce the pathogen in infected *Brassica* seeds. Soft rot/curd rot caused by *Erwinia carotovora* is a common disease of almost all vegetables in field, transit and storage. Since the pathogen is a wound parasite, care must be taken to avoid causing wounds and bruises while conducting cultural operations and at the time of harvest (Fritz and Honma, 1987). Application of streptocycline in combination with copper oxychloride has been recommended for the control of this disease (Kapoor, 1999).

Bacterial wilt caused by *Erwinia tracheiphile* is an important problem of melon and cucumber (Latin, 1996). Integrated approach including cultural practices, vector control and host resistance are important, wilted plants need to be rouged out at early stages and the disease can be managed to a large extent by controlling cucumber beetles which serve as vector. In disease prone areas, the use of a systemic insecticide applied to soil and timely spray of contact insecticides are recommended for economical production of cucurbits. Cultural practices like collection and destruction of infected plant debris, crop rotation excluding cucurbitaceous crops and use of disease free seed produced in dry areas helps in reducing the disease. Seed borne infection is effectively reduced by hot water treatments of the seed or by soaking in antibiotics and inorganic salts.

15.3.3 Viral Diseases

In general viruses are spread by use of infected seed, cuttings, and tubers and by insect feeding. No control measure is effective once the virus is established in the host. The measures for preventing the infection include planting certified virus-free material, using virus resistant cultivars, mowing weeds around the field, avoiding nearby sources of virus and reducing insect vector population (Boudreaux, 1991). Using reflective plastic mulch to delay the onset of aphid-transmitted viral diseases has also been effective to combat the viral diseases (Brown et al., 1993).

Commercial propagation of potato is normally done vegetatively, using seed tubers resulting in continuity of several viral pathogens, resulting in annual losses of $100–125 million due to viral diseases in India (Khurana, 1992). For management of different viral diseases of potato, it is normally recommended to use an integrated control package such as selection of vector free period and location, crop sanitation, use of healthy stocks, rouging, use of pesticides for control of aphid vectors, inspection and certification. A combination of chemo- and thermo-therapy coupled with meristem culture at alternating high (36°C for 16 h) and low (29°C for 8 h) temperatures assures greater virus freedom in the mericlones (Conrad, 1991; Slack and Tuford, 1995). Use of true potato seed (TPS) also holds promise for areas where quality seed is not available. However, prevention is the best policy for virus management, which can be achieved by controlling spread of viruses through avoiding contact and injury of seed/plants. Besides, movement of men, farm machinery from infected to healthy fields should be minimized (Khurana and Singh, 1997).

Tomato leaf curl caused by Tomato Yellow Leaf Curl Virus (TYLCV) inflicts heavy losses in yield depending on the stage and severity of infection (Kalloo, 1988). The disease is neither seed nor sap transmissible and the sole agency of its transmission is white fly (*Bemisia tabaci*). Adoption of an integrated management strategy taking into account crop sanitation, cultural practices, host resistance and timely use of insecticides has been found effective to reduce the disease. Careful selection of sowing dates and destruction of weeds serving as alternate or collateral hosts for the virus should be destroyed, soil mulching with straw has been found effective to repel white flies (Nitzany et al., 1964).

Tomato mosaic is a serious threat worldwide where resistant cultivars are not available. It is caused by Tomato Mosaic Virus (ToMV), the association of this virus with the disease was first reported from Connecticut (Clinton, 1909). ToMV is readily transferred from plant to plant by workers' hands, tools and clothing and in rare cases by insects (Jones et al., 1991). Various methods for the control of disease such as removal of all diseased plant parts, weeds and volunteer plants have been advocated. Cross protection by inoculation of tomato seedlings with attenuated strains of the virus by mixing 100 ml of diluted virus suspension with 1 g carborandum powder helps to protect against severe strains.

Among the viral diseases of cucurbits cucumber mosaic is the most prevalent. The disease is caused by cucumber mosaic virus (CMV). Since the virus has a very wide host range, integrated approaches including planting of resistant varieties and control of vectors by application of insecticides like dimethoate and malathion can be helpful. Mineral oils are also effective for the control of aphids.

15.4 Conclusion

Considering all the aspects of integrated disease management as discussed above, it can be concluded that while formulating any disease management schedule all the basic concepts of principles of plant disease management should be considered judiciously. Firstly, selecting locally adapted crops and cultivars that are resistant to common pathogens is an important way to reduce or prevent disease problems. Cultural practices that promote vigorous but balanced plant growth are the first line of defense against any disease, at the same time balanced irrigation and fertilizers is also important, because succulent growth of plants due to excessive water and nitrogen encourages certain pathogens. On the other hand, stress plants, especially those low in potassium and calcium, are more vulnerable to diseases such as early dying and to physiological disorders such as blossom end rot of tomatoes. The most important water management practice is providing drainage to avoid waterloging in soil around root zone, because seeds and seedlings are likely to rot in wet soil. It is always possible to reduce the disease-spreading inoculum in the field by using disease free planting material, careful crop rotation, increased soil organic matter content and good sanitation. Increasing the organic content of soil enhances saprophytic microbial activity, which lowers population densities of soil borne pathogens. All these factors can be manipulated to contribute toward achieving the goals of IPM. The concepts of disease management also highlight that IPM requires a long-term understanding of the ecosystem and the approach must fit within a farming system context and not be perceived as an add-on.

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Chapter 16
When Is a Rice Insect a Pest: Yield Loss and the Green Revolution

James A. Litsinger

Abstract As land area to expand rice production is limited most increases in crop production in Asia must come from increasing yields on farms already under production. Insect pests are among the most important biological constraints limiting yield potential of modern rices but the extent of damage depends on how vigorous the crop is growing as well as the number of biotic and abiotic stresses affecting the crop that season. Yield loss data is useful for farmers, extension workers, researchers, and policy makers. A number of methods to estimate losses are available and more than one should be used. As accurate crop loss assessments are expensive to obtain for a nation on a regular basis, estimates are only available for limited areas of countries. Insect pest resistance exists for epidemic pests but not for chronic pests, the insect pest group that causes greater losses every year. Modern high tillering rices have greater capacity than traditional rices for compensation from insect pest damage and that capacity is enhanced by agronomic practices thus integrated pest management should be thought of within the context of crop management. For making better control decisions farmers need to assess the compensatory status of the crop and severity of crop stress acting on it. Due to crop compensation capacity, farmers need not correct all stresses to obtain high yields thus can combat the easiest or least expensive constraints and let the crop compensate for the rest. If nations are to get a handle on the extent of losses, farmers will need to be involved in the data gathering.

Keywords Rice yield loss · Asia · Insect pests · Crop loss assessment methods · Yield gaps · Biological constraints · Integrated pest management · Rice environments · Compensation and tolerance

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J.A. Litsinger (✉)
IPM and Farming Systems Specialist, 1365 Jacobs Place, Dixon CA 95620 USA
e-mail: jlitsinger@thegrid.net

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16.1 Introduction

On a worldwide basis, rice is the most important food crop, constituting the staple for over half of the people. It is primarily a subsistence crop as more than half of the world's harvest is consumed on the farms where it is grown. In Asia most land suitable for growing rice is already dedicated and only limited additional land is available for expansion. Irrigation, which would allow an extra rice crop to be planted, is dependent on an increasingly scarce commodity, water. Ultimately the world must now focus on increasing the yield potential on existing fields as a means of increasing production (Barr et al., 1975). Yet world production has barely been able to keep pace with its increasing population setting off a vicious cycle as adequate nourishment is seen by some as a prerequisite for self regulation of human reproduction (Way, 1976).

World production of rice continues to face a critical stage as the Green Revolution's contribution has been declining in light of increasing population and urbanization. World population increase has also meant that the average farm size is steadily decreasing thus greater production is needed on an ever smaller land base. The past 10 years has witnessed a fatigue in the Green Revolution with the growth rate in food grain production falling below population growth (Swaminathan, 2006). A famine of jobs/livelihoods is the result of poor growth of opportunities for employment in the rural non-farm and off-farm sectors, and along with rising prices is leading to a famine of food at the household level.

Globally food production will need to double in the next 25–30 years (Tillman, 1999). The Indian prime minister recently emphasized the need to double that nation's annual food grain production from the present 160 million tons of rice by 2015 (Swaminathan, 2006). Since farm sizes are shrinking, this job is made even harder as in India 80% of farms belong to the marginal and small farmer (< 1 ha) categories. The cost of agricultural production is rising higher than the minimum support price due to ever-increasing prices of inputs including energy. Investment in agriculture has declined over the past two decades. This has affected irrigation and rural infrastructure development. Due to the constellation of hardships faced by small-scale farmers, the number of Indian farmer suicides has reached alarming numbers. Farm indebtedness is rising. Average monthly per capita consumption expenditure of farm households nationally is around $12. Endemic hunger is high both in families without assets of land or livestock, as well as in families with small holdings without access to irrigation.

In response to the food needs of developing countries in the 1960s, international agriculture research centers were established in Mexico for wheat (CIMMYT) and the Philippines for rice (IRRI). Soon new high yielding rices were bred which doubled the yield potential, and as they were photoperiod insensitive, two rice crops could be grown instead of one. Production thus was quadrupled. The optimism produced by the modern rices of the Green Revolution was quickly dashed by the large insect pest and vectored disease outbreaks throughout Asia (Litsinger, 1989). In the 1970s, a combination of bad weather and planthopper and leafhopper induced epidemics caused production in a number of countries to fall by an order of 30%

or more (Barr et al., 1975). Outbreaks from insect pests have been recorded on rice since 18 AD in Korea and from 701 AD in Japan with the most frequently recorded from rice planthoppers leading in some years to localized famine (Mochida et al., 1977). These calamities showed that sudden unpredictable events can shake the confidence of seemingly normal conditions. The world's food supply is always under threat from such unknown events. With the effects of global warming upon us we can expect an increase of such situations worldwide.

Until the population growth rate stabilizes worldwide, food production will have to be accelerated to keep up with demand. This increase in production can be achieved in four ways: (1) expansion of cultivated land, (2) annual multiple cropping, (3) increase in yields obtained from inputs (varieties, fertilizers, irrigation, etc.), or (4) reduction in losses due to crop stresses including pests. In the latter case large increases in food supplies can be achieved rather rapidly simply through wider adoption of current technology. Losses from all types of pests each year in grain alone are estimated to exceed the gross and net food grain deficits of the developing world (NRI, 1991). It is clear that if these losses could be reduced, food supplies would be increased without bringing new land or other limited resources into play.

In order to cope with the burgeoning pest problems in the 1970s, the concept of integrated pest management (IPM) based on ecological principles was introduced into Asia from industrialized countries and over time the new knowledge gained has resulted in management systems that have mostly pacified the once turbulent pest outbreak situation (Matteson et al., 1984, Gallagher et al., 1994). Savary et al. (2006) wondered why there are so few crop loss studies despite the fact that the basis for economic entomology is quantitative knowledge of losses. Still few reliable estimates exist in the literature as so many of us take for granted the need to control a pest. The first step in IPM is to identify the problems to be managed (Apple, 1980) which includes a determination of losses as well as the correct identity of the pests responsible. Thus crop loss assessment may be viewed as a problem definition discipline providing the necessary information for assessing and evaluating system performance. Crop loss assessment links pest injuries to possible qualitative and quantitative damage and yield loss to resulting economic cost. The framework advocated by Savary et al. (2006) links different types of knowledge on crop loss (e.g., damage functions, compensation/crop tolerance, injury profiles, multi-pests and multi-stresses, crop management, weather, and plant maturity and genetics) to a range of decision categories from tactical and short and long term strategic decisions including probabilistic treatments of injury-damage relationships. Neither insect pest populations nor crop losses are static – they tend to vary by season and location. Even when infestation/damage to rice appears high, the losses may be small and control would be uneconomical. The intensity and effect of damage depends on the stage of the crop and confluence of the many biotic and abiotic factors that influence crop growth. Entomologists can measure plant damage but often do not know the relationship between yield loss and infestation level needed in the design of corrective control decision-making thresholds.

Information on the amount of food lost to insect pests and vectored diseases is even more unreliable or has simply never been assessed in some countries because of the lack of manpower, knowledge, or resources (Walker, 1975). Crop loss assessment requires data on pest density, their biology, distribution in space and time, and the relation between pest damage and yield. Estimates of crop losses are few and scattered in the literature (Cohen et al., 1998). Wide areas of uncertainty exist which can and do influence assessments from:

1. Influence of climate that can upset food production projections,
2. Problem of the interaction of losses due to several factors such as two insects, a disease, lack of fertilizer, drought, and flooding where the contribution of each may or may not be additive,
3. Effect of rapid changes in normal crop production from introduction of new varieties, a new irrigation system, etc. and
4. Influence of economic factors such as price changes.

There are some 800 insect pest species that have been recorded to feed on rice (Grist and Lever, 1969). In tropical Asia there are some 18–20 species that are considered to be pests of major importance and regular occurrence (Pathak, 1968). Rice stemborers are probably the most serious group and usually 1–4 species are important in any given area.

Among the pest groups (weeds, diseases, etc.), rice suffers the most losses from insects. In Japan, where farmers utilize maximum crop protection measures, loss from insect pests is $< 2\%$ annually (Cramer, 1967); if India adopted these measures it could double food production as Cramer calculated a 36% annual loss there. Despite impressive technological advances during the first decade of the International Rice Research Institute's (IRRI's) existence, national production data showed increases barely able to keep pace with population growth in developing countries despite the Green Revolution (Barker, 1979).

There is tendency, however, for rice loss figures once published, to get passed on through the years in the literature, to become often quoted values for want of anything else, when its relevancy to the average annual situation or to current conditions should probably be suspect (Barr et al., 1975). The literature abounds with phases such as 'most destructive pest', 'serious pest', 'heavy crop losses' and 'major losses annually' rather than precise figures. Estimates of crop losses caused by insect pests are generally based on educated guesses or on a small number of experiments in limited locations and therefore are not reliable and objective (Khosla, 1977; Cohen et al., 1998).

Even when figures are available, often a distinction is not made as to whether the losses given pertain to a particularly bad year or to a more normal year, and often estimates appear to apply to the area badly affected by the pest with no accompanying information as to the extent of the affected area (Barr et al., 1975). Despite these obvious shortcomings, the information which exists when taken together gives a sense of the enormity of losses in developing countries although the magnitude of the enormity may not be known precisely. Due to great methodological difficulties of accurately sampling and measuring levels of pests of all kinds and correlating these with losses in yield, no detailed statistical studies have been made to consider the collective importance of all rice pests over sizeable areas.

16.2 Dynamic Nature of Yield and Loss

The dynamics of harmful pests may lead to plant injury on the standing crop which may or may not be visible to the observer. Injury leads to damage which may or may not lead to yield loss or reduction of crop value in economic terms (Litsinger, 1991). Pest assessment studies frequently show that crops vary greatly between sites and between years in their response to attacks even by similar densities of insects (Litsinger et al., 2005). At the other end of the scale there can also be great variability in the reaction of individual plants of the same crop. Damage is not always proportional to the size of the pest population, and therefore productivity (ie., food consumption and utilization) is no index of the damage done (Bardner and Fletcher, 1974). Studying the effects of insects on crop yield usually entails investigating the effects of populations of insects on populations of plants. These effects cannot often be predicted by extrapolation from the results of experiments with individual insects or individual plants because they are usually in competition with others of the same species for resources needed to grow, survive, and reproduce. Even individual organs on plants are in competition with each other for light and photosynthetic assimilates.

The damage from rice stemborers such as the larva of the stalk-eyed fly *Diopsis* spp. may be compensated if conditions are favorable, thus all insect damage is not necessarily negative (Feijen, 1979). There are reports of indirect yield benefits from insect damage (Brown and Marten, 1986). Akinsola (1984) found field studies sometimes gave erratic results as there were instances where hills containing tillers bored by *Maliarpha separatella* in Ivory Coast produced higher yields than unattacked hills. In addition some varieties recuperated more than others after a severe infestation of rice hispa *Dicladispa armigera* in Madhya Pradesh, India protected with insecticide sprays (Rawat et al., 1980a). The variety Ratna recouped almost six-fold compared to untreated. Both of these examples show the importance of basic data on losses in relation to insect infestation, and that data are often lacking or conflicting (Schulten, 1989).

Another observation that influences the dynamic nature of crop loss assessment is the large variation in field to field yields common within Asian rice farm communities. A normal result from a large sample is that yield will vary between 1 and 9 t/ha over a population of farmers (DeDatta et al., 1979; Pingali et al., 1990). The range of yields in the Filipino farmer populations of three sites is shown in Fig. 16.1 for the wet and dry seasons confirming these results. The data are averages of individual crops as reported by 20–40 farmer respondents randomly selected over the range of planting dates each season for over a decade. Due to the monsoon climate affecting Luzon Island, the yield ranges between Zaragoza and Guimba sites in Nueva Ecija were on average 1 t/ha lower than in Koronadal, the Mindanao Island site, which is under the influence of the Intertropical Convergence Zone climate. Differences relaxed in the dry season for all three sites. The range in yields was between 2 and 8 t/ha. Such large differences are often attributed to differences in management skills between farmers. Some farmers in such a sample equaled or surpassed yields registered on research stations, while others mismanaged their

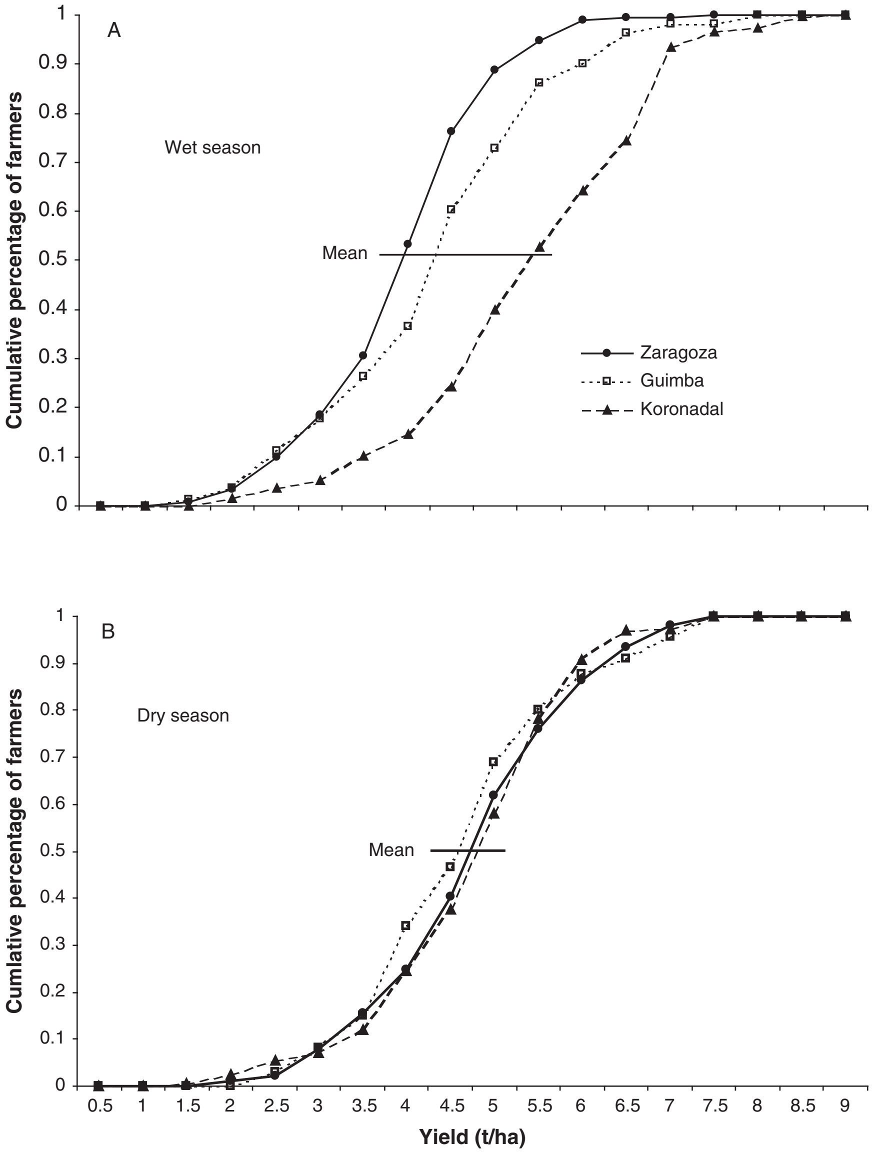

Fig. 16.1 Range of yield as reported in the wet (**A**) and dry (**B**) seasons by farmers surveyed in three irrigated rice sites in the Philippines 1981–1991. Some 20–40 farmers were interviewed per crop over 14 crops in Zaragoza, 11 in Guimba, and 18 in Koronadal (after Litsinger et al., 2005)

fields through poor pest, water, and fertility management among other causes or experienced unfavorable weather. The wide range of yields points to a large proportion of rice crops in the Philippines being under stress from a number of potential causes.

Analysis of the above farm record keeping database revealed a surprisingly different reality: the same farmer can experience yield swings of the magnitude shown above from season to season (Table 16.1). With each of the four farmers from two provinces, one can note the disparity of yield even within the same season for a pair farmers from the same location. This calls to question DeDatta's and Pingali's classifications of farmers which inferred that the best managers always attained the highest yields. This classification perhaps should be amended to the best managers 'per crop'. It also points out that even the best managers can get very low yields from

Table 16.1 Survey results of four farmers from two locations over a decade showing the season to season yield variability, Zaragoza and Koronadal, Philippines, 1982–1991[1]

		Zaragoza, Nueva Ecija				Koronadal, South Cotabato			
		Mr. Espiritu, 2.5 ha		Mr. Legazon, 2.5 ha		Mr. Rombaoa, 1.75 ha		Mr. Nelmeda, 1.5 ha	
Year	Crop	Cultivar	Yield (t/ha)	Cultivar	Yield (t/ha)	Cultivar	Yield (t/ha)	Cultivar	Yield (t/ha)
′82	WS	IR36							
′83	DS	IR42	2.5			IR56	4.7	"43"	5.1
′83	WS					IR60	4.4	IR60	5.9
′84	DS					"4.3"	5.5	Ri-10	4.8
′84	WS	IR42	2.4	IR42	4.5	IR60	7.1	IR60	5.7
′85	DS	IR56	5.4	IR36 IR42	4.4	IR60	1.8	IR60	4.7
′85	WS	IR62	3.5			IR64		IR60	5.3
′86	DS	IR64	6.0	IR64	5.4	IR60	4.8		
′86	WS	IR64	4.3	IR64	2.9	IR60	3.7		
′87	DS	IR42	6.5	IR64	5.0	IR64	5.0	IR66	5.6
′87	WS	IR66	5.1	IR42	4.2	"56"	4.3	"–6"	5.6
′88	DS					"43" "56"	6.4	IR72	2.7
	WS								
′88	DS					"56"	5.0		
′89	WS					IR74		"36"	5.5
′89	DS					IR74	6.2	"–36"	3.9
′90	WS					IR64	6.0	"90"	5.3
′90	DS					"90"	5.3	"90"	5.0
′91	DS					"90"	6.6	IR72	4.8
′91	WS	IR64 RC2	4.4	IR60 AG-O-O Milagrosa	2.8	IR60	5.6	"–33"	5.1

[1] WS = wet season, DS = dry season. Farm size in hectares is given for each farmer, yields in bold font show extremes per farmer.

forces apparently beyond their control. Thus the level of risk that irrigated wetland farmers face, which is the most stable of rice environments, is high.

There are also a number of issues that affect the interpretation of crop loss data as spelled out by Teng and Revilla (1996). The first is the time frame over which the data is collected. Most crop loss assessments are carried out for only a few crop seasons while they advocate that an ideal time series would be at best 10 years. Also the area covered in the studies is often very limited in geographic scale and may not be representative of major rice growing regions in the nation. Controlled studies are carried out in greenhouses may not be reliably extrapolated to farmers' fields. Finally the data are only applicable to certain crop management practices such as transplanted rice and may need to be recalculated if direct seeding were introduced, new genetic plant types grown, or IPM was introduced. Even when data are collected from many years or over a whole country the results can vary tremendously, for example stemborers in India and Indonesia losses were found to vary between 0 and 95%. Teng and Revilla (1996) point out that most data relates to small geographic areas as in no case did a country suffer 95% loss in rice production in a given year.

16.3 Framework of Yield Loss Concepts and Aims of Crop Loss Assessment

Teng and Revilla (1996) outlined a schematic diagram that defined the various yield gaps associated with crop loss assessment. They recognized three yield levels, the first of which is the actual farmer's yield that is under influence of yield reducing biotic and abiotic stresses. Farmers have the potential to reduce pest losses to obtain an economic yield potential which gap represents the crop loss measured by most national programs. A higher yield level can be obtained in most research stations where yield reducing constraints can be eliminated to a greater extent than can be done on farmers' fields to attain yield level 2 and the gap between farmers' actual yield and researchers' attainable yield is the crop loss measured by FAO. An even higher yield level 3 is the maximum potential yield that can be obtained in a certain environment as determined theoretically by crop modelling which defines the last yield gap if abiotic and genetic inputs were optimal.

Savary et al. (2006) outlined a series of steps in the evolution of crop loss assessment aims reflecting context and use. The first is empirical knowledge of environment-pest injury relationships that often lead to insecticide decisions based on assumptions on harmfulness. These are often wrong leading to overprotection or underprotection. A second step is empirically derived decision models and economic thresholds. The third is mechanistic single pest simulation models linking single pests to crop growth models to understand plant physiological relationships while the fourth introduces multiple pests and stresses. The fifth step is to scale up from the field level to larger geographic units that allow relating field survey data to crop loss estimates. Finally probabalistic data regarding a particular location that includes levels of risk of pest damage.

16.4 Rationale for Measuring Yield Losses

Pest populations building up in crops may have economic, social, and even political consequences. These consequences stem from the diversity of effects or injuries caused by pests: direct losses (in yield, in quality, or costs of replanting), or indirect losses (at the farm, community, or consumer level). Government food grain agencies need to manage buffer stocks based on predicted crop production to ensure steady food supply (Schulten, 1989). Errors in this calculation can have serious consequences which in times past have led to riots resulting from rice shortages causing changes in governments in Liberia and the Philippines. Defining the economic status of pests is also needed to budget public funding for research, extension, and training activities in plant protection (Agyen-Sampong, 1988).

Crop loss assessment is also central to one of the basic tenets of IPM which is to minimize insecticide usage. The main tools for insecticide decisions are economic thresholds which are pest densities that trigger a corrective action before the damage reaches the critical economic injury level (Norton and Mumford, 1993; Morse and Buhler, 1997). These tools are based on the economic injury levels determined from the relationship between increasing pest densities and yield loss termed the damage function. Action thresholds are surrogates for an economic threshold that are determined empirically if the damage function is not known (Bandong and Litsinger, 1988; Smith et al., 1988). Savary et al. (2006) categorized this as tactical decision making. The economic injury level concept is unique in that it integrates the disciplines of biology and economics.

In addition crop loss assessment is useful to estimate the effectiveness of control measures and introduced strategies and methods of pest control. Loss data can also play an important role in creating awareness of the need for pest control and the need to improve management strategies. Savary et al. (2006) distinguished short and long term strategic goals. Short term includes decisions on the choice of variety, planting time, prophylactic insecticides, nutrient management to bolster tolerance, and avoid resurgence causing insecticide. Long term strategic goals guide in selecting between highly resistant or moderately resistant genotypes or creating pest risk zones. Yield loss data attributable to pests are all the more necessary when agricultural systems are undergoing rapid and important transformations, such as from changes to direct seeding in place of transplanting or with hybrid rices instead of open pollinated types, so that the risk associated with such changes can be assessed from a plant protection viewpoint (Walker, 1975).

16.5 Crop Loss Information for Whom?

Clients of IPM programs such as farmers, extension workers, and agricultural policy makers want more management options to respond to pest threats they perceive (Kenmore, 1987). Such clients have been managing pests for years, using their own perceptions of crop losses and developing attitudes to crop losses from pests. They want to know what to do for the crop at hand and possibly for one crop in the future. Farmers and administrators usually perceive pest losses to be intolerable. They regard chemicals and especially insecticides as essential to rice production. In contrast field data suggest that insecticides are not essential in every rice crop. No more than half of the crops studied in Filipino farmers' fields exhibit significant yield increases with insecticides (Litsinger, 1984). Practical IPM programs must stay close to the clients and provide advice that they can understand and use. Where these large discrepancies between clients' perceptions and IPM field results come from needs to be addressed.

16.5.1 Researchers

A number of researchers studied crop losses to determine the causes due to injury from single insect pests or multiple pests or all types including abiotic crop stresses. This line of research should lead to better pest control technologies which will produce the greatest yield gains. From the scientists' point of view, identifications of discrete pest entities and their causal relationships to yield losses are pre-requisites for successful understanding and use of IPM (Goodell, 1984). A pillar of IPM is knowledge of the contribution of each pest to total yield loss. If the loss is subeconomic then there is no value in attempting control. Often crop loss assessment is added after the IPM program is already launched, thus programs have to rely on scientists' viewpoints which are largely best guesses. Normally neither extensionists nor farmers are consulted.

There are also researchers who have been publishing articles on losses using more refined approaches, most of which seem to be written for other scientists and not for clients with problems. Researchers' main concern when doing yield loss studies is to determine which pests warrant expenditure of scarce funding. One needs to justify this to research managers. When researchers speak to clients they present formulations full of internal rigor but with little evidence of the clients' expressed needs. Practical IPM programs and research managers must borrow from the literature to answer some of the questions asked by clients.

16.5.2 Extensionists

Without crop loss assessment, extensionists who are invariably blamed for the failure of such campaigns have no means of estimating the difficulty they actually face in promoting IPM, no means of measuring what proportion of yield increases can be attributed to IPM adoption, and no means appraising different IPM measures (Goodell, 1984). Most extension workers, let alone farmers, are not able to distinguish between damage and decision thresholds due to lack of training. While researchers have more skills to assess losses they are ill equipped to do so due to budget and manpower constraints. Extension agents, however, have the manpower to measure losses and are stationed throughout rice growing areas but such a job is highly demanding and is a low priority activity in most countries (Teng and Revilla, 1996). If yield loss relationships were determined, all the extension workers would need to do would be to monitor pest abundance.

16.5.3 Farmers

Goodell (1984) concluded more research is needed to measure crop loss and it is time to incorporate the farmers' perception of loss. Farmers' perceptions of crop loss should be compared to replicated yield loss studies to assess accuracy. Farmers tend to overestimate losses from chronic pests probably based on their experience from epidemic pests prompting insecticide overuse (Heong and Escalada, 1997).

When crop loss assessments of rainfed rice farmers are placed in the context of their entire economic portfolio, many may find any type of insect control unrealistic (Goodell, 1984). If farmers are already suffering yield reductions of 50% or more due to drought stress and declining soil fertility, and if for centuries they have kept livestock to buffer them during periods of crisis, then even a 30% loss to pests may not justify their adopting IPM. To estimate these felt crop losses for the purpose of planning, extension entomologists probably need to enlist social scientists. Occasionally the attitudes and perceptions of farmers can be changed through training (Escalada et al., 1999). Awareness training may bring the clients closer to what analytical or reductionist scientists can offer (Kenmore, 1987).

When farmers misidentify the causes of damage observed in their fields, they may spray an insecticide to combat a fungus. Without objective standards for evaluating the impact of yield and profits of each chemical treatment, they may conclude that their yield was saved even when there was no effect (Kenmore, 1987).

As some of these interactions may take place at low densities, the farmer has reason to feel insecure about ignoring low density populations, even though IPM demonstrations show that yields will not be affected by such low populations. If farmers apply insecticides and yields are high because pest populations never reached yield reducing levels, they will be reinforced in this behavior, all because practical field assessments of crop losses have not been done (Kenmore, 1987).

The majority of irrigated rice farmers in the Philippines regard pest damage as intolerable and unavoidable if no action is taken (Marciano et al., 1981; Brunold, 1981). This is true of farmers worldwide whose motivation is apply insecticide to their crops as insurance against loss rather than as an investment because they always perceive the pest threat as quite serious. More rice farmers use pesticides in irrigated rice than fertilizers in some areas. In a survey in Leyte 65% of farmers said calendar spraying was the best method and in addition 67% said the more one sprays the higher the profit, while 71% said sighting a few butterflies in the field meant to start spraying (Kenmore, 1987).

In the same study, there were different responses by farmers with different income levels: 56% of richer farmers said prevention was their biggest problem while none in the poorer villages said so but named specific pests as threats that had already invaded their fields (Kenmore, 1987). Thus richer farmers overestimated the threat as compared to field trial results far more than poorer farmers. Richer farmers tend to hire others to do crop monitoring and have more money invested so they want insurance. They also want to protect their social status as progressive farmers and impress the extension worker. Poorer farmers know what pests are present and have less money invested.

To answer our question of why the difference in farmers' behavior with field evidence:

1. One reason may be they have misidentified pest damage,
2. Farmers also want insurance (due to their ignorance) and feel that pests, unlike weather, can be controlled with insecticides,
3. Some of it is the interaction of crop growth stage with multiple pests, and
4. Also yield is very difficult to estimate as the difference may be 30% due to solar radiation from planting a month later or earlier (Evans and DeDatta, 1979)

With these uncertainties it is reasonable for farmers to conclude that losses are unavoidable and treatment is always needed (Kenmore, 1987). Farmers still need better crop loss assessment to help them rank and select their crop management options before and after each season.

16.5.4 Administrators

The objectives of administrators and policy makers is to ensure adequate food supplies for a nation. They are even several steps removed from the field, and must rely on reports from overworked or unreliable field scouts, thus are even in weaker positions to judge the benefits derived from chemical treatment (Kenmore, 1987). As they often prefer to act quickly and appear decisive they may order treatments and never evaluate them because the action alone serves their political purpose and a negative evaluation can only weaken that purpose. Clients continue to perceive pesticides as essential and act accordingly without testing that perception.

Like farmers their attitude is qualitative not quantitative and they tend to exaggerate damage (e.g., epidemics of tungro and brown planthopper *Nilaparvata lugens*) when there was little evidence of any yield actually loss. Thus they order insecticides before the season to prepare for a 'panic threshold' to be reached and as essential production boosters. Rice is a political crop, as cheap rice means political stability in the urban areas.

16.6 Where to Measure Losses

16.6.1 Research Stations

Research stations have been used as reference points to determine the yield potential of rice compared to farmers' fields. In the 1970s there was a lag phase in the adoption of modern rices and their management which was measured as the yield gap between research stations and farmers' fields (Barker, 1979). The yields taken on research stations were considered to be the highest attainable because of the more optimal conditions of water management, soil, and pest control that could be attained there. IRRI launched the Constraints Program to determine why farmers' yields were not reaching the potential of research stations. The constraints were categorized as environmental, technical, economic, and institutional (DeDatta et al., 1979). A number of environmental constraints are recognized to keep farmers' yields low: lack of sufficient and timely rains, floods, problem soils, and low solar radiation in the wet season. Technical and management constraints are inadequate irrigation water and pest control, use of lodging varieties, and ill timed and low fertilizer rates. Economic constraints include high costs of inputs, increased labor requirements, farmers' education level, and unavailability of inputs. Institutional constraints include lack of affordable credit, lack of timely input supply, irrigation system in disrepair.

Trials were set out in experiment stations and farmers' fields that looked at the contribution of fertilizer, weed control, and insect control on yield in the Constraints Program. The results differed by location but in general highest yields were obtained at research stations (IRRI, 1979). Barker (1979) described the phenomenon. The introduction of a new technology creates a yield gap and what economists call 'economic slack'. This is the difference between the present product of a sector and the product that could be realized if all resources were optimally utilized. It took Filipino farmers until the late 1980s to master the management of agro-inputs. The illuminative study in Luzon of Pingali et al. (1990) showed that by the late 1980s yields of the top one third of farmers matched those of research stations where the top one third of farmers achieved yields over 5.5 t/ha in the dry season and 4.5 t/ha in the wet season. As was seen in Fig. 16.1 but not appreciated by the study is that the top and bottom yielders could be the same farmer in a different season.

Research stations, however, are not always the most ideal of environments to attain high yields. On the IRRI Experimental Farm breeders grow susceptible cultivars in order to subject the latest lines to insect pest and disease pressure. Consequently the IRRI Farm had a high endemic tungro incidence which can affect the estimation of pest losses as yield of the untreated check will be lower than normal. Pathak and Dyck (1973) reported insect pest losses measured by the insecticide check method on the IRRI Farm from 1964 to 1971 where protected trials averaged 5.8 t/ha compared to 3.1 t/ha without. This resulted in almost 50% yield loss determination. However the fields were planted to susceptible varieties in order to test insecticides and thus were not representative of farmers' conditions. These high losses were widely circulated as were others from Philippine research stations that led the perception that insecticides were 'required' for high yields. The government therefore recommended prophylactic insecticide protection in its Masagana 99 rice production program. It was concluded from this data that to grow rice one needed to apply 4–5 insecticide applications. Studies later showed that this was a misconception (Gallagher et al., 1994). Cramer's (1967) often quoted losses were also taken from insecticide trials, many of which were conducted on research stations and timed when the highest populations occur.

16.6.2 Farmers' Fields

The Constraints Program early on identified two common concepts (Barker, 1979). One is to compare the potential yield from experiment stations with the present yield in farmers' fields as explained above. The second was to compare the yield of the best farms with the poorest. He concluded that yield gaps need to be determined within each location with its own yield ceiling. We saw from Fig. 16.1 if one measured the yield gap between the best and poorest farmers the wrong conclusion would emerge. It is not necessarily that the farmers with the lowest yield do not know how to manage their farms but that other factors are to blame. Economists should now determine what these are but high on the list should be effects of the weather. Zaragoza is located at the end of a large irrigation system and the wet season crop often matures at the time of the arrival of large scale typhoons. On the other hand Koronadal under the influence of the Intertropical Convergence Zone is regularly affected by El Niño droughts. Farmers often are not in charge of determining the timing of irrigation water delivery so chance plays a large role.

Constraints to high yield can be classified into two categories: those that affect the yield potential of the crop under the farmers' environment and those that affect the farmers' ability and willingness to achieve the yield potential on their own farms. The first is related to the potential of the new technology itself based on research and the local environment while the second encompasses the ability of farmers to learn how to apply the new technologies with optimal results (extension success) and knowledge building as well as overcoming institutional constraints of input supply, credit, water delivery, and land ownership.

16.7 Typology of Insect Plant Injury

Metcalf and Flint (1962) provide the most comprehensive description of the multitude of insect injuries to crops. The most conspicuous are those caused by insects feeding on plant tissue or sap (Bardner and Fletcher, 1974). Aside from direct plant injuries other major causes associated with feeding are injection of toxins, infection by plant pathogens, and the fouling of plant organs with insect bodies and insect products. Injuries less frequently encountered include laying of eggs on or in plants and the use of plants for the construction of shelters.

The reactions of plants to injury are often very complex. Although the nature, site, and intensity of the injury are important, the effects of injuries on yield depend very much on the growth process of the plant, its genetic constitution, stage of development, and on various environmental factors affecting its growth (Bardner and Fletcher, 1974). An understanding of some of these processes is provided by the results and theories of crop physiology, especially the techniques of plant growth analysis, which evaluate growth in terms of effective photosynthetic area and the production of dry matter and its distribution between various plant organs.

Differentiation of insect pest guilds can be made based on the effect of plant injury on the growth processes of a plant (Litsinger, 1991):

1. Tissue consumers = defoliators
2. Leaf senescence accelerators = planthoppers, leafhoppers
3. Stand reducers = armyworms, caseworms
4. Light stealers = planthopper honeydew and sooty mold
5. Photosynthetic rate reducers = whorl maggot *Hydrellia philippina* and stemborers
6. Assimilate sappers = planthoppers, leafhoppers, seed bugs
7. Turgor reducers = root feeders and stemborers

As can be seen a single insect pest may affect more than one physiological pathway. The first four guilds affect the amount of solar radiation intercepted while the last three on how efficiently it is used. Tissue removers do more damage than sappers because the plant has to allocate energy for tissue replacement as well as photosynthate. Plants are not passive recipients of damage and can repair, regenerate, and compensate.

The causes of decreased yields are easily identified when attacks kill plants or destroy yield-forming organs. Even so the quantitative relationship between the number of pests or injuries and yield can be complex if there is compensatory growth in the surviving plants, or if resistance to attack varies with crop age. For example, damage by both an armyworm larva and rice caseworm, injuries are confined to the destruction of leaf tissue and can be simulated artificially. Differences between the effects on yield of various combinations of insect injuries were shown to be caused by variations in the amount of leaves eaten and the distribution of injuries between leaves, both of which affected the production of dry matter. The growth pattern of the plant was also important as it determined the distribution of dry matter between roots and leaves. The decreased yield of roots and leaves resulting from attack by one larva was between 0 and 22 times the energy content of the leaf tissue eaten by the insect, depending on the effectiveness of compensation (Bardner and Fletcher, 1974).

Plant physiologists have found that in some cases the yield of the rice grain (metabolic sink) is limited by its inability to store all the photosynthate produced by green tissues and stems (the source) (Bardner and Fletcher, 1974). Under these conditions some loss of foliage might be tolerated without affecting yield. Yield formation in rice provides an explanation of the effects of attacks by stemborers. In unattacked crops wide variation in sowing rate results in similar numbers of panicles per hectare and similar yields. But the maximum number of shoots is usually several times as great as those which survive to produce panicles, many dying at an early stage through competition for light, nutrients, and space (Yoshida, 1981). Larvae feed during the period of shoot production and they cannot affect yield directly as very little of the dry matter produced by the plant before panicle emergence finds its way into the grain, which obtains most of its dry matter from photosynthesis in the flag leaf, the stem above this, and the panicle itself. The principal effect of the larvae is to kill potential ear bearing shoots, and as these are produced in excess, considerable compensation by the crop is possible.

One effect of sucking insects is to create an extra sink for assimilates which interferes with the normal partition of these products among the various plant organs. The effects on growth are complex especially as many sucking insects also have toxic saliva. Fouling of honeydew and subsequent sooty mold can be a secondary cause of loss in crops attacked by planthoppers because this encourages the growth of molds and lessens the amount of light reaching chloroplasts.

16.8 Methods to Measure Yield Loss

Barr et al. (1975) concluded that it is not surprising that most developing countries do not have the capability to conduct comprehensive surveys designed to assess losses due to various types of pests on any reliable and consistent basis, let alone on a detailed annual basis. A serious pest in the wet season rice crop may not occur in the dry season and vice versa. An insect pest which greatly damages dryland or rainfed wetland rice will not affect an irrigated crop as much and vice versa. One variety under cultivation may be devastated if a pest occurs in large numbers while another may have inherent resistance or tolerance and sustain relatively minor damage. Since the size of losses may vary with the year, the growing season, the type of culture, the variety being cultivated, the composition of the pest complex, etc., the design of an experiment to estimate loss needs careful examination and once determined needs to be defined under specific conditions. Crop loss assessment is a science in itself, requiring the best efforts of crop protection specialists, statisticians, and other experts to arrive at reasonably sound figures. Many projections of losses lack corroborative data on actual field losses. Zadoks (1987) outlined its historical development.

Serious and often catastrophic attacks by insects on crops have been recorded throughout history, though objective attempts to measure losses caused by insects only began in the 20th century. Pest assessment both on a local and on a national scale is now a well established branch of agricultural entomology and many methodologies of crop loss assessment have been developed. FAO pioneered efforts to standarize concepts, methods, and estimates of losses on a global basis (Litsinger, 1991).

Crop loss assessment researchers need to take note of the following factors that may influence the validity on loss data before extrapolating results from small scale trials to regional loss figures (Litsinger, 1991):

- Experimental fields are not representative,
- Influence of crop management which should be tested under typical conditions,
- Low yields may be viewed as normal due to hidden damage,
- Damage by several pests on the same crop may be synergistic, neutral, or antagonistic,
- Losses may be due to other causes than pests, and
- Methods to measure losses may be inaccurate.

Accurate estimates of insect damage and the economics of preventing pest damage are difficult to make because pest populations vary from season to season. Given the importance of variability in insect pressure, valid indicators of yield losses must be based on large samples of observations and be representative of some particular area. Moreover data should be analyzed as a sample from a population: no observation should be considered as separate or unrelated. Yield loss determinations for a single pest when other pests are present is particularly difficult.

Many methods to estimate yield loss from insects were reviewed by Litsinger (1991) and the present discourse will be an update. Estimation of the crop response (yield loss or gain) to a single pest attack or abiotic stress factor (moisture availability, temperature, etc.) is an equally difficult research objective. Conventional approaches that have been used to assess crop response to insect attack can be grouped into one of four categories: (1) observation of natural populations, (2) modification of natural populations, (3) establishment of artificial populations, and (4) damage simulation.

16.8.1 Key Informant Surveys

The relative importance of rice pests was determined in Indonesia (Geddes, 1992) and from five countries in South Asia (Geddes and Iles, 1991) where the country or region was divided into agro-climate zones and a large number of experts were interviewed to rank all categories of pests on the main crops from each region. A scale was made to rank the responses and summarize the results from all categories of pests ranked together. This method is the least analytical as perceptions are involved rather than field studies.

16.8.2 Comparing Damaged and Undamaged Plants

This method usually involves taking insect counts on individual plants from several fields, first exemplified by Ishikura (1967) in Japan to assess losses from second generation rice stemborers. Samples of damaged and undamaged panicles were taken and the decrease in grain weight of infested stems was multiplied by the number of infested tillers per unit area. This method seemed satisfactory, except if the infestation is light or when infestation occurs late in the crop cycle. But Ishikura noted that moths generally prefer rice plants of luxuriant growth for oviposition, thus assessment of loss is influenced by the selective nature of the pest and as such losses are underestimated when selecting panicles from both infested and uninfested ones.

Brenière and Walker (1971) assessed the loss due to *Maliarpha* stemborer in Madagascar by recording the number of tillers bearing filled panicles, partly empty panicles, and dry empty panicles. The weight of fully developed panicles and partly empty panicles was also recorded to give the yield reduction ratio. Yield loss was calculated by multiplying the total yield/ha by the yield reduction ratio. This method gives loss in terms of real yield but overestimates loss due to *Maliarpha* as it does not eliminate loss from other causes.

van Dinther (1971) assessed losses from two stemborer species *Rupela albinella* and *Diatraea saccharalis* in Surinam that best exemplifies this method. He selected 200 plants one week before harvest and by dissecting the tillers he quantified the number that were infested or uninfested. The density of panicles was assessed per m^2. He noted compensation would have little role in the plantations as the crop is harvested right at physiological maturity thus late developing tillers do not have time for their panicles to mature. A formula was used to estimate yield loss by each species: loss = (A–B) NP where A = mean panicle weight of uninfested panicles and B = weight of infested panicles, with N = no. panicles/m^2 and P = % infested panicles.

Lim et al. (1980) sampled damaged and undamaged areas of brown planthopper affected fields in an outbreak situation in Malaysia. They took 100 m^2 yield cuts from 6 to 15 fields in each of three sites from heavily infested (20–30 hoppers/hill) and highly infested (500–1000 hoppers/hill) fields and compared them with uninfested fields in the same irrigation system. These fields had become heavily infested 30–45 days after transplanting, but samples taken from sites where similar infestation levels occurred near harvest had much lower losses.

16.8.3 Extrapolation of Damage Caused by Individual Insects

This method is best exemplified by the rice bug *Leptocorisa* where Rothschild (1970a), through field and screen house cage experiments with traditional varieties, determined the feeding rates of individual adults and nymphs. He found that only the last instar nymphs and adults damaged the rice plant. Damage of the last instar nymph was found to be only equivalent to 0.4 adults so he used the term of 'adult equivalent' so that both mature and immature stages could be measured together. The difference between the feeding rates of both sexes was not significant. He also found that adults and last instar stadia lasted 13 and 5 days, respectively. He also determined the percentage of grains attacked and calculated that 1 adult equivalent/m^2 would cause 1% yield loss in a traditional variety. The calculations were questioned by van den Berg and Soehardi (2000) as subsequent studies by Litsinger et al. (1998) showed lower feeding rates in general and by males specifically and that compensation was not taken into account. Modern rices although have lower 1000 grain weights produce greater densities of spikelets. Furthermore van den Berg and Soehardi (2000) point out that adults, being highly mobile, also feed in grassy areas and shade provided by the cages extended the feeding periods during daytime.

16.8.4 Compare to Potential Yield

The first example of this method which assesses the potential yield of a wheat crop in an area comes from disease management in wheat in Montana in the US (Nissen and

Juhnke, 1984). Historical data was used to provide an estimate of potential yield for the locality which was then compared to actual yield. Potential yield was assessed based on crop water availability, crop management (variety, fertilizer, planting date, seeding rate), climate (temperature), weeds, insects, and diseases. The interaction of disease incidence with water stress was highly significant.

The same approach was used in rainfed and irrigated rice in Java using simulation models (Boling et al., 2004). Both environments were examined side by side in plots with plastic sheeting preventing lateral water movement. Drought, nutrient stress, and pest infestation or combinations thereof were set out in the experimental layout. Pests were monitored and injury to leaves and panicles assessed. The data was entered into a rice growth model to compare actual yields to potential yields in pest free conditions. Normal farmers' practices were followed including farmers' insecticide applications. Greatest yield loss occurred in the dry seasons from yellow stemborer *Scirpophaga incertulas*, brown spot *Helminthosporium oryzae*, and narrow brown spot *Cercospora oryzae*. Low yields were associated with high levels of panicle damage and losses when compared to the potential-yield estimates in the crop model (56% or 2.5 t/ha loss and 59% or 2.3 t/ha loss in the dry seasons of 1998 and 1999 crops, respectively). These high losses were due to the late plantings that occurred in each test year. Higher losses were associated with low potassium and low nitrogen plots. The pest losses were exacerbated by drought stress a fact which was corroborated by trials in Guimba, Nueva Ecija, Philippines in irrigated rice (Litsinger et al., 2005).

van den Berg and Soehardi (2000) working with rice bug organized trained 94 farmer groups in four districts in East Java to take field samples of rice bug densities from 45 hills three times per field during a crop from panicle emergence to milky stage in a stratified manner. These data were averaged and related to yield taken from each field of IR64 rice by linear regression analysis. Yields ranged from 4 to 10 t/ha over a range of 0–36 adults/m^2 per site, with most sites averaging $< 6/m^2$. This large sample size taken from a crop under farmer management showed a wide range of rice bug densities but there was no relationship to yield loss. Such exercises could be carried out by farmers organized over a region trained by farmer field schools over a number of crops to establish an historical yield potential as a measure of potential yield.

16.8.5 Compare Infestations on Susceptible and Resistant Varieties

This method was suggested by Israel and Abraham (1967) but the key is to find varieties of each which are of the same growth maturity and yield potential. With the advent of genetic engineering this method should have great promise in the future if designer cultivars of the same genotype can be fashioned each having resistance to individual pests. Losses could be readily measured for specific pests in a trial where all lines were sown in plots compared to the susceptible check. Such a method would be ideal for determining if pest combinations were additive, synergistic, or antagonistic. Bt rice (endotoxin of the bacterium *Bacillus thuringiensis,* a pathogen of lepidopterous insect pests (Cohen et al., 2000), could be a first example of the utility of this method which could be compared to the same genotype without the endotoxin.

16.8.6 Insecticide Check Method

Attempted elimination of insect pest populations by insecticides to quantify losses compared to an untreated check has been a widely used procedure. The method frequently is more practical with severe or perennial insect pest problems than with occasional pests as it depends on natural field infestations which are often not very high thus it is often difficult to generate damage functions. For example a range of deadhearts from 0 to 10% will be less useful than one 0–60%. It is important that the insecticides selected have no influence on crop growth. Unfortunately carbofuran which has been used extensively in rice in insecticide check trials due to its systemic properties and broad spectrum efficacy is phytotonic and will bias results to exaggerate losses (Venugopal and Litsinger, 1984; Moyal, 1988). The phytotonic effect is particularly evident if carbofuran is applied at or just after transplanting. Dosages that stimulated crop growth are higher than needed for control efficacy. The government of Korea even recommended carbofuran to be used as a ‘growth hormone’with the effect of accelerating crop maturity up to 7–10 days to avoid seasonal cold temperatures. It is also known to be a nematicide but the explanation for its physiological properties has not been found. Soil pests were eliminated from consideration in the trials of Venugopal and Litsinger as the phytotonic effect was found not only on rice but on wheat and several weeds even in hydroponic culture.

An early example of use of the insecticide check method on rice was by Fernando (1959) in Sri Lanka with paired plots in farmers’ fields (10 locations in each of 3 districts). One of the 30 m^2 plots was sprayed with endrin every two weeks. Two other examples are given. Another study was carried out in India in 54 m^2 field plots each with 15 different varieties and planted in a season of high gall midge *Orseolia oryzae* incidence (Prakasa Rao, 1989). Diazinon, which is not phytotonic, protected one of the plots. The method was used to evaluate the insect resistance mechanism of rice varieties. Those varieties showing least difference to insecticide protection were considered to be the most resistant. Catling et al. (1987) used the insecticide check method over several years and carbofuran applications were later replaced by diazinon. Insecticides gave only a 60% reduction in stem damage and 45% reduction in whiteheads which did not result in a significant difference in yield. Another problem was that sprays of chlorpyrifos caused resurgence of brown planthopper further confounding the results.

16.8.6.1 Growth-stage Partitioned Yield Loss

It is difficult to find selective insecticides that are specific for one pest group, thus another way of determining the key pests is to quantify losses by growth stages. The insecticide check method was used to measure losses from all insect pests in each of the three major rice growth stages: vegetative, reproductive (maximum tillering to panicle initiation), and ripening (Yoshida, 1981). In a typical 110-day variety, the reproductive stage would begin about 40 days after transplanting (d.a.t.) and end about 30 days later.

Aside from transplanted rice using wetbeds the method was carried out in a wide variety of rice environments and cultural practices such as direct seeded pre-germinated rice as well as rainfed wetland and dryland environments including slash and burn culture. The method was perfected through a series of ancillary experiments. The first was to find plant-growth-neutral insecticides (Litsinger et al., 1980; Venugopal and Litsinger, 1984). The second tested the effect of plot size on insect pest infestations in adjacent treatments of insecticide treated and untreated side by side (Litsinger et al., 1987a). Plots need to be large enough where natural rates of arthropod colonization occur and the effect of a neighboring plot being treated would not influence pest and natural enemy buildup. A 50 m^2 plot was found to be too small but plots > 100 m^2 acted similarly with 1000 m^2 plots which were assumed to be identical with natural field sizes. Yield cuts at first followed IRRI's recommended 10 m^2 size established for research stations (Gomez, 1977). But when the same yield cuts were taken from on-farm trials, the coefficient of variability (CV) was often unacceptably high ($>10\%$). Larger yield cuts of 5 samples of 5 m^2 (25 m^2total) were found to provide acceptable CVs. In the randomized complete block design replications were farms with the number ranging from 4 to 8 per crop.

A further refinement was to prevent insecticide drift to unsprayed plots by having workers follow the spray man downwind with a mosquito-cloth mesh spread across a 1– × 6– × 3–m wood frame. Although dosages were at the high range of manufacturers' recommendations and frequencies of weekly or 10-day intervals, insecticide applications of broad spectrum materials (applied at recommended spray volumes), insect pest control was not as high as desired (Litsinger et al., 2005). This shows the limitation of insecticides as an IPM tool as farmers would achieve much lower levels of efficacy than were achieved in our trials. Highest efficacy occurred against leaffolders (*Cnaphalocrocis medinalis* and *Marasmia* spp.) averaging 83% control based on damaged leaves, followed by defoliators (green semi-looper *Naranga aenescens* and green hairy caterpillar *Rivula atimeta*) at 71% control also based on damaged leaves and stemborers at 67% control based on deadhearts and whiteheads. But the greatest disappointment came with whorl maggot with only 55% control. As a result in later trials the 0.75 kg a.i./ha monocrotophos sprays were replaced by seedling root soak (seedlings immersed in isofenphos or carbosulfan solution for 12 h). Efficacies increased but still did not rise above 80% control in most trials.

Three other growth stage partitioned yield loss trials were encountered in the literature that deserve comment regarding experimental technique. Kushwaha and Kapoor (1986) conducted an experiment in two consecutive wet seasons under high whitebacked planthopper *Sogatella furcifera* infestations and Pandya et al. (1989) against chronic pests over two crops. In both series of experiments, plot sizes were small (20 m^2) and carbofuran G was applied. An additional 3–4 treatments provided control in only each growth stage rather than omitting control from single growth stages to estimate loss by stage. In the trials of Litsinger et al. (1987a, 2005), loss in each of the growth stages was summed and adjusted upwards or downwards proportionally so that the total of the three stages equaled the total yield loss (complete control treatment less the untreated check). The use of carbofuran in Kushwaha and Kapoor (1986) and Pandya et al. (1989) biased the data but it would have been interesting to verify if the losses per growth stage added up in both sets of treatments. For example from protecting only the vegetative stage, one estimates the losses in the other two stages combined. There is no doubt that interactions occurred between growth stages as insecticides applied in the reproductive stage would not kill stemborer larvae already in the crop that would continue feeding into the ripening stage (Litsinger et al., 2006c). This is a limitation of the insecticide partitioned growth stage method. Pabbage (1989) undertook a trial in Sulawesi, Indonesia on dryland rice and omitted insecticide protection in four growth stages. Unfortunately he used carbofuran thus the losses may be overestimated. He also did not apportion the yield loss by growth stage thus the total loss was calculated to be 26% but when losses from the four growth stages were added it was double (59%) on a 2.4 t/ha crop.

The Philippine yield loss data was used to evaluate action thresholds which were tested empirically in farmers' fields. The insect pest infestation and yield loss were both scored against benchmark infestation levels and associated loss in each growth stage. The method was developed in order to evaluate action thresholds for each pest individually. The benchmark levels were based on the results of Smith et al. (1988). The benchmark justifying insecticide application was based on yield loss (250 kg/ha per growth stage) for all pests as well as damage levels. Combining pest damage and yield loss into a single benchmark was necessary as yield loss could only be calculated in a given growth stage and not by pest. For whorl maggot or defoliators the damage benchmark was 15% damaged leaves in the vegetative stage. The standardized infestation levels for leaffolders were set at 15% damaged leaves in the vegetative stage but lowered to 10% in the reproductive and ripening stages due to less compensation. For stemborers it was set based on percentage deadhearts in a ratio of 10:15:5 for each of the three growth stages based on (Dyck et al., 1981; Bandong and Litsinger, 2005). Action thresholds were then scored on a per field basis. Four outcomes emerged: (1) if the threshold was not surpassed and was not justified based on both benchmarks of yield and damage, it was scored 'correct not to treat', (2) if the threshold was surpassed and was justified by both benchmarks it was scored 'correct to treat', (3) if the threshold was not surpassed but was justified it was scored 'should have treated', and (4) if the threshold was reached but was not justified it was scored 'should not have treated'. The frequencies of these four outcomes add to 100%. An important point was that the trials were conducted under the prevailing management practices of the farmers with the exception of variety selection per crop. Farmers were selected over the whole range of planting dates each season so that the results would not be biased for early or late planting. Farmers were changed each season for the most part so that a more typical range of management practices would be incorporated so the results could be extrapolated over the site.

Various threshold characters were tested over the period of the trials in an iterative approach. For example for stemborers egg mass and moth densities were compared to deadhearts. Each character was tested at two levels each season in order to improve precision. A high level and a low level of each character was tested as separate threshold treatments intermixed with five other treatments to measure yield loss in a growth-stage, partitioned yield loss trial design which also included a farmer's practice and prophylactic best recommendation treatments. The trials were carried in four irrigated rice sites (recommendation domains).

16.8.6.2 Yield Gap Studies

The insecticide check method was employed by the IRRI Constraints Program to measure the 'yield gap' (the difference between researchers' insect control efforts and those of farmers) in a number of Asian countries. Complete factorial experiments and later split-plot design tested the main factors of the farmers' practice, high input, intermediate input, and other levels as appropriate for insect control (DeDatta et al., 1978; Gomez et al., 1979). The high input treatment is equivalent to the 'complete control' treatment of our yield loss trials (Litsinger et al., 2005). The statistician determined that the ideal number of replications was 20 in a given season per site. Plot size was 20 m^2 and a yield cut was taken in the center 10 m^2. Comparisons in the main trial were normally fertilizer rates, insect control, and weed control. Insect control was the use of insecticides which varied but often included vegetative stage applications of carbofuran granules. Using carbofuran and small plot sizes were not ideal to measure yield gaps due to insects based on evidence learned later on. Often the high input treatments lodged as the plants grew too tall giving a lower yield than the untreated (DeDatta et al., 1979). Fertilizer plots were bunded but an earlier ancillary trial showed that bunded plots tended to yield more due to a concentration effect of the applied chemicals. Therefore a practice of making an opening in one side allowed water to flow to depths equal to those in the field. The opening was on the side away from the water inlet so no current entered the plot.

The farmer practice treatment began with researchers attempting to copy the farmers' method in the trials by frequently surveying them during the crop. This often ended up not being exactly the farmers' method due to delays in reporting. Yield cuts were taken from the farmers' own fields where the trial was run in addition to within the experimental plot area as a cross check. In other studies the farmers' method was contrived as an average of practices based on a survey carried out previously. This of course will be highly inaccurate as we saw from Table. 16.1 that each farmer may change his practice each cropping season and has no preconceived practice that can be elicited by surveys before the crop is grown. Farmers for the most part respond to the prevailing conditions during crop growth.

Gaps were measured as the yield difference between the researchers' best technology (highest input treatment) on the farmer's field subtracted from the same treatment on the research station. The difference would be due to non-transferable technology and environmental differences. A second gap is the yield in the farmers' treatment subtracted from the researchers' best technology on the farmers' fields. This would be due to biological and socio-economic constraints and was partitioned between the main factors tested both in percentages and in absolute terms. This differs from the yield loss experiments in that there is no untreated check, although the farmers' practice approximates it (Litsinger et al., 2005). Intermediate input level treatments were also included and an economic analysis was carried out to determine the costs and benefits of all of the treatments.

Because the objective was to represent an entire area and not specific villages, proportional sampling was used. Surveys were launched to determine socio-economic constraints from a minimum sample of 100 farmers. Surveys were carried out to determine how farmers perceive the most important constraints being tested. If farmers did not see a particular factor as a constraint one would not expect them to take action to overcome it. Researchers also recognized psychological constraints which would occur if farmers did not believe the new varieties and concomitant management practices would actually result in higher production and benefit.

16.8.7 Damage Simulation Methods

Damage simulation (surrogate damage) is one of the most controversial of the crop loss assessment methods (Poston et al., 1983). In this instance surrogate damage is imposed on the plant in the absence of natural pest populations. The primary advantage of this method stems from the ability to precisely control the degree of injury and to assess crop losses, even when economic pest populations are lacking. The method often allows the researcher more latitude in investigating the biology of the plant/crop response to insect injury. Most criticism of this approach stems from questions regarding fidelity of surrogate to actual insect injury. Therefore much biological data must be gathered and substantial equivalency information acquired before employing this technique.

A case in point is the use of injected herbicide to simulate stemborer deadhearts. The herbicide did cause deadheart symptoms but also affected plant growth in other ways and the results when various damage levels were regressed with yield showed it did not relate as well as cutting tillers carried out with scissors and to predictions based on crop modeling (Rubia et al., 1990a).

There have been various mechanical methods to simulate deadhearts. A number of other workers also resorted to scissors. Dang (1986) simulated *Maliarpha* damage produced two types: the first was to completely cut off the tillers at their base while the second was to approximate how *Maliarpha* damages tillers by making a cut half way across. Results were similar using both methods. Htun (1976) used a needle to cut the base of tillers to induce deadhearts. Feijen (1979) pulled the terminal leaf out of the stem.

Damage simulation for defoliators such as armyworm was is most often carried out by scissors but Bowling (1978) mechanized it with a rotary power mower with the height of the cutting blade adjusted to removed 25 and 50% of the above ground portion of the plants during the seedling and tillering stages.

16.8.8 Artificial Infestation

Augmentation of numbers rather than waiting for a wide range of naturally occurring pest densities to conduct the study may be preferred with chronic and occasional pests. Creating artificial populations is another technique that has been used frequently when precise control of numbers has been desired. This procedure usually involves rearing or collecting the pest and artificially infesting small plots. The pest may be restrained with cages or other barriers or unrestrained depending on the mobility of the damaging stage.

Small plots (4 m^2) made by concrete bunds in the screenhouse with plants sown in soil were infested with yellow stemborer egg masses at 5, 7, 9, and 11 w.a.t. (Soejitno, 1977). Similar trials were conducted in the Philippines with caseworm *Nymphula depunctalis* (Heinrichs and Viajante, 1987). Both studies were conducted without restraining cages which then allowed more natural sunlight.

More common is to infest caged plants in the field. The cages are left in the field for various periods of time, from one week after infestation (Bandong and Litsinger, 2005) to over the entire crop period to harvest (Heinrichs and Viajante, 1987). As cages affect the microclimate and reduce solar radiation their use will affect the quality of the results. In a study on deepwater rice, after infestation of yellow stemborer 6–8 weeks after transplanting (w.a.t.) tanks were caged to harvest (Catling et al., 1987). Viajante and Heinrichs (1987) made the observation that where cages were not used yield loss was always less than the caged condition. Thus plant shading by cages caused the plants to be stressed which combined with insect damage accentuated losses and reduced the plants' ability to compensate. Kenmore et al. (1984) reported the role solar radiation plays in manifestation of damage as hopperburn from brown planthopper occurred more on cloudy days; when the sun was shining the crop could outgrow the damage. Delpachitra and Wickramasinghe (1986) working with rice bug placed clear plastic cylindrical cages on single panicles that allowed natural solar radiation beginning at flowering after having protected the plots with insecticides until flowering. Six rice bug nymphs were placed in each cage which was checked daily to replace any that had died.

Dang (1986) infested 10 blackhead stage egg masses of *Maliarpha* on 10 random hills each in the field (an egg mass has ca. 50 eggs) in three growth stages: at early vegetative stage 20 d.a.t., maximum tillering 55 d.a.t., and pre-flowering 75 d.a.t. No caging was used thus the egg masses could have fallen prey to numerous predators to reduce populations between treatments to bias results. In the Philippines a more rigorous system involving three steps to prevent natural enemies from biasing results (Bandong and Litsinger, 2005). The trial was timed at the beginning of the planting season when natural infestation rates of stemborers and their natural enemies were low as determined by experience in the site. Moths were netted from the field and held overnight on potted rice plants. As one of the major egg parasitoids is phoretic an attempt was made to remove it from the moth by removing the anal tuft covering before oviposition occurred. As the method was not perfect, all egg masses were held in petri dishes until the blackhead stage when parasitized egg masses could be distinguished and discarded. Plots were infested weekly during the growth of the crop. During each infestation, leaf sections bearing blackhead stage egg masses were fastened to plants in the field with paper clips. Three egg masses were placed per 1-m^2plot distributed equi-distantly for each treatment except the uninfested check. Before the plots were infested, predators were removed by a motorized suction machine. As a third method, each plot was protected for 1 week with a cage with nylon mesh (0.5 mm) top and siding to exclude predators until the first instar larva entered a plant to escape predators. Using this method, near uniform densities of stemborer larvae were produced under near natural field conditions. Caging for only one week minimized the effect of shading on crop growth.

16.8.9 Crop Modeling

Crop modeling takes a dramatically different approach. Mechanistic crop growth models have been used to simulate the effects of pest damage on crop growth and yield by linking the damage effects of pest population levels to physiological rate and state variables of these models (Pinnschmidt et al., 1995). Such a model considers all of the main processes of rice growth. The daily accumulation of biomass is simulated by a growth rate which is proportional to an intrinsic rate of growth, the daily solar radiation, and the light intercepted by the canopy. The intrinsic rate of growth embeds the efficiency of several processes: gross photosynthesis, respiration, and transportation of photosynthates and synthesis of complex molecules. The biomass is then distributed to different rice organs (leaves, stems, roots, and panicles) according to partitioning coefficients that vary over time, depending on the development stage of the crop. Tillering depends on the amount of biomass partitioned daily into leaves and stems.

Empirical pest levels can be introduced into the crop simulation, but some cases represent true pest-crop models, where pest development is driven by crop variables and vice versa. For example a simulation model for the population dynamics of rice leaffolders interacting with rice was designed to improve the understanding of its role as an element of the rice ecosystem and to detect crucial knowledge gaps in view of a holistic assessment of its pest status (Graf et al., 1992). Pests are linked to crop models in physiological coupling points, and in some cases, pest effects could be measured quantitatively and in other cases damage consideration was only qualitative. Only quantitative data are suitable for simulation. Daily leaf consumption rates of leaffolders can be directly used for formalizing and parameterizing pest damage effects in crop simulations. Plant age, leaffolder larval age, varietal resistance, and temperature might affect feeding activities and have to be appropriately considered. The leaffolder model represents a synthesis of experimental results on biology and behavior. Based on the metabolic pool approach, leaffolder feeding and hence leaf mass losses were described with a generalized functional response model which is source and sink driven. An age structured submodel for the population dynamics was incorporated into the model for rice growth and development.

In another study the effect of stemborer deadhearts was simulated by subtracting the number of deadhearts from the number of vegetative tillers (Chander et al., 2002).

The removal of vegetative tillers was numerically linked to a corresponding loss in dry matter of leaves and stems. Stemborer incidence during the vegetative stage is an input of the number of deadhearts per day per unit area. The effect of whiteheads on crop yield can be simulated by reducing panicle weight in proportion to the whitehead fraction. The models were used to simulate the effect of stemborer damage by detillering 5, 15, 30, and 60% of vegetative, panicle initiation, and ripening stages on yield. Computer modeling combined with a few well chosen experiments permits more effective testing of hypotheses compared with field experiments (Rubia and Penning de Vries, 1990a). In both studies the effect of damage simulation was compared to experimental results.

Yield loss resulting from single as well as multiple pest scenarios can be simulated for any chronological pattern of pest occurrence and for any crop condition (Pinnschmidt et al., 1995). But in many cases parameterization of the pest damage mechanisms was done based on educated guesses, due to a lack of quantitative data. The simulation of pest effects with pest-coupled crop models requires knowledge of the mechanisms of pest damage. If direct observations of damage mechanisms are difficult, researchers can use indirect methods. Thus measurements of honeydew production are used to measure brown planthopper feeding rates while damage effects of stemborers are studied by artificial tiller removal. Quantitative estimates of pest effects can be obtained by characterizing the pathways of pest-crop interactions through observation and identifying the physiological crop processes affected by the pest (Pinnschmidt et al., 1995). The feeding habits of brown planthopper and the causes of hopperburn were thus studied as well as the damage activities of leaffolders and crop physiological process affected by sheath blight *Rhizoctonia solani*. Although qualitative data cannot be directly used by crop models, they do give important information about the physiological basis for simulating pest damage effects.

The basic task of yield studies is to estimate the rate at which a given amount of pest damage causes a crop to lose yield at each instant during the growing season. Because of their flexibility, pest-coupled models become the ideal tool for developing control tactics and strategies and thus improving decision making in IPM. They provide means to incorporate the crop and its growing conditions as a component of yield loss predictions and to estimate pest-free and pest-affected yields under variable conditions. By including economic values such as yield, price per unit of yield, control costs, and benefit from control in the consideration, damage thresholds can be suggested at which actions to control specific pests are economically justifiable. Least-loss strategies thus can be developed and pesticide application schemes optimized. An additional advantage of pest-coupled crop models over conventional methods consists of the fact that dynamic rather than static damage thresholds can be developed that account for the variability in the chronological patterns of pest or damage development.

16.8.10 Adding Environmental Factors to Crop Loss Assessment

Crop loss assessments for single pests have been estimated, but precise as they may be, their prediction is limited to a single pest interaction (Gangwar et al., 1986).

Crops, however, are under attack from a number of pests and other physiological stresses at any one growth stage, which estimation of yield loss should be taken into account. As we saw in Table 16.1, yields can vary widely on a given farm over years. Baumbärtner et al. (1990) felt that pest densities and yield loss should not be studied independently from other yield forming processes but should be incorporated into a comprehensive study of the production system. This objective, however, cannot be met by relying exclusively on traditional experimentation with individual factors but requires a systems approach. With this approach a production system can be achieved wherein all relevant resources, factors, and processes are evaluated simultaneously. The diversity of pests can be condensed into a small number of guilds, each functionally corresponding to one type of physiological injury mechanism. Savary et al. (2006) developed injury profiles to lump different pests and stresses into single units.

Because production levels and multiple pest infestations significantly affect control thresholds, a flexible approach to quantifying pest-induced yield losses has to consider them appropriately. Several empirical models have been developed to quantify the relationship between pest damage and yield loss (Pinnschmidt et al., 1995). But their application is limited to the specific environmental conditions, genotype, and soils. Crop growth simulation models are based on the quantitative understanding of the effect of weather, soils, plant maturity, and management on the dynamic crop growth. Crop models can enable the user to simulate the performance of crops under different regimes of climate, soil type, and cultural practices.

There has been little work in quantifying losses associated with multiple pests and complex plant stress factors. Conventional procedures provide no clues as to how to integrate single species measurements to estimate yield losses from combinations of problems (Poston et al., 1983). About the only possible choice is to assume that all yield reductions are additive (i.e., that yield reductions caused by two pests attacking one plant is the sum of the reductions when the same species each attack separate plants). By using the results from this approach, however, a pest manager could estimate plant yield reduction from multiple pests at greater than 100%. Therefore the possibility of non-additive antagonistic or synergistic interactions when dealing with multiple pests or stress factors cannot be ignored. To design a plot experiment to include all of the possible interactions is impractical. The reason so many plots are required is that entomologists typically ignore internal plant processes despite their primary role in determining experimental results. Injury is observed or induced and yield is measured.

By not building existing agronomic information into experimental designs, entomologists are forced by laws of statistics to do an amount of work equivalent to the rediscovery of these internal plant dynamics (Poston et al., 1983). This results in the impossible design of so many plots. In addition to the obvious impracticality of such an experiment, the applicability of results from one region to another would be limited. Changes in cultural practices, host varieties, stress factors, or pest complexes vary from one region to another and over time would necessitate completion of similar studies at each location periodically. A potentially more viable approach is for entomologists to begin to view the plant as a set of interacting components

(Poston et al., 1983). This viewpoint involves separating the injury-crop response question into three steps: (1) the researcher must decide which plant component or process is affected by the insect injury, e.g., an insect defoliator may remove leaf tissue and thus affect plant photosynthesis and water balance. (2) The response of the affected components or processes must be determined over a range of damage levels. In some cases such as insect defoliation, the change in the anatomy of the plant resulting from the defoliation may be used as an index of the magnitude of the damage. (3) The impact of the changes in affected components on yield must be quantified.

As an illustration, if two different stemborers show from past experience that the crop response was not additive, in step 1 we might determine that the main effect of larval tunneling is to upset the water balance (Poston et al., 1983). Step 2 would be to quantify the impact of injury on plant water use. Finding a non-linear antagonistic or synergistic relationship would account for the non-additivity of crop response to damage. Step 3 would entail determination of the influence of plant water use on yield. This would allow an indirect estimate of the impact of both pests on yield. By delving into plant physiology we have in effect found common grounds for additive responses. The total amount of tunneling is indeed the sum of each species' contribution. Thus plant response could be studied as a function of total tissue damage. Cumbersome factorial experiments may be replaced with a series of single factor experiments each corresponding to one of the steps above with a consequent large reduction in required field work.

Most estimates of yield loss are based on estimates from empirical methods and statistical comparisons between yields obtained at experimental farms and farmers' fields (Gangwar et al., 1986). One of the most important criticisms of the methods used is the assumption of the empiricity of crop loss assessment. A survey procedure was developed by Savary et al. (1994) to incorporate environmental factors inherent in the cropping system into the crop loss assessment. This method was followed in two large studies. The first occurred in C. Luzon in the Philippines on double-cropped irrigated rice (Savary et al., 1994) and the second in India in a rice-wheat rotational system (Savary et al., 1997). Two analytical approaches were used, the emphasis shifting from yield determining variables that are mostly qualitative in nature to quantitative and predominantly yield-reducing variables. The first approach was intended to characterize relationships among cluster and correspondence analyses while the second approach was aimed at generating yield loss estimates using combinations of principal components and step-wise multiple regressions.

For example, in the rice-wheat system the research team collected data for three consecutive years in 251 fields. Seven patterns of cropping practices were distinguished reflecting a wide variation in production systems especially in terms of use of inorganic fertilizers, manure, and degree of water control. Six types of disease profiles, four insect injury profiles, and four weed infestation patterns were identified. Correspondence analysis based on patterns of cropping practices and injury profiles yielded a path of increasing attainable yield associated with varying levels of intensification and combinations of injuries. The use of principal component analysis with multiple regression generated estimates of yield reductions due to rice diseases, insect pests, and weeds.

16.9 Analytical Methods

16.9.1 Direct Measurement

16.9.1.1 Simple Regression

Using data from the insecticide check method, damage functions derived from regression models showed that the relationship of pest populations and yield loss caused by them is usually linear except for the extreme upper and lower levels (Smith et al., 1988). In general when pest populations are very low, the effect on yield is minimal. At higher regions of the curve the effect of additional pests on yield loss tapers off. For each pest, the curve may change between locations. Non-linearity implies that other factors need to be considered in addition to the level of insect pest damage such as age of crop when infested.

Accuracy of sampling is influenced by the sampling method (Gomez and Bernardo, 1974). When hills were counted for stemborer damage this was less accurate than a per m^2 method as there was great variation between hills in tiller number and height. They found distribution of infested hills also influenced yield. Thus yield reduction may vary depending on whether incidence is spread widely or concentrated in a few hills. Also infested hills had more tillers showing the compensation effect had taken place. Larger sampling units were needed in the wet season than the dry season to produce the same statistical precision. They concluded that the presence of other insect pests and diseases should be considered because they could affect the yield loss estimate.

The use of absolute yield as the dependent variable in relating stemborer incidence is appropriate only if the yield loss estimate is for farms planting the same variety under the similar conditions (Gomez and Bernardo, 1974). They recognized that yield loss estimates vary greatly by growing conditions of season, variety, time of planting, and management. Damage functions can only be meaningfully made by samples taken under similar environmental conditions which effectively means taken from the same field and not mixing fields even of the same variety. Sample size has to be large >2 m^2.

Gomez and Bernardo (1974) found a linear relation between percent yield loss and percent whiteheads for most of the curve from 2 to 4 percent (the top range) although an exponential equation was the best overall fit. Thus percent yield loss varied with the yield, 2 percent deadhearts and 2 percent whiteheads caused 4.4 percent loss in fields yielding 3 t/ha whereas the same damage level caused 6.4% loss in a 4 t/ha crop, indicating that little compensation occurred. Ishikura (1967) found non-linear relationships between stemborer infestation rates and yield in numerous studies in Japan. In one of the earliest reports, Wyatt (1957) in Malaysia simulated varying degrees of stemborer incidence by removing 10–70% of the tillers at random from each hill 3 weeks before flowering. He showed that for each 1% increase in stemborer deadhearts before maximum tillering that 1.3% loss occurred. In Indonesia small plots in the screen house infested with yellow stemborer egg masses at 5, 7, 9, and 11 w.a.t. all produced linear regression relationships between damaged tillers and yield when yields were taken per hill (Soejitno, 1977). Barr et al. (1975) report a similar exercise in India where a loss of 0.3% was predicted for every 1% increase in deadhearts before maximum tillering and 0.6% loss at heading. Summarizing field data in a number of states from 1965 to 1992, Muralidharan and Pasalu (2005) found that for every 1% increase in deadhearts, whiteheads, or both, losses were predicted to be 2.5, 4.0, and 6.4% yield loss, respectively. In terms of grain production loss over ecosystems, 1% deadhearts, or whiteheads, or both phases would be 108, 174 and 278 kg/ha, respectively. Van Haltern (1979) found a linear relationship of each increase of 1% whiteheads resulted 1.2% loss with *S. innotata*. All of these damage functions differed because the growing conditions and management were different. Researchers think that these damage functions for each pest species are immutable but there is no right or wrong damage function but infinite numbers of damage functions due to the many interacting factors. Because of this variability in damage functions it follows that economic thresholds will also vary accordingly.

Damage caused by *Maliarpha* is manifested as percentage empty grains. The formula using percentage of empty grains was proposed for the assessment of loss and was found to be related to larval tunnel length in a linear fashion (Dang et al., 1983). The proportion of empty grains can be affected by many factors including crop management, diseases, soil, and adverse conditions and calamities such as drought and cold. In another study the principal parameter that can be used for assessment of the level of *Maliarpha* damage is percent tiller infestation and the relationship was non-linear, indicating that proportionally greater yield losses occurred as damage levels increased (Dang, 1986).

Whereas non-linear relations are the norm due to compensation there are notable exceptions. van Dinther (1971) selected 200 plants one week before harvest and by dissecting the tillers he formed five categories separating the panicles damaged by: (1) young *Rupela* larvae, (2) older *Rupela* larvae, (3) young *Diatraea* larvae, (4) older *Diatraea* larvae, and (5) uninfested. His data was graphed to show highly linear relationships between a wide range of damage levels and yield loss (van Dinther, 1971) (Fig. 16.2). Damage of *Rupela* was much less than *Diatraea* for equal infestation levels. *Rupela* develops within one internode and the nodal septum is not destroyed thus does not cause deadhearts or whiteheads in the same manner as *Maliarpha* in Africa.

Reddy (1967) reported with gall midge in India that yield was linearly correlated with percentage of damaged tillers that for every 1% of damage there is a loss of 0.5% yield. Williams et al. (1999) working with African gall midge *Orseolia oryzivora*, after excluding plots with infestation levels $> 30\%$, found a linear regression relating a 2.9% loss per 1% increase in infested tillers.

Van Haltern (1979) monitored 35 sites on the Maros experiment station in Sulawesi, Indonesia and recorded the mean number of rice bugs per m^2 daily over the ripening stage for 21 days. At harvest time he sampled 10 panicles per m^2 where he monitored the feeding sheaths by a staining method to determine percentage of damaged grains which he plotted a linear regression with rice bug density expressed in rice bug-days. A rice bug day is the mean number of bugs multiplied by the number of days of observation which was 21. He then assumed that the percentage

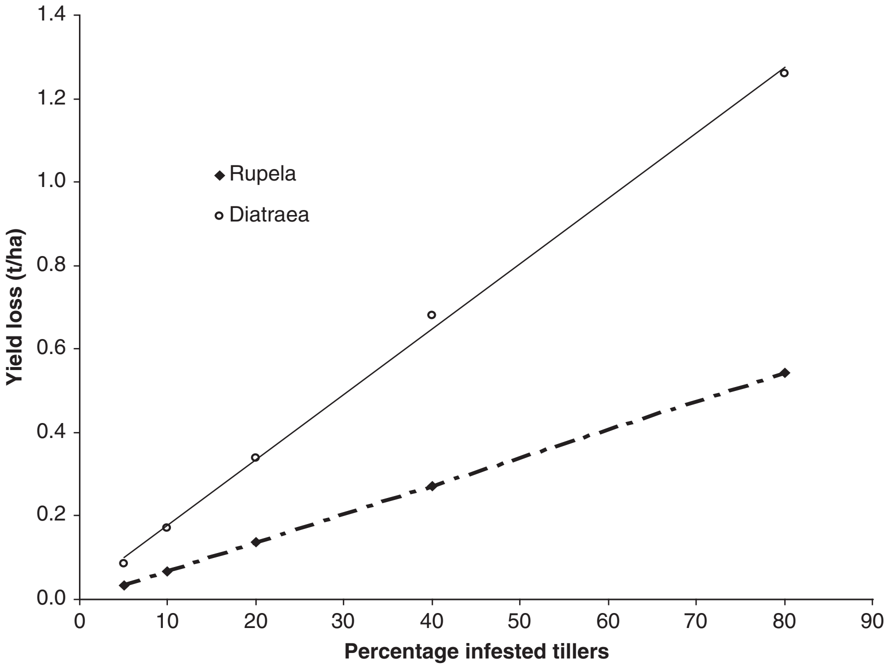

Fig. 16.2 Relationship between stemborer infestation rates and yield loss from two rice stemborers *Rupela albinella* and *Diatraea saccharalis* in Surinam. Data modified from van Dinther (1971) and show linear relationships and damage from *Diatraea* cause more loss than that from *Rupela*

of fed upon grains was equivalent to percentage yield loss in the analysis such that 5% damage will occur per 15 bug days/m^{2}which undoubtedly produced a bias as compensation documented by Litsinger et al. (1998) and later van den Berg and Soehardi (2000) was not taken into consideration.

16.9.1.2 Damage Functions

The economic injury level (EIL) concept has been generally accepted by entomologists as the backbone of progressive concepts in insect control, namely IPM. The concept serves as the economic foundation in decision-making processes. In sharp contrast to their theoretical importance, EILs have often been the weakest component in management programs (Poston et al., 1983). In fact very few firm research-based EILs have been established. Many in use are static and do not reflect changes in prices or other factors. This weakness has persisted for several reasons. Most of the IPM research effort has been devoted to pest ecology and especially to development of appropriate management tactics rather than the determination of explicit EILs. When attempts have been made they have been found to be notoriously difficult to measure. Also weaknesses in application of the EIL concept have become more obvious as specialists assume management tasks of greater complexity, e.g., multiple pests in a single crop or one pest in several crops. In these complex situations the EIL, at least in practice, becomes conceptually fatigued. Although the EIL was a major breakthrough when first proposed, it is now clear that some revision, re-interpretation, or expansion of the concept is needed if further progress is to be made. Many of the problems with current research stem from a lack of consideration for plant physiology. To correct this an improved research methodology is proposed which breaks the pest-host interaction into three separate types termed susceptive, tolerant, and over compensatory (Poston et al., 1983; Pedigo et al., 1986).

Susceptive is a linear relation, ie., every increment in damage results in a given incremental loss in yield (Fig. 16.3A). In many cases the responses may be linear over the range of damage increments tested. Many plant species compensate or tolerate substantial insect damage. If the range of damage increments in these studies is increased, the tolerance or compensation response may be exhibited. Consequently many of the damage functions reported probably are not susceptive responses. For practical purposes they may be considered susceptive because the range of damage increments tested encompasses values needed for EIL determinations. In the tolerant plant response to insect damage, probably the most common is sigmoidal (Fig. 16.3B). With this situation the plant will tolerate or compensate for some quantity of injury without reducing marketable yield until a critical point is reached. At this point the plant's ability to tolerate injury is exceeded and yield is reduced. After this stage yield is reduced with each additional increment of injury until a lower plateau is reached (the point after which additional injury does not cause a yield reduction). This lower level may reflect the plant's priority for energy allocation to reproductive parts or plant yield that was generated and stored before the insect attack. The overcompensatory relationship probably is the least documented plant response to injury (Fig. 16.3C). It differs from the tolerant response only at lower damage levels where the plant is stimulated to increase its marketable yield. This may result from the induction of tillering or other morphological or physiological changes in the plant. At higher damage levels the overcompensatory response is similar to the tolerant response.

16.9.1.3 Multiple-Regression

The rice crop is affected by a large number of abiotic and biotic constraints each of which alone or in combination will influence crop growth and thus yield loss. Confounding the determination of single pest relationships with yield is that there are normally several pests attacking the crop in any growth stage. In response to this, multiple decision thresholds have been developed which incorporate several pests that occur in a particular growth stage to be developed (Palis et al., 1990). However the rice crop and consequent losses which form the basis of developing thresholds are under the influence of not only insects, but as has been mentioned also from other abiotic and biotic stresses.

Savary et al. (1994) has attempted to take many of these into account with his crop loss assessment method that takes large samples of fields and monitors each frequently trying to quantify as many important variables as practical. They found

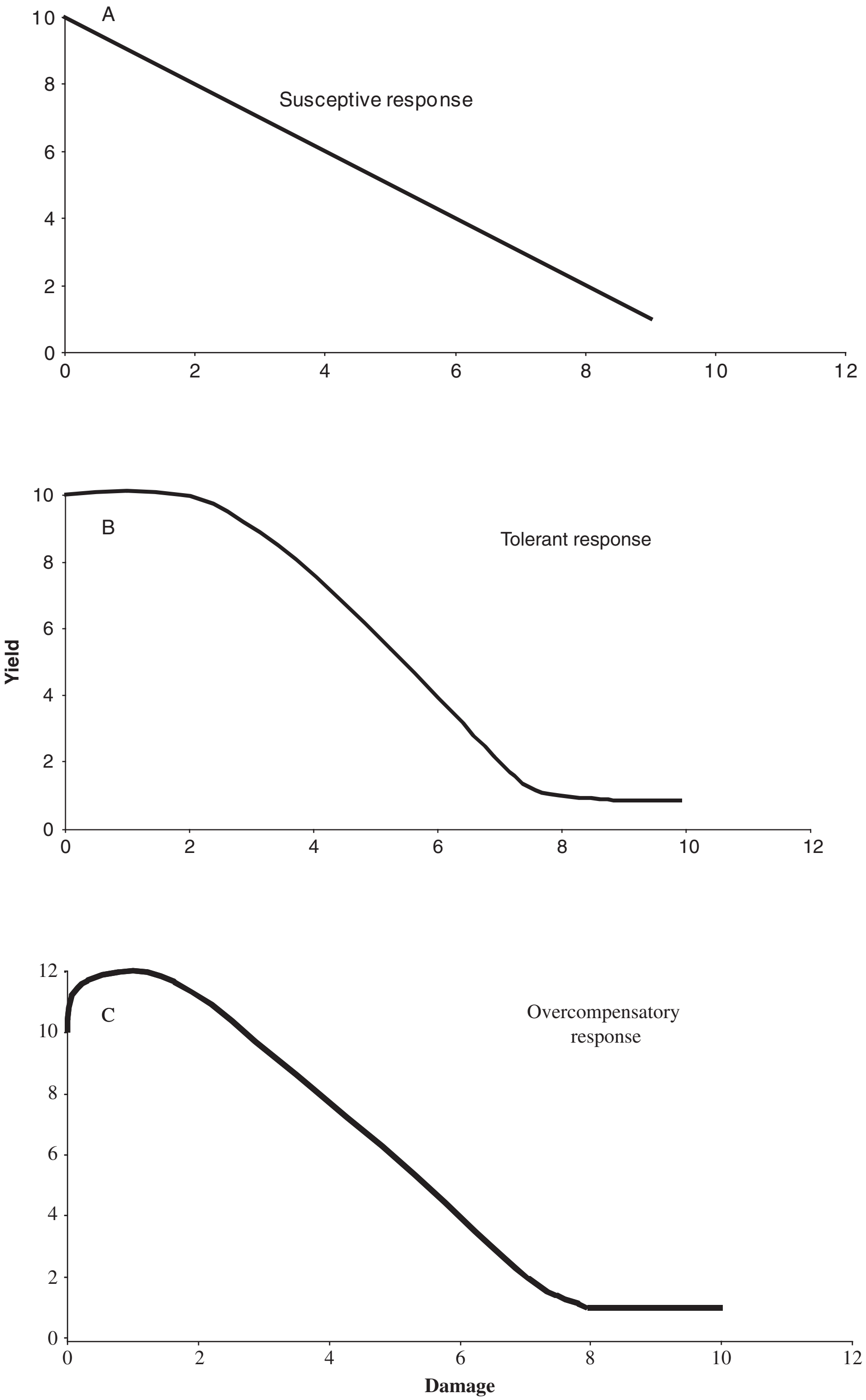

Fig. 16.3 Representation of the most common three (**A–C**) generalized damage functions that relate insect pest damage to yield (data adapted from Poston et al., 1983)

low yields were the result of combinations of many of these factors that alone were subeconomic but in combination became economic (Savary et al., 1994; Willocquet et al., 2000). It is no wonder that rice yields are so variable even within a farm community as the crop can be affected by literally > 30 stresses each season, any one of which or of the multitude of combinations can affect yield. This number becomes even larger if we measure incidence over crop growth stages. The combinations are enormous and defy measurement. We know that a certain abundance of stemborer deadhearts has a different yield loss effect in each growth stage.

Multiple regression, as an analytical tool has been used to relate a wide set of biotic and abiotic variables to yield. Israel and Abraham (1967) worked out a multiple regression equation to incorporate loss at early growth and late growth for stemborers and then for all pests. They admitted that the equation does not take into account any possible relation between plant vigor and level of incidence in the field.

Williams et al. (1999) working on African gall midge recognized that variables such as topography, water level, fertilizer use in the nursery, and plant spacing had significant partial regression coefficients as well. Other stresses were also prevalent such as nutrient deficiencies, iron toxicity, and drought at ripening. They concluded that translation of injury to yield is dependent on the plant's physiological status (food reserves), genetics, crop stage, and environmental influences.

Gangwar et al. (1986) stated that various methods were available for estimating yield loss in rice in multiple pest situations. Surveillance in farmers' fields and the utilization of multiple regression analysis can be a useful tool for synoptic assessment of the contributions made by different pest variables on yield and in identifying the key pests. Such an exercise is particularly important in determining the threshold levels for pathogens and weeds. They assessed yield loss from surveillance data of rice yield and incidence of various pests in farmers' fields by multiple regression, with a view to obtaining a simple yet reliable tool which may be applicable in farmers' fields. Insects were evaluated in 1 m^2 areas as deadhearts, number of cut or folded leaves, or number of insects in net sweeps for hoppers or rice bug. Data were also taken on diseases where fungicide was applied to measure loss. Traditional and modern varieties were aggregated separately. In regression models yellow stemborer was the only insect to be found to cause significant loss in both traditional and modern varieties, however, all pests produced significant correlation coefficients. Yellow stemborer alone explained 69% of yield variation in modern varieties and 62% in traditional varieties. But a combination of pests explained variations in yield better than did any individual pest.

Seth et al. (1969, 1970) and Singh et al. (1972) from the Institute of Agricultural Research Statistics in Delhi undertook a large scale study in several states with the objective of estimating the incidence of pest populations and relating the level of incidence to yield and yield loss. They noted that relating incidence with yield (damage function) is difficult because yield is affected by a number of abiotic and biotic factors aside from pests such as variety, fertility, cultural, and manurial practices. Thus if yield loss studies are done in controlled conditions on experimental stations to derive the damage functions these effects will be missing and the results are not extrapolatable.

In the multi-year studies, each district within a state was divided into nine zones, and six villages were selected randomly from each zone, and within each village four fields were selected for observations and field trials. In two fields they were paired with another two fields of similar variety, manuring schedule, topography, soil type, and cultural practices. Three activities were carried out in the test fields:

1. Avoidable yield was measured by spraying one field of the pairs with insecticide in the seedbed, at 30 d.a.t., and again at heading.
2. In each field four plots of 1 m^2 each were selected to monitor stemborer and fungal diseases and yield,
3. Five plants were for tiller counts, and
4. Yield cut was only 4 m^2.

Estimates of damage functions were determined from our data in the Philippines using multiple regression for rice whorl maggot, leaffolders, stemborers, and white-backed planthopper but only the first two were significant over ten crops and five years of data (Smith et al., 1988).

16.10 Physiological Basis of Yield Loss and Compensation

The leaf blade is the most important photosynthesizing plant part. Any detrimental effect of leaf removal is directly related to loss of photosynthetic tissue and will generally retard plant growth. Tall, traditional rices have a different mechanism for compensation than for the semi-dwarf modern types. With tall varieties it was a common practice for the farmers to lop the tops off of > 40-day old, leafy seedlings before transplanting to stimulate tillering. An additional practice with traditional varieties was to remove the tops of vegetative stage plants to provide quality livestock feed and stimulate tillering without loss of yield. Plants growing in rich bottomland which produce luxuriant vegetative growth that would lead to lodging or cause mutual shading of lower lying leaves were most selected for this practice. Longer culms of traditional rices can accumulate more assimilate which later can be translocated to the grain as a mechanism of compensation. But taller plants have a higher proportion of non-photosynthetic tissue and a major disadvantage is their proneness to lodging.

In a number of tall varieties, yields actually increased up to 30% even with as high as 25–50% leaf removal at 40–55 d.a.t. (Kupkanchanakul and Vergara, 1991). Under good cultural conditions in the wet season, removal of ½, 2/3, or all of the foliage of traditional rices can increase yield 32, 28, and 9%, respectively, when this is done before tillering (Taylor, 1972). Furthermore he reported defoliation of rice may have a rejuvenating effect and result in faster growth and more grains if there were enough time for recovery before flowers were initiated. Recovery was most for the longer maturing varieties and least for the shorter maturing ones. In plots where 30 cm of the leaf blades were removed from the tips at 34 d.a.t., rice yield increased 45% in a traditional variety yielding 2.1 t/ha (Rawat et al., 1980b).

Plant physiological studies showed pruning may actually increase the net assimilation rate (Kupkanchanakul and Vergara, 1991). If part of the green tissue is removed, the photosynthetic rate of the remaining green tissue increases to compensate for the loss. In some cases, however, removal of leaves will reduce yield, the balance (plus or minus) depending on the rate of crop regrowth. Leaf regrowth after cutting is associated with residual leaf area, current photosynthesis, and the utilization of accumulated carbohydrates in the stubble or roots. Starch content in the stem and leaf sheath is reduced as a result of defoliation since most of the reserve is consumed to make up for compensatory growth of the new leaf. Tillering can be inhibited, promoted, or unaffected by pruning. The controversial effects of cutting on tiller production can be traced to the photosynthate status of the rice plant. Readily available carbohydrate will be used primarily for the renewal of foliage and later for tiller growth. Removal of leaf blades retards growth of tiller buds as well as the accumulation of dry weight. Tiller formation can be promoted by herbage removal through suppression of apical dominance. Removal of growth apices stimulates tillering where new shoots arise from axillary buds. Over-vegetative growth leads to the death of young or developing tillers through heavy shading (Yoshida, 1981). Leaf pruning at later growth stages when most tillers have been initiated and are well developed, will not likely reduce tillering much. It may certainly prevent the death of tillers.

Increased grain yield resulting from pruning could be associated with an increase in panicle number per unit area. Apart from that, the growth of small and more erect leaves is enhanced. Rice plants with erect leaves intercept solar energy more efficiently, thus increasing grain production. Grain yield is reduced if leaves are removed at the reproductive stage. The yield component that is most greatly affected is the number of spikelets per panicle. This component decreases progressively with late cutting. Lower numbers of spikelets indicate an inadequate supply of assimilates from a small leaf area. Decreased grain yield as a result of flag leaf removal was also reported (Kupkanchanakul and Vergara, 1991). Varieties of a very long duration are least prone to grain loss from vegetative pruning. Leaf removal can reduce fertility percentage and grain weight. These yield components could be affected due to cutting by changes in light distribution and translocation of photosynthate during flowering and ripening. Critical stages of leaf removal that will adversely affect fertility percentage and grain weight occur between reduction division stage and grain filling.

Herbage removal may increase or decrease grain yield depending on such factors as varietal characteristics (leaf length, growth duration), growth stage at cutting, percentage and intensity of herbage removal, cultural practices, soil fertility, and environment (Kupkanchanakul and Vergara, 1991). Last cutting should be imposed not later than 30 days before panicle initiation so as not to limit leaf area for photosynthetic activity at flowering. Leaf cutting in deepwater rice reduced the rate of dry matter production but plant recovery was rapid and dry matter weight was the same as the control at harvest. The relative growth rate dropped severely after cutting due to low photosynthesis resulting from less active leaf area, causing negative net assimilation. Later relative growth rate in the cut plot increased and was similar to that of the control within 3–4 weeks, indicating that normal growth can be achieved with in 4 weeks of cutting.

Leaf cutting was reported to delay flowering from 1 to 37 days depending on the cultivar (Kupkanchanakul and Vergara, 1991). Although top growth removal produced variable responses in above-ground parts, root growth was always depressed. Removal of more than 50% of the plant's top stopped root growth within 24 hours and no new root growth occurred for 6–18 days afterward. Nitrogen application increases nitrogen uptake by the plant, and leaf area which results in increased net fixed energy and finally higher biomass production. Increasing total biomass production through increased nitrogen uptake also increases respiration losses and lodging susceptibility proportionally especially in tall traditional varieties. These negative effects can be overcome by herbage removal.

Compensation is the process by which plants respond positively to the effects of injury by insects and the decrease the negative effect of insect injury on yield (Bardner and Fletcher, 1974; Pedigo, 1991). It is also known that modern rices, as opposed to traditional rices, have a higher yield potential from their high tillering habit and actually possess a higher compensatory ability against a wide array of stresses, although as we have seen, traditional rices have great latitudes for compensation but more mechanisms are involved in the semi-dwarfs. They also can tolerate pruning although to a lesser degree and make up for their short stature by producing more tillers, thus they can store more reserve photosynthate to reallocate to injured plant parts or to fill more grains. They also have larger physiological sinks from greater spikelet densities. Tillers of modern rices grow to fill in open spaces in fields which ability traditional varieties lack. Thus if tillers are killed by stemborer larvae then new tillers can form or fewer will naturally die after maximum tillering. Many tillers die naturally from competition between their neighbors for light, space, and nutrients (Yoshida, 1981). Modern rices have a high capacity to compensate from stemborer injury particularly at the vegetative stage (Rubia et al., 1990a).

Compensation is possible via production of new tillers and by increasing the number of productive tillers and grain weight (Rubia et al., 1996). Defoliation lets in more solar radiation to the lower canopy, or stimulates nutrients to be allocated to grain filling vs. vegetative growth. El-Abdallah and Metwally (1984) observed a heavier 1000-grain weight at 10% deadhearts and at 2 and 6% whiteheads from *Chilo agamemnon* damaged rice relative to uninfested controls. In healthy plants an increase in grain weight may be due to increased translocation of photosynthetic products between tillers during grain filling (Rubia et al., 1996). Some insect pest damage can even increase grain quality via higher protein content.

Computer simulations predicted that up to 20% deadhearts can be tolerated without significant yield loss in the vegetative stage (Rubia and Penning de Vries, 1990a). Damage that prevents grain filling causes almost a proportionate yield reduction. While high use of nitrogen can increase compensation, shading would have an opposite effect. In use of detillering as an artificial simulation method, removal of tillers decreased shading, thus producing a bias. A corrective factor was developed which is needed to be used to agree with natural stemborer damage of a tiller slowly withering.

Results are not always straightforward as field studies by Akinsola (1984) showed there were instances where hills containing tillers bored by *Maliarpha* produced higher yields (overcompensation) than unattacked hills. The relationship between tiller damage and yield loss is multifaceted as stemborer effects on yield vary with pest population density, time of damage, and growing conditions (Rubia et al., 1990a). Some of the discrepancies can be explained by intra-plant and inter-plant effects. Within a plant there is compensation between tillers, and between plants there is compensation of uninfested neighboring plants which grow better alongside an infested plant. Environmental influences, however, determine how much compensation can occur at a given time.

One of the earliest reports of compensation comes from work on stemborers Ishikura (1967). He reported that generally there were more grains per panicle in the healthy tillers of an infested plant than in the uninfested plant although there were far fewer grains in the surviving infested tillers. Apparently infested plants made up for loss from injury by increasing the number of grains on the tillers that escaped infestation. Dang et al. (1983) likewise reported that sometimes there were greater numbers of grains per panicle in *Maliarpha* infested than uninfested crops.

In some crops even a low infestation can increase yield. Compensation virtually enters into all aspects of rice crop physiology. In most annual crops, the individual plants are in competition with each other. Competition tends to accentuate differences in yield between attacked and unattacked plants in an attacked crop. Unattacked or slightly injured plants yield more than do individual plants in an unattacked crop, filling the space of plants which have been killed, or where growth is badly affected. These features are well illustrated by rice where competition is intense. An isolated plant can yield more than 25 times more than a plant sown at normal field densities. There is a considerable capacity for compensatory growth by young plants should any of their neighbors be killed (Judenko, 1973). Cereals also show competition between organs of the same plant, for at normal spacing not all the shoots which are produced can survive to produce ears. The rice plant normally produces a large sink of grains via many tillers and leaves. More often than not the environmental conditions cannot sustain the anticipated high level of photosynthesis resulting in empty grains. It is not unusual for modern rices to average 15% unfilled grains (Yoshida, 1981).

According to Bardner and Fletcher (1974) compensation involves one or more of the following three processes:

1. Attacked plants or organs are competing with others for space in which to absorb water, plant nutrients, or light. This is commonly seen in cereals that have a relatively constant yield for a wide range of sowing rates. Where injury occurs early in the life of the crop, the surviving plants (especially those that are uninjured) grow larger and have more panicle-bearing shoots than normal. Surviving plants also produce heavier ears than normal.
2. Attacked organs can still provide what is needed. This can happen if the source of water, plant nutrients, and photosynthetic products is larger than the sink.

3. Harvested organs are attacked, but many are superfluous. This is the reverse of (2) and occurs when the sink is larger than the source and is common in crops of indefinite growth. Pruning that stimulates yield is another example.

An important caveat applies to reports documenting increases in photosynthetic activity following defoliation. Many experiments have been interpreted too broadly (Trumble et al., 1993). Although the tissues remaining after partial defoliation may increase photosynthetic activity, the increase may not be adequate to replace the productivity of the leaf area lost.

In natural systems, plant species that can tolerate or compensate (e.g., recover equivalent yield or fitness) for herbivore feeding have obvious selective advantages that lead to genotype maintenance (Trumble et al., 1993). Scientists often cite an optimal strategy for enhancing fitness. Historically one of the most significant problems delaying an understanding of compensatory processes has been the erroneous assumption of linearity between plant growth (usually assumed to be equal to yield) and leaf area based simply on the presumption that carbohydrate production increases proportionately with leaf area. During the 1960–1970s this generally accepted presumption greatly inhibited the understanding of compensatory responses.

Because differences in growth versus yield can be dramatic, with arthropod damage to foliage greatly stimulating one at the expense of the other, conclusions were often apparently contradictory (Trumble et al., 1993). In addition the relative importance of growth versus yield is substantial when comparing evolutionary or ecological fitness with agricultural suitability, but these concepts were often considered equivalent. Fortunately the pursuit of this hypothesized linear relationship between leaf area and yield led to a body of knowledge that allowed researchers to recognize the limitations of this assumption and stimulated investigation into a variety of important mechanisms affecting plant compensation. Probably the foremost reason for the lack of a consistent linear relationship between carbohydrate production and growth or yield is the complexity and variability of the plant resource-allocation infrastructure. The exact mechanisms associated with the partitioning and allocation of photo-assimilates in plants are poorly understood at best. Plants such as monocots with a limited number of sinks and extensive vascular systems may not show such restricted allocation (Trumble et al., 1993). Other factors can impact the complexity of plant responses. Variability in environments creates a mosaic of possible outcomes from herbivory which is further complicated by changes in plant physiology and concomitant compensatory events that vary with vegetative or reproductive stages.

Endogenous factors affecting plant compensation are defined as those mechanisms that are primarily influenced by allocation or reallocation of resources within the plant (Trumble et al., 1993). These include regrowth patterns, photosynthetic activity, senescence, leaf morphology, and canopy architecture. Variable distribution of resources can result in major changes in the form of plant compensatory responses and is strongly influenced by source-sink relationships. Sink-limited plants are characterized by lack of yield reduction following leaf loss. In such plants carbohydrates may be stored in structures other than leaves; up to 40% of the stem weight may be sucrose.

Judging the degree of sink limitation is often difficult because of variable importance of other compensatory factors, including hormonal balance effects on translocation or assimilate release by senescing tissues (Trumble et al., 1993). In contrast source-limited plants usually suffer marked growth or yield reductions following a decrease in leaf area. Many common crop plants are source-limited, and the literature provides numerous examples of yield loss due to arthropod removal of leaf area. The relative effects of sink or source limitation on yield in agricultural crops are likely to vary with cultivar, growing conditions, and stress. This variability represents a major challenge for plant breeders attempting to utilize plant compensation for arthropod resistance.

An increase in net photosynthesis activity may occur following arthropod damage because leaves often function below maximum capacity particularly in monsoon season crops (Trumble et al., 1993). Less leaf area may improve water availability for the remaining leaves thereby improving water status resulting in stomata remaining open longer in dry periods. Similarly an increased availability of nitrogen due to either reduced leaf area or a feeding-induced (premature) senescence could enhance protein synthesis. Defoliation during the critical stage of grain set frequently results in reduced yields.

Exogenous factors that impact compensatory responses are not directly under the physiological control of the plant (Trumble et al., 1993). These include such environmental factors as nutrient availability, intensity and timing of defoliation, and herbivore distribution. Predicting plant compensation responses for arthropod damage is complicated by variance in nutrient availability which can affect not only growth but also the allocation of resources within the plant. Nutrient pulses which occur in both natural and agricultural systems variably affect leaf- and root-relative growth rates and allocation of reproductive structures. The relative level of optimal versus substandard nutrient availability as well as accessibility of growth related nutrients (N, P, S) versus other nutrients (K etc.) will influence biomass allocation (Trumble et al., 1983). Thus because nutrient availability to the roots changes relative sink strengths, and sink strength relates directly to compensation through resource allocation, the nutritional status of the root medium plays a significant role in compensatory responses.

Intensity of defoliation includes both degree of leaf loss and number of successive episodes of defoliation (Trumble et al., 1983). Although plants generally compensate less for multiple defoliations due to chronic herbivory than for episodes of single defoliations, some plants can effectively compensate for more than one partial defoliation.

The relationship between timing of arthropod damage and plant phenological state is critical to understanding compensation responses. Bardner and Fletcher (1974) reported that the relationship between injury and yield varies with growth stage at the time of injury resulted in the following generalized pattern for annual plants:

1) Plants are intolerant of damage and compensate little immediately following germination,
2) As vegetative growth proceeds, plants become increasingly tolerant,

3) At the onset of flower production, plants become less able to compensate (specifically those species with short flowering periods), and
4) As reproductive structures ripen, plants again become tolerant to arthropod defoliation.

The injury to the rice plant as well as the loss in yield caused by stemborers is complicated by diverse factors (Ishikura, 1967). The recovery of the infested plant from injury caused by the first stemborer generation is remarkable and is affected by plant characteristics, soil fertility, and climate.

Water and temperature stress can significantly impact plant compensatory capacity, mostly through alteration of allocation and reallocation of resources and stomatal closure effects on gas exchange and photosynthetic capacity (Trumble et al., 1983). Most of the physiological changes due to water and temperature stress that influence plant compensation are similar. The rate of leaf photosynthesis at light intensities is proportional to the leaf nitrogen content (Rubia and Penning de Vries, 1990a). In the case of low nitrogen supply there was always little compensation so that the yield reduction is approximately proportional to the incidence level. These results suggest that applying fertilizers will suppress yield reduction caused by stemborer.

Results show that rice may compensate for stemborer injury by increase the rate of photosynthesis of leaves adjacent to the stemborer killed leaves (Rubia et al., 1996). There are at least three mechanisms that could explain this increase:

1) Partial defoliation can cause increase in photosynthesis in the remaining leaves, allowing for an improved supply of cytokinins to the remaining leaves by removal of sinks and leading to an increase of carboxylation enzymes,
2) An increase in assimilate demand by previously existing or new sinks (e.g., replacement tissue) can increase photosynthesis in the remaining leaves, and
3) There may be translocation of nitrogen from dying leaves to healthy leaves to increase nitrogen concentration in the leaf blades.

At the vegetative stage, rice plants actively produce tillers, and some tillers including leaves of those tillers may be lost without reducing grain yield because the number of productive tillers is determined at the maximum tillering stage. Simulated damage was made by removing tillers with scissors showed that the vegetative damage could tolerate a 30% loss through this physiological mechanism (Rubia et al., 1990a). There was no effect on the total number of panicles formed if the rate of productive tiller formation is as fast as the rate of tiller loss due to stemborers.

The rate of induction of new tillers, spikelets, and grains depends on the rate of production of carbohydrates. The amount of carbohydrates required to initiate a tiller determines the maximum number of tillers that the crop can support in the prevailing environment and this amount increases with plant age. Spikelet and grain formation rates are proportional to the rate of carbohydrate production and independent of the number of tillers until the maximum number of spikelets per tiller or the maximum grain weight is reached (Rubia and Penning de Vries, 1990a).

Reproductive stage infestation leads to greater yield reduction, and physical factors such as low solar radiation can especially aggravate the effect of stemborer on yield (Rubia et al., 1996). Rice plants can compensate for stemborer injury by translocating assimilates from injured to healthy tillers. There appears to be less active translocation at the reproductive stage and less photosynthetic activity in the primary tillers, roots, and cut stems. That implies the later the injury the slower the plants can compensate by translocating assimilates from injured to healthy tillers.

The results by Rubia-Sanchez et al. (1999) suggest that primary tillers, not infested by brown planthopper, translocate nutrients and assimilates to the main shoot as a compensatory mechanism. Brown planthopper sucking on the main shoot reduced height, leaf area, average photosynthetic rate of the two upper leaves, leaf and stem nitrogen content, and shoot dry weight. Brown planthopper-susceptible cultivars with few tillers may not be able to compensate sufficiently for injury at the vegetative stage. Thus cultivars with high photosynthetic capacity and faster translocation ability may suffer less. Photosynthesis and transfer of nutrients and assimilates from tiller to tiller is an important aspect in plant compensation from brown planthopper.

Evidence of compensation also occurred with studies on the rice bug which was based on the fact that over 95% of stylet sheaths (left on the plant after feeding) were located on filled grains (Litsinger et al., 1998). This observation goes contrary to the belief that rice bug feeding at the milky stage causes empty grains. Rice bug feeding does cause empty grains but the evidence points to the cause of unfilled grains as being indirect. After the rice bug stops feeding the plant apparently redistributes photosynthates to the fed-upon grain at the expense of a younger spikelet which goes unfilled.

16.10.1 Field Distribution of Damage

The distribution of insect infestations on and between plants affects the ability of a crop to make compensatory growth in response to injury (Bardner and Fletcher, 1974). Compensation is less effective if killed or injured plants are aggregated such as hopperburn, a caseworm attack and stemborers. Colonization of planthoppers is in patches and once they kill a plant they disperse to neighboring living ones and after these in turn are killed keep migrating in an ever concentrated ring outwards causing a growing patch of damage. The cause of aggregation for caseworms is wind blown or water driven larvae in their floating cases and for stemborers by short larval dispersal from egg masses. Sometimes the edges of a field are most heavily infested due to dispersal and host seeking behavior. Small insects such as hoppers can be windborne for many miles and fall out on the windward side of barriers such as wind breaks or hills. In agricultural systems, plant spacing is such that small losses to the canopy can be readily filled but if larger areas are damaged adjacent plants cannot easily compensate.

Arthropods that feed in aggregated or clumped dispersion patterns are likely to cause such damage at lower population levels than those with random or systematic dispersion. Bardner and Fletcher (1974) discuss several mechanisms responsible for aggregated dispersions including edge effects, obstruction effects, plant density, and plant heterogeneity. Other potential mechanisms include protection or self defense, mating behaviors, feeding strategies, pesticide application, and oviposition patterns. The feeding site preferences of arthropods can impact the compensatory responses of plants.

Judenko (1973) proposed in his analytical method of crop loss assessment that undamaged plants can yield more than normal if neighboring plants or tillers were damaged (case B in Fig. 1.3 in Litsinger, 1991). An unattacked plant adjacent to an attacked plant could better compensate in the same way border plants grow better in the absence of a 360° complement of competing neighbors. Damaged plants are stunted and compete less for nutrients and sunlight. Whereas a damaged plant located next to an undamaged plant would have less ability to compensate (case C). In case A all plants are damaged and there is no compensation and the same if all plants were undamaged.

This result was corroborated in the simulation of Rubia-Sanchez et al. (1999) where with random distribution of damaged hills there was less compensation than if there were aggregated areas or clumps of damaged areas. In some instances hills with one whitehead, yield was more than hills without whiteheads. This may have been that the whiteheads were in secondary or tillers that contributed little to yield.

16.10.2 Within-Plant Distribution of Feeding Insects

Rice stemborer moths and larvae prefer the most vigorous tillers in which to oviposit and penetrate. Ishikura (1967) pointed out that both striped stemborer generations prefer stouter and more vigorous stems, which potentially are more productive. The same conclusion was noted with *Maliarpha* where infested tillers produce the heaviest panicles due to the behavior of the females to oviposit on the most vigorous plants and first instar larvae which enter internodes of the thickest tillers (Delucchi et al., 1996). Rice leaffolders feeding on the leaf sheaths cause greater damage than on leaf blades (Graf et al., 1992).

16.10.3 Crop Age

Numerous trials have shown that a young rice crop can tolerate damage more than an older crop. Van Haltern (1979) examined effects of removing the top 25 and 50% of leaves by scissors to Pelita rice in plants of varying weekly age from 1 to 11 w.a.t.. The results showed only 12% loss from 25% leaf removal from 1 to 6 w.a.t. with greatest loss increasing from 7 to 9 w.a.t. which lessened at 10–11 w.a.t. (Fig. 16.4). Similarly with 50% leaf removal there was negligible loss from 1 to 6 w.a.t. but greatest loss from 7 to 9 w.a.t. Van Haltern (1979) followed up this trial conducted on small plots with a larger field experiment. Removing the leaf area from 50 to 100% (to ground level) at 2 w.a.t. showed 9 and 15% loss in yield respectively with no significant difference between cutting heights on Pelita cultivar.

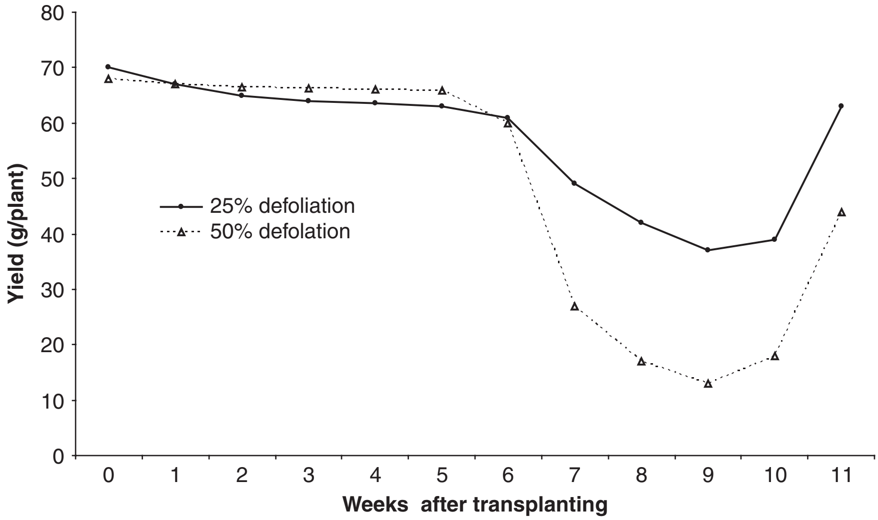

Fig. 16.4 Average grain yield per plant after artificial defoliation with scissors of the top quarter (25%) and the top half (50%) of the leaf blades from plants aged 1–11 weeks after transplanting. Plants at zero weeks after transplanted equal the uncut control. One single defoliation at the specified week after transplanting on Pelita rice in the field, Maros Research Station, Sulawesi, Indonesia, 1974 (adapted from Van Haltern, 1979)

It has been generally assumed that any reduction in leaf area would result in loss caused by armyworms. Navas (1976) in dryland rice concluded from studies in Panama that plants could withstand extensive leaf removal by artificial methods or by natural populations of armyworm particularly in the vegetative stage. Bowling (1978) removed 25 and 50% of leaf tips at the seedling stage (simulating armyworm damage) which reduced yield only 3 and 8% and similarly at the tillering stage only 5 and 12%. Although yields were reduced in all treatments the scale of loss was not as great as expected. He concluded that rice plants were able to recover from extensive leaf removal in the early vegetative stages of growth. In addition leaf removal did reduce yields proportionally.

Defoliation damage although has been found to be greatest at the flag leaf stage where losses at times can be lower than expected. Tripathi and Purohit (1971) found that when leaves were cut in half or fully removed at panicle initiation on Basmati rice, yields were only reduced by 14 (top half removed) or 19% (fully removed). Likewise the number of grains per panicle was reduced 5 and 13%, respectively, and sterility was 9 and 18%.

For pests such as gall midge and stemborers causing damage to tillers, there is a somewhat different relationship. Greatest correlation of gall midge to yield loss occurred from sampling at 7 w.a.t. and not a younger or older crop (Williams et al., 1999). Ishikura (1967) reported from studies in Japan that the second generation striped stemborer attacked the main stem and primary tillers VI, VII, and VIII. Most infested stems were main stems and tillers branching from lower nodes which potentially bear more grains. The more frequent injury to the main stem and to tillers from the lower nodes seemed to have been caused by extended exposure to the attack and not by the preference of the larvae for larger stems and tillers. Of the infested tillers, 9–56% tolerated the injury and survived. The date of heading was almost the same in both infested and uninfested plants and even in surviving infested tillers. The average number of grains per panicle was 5 and 14% more in infested plants than in healthy plants in two experiments in 1936 and 9% more in infested than healthy plants in 1937.

An experiment in Malaysia (Wyatt, 1957) in which researchers placed stemborer larvae on potted plants of various ages demonstrated their effect on yield. The infestation rate was 1 larva per 2 tillers, approximately equal to the level at that time in peninsular Malaysia. The experiment showed that although the size of the loss depended on the age of the plant when infested, infested plants of all ages suffered some loss. Loss was greatest on 50–65 day old plants (31–58%).

Infestations at 7 and 9 w.a.t. appeared to be more severe (steeper slope in linear regression) than at 5 w.a.t. which Soejitno (1977) attributed to compensation by the formation of new tillers. He attributed the greater damage to loss in plant vigor. Bandong and Litsinger (2005) hypothesized a different mechanism and found rice is most susceptible to yellow stemborer during periods of elongation which occurs at maximum tillering (to give the most deadhearts) and at panicle exsersion (to give the most whiteheads), in between these two periods stems toughen due to silica and lignin making penetration by the first instar stemborer larva less successful. A similar result also has been recorded for *Maliarpha* (Delucchi et al., 1996) who reported there was only one sensitive period which is at booting development beginning 42–65 d.a.t. (beginning 3 weeks from the end of tillering). Before this period larval mortality is high and the plant can compensate. After this period the severity of damage is negligible.

In deepwater rice culture defoliation from hispa at the maximum tillering stage produces higher losses than when it occurs at tiller elongation as the rising water prevents compensation from increased tillering that would be expected in normal rice culture (Islam, 1989).

Heong (1990) reported an exponential increase in the per capita leaf area consumption with leaffolder larval age but a decrease with host-plant age. The same relationship emerged from modeling. Rice appears to be sensitive to leaffolder damage only during booting to heading. During the same period the plant is also most attractive to immigrating moths and more so if the crop is highly fertilized (de Kraker et al., 2000). Despite the high attraction between booting and heading, the crop is highly tolerant of leaf removal during this time.

16.10.4 Effect of Cultivar

Genetic resistance to insect pests is well established in rice (Heinrichs, 1994). Tolerant varieties have also been identified. However there are also a number of reports of susceptible and non-tolerant rice cultivars that at times do not suffer significant losses from high levels of insect pest damage. Litsinger et al. (1987a) showed a

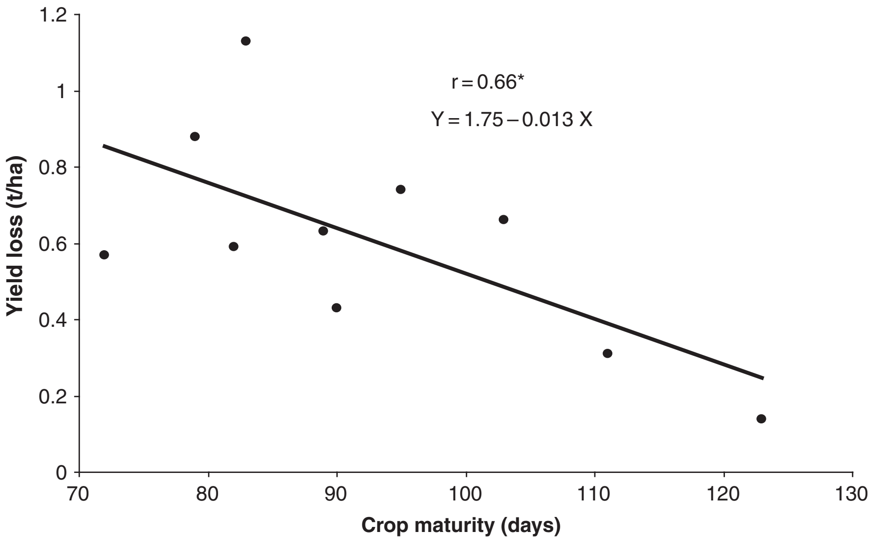

Fig. 16.5 Relationship of yield loss to crop maturity across ten sites in transplanted irrigated and rainfed rice environments in the Philippines, 1976–1986 (after Litsinger et al., 1987a)

linear relation between declining yield loss with increased plant maturity of cultivars (Fig. 16.5). This is a generalized relationship that has nothing to do with genetic resistance and the only factor is longer maturity. There are exceptions to this, however, as Rubia-Sanchez et al. (1997) showed that IR64 compensated more than Cisandane for damage even though Cisandane was longer maturing. Litsinger (1993) compared a medium and early maturity variety using the insecticide check method where there was significant yield loss in the early maturing variety but not the longer maturing one.

The apparent tolerance of yellow stemborer by deepwater rice varieties is consistent with their being a primitive group of cultivated rices (Taylor, 1988). With the loss of main stems and basal tillers there was usually a compensatory increase in nodal tillers (Catling et al., 1987). Vigorous nodal tillering must help compensate the plant for early stem losses (from stemborer, drought, rats, and flooding). Nodal tillers account for more than 30% of the total stem population in some Bangladesh fields attacked by yellow stemborer.

16.10.5 Evidence for Compensation

A number of studies have pointed to different expressions of compensation.

16.10.5.1 High Pest Counts and Low Loss

Modern rices have been known to tolerate high levels of insect pest damage which instances are often quoted (Litsinger et al., 2005) and used as justification for reducing insecticide usage in rice (Heong, 1998) essentially by raising action threshold levels. Miyashita (1985) showed that a crop in Japan with even 67% damaged leaves from leaffolder did not result in significant yield loss. Research has shown that up to 30% stemborer deadhearts and 10% whiteheads (Rubia et al., 1996) and 3 whiteheads/hill (Litsinger, 1993) can be tolerated by modern rices without yield loss. In another study, rice fields with high nitrogen can tolerate up to 60% deadhearts and 20% whiteheads without a significant effect on yield (Rubia and Penning de Vries, 1990a). Swarna a 145 day modern variety common in Chhattisgarh, India can tolerate up to 25% silver shoots from gall midge without significant yield loss (RK Sahu personnel communication).

16.10.5.2 Slope of Regression of Yield Loss with Yield

Rubia-Sanchez et al. (1997) took the yields on a per-hill basis in fields of varying white stemborer *Scirpophaga innotata* infestation rates. When a regression relating damage to yield the slope was flat, they suspected compensation was responsible for this outcome. As a result they commented it would be difficult to generalize yield reduction as a result of white stemborer damage unless conditions affecting plant vigor were known. Stemborers causing deadhearts before tiller number is fixed will have very little effect. The compensatory mechanism from gall midge, rice whorl maggot, and stemborers to injury is for the plant to produce more tillers.

In a multi-crop study in the Philippines across four sites found crop compensation in five of the eight wet and dry season crops (Fig. 16.6). A crop in this case refers to a seasonal average over a number of years. Compensation was measured as an insignificant slope when yield loss was regressed with yield over crops. One notes that higher yielding crops had relatively lower losses, i.e., more vigorous crops tolerated more damage. In addition high compensation was observed in Guimba and Calauan sites in both wet and dry season crops where pest incidence was generally low and nitrogen inputs high. In Zaragoza under high pest pressure, high compensation occurred during the dry season, whereas in the wet season, the crop could not outgrow damage. In Koronadal pest incidence was high and compensation was not recorded in any crop probably as nitrogen levels were too low.

16.10.5.3 Role of Solar Radiation in Crop Compensation

Among the abiotic physical factors affecting rice yield, solar radiation is one of the most important. Low yields in the monsoon season are attributed to lack of adequate irradiance. Irradiance becomes a limiting factor during seasons of short day lengths. This is seen in the average solar radiation measured at the IRRI Experimental Farm over a 11 year period (Fig. 16.7). The authors noted that there was considerable variation year to year based on cloud cover due to monsoon weather and the fact that IRRI sits next to the 1100 m Mt. Makiling volcano that creates its own weather. The wet season crop begins in June or July and as can be seen will mature during increasingly lower irradiance which is a combination of cloud cover and short day

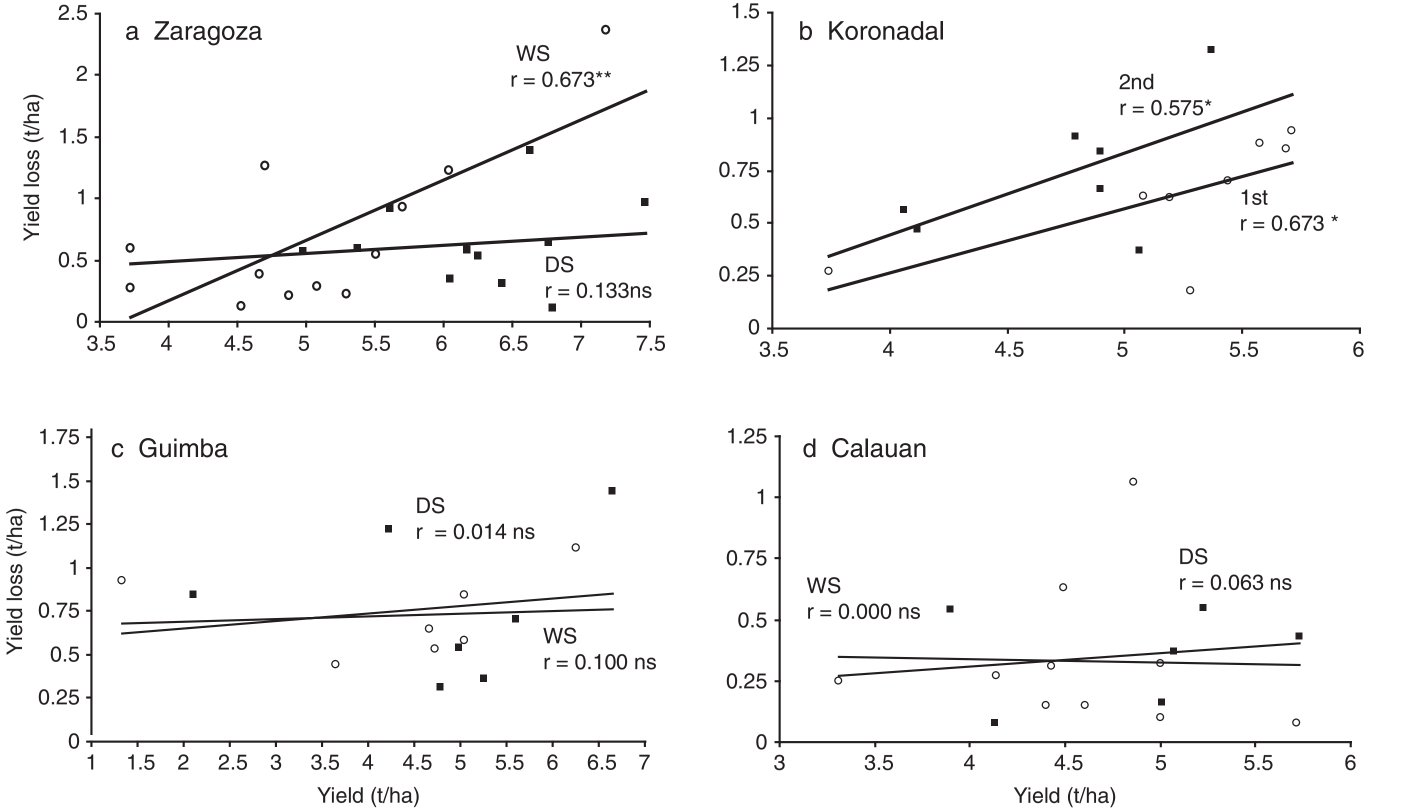

Fig. 16.6 Relationship between yield and insect pest-caused yield loss in four sites showing compensatory capacity in those crops with significant slopes in the regression equation: for WS or first (o wet season) and DS or second (■ dry season) crops (**a**) Zaragoza, (**b**) Koronadal, (**c**) Guimba, and (**d**) Calauan, Philippines. (after Litsinger et al., 2005)

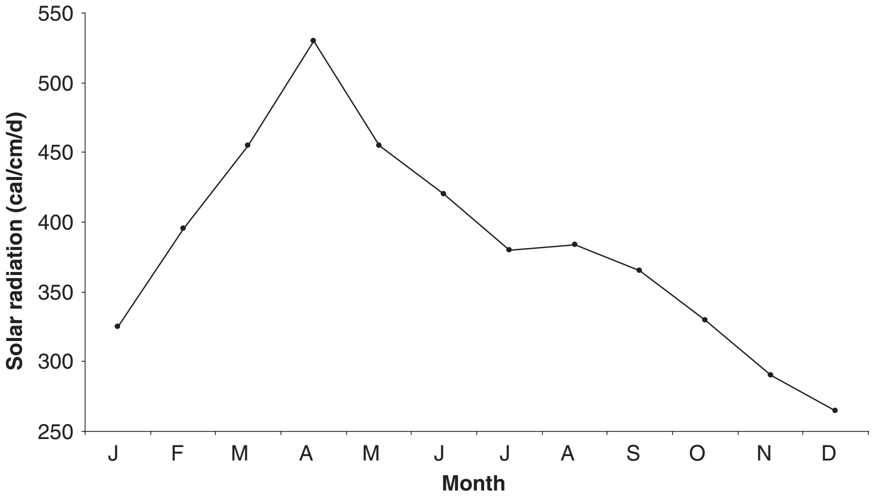

Fig. 16.7 Monthly solar radiation on the IRRI Farm over an eleven year period, Los Baños, Philippines, 1966–1976 (after Evans and DeDatta, 1979)

lengths. However, the dry season crop is cultivated during periods of the highest irradiance levels due to longer day lengths and cloudless weather.

Evans and DeDatta (1979) related incidence of solar radiation to yields taken from the top ten cultivars in production trials during an 11-year span over varying periods of crop growth. Irradiance influenced yield components in the order in which they were determined, the earliest being number of panicles/m^2, followed in turn by spikelets/m^2, and grains/m^2. The correlations were highest for crops grown under high irradiance, and were lowest for crops grown during the wet season, probably because of pests. Regardless of whether irradiance was progressively rising or falling, high irradiance at any stage after panicle initiation was associated with higher yields in both traditional and modern varieties. Yields of all varieties were most significantly correlated with irradiance (over 20- or 30-day intervals) during both the reproductive and the ripening stages, but the most important period was 20–30 days before maturity, depending on the cultivar. With Peta variety the correlation was high even for irradiance during only the last 20 days before maturity, whereas it was relatively low for irradiance at that stages for TN1 and Milfor 6 and highest when irradiance during the 15 days before flowering was also included in the correlation. Responsiveness to irradiance was also greater at higher levels of nitrogen fertilization. High irradiance at any time after panicle initiation could contribute to higher yield even when preceded or followed by a period of lower irradiance. But high early irradiance may have encouraged tillering to an extent that was disadvantageous under conditions of rapidly falling irradiance.

Kenmore et al. (1984) noted that hopperburn in fields with heavy infestations of brown planthopper happened on cloudy days in the wet season. They noted that solar radiation can vary as much as 30% from planting either a month earlier or later. During the monsoon season, solar radiation in most years is a limiting factor to yield and the crop is often under stress as photosynthesis cannot keep up with physiological demands. Brown planthoppers remove phloem sap which is necessary to manufacture carbohydrates which are basic material for growth, and shading reduces the supply of sap creating a deficit in plant needs. Kenmore et al. (1984) hypothesized that hopperburn is due to the accumulation of ammonia as a by product of plant metabolism.

16.10.5.4 Crop Management to Enhance Compensation

Some of the earliest work to enhance compensation by crop management came from Japan. Ishikura (1967) summarized research where it was noted that an increase in the application of nitrogen fertilizer increased the compensatory ability of rice plants to striped stemborer injury. This practice was used by farmers before the synthetic pesticide era, although the mechanism of how plants recovered from damage was unclear. Ishikura (1967) concluded that this practice could be used for the management of stemborers, but that the right concentration and timing of applications should be determined in order to avoid the positive effect of nitrogen on stemborer population dynamics.

Rubia-Sanchez et al. (1997) noted that the relationship between white stemborer whiteheads and yield was location specific, most likely due to variation in farmers' practices and environmental conditions and concluded that insufficient knowledge of the various factors influencing the relationship may lead to an overestimation of damage. Since tillering is strongly influenced by nitrogen supply, plant recovery to stemborer injury may be enhanced by fertilizer application. Topdressing with nitrogen aiding plants to recover from stemborer injury has been a recommended practice in India (Rubia et al., 1996). Applications of nitrogen in later growth stages favor compensation from leaffolder and stemborer damage by delaying leaf senescence (Peng et al., 1996), however this application also prolongs pest attack. Litsinger (1993) showed that increasing nitrogen rates over a range of 0–90 kg/ha led to progressively less yield loss from combined damage from whorl maggot and defoliators.

16.10.6 Yield Loss Paradox

We have discussed how high pest populations can result in low yield losses via crop compensation. Data from some trials, however, show evidence for the opposite phenomenon where low pest numbers are associated with high losses. Baumbärtner et al. (1990) in Madagascar, for example, recorded high losses with the insecticide check method using phosphamidon when sub-economic insect pest numbers were detected. In the Philippines the numerous insecticide check trials also produced 11 crops where high losses were recorded while sampling revealed below average insect pest numbers (Table 16.2). Such trials occurred in virtually all sites and either wet or dry seasons. The paradox has been discussed by Litsinger et al. (2006b,c)

Table 16.2 High yield losses unexplained by insect pest counts in insecticide check trials in rainfed and irrigated rice culture, Philippines,1976–1989[1]

Province	Town	Year	month	Cultivar	Yield(t/ha)		Yield loss (%)
					Complete protection	Untreated	
Rainfed wetland culture							
Pangasinan	Manaoag	1976	Nov	IR36	3.82	2.28	40
		1978	Aug	IR36	3.65	2.14	41
		1978	Oct	IR36	2.23	1.44	35
lloilo	Oton	1978	Aug	IR36	5.01	3.57	29
Cagayan	Solana	1980	Oct	Wagwag	1.27	0.45	35
Irrigated wetland culture							
Laguna	Calauan	1988	WS	C1	4.86	3.8	22
N. Ecija	Guimba	1984	WS	IR58	1.33	0.41	69
N. Ecija	Zaragoza	1979	WS	IR36	7.18	4.81	33
		1988	DS	IR64	6.63	5.25	21
		1989	DS	IR64	7.47	6.57	13
S. Cotabato	Koronadal	1986	2nd	IR62	5.37	4.15	25
		1987	1st	IR62	5.69	4.84	15

[1]Data from Litsinger et al. (2005).

in instances where high yield gains from insecticide protection occurred on crops where sampling showed insect pest infestations to be below action threshold levels. The very large yield gain in the 1979 wet season in Zaragoza is explained by the 1978 wet season crop which was destroyed by a typhoon near harvest. It in effect became a green manure crop for succeeding crops. The effect was only modest in the 1979 dry season, however, as perhaps the organic matter had not decomposed sufficiently. The 1984 wet season crop in Guimba was severely affected by the combined action of drought and stemborer whiteheads (14%) which together accentuated yield loss. All the other trials in Table 16.2 had modest insect pest infestations.

An explanation, of course, is that the insecticides used in the experiments stimulated rice growth thus giving false high yields in the complete control plots compared to the untreated checks. Being aware of the potential problem we had tested the range of insecticides commonly used in greenhouse trials for exactly this source of error in the insecticide check method. We only found carbofuran that had phytotonic effects (Venugopal and Litsinger, 1984). Carbofuran was used through 1978, but not thereafter in our yield loss trials. But if this were true, then all trials would have been similarly affected, and in half of the crops there was no significant yield gain (Litsinger, 1984). There may be an environmental interaction which varies field to field from unknown factors so we cannot fully discount this effect.

However there is another possible explanation. The effects of several pests attacking at once has been pursued which show heightened losses in field trials (Table 16.3). In these trials sub-economic insect pest densities of rice whorl maggot, defoliators, and yellow stemborer were artificially infested onto caged plants as single and combinations of species. Only yellow stemborer resulted in loss when

Table 16.3 Yield of IR36 based on single and multiple artificial infestations by three insect pesets, IRRI field, Philippines,1982 wet season

Pest	Yield (g/m^2)
Caseworm (1)	514a
Whorl maggot (2)	514a
Yellow stemborer (3)	458b
1+2	426bc
1+3	413c
2+3	419c
1+2+3	402c

[1]Average of four replicates. In a column, means followed by a common letter are not significantly different ($p \leq 0.05$) by LSD test. (IRRI Annual Report for 1982, p.204).

caged without other species but each combination increased yield loss significantly. Synergistic losses have been documented from nematodes (Noling, 1987) where higher than anticipated losses occurred from the simultaneous attack of two pests where the results were more than additive. Andow and Hidaka (1998) compared the effects of simulated defoliation on organic and inorganic rice farms and concluded that insect pests and diseases may have affected yield loss independently in natural farming, but in conventional paddies, multiple pest injury may have interacted synergistically compounding yield loss. They concluded the reason for this result remains uncertain but it could be to rice physiology or competition. Conventional rice has thinner cell walls which makes it more susceptible to rice blast. Removal of leaf tissue might have resulted in a greater susceptibility to infection in conventional rice by altering cell wall thickness or another physiological defense. In addition, biomass was greater in conventional rice so the surrounding hills might have competitively suppressed the clipped hills more in conventional rice causing them to be more susceptible to infection. This level of complexity is likely to occur in many crops and cropping systems.

Multiple stresses acting on a single growth stage influencing the yield loss relationship may provide the most important insight into explaining the yield loss paradox. It is hypothesized that there is a synergistic effect of the occurrence of multiple pests/stresses on yield loss documented by Table 16.3 and the results of Savary et al. (1994) and as elaborated by Litsinger (1991). Thus, when occurring in combination with other pests and/or stresses, even a low stemborer population can become magnified synergistically as a significant yield loss, much more so than would be expected if stemborers were the only stress present. Thus, when stemborer numbers are even partially controlled, the plant's physiological compensatory abilities are released to partially overcome not only stemborer damage but that from other stresses, producing a concomitant *synergistic yield gain*. This mechanism is offered to explain the yield paradox and is the opposite of synergistic yield losses described above.

Litsinger et al. (2006b, c) postulated that if synergistic losses can occur, the corollary can also occur. If one stress is lessened then a synergistic yield gain can occur from release of compensatory ability for any source of stress. The stresses as described previously can be from any cause, biotic and abiotic, not just insect pests.

Therefore the following interpretation of the above observations can be made. High tillering rice crops can tolerate high levels of insect damage, especially those that are growing vigorously due to good management, under good growing conditions such as sufficient water and solar radiation, and free of significant environmental stresses. There is a large body of research results that has been reviewed herein that supports this hypothesis. However researchers have used this data to assume that this happens in all crops thus concluding that insecticide control measures would be rarely needed. Evidence presented earlier where we showed that even the same farmer can experience dramatic swings in yield mostly from factors that are not under his control supports the reality that these ideal conditions are not the norm.

The crop's ability to compensate becomes increasingly less as the number and intensity of stresses increase, particularly for stresses that affect different physiological processes which are more likely to cause synergistic effects. Those, such as several species of defoliators, reduce photosynthetic surface area and their effect is additive while those such as either whorl maggot or stemborers combined with defoliators not only reduce photosynthetic area but block the movement of water and nutrient flows in vascular tissue.

Crops are low yielding as they suffer from multiple stresses due to suboptimal environmental conditions and perhaps from poor management, either under the farmer's control or not. As these stresses become lessened from corrective actions such as the applied insecticide in the insecticide check method, the resulting yield gain becomes accentuated or synergistic. Thus the control exerted against insect pests relieves one stress which in turn frees up physiological capacity that can compensate from stresses due to other causes. From the example of wheat in Montana, controlling fungal diseases allowed the crop to overcome some of the negative effects from drought stress as well (Nissen and Juhnke, 1984). This would explain the observed high yield gains from controlling low incidence of insect pests as the crop then compensated for other stresses. The greater the stress load the greater the yield gain when stresses are released.

If this hypothesis is true, then the yield losses measured by the insecticide check method are not strictly due to insect pests and the conclusions from using this method of crop loss assessment needs to be reassessed. Due to the ability of modern rices to tolerate stresses and the high response to favorable management or weather, losses measured by the insecticide check method are therefore combined with losses due to other stresses. The conclusion therefore is that the oft used insecticide check method is not applicable for measuring losses from insect pests per se and the effects should be termed *yield gain* from insecticide use. A given infestation level of an insect pest therefore can cause very different loss levels depending on the type and severity other stresses, management practices, and the prevailing physical environment at the time.

16.10.7 Tolerance as A Mechanism of Plant Resistance

The tolerant plant response to insect damage is probably the most common of damage function relationships and is sigmoidal (Fig. 16.3B) (Poston et al., 1983; Pedigo et al., 1986). In this situation the plant will compensate for some quantity of injury without reducing marketable yield until a critical point is reached. At this point the plant's ability to tolerate injury is exceeded and yield is reduced. After this stage yield is reduced with each additional increment of injury until a lower plateau is reached (the point after which additional injury does not cause a yield reduction). This lower level may reflect the plant's priority for energy allocation to reproductive parts or plant yield that was generated and stored before the insect attack.

Tolerance is a basis of resistance in which the plant possesses an ability to grow and reproduce or to repair injury to a marked degree despite supporting a pest population approximately equal to that damaging a susceptible host. The basic triad of resistance mechanisms: (1) non preference, (2) antibiosis, and (3) tolerance usually have been found to result from independent genetic characters which are interrelated in their effects. The expression of genetic factors resulting in these three mechanisms is frequently modified by various ecological conditions and by other genes.

Painter (1958) emphasized, that in most cases of resistance, preference, antibiosis, and tolerance work in combination even though the contribution made by one might be very much greater than that of the other two. Beck (1965) underscored the presence of the complex nature of resistance mechanisms and emphasized the importance of interactions between insect behavior and chemicals produced by the plant. The main mechanism of tolerance is compensation. Conditions for plant growth also affect the compensation of the plant or crop to insect attack. The relationship between sowing dates and the ability of crops to tolerate infestations is often significant but plant nutrition is also important because crops grown in nutrient deficient soil grow more slowly and remain vulnerable to attack longer. Crops of rice in potassium deficient soil are damaged more by stemborers than those with infestations of a similar size on well fertilized land by balanced nutrients (Litsinger, 1994). Tolerance of injury also depends greatly on the pattern or growth of the crop or plant. Often tolerance can only be effective if sufficient time elapses between the infliction of injury and the end of the yield-forming process. This is why longer maturing rices can tolerate more damage (Litsinger et al., 1987a).

Two examples of tolerance can be cited from work on the brown planthopper with traditional varieties Triveni and Utri Rajapan (Dang et al., 1982). Seedling screening and survival and population growth studies on 30-day-old plants indicated similar degrees of susceptibility on TN1 and Triveni cultivars. Studies in the screen house and field indicated that at both the vegetative and ripening stages Triveni possessed tolerance to insect damage expressed as the ability to survive and produce a higher percentage of productive tillers than TN1 at a similar insect population. Yield reduction caused by brown planthopper was 40% on Triveni infested with 400 insects on 35-, 50- or 75-day-old plants, whereas almost 100% on TN1 at the same ages. Photosynthetic activity of seedling stage Triveni was less affected than TN1 when severely damaged by feeding.

Feeding activity on IR26 measured as the area of honeydew spots was significantly higher than that on Utri Rajapan (Panda and Heinrichs, 1983). It was also observed that brown planthopper feeds primarily on the outer leaf sheaths of Utri Rajapan while on the main shoot of IR26. Hopperburn symptoms developed more slowly in plants where only the leaf sheaths were exposed in contrast to those where the main shoot was exposed. The higher feeding activity and the feeding on the main shoot of IR26 are two possible reasons for the greater plant damage.

A study on gall midge was carried out with 15 different varieties and planted in a season of high infestation using the insecticide check method (Prakasa Rao, 1989). Some varieties had no yield loss despite high infestations and were termed tolerant. In Nigeria, the cultivar Cisandane was compared by the farmers to their normal variety and on average Cisandane yielded 26% higher but African gall midge damage levels were only slightly less than the farmers' cultivars thus tolerance was suspected (Williams et al., 1999).

16.11 Measurements of Crop Loss

This section is presented to focus on more examples of crop loss results from the various methods described. In reporting losses caused by insect pests, the data presented is only meant to illustrate of the potential of each pest or pest group to cause damage. The data are in no means to be taken as annual averages for a mentioned country. Also presented are a number of references that can be used to source more information on yield loss. Teng and Revilla (1996) make the point that although many crop loss assessment methods have been developed their use has not always resulted in more accurate or extensive loss estimates and that a gap exists.

16.11.1 Chronic vs. Epidemic Pests

The terminology for chronic and epidemic pest classifications commonly found in the literature is comprised of temporal and density (severity) components. A pest is an insect that causes economic damage. Chronic pests are those that are commonly present on a crop and occur each season. Occasional pests only occur in economic densities from time to time. A chronic or occasional pest can cause various degrees of damage that range from non-economic to highly economic. Occasional pests which cause severe damage are termed epidemic pests.

Some areas experience high losses from chronic pests each year which approach epidemic loss proportions. Some examples are gall midge and rice hispa in endemic areas mentioned below. White stemborer can also attain this ranking within its limited distribution as can yellow stemborer in deep water rice. Fortunately these areas are limited in size. We only found one reference that stated that farmers ceased growing rice because of annual high losses. Barr et al. (1975) cited an example in India where the damage to the first rice crop was so great from stemborers that farmers were hesitant to plant a second in irrigated conditions. But such reports are rare mainly due to the high value farmers give to rice as a food. Losses nationwide from chronic pests normally outstrip the losses from occasional epidemics as the former occur every year in most rice growing regions, and often farmers do not notice the subtle symptoms which they believe are what a 'normal' rice crop looks like (Barr et al., 1975).

Quelling chronic losses should be important to policy makers interested in increasing rice production in a region or country. If an intensive extension program, focused on improved insect pest control, could increase yields by 5%, that would be a significant boost in food supplies for a nation. Epidemic pests normally affect only a small number of farms in a country and generally are not important to national production but severely affect individual farmers. Thus epidemic pests garner the greatest headlines, some warranted but most not in terms of threatening national food supplies. In 1983 a headline in a Kuala Lumpur newspaper stated that the Department of Agriculture reported that the current rice crop was threatened by a pest menace that could cause complete loss (Kenmore, 1987). A follow-up study showed that only 8% of the area discussed was infested by tungro where only 2% was severely damaged. Production loss was estimated to be less than 1% in Malaysia. As our yield data show that each crop there are farmers who harvest meager yields from many different causes.

Similar reports on brown planthopper were repeated in Indonesia, Sri Lanka, and the Philippines over the same period but fortunately were rare occurrences. This is termed the ‘political pest outbreak panic threshold’. With knowledge that indiscriminant insecticide usage spurs such outbreaks has led to more ecologically sound management practices that can temper them (Heinrichs et al., 1982; Gallagher et al., 1994). At the time of this writing there was only one recent report of an outbreak in Asia and that was from brown planthopper and grassy stunt in the Mekong Delta of Vietnam (KL Heong personal communication). In this area, triple rice cropping is practiced and farmers use insecticides indiscriminately that led to resurgence of brown planthopper and possible breakdown of resistant rices. Reports of this nature are often exaggerated in terms of the threat to rice production in the region, still many farmers no doubt suffer high losses as a result.

16.11.2 Losses by Growth Stage

Yield losses have been determined for the major rice growth stages in a number of studies. Losses in the seedbed have been the least studied but some data is available in the Philippines. However 26 trials conducted by IRRI researchers from 1978 to 1982 (Table 16.4) show that in none of trials was seedbed loss significantly different from the complete protection treatment in the partitioned growth stage insecticide check method (Reissig et al., 1981). As a result a separate treatment to protect the seedbed was discontinued from future trials order to economize on research costs. But the percentage of Filipino farmers applying insecticide to the seedbed as determined from surveys averaged 39% in Koronadal, South Cotabato and 71% in Zaragoza, Nueva Ecija (Litsinger et al., 2008). In Guimba (also in Nueva Ecija) 95% of farmers surveyed applied insecticides to the seedbed and two thirds of these were prophylactic in nature (Fajardo et al., 2000). One wonders why so many Filipino farmers applied insecticide to their seedbeds. Recommendations to control insect pests in the seedbed that would have justification would be to control green leafhoppers *Nephotettix* spp. to prevent tungro disease transmission or white

Table 16.4 Insecticide check method of determining yield loss in the rice seedbed stage of 26 trials on farmers' fields. Data presented here incude only the full protection (insect pest-free over the entire crop) and omitting protection in the seedbed, irrigated and rainfed locations in the philippines with modern and and traditional varieties, 1978–82

Town	Province	Culture	Variety	Season	Year	Yield (t/ha)[1]		
						Complete protection	No Seedbed protection	Untreated
Talavera	Nueva Ecija	Irrigated	IR42	WS	1979	6.7a	7.3a	6.2a
			IR36	DS	1980	4.6a	4.6a	3.9b
			IR54	WS	1981	5.53a	5.52a	5.00a
Cabanatuan	Nueva Ecija	Irrigated	IR36	DS	1979	6.26a	6.01a	5.73b
			IR36	DS	1980	6.05a	6.01a	5.70b
			IR36	WS	1980	3.72a	3.78a	3.77a
			IR36	WS	1981	7.18a	7.08a	4.81b
Santa Maria	Laguna	Irrigated	IR42	WS	1982	4.40a	4.40a	4.28b
			IR46	DS	1982	5.73a	5.19a	5.26a
Victoria	Laguna	Irrigated	IR22	WS	1981	4.84a	5.10a	3.69b
			IR54	WS	1981	4.27a	4.55a	3.66b
Managoag	Pangasinan	Rainfed	IR36	WS	1978	3.65a	3.33ab	2.14b
			IR36	WS	1978	3.70a	3.27ab	2.63b
			Wagwag	WS	1978	2.94a	2.89a	2.14b
			IR36	WS	1979	5.63a	5.54a	4.27b
			IR36	WS	1979	3.53a	3.56a	2.85b
			Wagwag	WS	1979	1.27a	1.22a	0.82b
			IR36	WS	1980	2.59a	2.58a	2.52b
			IR36	WS	1980	4.23a	4.23a	3.76b
			IR36	WS	1980	2.77a	3.83a	2.45b
			Wagwag	WS	1980	2.22a	2.26a	1.73b
Solana	Cagayan	Rainfed	IR36	WS	1980	1.57a	0.96a	0.94a
			IR52	WS	1981	3.6a	3.4a	3.1a
			Wagwag	WS	1981	3.18a	3.43a	3.44a
			IR52	WS	1982	1.84a	1.81a	1.69a
			Wagwag	WS	1982	1.06a	1.16a	0.92a

[1] Yield loss trials were conducted on 4–8 farmers' fields (replications) per crop. Treatements were unreplicated on each field, plot sizes were 100 m^2 and yield cuts were 25 m^2. In a row, means followed by a common letter, are not significantly different ($P \leq 0.05$). Complete protection consisted of 9–11 insecticide applications including weekly sprays in the seedbed beginning 1 week after sowing and every 10 days on the main crop.

stemborer during an outbreak. Otherwise research has shown that farmers who apply insecticides to seedbeds waste capital and effort.

Yield losses on the main crop based on the insecticide check method in four irrigated double-cropped locations in Philippine rice bowls (Litsinger et al., 2005) were significant and were almost equally distributed for each of the three crop growth stages of rice (0.23 t/ha in the vegetative stage, 0.24 t/ha in the reproductive stage, and 0.15 t/ha in the ripening stage).

Another research group from IRRI conducted similar partitioned growth stage insecticide check trials nearby to Zaragoza in the same irrigation system from 1979 to 1981. Although this represented a different research team (supervised by

Table 16.5 Comparison of yield loss results using the partitioned growth stage yield loss method between nearby sites by two different research teams using the same methodology on irrigated, double-cropped rice, Nueva Ecija Province, Philippines,1978–1991[1]

Site	Crops (no.)	Years	Yield(t/ha)[2]		Yield loss		Yield loss (%) by rice growth stage		
			Complete protection	Untreated	t/ha	%	Vegetative	Reproductive	Ripening
Zaragoza	22	1978–91	5.6 ± 1.0	4.9 ± 0.8	0.67	11.5	4.2	4.6	2.4
Talavera	5	1979–81	5.9 ± 0.9	5.0 ± 1.0	0.89	15.3	2.8	6.8	5.7

[1] All trials were conducted on farmers' fields growing modern pest-resistant IRRI varieties.
[2] Means ± standard error.

Table 16.6 Comparison of the yield loss in insect resistant and susceptible varieties, Masapang and Victoria, Laguna, Philippines, 1979–1981[1]

Variety[2]		Yield (t/ha)		Yield loss	
		Protected	Unprotected	t/ha	%
IR 22	Susceptible	4.75a	3.78b	0.98	20.5
IR36, IR54	Resistant	4.39a	3.41b	0.98	22.1

[1]Total of 4 crops grown in farmers' fields using the insecticide check yield loss method. In a row means followed by a common letter are not significantly different ($P < 0.01$)by LSD test.
[2]Susceptibility ratings are in relation to epidemic insect pests, brown planthopper and green leafhopper.

E.A. Heinrichs) and different site and even shorter span of years, the results were almost identical, with total loss equal to 12–15% and greatest loss in the reproductive stage (Table 16.5). The two Philippine data sets described above were all performed using the latest insect resistant varieties (highly resistant to brown planthopper and green leafhopper and with moderate resistance to stemborers). This results suggest that at least in some sites that yield loss figures can be gathered after only a few years of effort in a location.

A similar set of trials in Laguna province also under the direction of E.A. Heinrichs compared an insect susceptible variety IR22 to resistant varieties using the insecticide check method. Even when brown planthopper populations averaged 8 per hill and one crop had 23% of hills infected with tungro, there was no significant difference in yield loss between varietal types (Table 16.6). Losses from chronic pests were identical at nearly 1 t/ha per crop representing 20% reduction in yield. Thus both pest susceptible and resistant varietal types suffered equally from chronic pests which in the case of these trials were mainly stemborers. The Laguna trials were planted at the end of the planting seasons to encourage epidemic pests so are not averages for the Laguna farmer.

16.11.3 Damage Functions and EIL and Decision Thresholds

As seen from the data presented, reliable correlations of insect pest densities to yield (damage functions) are seen to be difficult to achieve in rice, especially when natural infestations are employed on plot levels versus on a per hill level or when artificial infestation is used (Litsinger et al., 1987a; Litsinger, 1991). Most of the problem is that the range in pest infestation is too narrow for relationships to emerge such as would occur if the damage range were from 0 to 3 on the scale in Figure 16.3B, the most common model. Damage functions, however, are an integral part of EIL determination. Traditionally the EIL is viewed as having five primary determinants: (1) control costs, (2) crop market value, (3) proportionate injury per individual pest, (4) crop response to injury vs. yield, and (5) the insecticide kill coefficient (Poston et al., 1983; Pedigo et al., 1986). Although the mathematical relationship of these variables to the EIL is quite straightforward, it is difficult to estimate values for the pest injury potential and the resulting crop response (to calculate damage functions). The difficulty arises because these variables are not simple constants but rather complex biological processes, ie., mechanisms that operate through space and time.

The intractability of the pest intensity-yield loss function is most apparent when attempts are made to estimate the potential damage from a single density estimate in the field (Poston et al., 1983). The pest density measured at a point in time relates most directly to the increment of damage inflicted at that time. At a later time, the pest population and consequently the corresponding damage increment will probably be different. To compare losses with control costs, accurate assessments of this loss from injury detection until harvest must be made. Thus the ability of a single pest density measurement to serve as an estimate of overall damage potential is dependent in part on the ability to reliably predict changes in the pest population through time. This problem may not arise in instances in which the population dynamics of the pest is simple (e.g., limited mortality within discrete generations) or when an accurate model exists that predicts changes in more complex populations (e.g., overlapping generations with variable mortality). Unfortunately these constitute only a minority of the cases with which pest managers must deal. In multiple-cropped tropical rice it is normal for generations to be overlapping particularly where planting is staggered (Perfect and Cook, 1994).

The way economic thresholds have been developed in Asia has been first to determine damage functions based on artificial infestation trials in the greenhouse (e.g., Dyck et al., 1981) or from taking samples from hills of rice in the field that display a wide range of damage (e.g.,Gomez and Bernardo, 1974). Economic thresholds were developed based on this data and initially researchers were surprised at the variability in the resulting figures (Way et al., 1991). For example for economic thresholds for stemborers in the Philippines, Dyck et al. (1981) came up with 10% deadhearts while Liu (1977) in China and Kulshrestha (1976) arrived at 5% deadhearts. Another way was to use large yield loss datasets such as that of Litsinger et al. (1987a) where individual fields or crops and not hills became the points on the regression curves (Waibel, 1987; Smith et al., 1988). This data is much more expensive and logistically challenging to derive and most national programs cannot conduct such investigations.

Some researchers recognized that there could be different damage functions by crop growth stage. Again with stemborers Israel and Abraham (1967) report that for each 1% increase in deadhearts was a 0.3% loss in the vegetative stage but 0.6% in the reproductive stage. Rubia and Penning de Vries (1990a) noted that stemborer threshold values can be 50% deadhearts in the early vegetative stage but 10% deadhearts in reproductive stage.

Rubia and Penning de Vries (1990a) opined that thresholds with low nitrogen should be lower. Indeed Litsinger (1993) showed that yield loss declined with increasing rates of nitrogen, with longer maturing varieties, and higher seeding rates. Rubia and Penning de Vries (1990b) also questioned how to measure a damage function for a single pest when some 3–4 chronic insect pests occurred in each growth stage and a greater number of fungal and bacterial chronic diseases. Indeed that is a major dilemma.

Thus the concept of action thresholds has evolved where researchers take their best estimate based on values from local research and then test them in the field to fine tune them. This was the approach used by Bandong and Litsinger (1988), Litsinger et al. (2006a–c) for chronic pests (whorl maggot, defoliators, leaffolders, and stemborers) in the Philippines. As a result of these evaluations, the best performing characters (> 90% correct decisions) for whorl maggot were 1–2 eggs/hill and 15–30% damaged leaves, for defoliators were 10% damaged leaves, for leaffolders as 15% damaged leaves, and for stemborers was 5–25% deadhearts depending on the growth stage. Despite the wide range of growing conditions, the resulting action threshold levels were surprisingly similar across sites. Although the accuracy of the action thresholds to predict growth stages with 250 kg/ha losses and significant pest damage was over 90%, the outcome was that the insecticide response applied by knapsack sprayers (even when performed by researchers) resulted in poor kill ratios and consequently low yield gains. Motorized sprayers should have given better control but very few farmers can afford them, besides most farmers are satisfied with the performance of insecticides applied with knapsack sprayers. The conclusion therefore became that farmers are best to use insecticides only if the crop is heavily infested and the crop otherwise has low capacity to compensate.

16.11.4 Yield Gaps

The impact of insect pests on rice yields was noted to be highly significant in the yield gap field trials which were basically insecticide check experiments conducted in a number of Asian countries from the mid to late 1970s as part of IRRI's Constraints Program. Yield gaps were measurements of the potential yield derived from better insecticide control technology compared to the farmers' current practice which often is not much different from an untreated check.

16.11.4.1 Philippines

Data from four locations showed losses from insect pests averaged 0.5 t/ha (10% below potential) in the wet season and 0.8 t/ha (14%) in the dry season (Table 16.7). Even though the method biased losses upwards due the use of carbofuran insecticide in the high input treatment (complete control), the figures are similar to those calculated by Litsinger et al. (2005) for similar irrigated rice locations. During the period when yield gaps were measured in the Philippines, inputs were subsidized by a government program and farmers' insecticide application frequency consequently was higher than normal (crop means of 1–7 times with averages of 3–5). Despite the high farmer insecticide frequency, the insect control gaps were on par with gaps measured from better fertilizer management. Farmers were better managers of weeds as that contribution to the yield gap was minimal. The average costs for the high input treatments were three times the average farmers' input over the four sites, and by spending the extra $122 they would have an increased profit of only $4 (Herdt et al., 1984). The high input treatment is equivalent to a prophylactic

Table 16.7 Yield gap as determined from the difference between high input and farmers' input levels for insect control, weed control, and fertilizer usage in four provinces, Phillippines, 1973–1979[1]

Province	Fields (no.)	Yield (t/ha)			Contribution (t/ha) of yield gap			
		Farmers' inputs	High inputs	Gap	Insecticide	Fertilizer	Weed control	Other
	Wet season							
Laguna	57	3.6	5.3	1.6	0.8	0.6	0.3	0
Nueva Ecija	78	3.9	4.8	0.9	0.5	0.4	0.1	0
Camarines Sur	47	3.9	4.7	0.8	0.1	0.2	0.1	0.4
Iloilo	38	3.8	5.2	1.3	0.5	0.7	0.3	0
All sites	*220*	*3.8*	*5.0*	*1.1*	*0.5*	*0.5*	*0.3*	*0.1*
	Dry season							
Laguna	57	4.4	6.5	2.1	1.0	0.4	0.2	0.5
Nueva Ecija	60	5.0	6.9	1.9	0.7	1.0	0.2	0
Camarines Sur	40	4.3	6.8	2.5	1.5	1.1	0.2	0
Iloilo	32	4.1	5.3	1.2	0.3	1.1	0.2	0
All sites	*189*	*4.5*	*6.3*	*1.9*	*0.8*	*0.9*	*0.2*	*0.1*

[1]Source: Herdt et al. (1984), cross tabulations sometimes do not add up due to rounding errors.

approach to insect control and the low returns therefore support an IPM approach to insect pest management.

Greatest seasonal variation came in Camarines Sur, a site in S. Luzon, where in the wet season no yield gap from insect control was measured, whereas in the dry season it rose to 19%. In terms of the proportions of the yield gap that measured fertilizer and weed control in addition to insect control, the latter made up 13% and 73% of the wet and dry seasons over five seasons. The only insect pest mentioned was whorl maggot but other chronic insect pests such as stemborers must have played a role. There was no entomologist in the team.

In Laguna a surprisingly large yield gap was attributed to insect pests, and was equivalent to 15% lower than the yield potential in both the wet and dry seasons equal to 0.8 and 1.0 t/ha, respectively (Table 16.7). Tungro was more prevalent in Laguna during this period and probably the control of its vector, the green leafhopper, by carbofuran, a systemic insecticide, contributed to most of the yield difference. Insect control made up 48 and 50% of the yield gap in both seasons respectively.

In Nueva Ecija yield gaps were calculated to be 10% in both growing seasons and the proportion of the yield gap attributed to poor insect control was 55% in the wet season and 37% in the dry season. A tungro outbreak occurred in the 1976 wet season that made up a large part of the yield gap. The farmers' fertilizer level was high but with little yield effect due to poor timing. Rat damage occurred in the 1977 dry season. C. Luzon is typhoon prone and wet season yields are often severely depressed. The 1978 wet season crop was a total loss from a super typhoon giving great economic hardship to farm communities.

The Iloilo site included both rainfed and irrigated areas and poor insecticide usage played a prominent role in the measured yield gaps which represented 38% and 25% in the wet and dry seasons. Direct seeding became popular in Iloilo which was the dominant crop establishment method due to chronic labor shortage. Yield loss from insect pests was estimated to be 10% in the wet season and 6% in the dry season. The major insect pests were stemborers, both yellow and white, as well as leaffolders. White stemborer was prominent in the rainfed culture which occurred away from the seashore towards the mountains while irrigated rice occupied a strip running along the shoreline in lower lying areas. This is one of the few wetland areas where both stemborer species exist side by side. Another large part of the gap was unreliable water supply and low and ill-timed fertilizer applications.

16.11.4.2 Indonesia

The constraints trials in Subang, W. Java, were preceded by a large baseline survey of farmers that showed modern rices were adopted extensively (Nataatmadja et al., 1979). Although farmers preferred the Pelita cultivar due to its better taste, it was susceptible to brown planthopper so farmers were forced to sow IR26, IR30, and IR36 as each became available. Due to labor shortages to transplant, farmers often transplanted seedlings > 30 days old which limited tiller production. For insecticides farmers followed their own timing and did not follow the government BIMAS program's recommended prophylactic prescriptions. It was realized that variation in the farmers' practice was so large that it would be difficult to select a typical farmer, thus from a baseline survey in 1974, they established an average farmer's practice which was followed in the factorial trials. As a result no plot accurately represented farmers' practices, and thus the associated yield.

In 1976, the first wet season, brown planthopper appeared toward the end of the season causing extensive damage. In the farmers' practice plots outside of the experimental plots, farmers had sprayed diazinon at 14 and 42 d.a.t. and when brown planthopper came they sprayed carbaryl at 3-day intervals beginning 56 d.a.t. followed by carbofuran G paddy water broadcast at 70 and 84 d.a.t. All the insecticide usage was in vain as the planthopper was not controlled, and to the contrary, usage undoubtedly caused insecticide-induced resurgence. Farmers applied inputs over 2.5 times the value of the high input treatment but harvested lower levels (2.5 t/ha). Indonesian farmers lying outside of the monsoon climate can apply high levels of nitrogen (> 100 kg/ha) with low risk of lodging. Therefore nitrogen was applied at higher rates than was common in the Philippines. The government BIMAS program suggested rates that were even higher (150 kg N/ha). In some sites there was a significant interaction between fertilizer and insecticide. It is well documented that brown planthopper numbers increase with higher use of nitrogen (Litsinger, 1994). Farmers typically applied carbofuran G and diazinon EC on their farms which were the insecticides available in government outlets. At the time of the trials all rice insecticides had to be procured from government stores. As inputs were highly subsidized farmers could afford the high insecticide and fertilizer usage. The total yield gap in the 1976 wet season was an astounding 4.6 t/ha with the highest contribution from insect control (1.7 t/ha) and with fertilizer much less (0.2 t/ha). Farmers were close to the optimum fertilizer level but did not apply basally. Their first application was > 20 d.a.t. for nitrogen and phosphorous. Farmers did not apply at the recommended higher fertilizer rate due to an aversion to debt, lack of capital, and believing the suggested rate of 150 kg N/ha was too high. Those using higher rates were in a better financial position and could better afford the risk of a large loss should the crop fail. The lack of technical proficiency was suggested as a constraint by the results. An additional constraint would also be the unavailability of insecticides in the government outlets.

The Constraints Program also gathered data in Yogyakarta. Due to brown planthopper and grassy stunt, the insect yield gap was relatively large, 0.8 t/ha in 1977 dry season (Widodo et al., 1979). Three years of research showed the highest gap was from fertilizer but higher levels only made the crop more susceptible to brown planthopper. Lack of adequate technical knowledge was the most serious socio-economic constraint. The epidemic encouraged farmers to adopt resistant varieties. The average yield gap from 1974 to 1977 for insect control was only 0.1 and 0.2 t/ha below the measured potential in the wet and dry seasons, respectively. The gaps for weed control were highest at 0.3 and 0.4 t/ha followed by fertilizer at 0.3 and 1.0 t/ha in the wet and dry seasons, respectively.

16.11.4.3 Thailand

In the baseline surveys, 24% of farmers said they had a serious insect pest problem, while 35% used no insecticide, mainly because they did not know how, were unfamiliar with the technology, and said insecticides were too costly (Adulavidhaya et al., 1979). As insecticide usage by farmers was low, insects were not included in the factorial experiment. Fertilizer was the largest yield gap, 0.5 t/ha below the potential. Technical constraints were inadequate water, low temperatures, and rats. The identified socio-economic constraints were lack of capital to purchase inputs, lack of technical knowledge, and unstable prices of inputs and rice. Fertilizer was only profitable on farms with good water control. Excess water was also a problem as field water levels ranged up to 39 cm deep. There was no systematic relationship between water depth and input usage apparently because none of the farmers believed that the prevailing conditions were so bad as to discourage usage.

16.11.4.4 Sri Lanka

According to Jogaratnam et al. (1979) insect control resulted in a gap of only < 0.2 t/ha over the two year study. A survey showed 80% of farmers were not familiar with insecticide or herbicide usage. Some 40% indicated there was no insect damage and for those that did, 90% did not follow the recommended practices. However 70% said yields were less than expected, primarily due to water problems, insect damage, fertilizer shortage, delayed planting, and rat and bird damage. Some 50% reported insecticides were not available on time and 7% stated heavy rains affected efficacy. Hand weeding was most preferred, but 25% did no weed control, only 3% weeded more than once, 90% used family labor, and 60% said they had no need for credit.

The yield gap studies revealed that recommended practices were too costly for farmers and were not often economical. Farmers also did not have sufficient training to know how to use inputs optimally for their rice crops thus in the first decades after modern rices farmers' yields were much below the potential of the varieties.

16.11.5 Losses From all Pest Groups

Crop loss data presented by Cramer (1967) showed that insect pests registered the highest losses with weeds lowest and diseases intermediate. This deserves some comment. Farmers have developed more effective practices in controlling weeds thus the losses provided by Cramer measured the difference between the farmers' practice and improved weed management. As farmers generally control weeds well this gap is small. It is well known however that if the farmer did not conduct weed control, losses would be almost 100% in most areas. Diseases are mostly controlled by varietal resistance as if a highly susceptible variety is grown total crop loss can be expected. This is why when new varieties are developed they have to be tested throughout the whole country before being released as if local strains exist that can develop well on the new rice then loss can be extreme. Thus losses from rice diseases are low as they are mainly controlled by genetic resistance. Losses are highest from insect pests as resistance levels are only against epidemic pests and farmers generally do not exert many cultural practices to minimize insect pests. In addition Cramer's data came from insecticide trials which are often done on late plantings when pest populations are highest thus do not represent the average insect pest situation.

Experts determined that in Indonesia that rats were the most important rice pests followed by stemborers, bacterial leaf blight, and brown planthopper (Geddes, 1992). A similar study in five countries in south Asia ranked rice pests as blast, yellow stemborer, bacterial leaf blight and brown planthopper (Geddes and Iles, 1991). A few studies combined both insect and disease pests in loss estimates. Losses of 44% in the wet season and 21% in the dry season were reported in India by Tandon (1973). More commonly, rather imprecise estimates based on the appearance of the rice crop were made for large areas. One estimate for all of India was 20% from insect pests and diseases (Reddy, 1967). While in Thailand an estimate of 15% representing 1 million t/year was given by Wongsiri and Kovitvadhi (1967). In the studies of Seth et al. (1969, 1970) in India, they found an overall 10.5% yield loss for long duration varieties and 14.4% for medium duration varieties. Avoidable yield loss was a meager 0.08 t/ha for the wet season and 0.2 t/ha for the dry season. Multiple regression found significant correlation of yield loss with blast in the reproductive and ripening stages, and false smut.

16.11.6 Losses from Insect Pests by Rice Environment

Average losses due to insects from potential rice production by Cramer (1967) calculated from extensive insecticide trials was 28% as a worldwide average with 34% occurring in Asia. These data are mainly from irrigated wetland rice environments. It was the highest loss of any of the commodities listed by FAO with the next highest being sugarcane at 20% followed by groundnuts at 18%. Although these figures are considered high others have found no good evidence to the contrary. Ahrens et al. (1982) in a similar study later on again using insecticide evaluation trials came up with 24% loss from a 12-year dataset. Pathak and Dhaliwal (1981) estimated losses of 35–44% in tropical rice while Way (1976) gave 35% for India and 16–30% for the Philippines.

A series of experiments conducted in farmers' fields by IRRI in collaboration with the Philippine Bureau of Plant Industry revealed that plots protected with insecticides yielded an average of 1 t/ha more than untreated (20–25% loss) (Pathak and Dyck, 1973). Experiments on the IRRI farm from 1964 to 1971 showed protected trials yielded 5.8 t/ha and only 3.1 t/ha in the untreated checks on highly susceptible varieties with high nitrogen application (Pathak and Dyck, 1973). An insecticide check trial in Zamboanga del Sur province in S. Mindanao in the 1984 dry season using plant growth neutral insecticides registered a 14% loss of 0.66 t/ha on a 4.7 t/ha crop (Pulmano, 1985).

A more recent effort was conducted in the Philippines as part of the National IPM program where in 50% of the 105 crops studied there was no significant yield loss between a complete insect control trial using insecticides (6–9 applications) compared to the untreated (Kenmore, 1987). The work of other IPM training programs in Asia reported similar results in India, Malaysia, and Indonesia. Another study in the Philippines over a 13-year period (1979–1991) in four sites representing 68 crops, Litsinger et al. (2005), estimated losses in irrigated rice from chronic insect pests on modern insect pest resistant rices. Losses were estimated to be a mean of 0.62 t/ha or 12.7% per crop. Upon inspection of the data on a per crop basis 68% of crops registered significant yield loss with the lowest being in Calauan in Laguna of only 23% of crops and the highest in Koronadal with 91%. But if this were broken down by growth stages, the stage with the highest losses was the reproductive stage in three of four sites. Calauan, with least total loss, had significant losses in the vegetative stage in only 15% of the crops and no significant losses in the other stages. Calauan farmers prefer longer maturing rices and being near to IRRI farmers were better managers thus there could have been more yield compensation as a result. Guimba in C. Luzon had high whitehead counts in most years which is the probable reason for the relatively high losses in the ripening stage. The electric pump for the irrigation system often had interrupted service leading to drought stress explaining the high total losses even though pest populations were more similar to those in Calauan.

Both Zaragoza (C. Luzon) and Koronadal (Mindanao) had above average pest densities both as a result of asynchronous cropping. Koronadal registered the highest number of crops with significant total losses but when partitioned by growth stage were lower than expected. This could have come from the high variability in yield loss data from averaging the results from two irrigation systems, the communal system which averaged 2.5 rice crops per year compared to a synchronous site with two rice crops per year. Mean yields per crop for the untreated check ranged between 3.9 and 4.9 t/ha in the four sites, which is a proxy for the farmers' yields as the trials were grown under farmer management. When the yield loss data were analyzed by including the cost of one insecticide application, less than half of the fields could economically justify applying a single insecticide applications to recover the losses (Litsinger, 1984).

In Sulawesi, Indonesia Van Haltern (1979) used carbofuran root zone application (0.5–1.0 kg ai/ha) to record an average yield loss of 34% on some trials from 1973 to 1977 on three research stations. Some published losses based on the insecticide check method in Japan from Mochida (1974) estimated 50% loss in the Kyushu National Agricultural Experiment Station from 1962 to 1971 due mostly to planthoppers and leafhoppers and vectored virus diseases.

In India where experts estimated that in three districts that 4–14% loss occurred depending on the district, growing season, and growth duration of rice varieties (Singh et al., 1972). Losses ranged from short (4–7%), medium (11–14%), and long (4–13%) season varieties. In the states of Tamil Nadu and Uttar Pradesh a mean 8% loss was measured in 1962–1966 (range 0–16% over the five year period) (Barr et al., 1975). In 1951 in Bangladesh 6% loss to insects was estimated (Alam, 1961).

Studies in Sri Lanka reported 10–20% loss annually (Barr et al., 1975), and in insecticide check plots in 77% of farmers' fields there was no significant yield response from 5 to 6 applications (Kenmore, 1987). Fernando, (1967) reported loss from all pests to range from 3 to 53% with an average of 34% depending on location.

Fewer studies on losses in rainfed wetland environments were found in the literature. The problem is that often authors do not state the rice cultural type in their reports. The most extensive were reported from three sites in the Philippines with both traditional and modern rices (Litsinger et al., 1987a). Two sites (Iloilo and Pangasinan) were classified as being favorable environments where flooding and drought stress were minimal and the other site (Solana in Cagayan Valley) is classified as unfavorable. Even in favorable environments yields were well below those from irrigated wetlands. Losses in traditional cultivars ranged from 18 to 25% in two sites and those from modern rices were similar, ranging from 11 to 22% per crop. Rainfed wetland rice sites registered lower pest densities as it is cropped only once a year, but received high loss figures percentage wise probably because of the additional stresses experienced from drought, low solar radiation, and low nutrient management. Losses were measured by the insecticide check method where perhaps the results were more synergistic yield gains than direct measurements of recovery from insect pest damage alone. Muralidharan and Pasalu (2005) found that stemborer deadheart damage had an 8–10 fold greater effect on yield in rainfed wetlands than in irrigated rice.

Deepwater rice which represents some 8% of rice area worldwide has been studied in Thailand and Bangladesh by Catling et al. (1987) where losses ranged from 27 to 34% but their yield loss figures have been challenged by Taylor (1988). In response Catling and Islam (1999), however, remain firm in their conclusions.

There have been some trials in Asia which measured losses on dryland rice culture all using the insecticide check method. Dryland rice has unique insect pest complexes and is generally suffers more stresses than wetland rice (Litsinger et al., 1987b). As a starter, dryland rice areas are entirely rainfed and rice among the major cereals has the lowest tolerance for drought. In Thailand, Katanyukul and Chandartat (1981) found losses were only 5% (range 1–13%) from 1976 to 1979. In Tanauan, Batangas province, Philippines, on favorable soils and diversified agriculture where the soil was frequently tilled with animal drawn moldboard plows losses from five years on a traditional variety averaged 5% from 1976 to 1980 (Litsinger et al., 1987b). Higher losses of 10% were recorded on an improved cultivar over three years 1978–1980 (Litsinger et al., 1987b). Losses were higher (19%) in another favorable dryland area in Tupi, S. Cotabato in Mindanao where farmers used modern cultivars 1987–1991 (Litsinger unpublished data). In Claveria, N. Mindanao on acidic soils with surrounding grasslands after deforestation, losses averaged 29% from 1985 to 1990 (Litsinger unpublished data). Elsewhere in other frontier sites high losses were recorded (Litsinger et al., 1987b). In Pangantucan, Bukidnon province also in Mindanao losses were 23% from a trial in 1980 and Dumarao, Capiz province on Panay Island, Visayas loss was 56% in 1979. Losses were highest 46% in a slash and burn area in a dipterocarp forest in Siniloan, Laguna where yields averaged < 1 t/ha (Litsinger unpublished data).

Litsinger (1993) developed a hypothesis to explain the wide variation in dryland rice losses in the Philippines which represent sites along a continuum of habitats beginning in recently cleared slash and burn forest such as Siniloan with the highest losses due to pest concentration on small fields, to moderate damage levels in grassland areas from older deforested areas such as in Claveria where grasslands replaced the forests and acted as a reservoir for key pests to very favorable areas such as Batangas and Tupi with very low losses due to the fact that most area was farmed and fields were frequently tilled limiting soil pests.

Dryland rice is the most important culture in Latin America and losses measured in Minas Gerais, Brazil, averaged 29% over three years (1977–1979) (range 24–35%) from mostly soil pests and spittlebug as determined from insecticide check method using carbofuran (Litsinger et al., 1987b). The lesser corn stalk borer attacks seedlings from underground webbed nests and can cause the farmers to replant. Pest populations are high because of the extensive forage grasses grown for livestock which act as a reservoir alternate host.

Cramer (1967) estimated losses in rice in Africa as 14% from insects which represents a wide range of rice environments. Agyen-Sampong (1988) reported losses from different countries such as Ivory Coast 25% or 1 t/ha loss. Losses were 25% in Senegal and 30% in Ghana where crop protection in farmers' fields gave yield increases of 3.3 and 5.7 t/ha. Moyal (1988) reported on trials in the first and second crops of irrigated rice in the savannah region of the Ivory Coast with losses of 29% and 20%, respectively, on 4.7 t/ha and 4.6 t/ha crops. Dryland rice in Ivory Coast registered losses of 15% averaged over two years 1977–1980 (Litsinger et al., 1987b). The main pests were stemborers and soil pests.

Catling et al. (1978) along with Litsinger et al. (1987a) were the only two studies found where insect pest losses were carried out in studies representing the major rice cultures for a country over a period of time. This observation agrees with Teng and Revilla (1996) who state that most yield loss datasets from a given location are normally less than three years. Catling et al. (1978) measured losses with the insecticide check method in four seasonal/cultural rice ecosystems in Bangladesh from 1974 to 1976. A mean 9% loss was calculated for the four classes. *Boro* is the dry season (winter) crop of irrigated wetland rice and averaged 4% loss in four sites. *Aus* (direct seeded pre-monsoon season) rainfed wetland rice averaged 6% loss in two sites. A*man* represents the main wet season crops of rainfed or irrigated transplanted rice which averaged 16% loss. Unfortunately the data were not segregated out for irrigated versus rainfed and deepwater rice was not included. Previous data on losses from Bangladesh as reported by Catling et al. (1978) on the basis of a review ranged from 4 to 15% and at times rising to 20% in some years. In neither of the two studies there was an attempt to apportion losses relative to national rice production statistics probably because the number of research sites were so few.

16.11.7 Losses from Individual Insect Pests

Most of the published information for this section comes from reports of high populations and infestations thus the literature paints a more severe picture of insect pest losses than is the norm. These reports, however, do show the potential harm of each pest or guild. Coverage of all pest groups also is not complete and the focus of this review is on wetland rice. Dryland rice has a large contingent of soil pests that cannot survive wetland flooding thus this rice culture has a larger fauna than wetland rice but is less well known particularly in Asia where its area is decreasing (Litsinger et al., 1987b).

16.11.7.1 Rice Whorl Maggot

Studies to measure the effect of rice whorl maggot *Hydrellia philippina* (an ephydrid fly) on yield has led to conflicting reports. Ferino (1968) recorded losses of $> 40\%$ from damage in the Philippines based on insecticide trials. While Shepard et al. (1990) found that even at 60–100% damaged leaves no significant loss was recorded. Viajante and Heinrichs (1986) reported similar results. Litsinger et al. (2006a) proposed a theory that could explain the contradictory findings. The trials that found rice whorl maggot not to cause yield loss were conducted on the IRRI Experimental Farm where seedlings are raised in communal beds of soft mud, the consistency of pea soup. When the seedlings are pulled there is little root damage and consequently transplanting shock is minimal. In farmers' seedbeds, however, in less prepared soil there is considerable root damage from pulling. The combined stress of transplanting shock and other early season insect pests can produce multiple stress and consequent high loss (Litsinger, 1993). In most locations the whorl maggot is usually one of a number of early season insect pests such as defoliators that form a complex.

16.11.7.2 Defoliators

Yield loss from the green hairy caterpillar *Rivula atimeta* was highest when rice was infested at a younger age and that a density of one moth per m^2 resulted in a loss of 7% (Viajante and Heinrichs, 1987). In the Philippines aside from whorl maggot two other insect pests normally occur with the green hairy caterpillar, namely the green semi-looper *Naranga aenescens* and rice caseworm *Nymphula depunctalis*.

Litsinger et al. (2005) recorded losses from this complex of 0.23 t/ha or (5%) in the vegetative stage. Losses from caseworm averaged 0.5 t/ha or 10% loss occurred when 30% of leaves were cut or 25% of the leaf area was removed (Heinrichs and Viajante, 1987). Losses can be patchy as the larvae which float on water are often windswept or taken by irrigation water currents to one side of the field where they become concentrated and larvae can kill off portions of the field. Even though compensation can occur from most damage, patches of killed rice lead to gaps in the field and thus high losses. Van Haltern (1979) reported losses in Sulawesi of 5–10% from this early season insect pest complex.

16.11.7.3 Armyworms

Armyworms (*Spodoptera* and *Mythimna*) as their name suggests can become highly abundant and devastating. Some species are migratory and can descend on an area in great numbers. They can attack a young crop or one near harvest. The common name of one species *Mythimna separata* is the ear-cutting caterpillar. Barr et al. (1975) also reported a 1967 outbreak in Malaysia affecting 10,000 ha and in India where in some fields yielded only 0.4 t/ha. Like caseworms, damage can be highly concentrated. Several outbreak years occurred in Bangladesh between 1939 and 1973 and in 1969 where 0.5 million ha were infested, with 50,000 ha severely damaged (Catling and Islam, 1999). An outbreak in 1966 in Ghana from a related species caused half of the fields became devastated as if grazed by cattle (Barr et al., 1975).

16.11.7.4 Rice Stemborers

Among all insect guilds, stemborers have been credited with being the most influential regarding contributing to annual losses (Barr et al., 1975; Litsinger et al., 2006c). Among the 20 or so species, the yellow stemborer is the most highly adapted to wetland rice in monsoon Asia while its cousin the white stemborer which is also monophagous on *Oryza* spp. is adapted to the Intertropical Convergent Zone wetland rice as well as dryland rice. Both co-evolved with rice throughout its origin and domestication and dispersed to different rice environments created by farmers clearing new rice lands. The former is adapted to an aquatic environment while the latter can withstand long periods of drought. While both species can enter diapause, yellow stemborer only does so in sub-tropical environments. Both are more adapted to narrow stemmed modern rices due to their narrower girth than *Chilo* species, the next most prevalent stemborer taxonomic group. Yellow and white rice stemborers can be considered together as the insect pest group which causes probably the greatest losses to mankind according to Catling and Islam (1999) due to their pervasiveness on the world's most important food crop, ability to attack throughout the life of the crop, dispersive abilities, and the nature of the injury which disrupts transport of nutrients and water throughout the plant. Yellow stemborer in deepwater rice can attain densities of 50 larvae and pupae/m^2 or ca. 0.5 million immatures/ha (Catling and Islam, 1999). Stemborers as a group were relatively more important on single crop long maturing rices that were prevalent before the shorter duration modern semi-dwarfs. Stemborer larvae are tissue consumers. Their damage is assumed to reduce the weights of green leaves, stems, and reproductive organs proportional to the fraction of tillers affected (Rubia and Penning de Vries, 1990b). Although damage becomes evident as deadhearts and whiteheads significant loss is inflicted by larvae that feed within the stem without severing the growing plant parts (tiller or panicle) to produce field symptoms. Two species of stemborers do not cause this visible damage (*Maliarpha* and *Rupela*) but are known to reduce yields through lessened plant vigor, production of fewer tillers, and many unfilled and partially filled grains. Bandong and Litsinger (2005) showed rice is especially susceptible during two growth periods, both involving elongation of the tillers (for deadhearts) or panicles (whiteheads). Plants are more resistant during non-elongation periods due to the deposition of silica and lignin hindering first instar larvae from boring into the plant. As stemborers are difficult to control with insecticides and for which only resistant varieties have not been developed (with the exception of Bt rice), rice crops therefore have never reached their full yield potential, and thus the amount of loss caused has not been fully appreciated.

Barr et al. (1975) reported losses in a number of Asian countries. In India and Indonesia losses ranged from 3 to 95% in given locations and years. These are data from the years prior to modern rices that rivaled the more recent epidemics of brown planthopper and green leafhopper in the same countries, thus Asia was no stranger to suffering high losses from insect pests. In 1970 in Pakistan after an outbreak fields were harvested for fodder or turned over to grazing animals because there were essentially no filled grains. In Bangladesh 30–70% loss occurred in epidemic years in some fields and 3–20% in normal years. In Malaysia there were reports of 4–5% loss in 1965 and a 33% loss in over 24,000 ha in an epidemic in N. Krian in 1955–1956. In the Philippines a normal year averages 7% loss but in Calamba in 1953, it rose to 48% loss (Cendaña and Calora, 1967). In 1989–1990 the white stemborer caused losses of more than 250,000 tons of rice in W. Java (Oka, 1979). Van der Goot (1925) reported high chronic losses in the early part of the 20th century in Java due to white stemborer. In 1903, 26,000 ha were severely affected and in 1912 28,000 ha suffered 50% loss. White stemborer is so damaging because of its synchronized emergence after the long aestivation period that overwhelms resident natural enemies. In addition traditional tall long duration of varieties sustained over five borer generations per crop. Highest losses occurred if the timing of larval eclosion of the last generation occurred at panicle exsertion.

Agyen-Sampong (1988) reported the following yield losses from Africa: (1) Egypt *Chilo agamennon* caused 10% loss in 1978 and (2) Ivory Coast five years of trials measured 50–70% infested tillers resulting in 13% loss from *M. separatella*. Soto and Siddiqi (1978) report that in the Ivory Coast a 33% increase in yield can come from insecticides directed at stemborers and in Sierra Leone similar insecticide protection would bring a 50% increase.

16.11.7.5 Gall Midge

Silver shoots or onion leaves produced by gall midge *Orseolia oryzae* larvae are the equivalent of deadhearts as only on rare occasions will a panicle will form on the tiller. The silver shoot is actually a transformation of the leaf sheath into a gall

(Reddy, 1967). As a result of its damage the crop responds by actively tillering which depletes its vigor and thus yield. Most of the new tillers will not form productive panicles. Reddy (1967) reported numerous instances of yield loss throughout its range in Asia and from its cousin in Africa. A 30% loss was documented in Bihar, India in 1917 where it first attracted attention to its importance. In the 1930s it was recorded causing 12% loss in West Bengal and 35% in Raipur Madyah Pradesh. In 1954 it caused 60% loss in Bangalore and 15% in Cuttack, Orissa. In Fukien province China losses of 30–40% occurred from 1939 to 1942 and in Vietnam in 1922 ranged from 50 to 100%. In N. Thailand losses of 50% per annum were common. In Cameroon, 75% of the crop was destroyed in 1954.

16.11.7.6 Rice Hispa

Both the adult and larva of the hispa beetle *Dicladispa armigera* defoliate rice. It is aquatic loving as all stages have a high moisture requirement (Catling and Islam, 1999) and populations can become very abundant even in flooded deepwater rice as well as irrigated rice and in Bangladesh losses of 10–65% of the 60,000 ha infested annually occurred (Barr et al., 1975). Adults can live over a month and are highly dispersive and may pass the off season in marshy areas. In India as well certain hot spots report high annual losses (Barr et al., 1975), up to 50% in some 10,000 ha were attacked annually in Bihar and 39–65% damaged leaves have been reported in other Indian states including 215,000 ha affected in 1985 in Assam and W. Bengal (Catling and Islam, 1999). In areas of Burma up to 50% damaged leaves are known (Barr et al., 1975).

16.11.7.7 Leaffolders

There are 4–5 leaffolder species that attack rice. Their damage is associated with damaging the flag leaf and the penultimate leaf in the grain filling period (Barrion et al., 1991). India in some areas losses of 50% in early 1970s occurred (Kushwaha and Singh, 1984), but normally damage ranged from 5 to 12% damaged leaves, but in the 1983 wet season levels rose to 60–70% damaged leaves and reached 20–29% elsewhere. Heavy rainfall was the cited as the cause but it is known that insecticide resurgence can also be the cause (Qadeer et al., 1988; Panda and Shi, 1989). Damage is higher on later transplanted crops.

16.11.7.8 Planthoppers

The brown and whitebacked planthoppers are examples of epidemic pests and have caused serious yield losses from hopperburn over millennia as well as in recent times particularly after modern rices became widespread (Litsinger, 1991; Gallagher et al., 1994). High populations have mostly been associated with resurgence or secondary pest outbreak phenomena or from farmers growing highly susceptible varieties. In earlier years, before synthetic insecticides, insecticide-induced resurgence could have been caused by whale oil and kerosene. Other causes could have been flooding that washed away natural enemies (Litsinger et al., 1986) or long distance immigration rapidly inundating an area to overwhelm local natural enemy populations (Kisimoto and Rosenberg, 1994). Outbreaks have been recorded since AD 18 in Korea and AD 697 in Japan and in Java during the 1930s and 40s, but planthoppers came to prominence in the early 1970s after the introduction of modern rices in virtually all major rice producing S. and SE Asian countries (Mochida et al., 1977). The scale of these outbreaks was large and in many instances created shock waves in governments that tried as best they could to contain them. In Indonesia in 1976–1977, some 30% of 450,000 ha was lost having an estimated value of over $100 million (Oka, 1979). This was enough rice to feed 3 million people for a year. In 1986 an outbreak in Java affected more than 50,000 ha which led President Soeharto to ban 57 insecticides and replace the minister of agriculture. In 1973 a serious outbreak of brown planthopper in Laguna, Philippines caused a loss of 150,000 tons ($20 million) from grassy stunt (Sanchez, 1983). A report from the Tanjong Karang Irrigation scheme in Malaysia registered 1,600 ha of total loss to brown planthopper in the 20,000 ha system in 1997 with losses valued at up to $4.2 million for the dry season crop and $0.2 million in the wet season (Lim et al., 1980). In severely infested areas, losses ranged from 53 to 75% while in less infested areas losses were 12–25% when high numbers began 30–45 d.a.t compared to only 3–5% when high populations occurred near harvest. Epidemic losses have occurred in most Asian countries even into the ‘90s where losses of $30 million occurred in Thailand and Vietnam (Holt et al., 1996). In India losses ranged from 1 to 33% (Jayaraj et al., 1974). In 1991 rice losses in China totaled more than $400 million from brown planthopper (Holt et al., 1996). Whitebacked planthopper was involved in the complete failure of the 1966 wet season crop in two states in India (Barr et al., 1975). In 1979 an epidemic of whitebacked planthopper in Kedah and Perlis states badly damaged 7,000 ha and only through a national campaign that included aerial insecticide application was a larger area saved in the Muda Irrigation Scheme (Ooi et al., 1978).

16.11.7.9 Leafhoppers

Several species of *Nephotettix* green leafhoppers are important pests of rice, usually through a role as vectors of tungro and other rice diseases. Some reports of direct damage have come in the past, e.g., in Bangladesh 50–80% (Alam, 1967) and in 1956 causing 20–50% loss at heading (Barr et al., 1975). Along with brown planthoppers, green leafhoppers have reached large epidemics in most Asian countries over the same period. Azzam and Chancellor (2002) list nine major epidemics that affected > 4000 ha each since 1980, while Sogawa (1976) enumerated earlier epidemics.

16.11.7.10 Rice Seed Bug

The rice seed bug *Leptocorisa* spp., as a relatively large insect, is highly mobile and can seek out isolated fields such as dryland rice or late planted wetland crops. It builds up during the wet season on wetland rice and alternate weed hosts and concentrates on late plantings particularly in areas of staggered plantings. Its habit of aestivating in the dry season mean that it is more abundant near wooded areas rather than in open plains. An understanding of the damage it does was not appreciated until recently when it was shown that rice bugs prefer to feed on pre-flowering spikelets in free-choice tests (Morrill, 1997). Epidemics are reported from most rice growing countries in Asia with losses ranging from 10 to 40% to some fields with almost complete losses in some occasions (Srivastava and Saxena, 1967). In Indonesia losses as high as 50% and even 100% are reported from rice seed bugs (Van Haltern, 1979). A paper in Dutch dated 1878 discusses failed crops in Java due to this pest (Koningsberger, 1878). In Malaysia losses ranged from 10 to 36% but include *Nezara* spp. stink bugs (Soon, 1971). Rice bug numbers can rise to 275 per 10 net sweeps. In 1924 in one area the losses were so high that farmers had to purchase rice six weeks after harvest (Barnes and South, 1925). Historically in the Philippines high losses have been recorded particularly if a farmer plants out of step with his neighbors where losses can be $> 70\%$ (Uichanco, 1921). Farmers in Tarlac province said that rice bugs were worse than locusts. The only pest that was worse was stemborers, however. In Sri Lanka, Delpachitra and Wickramasinghe (1986) artificially infested six rice bugs per panicle beginning at flowering which resulted in 100% unfilled grains compared to a caged untreated check with 20%. 100-grain weight was reduced 45%. Only one rice bug density was tested in their trial which if extrapolated to 25 hills of 10 panicles each would give an outrageous density of 1,500 rice bugs/m^2 density. Such a trial therefore shows the potential but the density was much beyond what would be even feasible in nature. In India loss was 10% over 3 million ha in 1952 (Pruthi, 1953).

16.11.8 Losses from Multiple Pests and Stresses

Bardner and Fletcher (1974) underscore a major conclusion from this chapter when they stated that damage functions are highly dynamic as a multitude of biotic and abiotic factors control the relationship between insect infestation and crop injury. These factors can be divided into two groups: (1) those that are relatively constant for any specific pest-crop relationship and (2) those that are variable. Constant factors are the growth patterns of the particular cultivar, the nature of the injuries, and their characteristic distribution on and between plants. Variable factors include the time of attack in relation to plant growth, the intensity of injuries, the duration of the attack, and the environmental factors affecting plant and crop growth. Of the constant factors, the nature of the injuries and their distribution have been much studied but researchers have been slow to make use of the ideas and results of crop physiologists.

The effects of insects on plant and crop growth and yield are often complex, but the number of ways in which plants can be injured is limited as are the general responses of the plant or crop to injury (Bardner and Fletcher, 1974). Knowledge of the physiology of growth and yield in unattacked crops can provide a useful insight into the probable nature of the relationships between attacks and their effects on growth and yield. The variable factors affect the quantitative relationships between infestation and yield, their effect being especially important on the often delicate balance between the rate at which injuries are inflicted and the capacity of the plant or crop to compensate for them. Farmers traditionally manipulate such factors as planting dates, sowing rates, and other cultural conditions to minimize the effects of possible pest infestation based on trial and error. On the other hand, uncontrollable variations in the time of attack, soil conditions, and weather often make it difficult to define economic injury levels and to forecast the effects of an attack on yield though, where it is possible to establish quantitative relationships between measurements of infestation and yield, these usually conform to some part of the generalized response curve or damage function.

The occurrence of two different injuries, simultaneously or in sequence may modify the damage function and their effect is not always additive but can be antagonistic or synergistic. In the rice-wheat cropping system in India, an estimate of absolute yield losses of all pest stresses taken together was 1.4 t/ha but if added individually that total came to 1.8 t/ha (Savary et al., 1997), thus there is evidence of antagonism between factors rather than being purely additive. In terms of relative losses the total was 29% and if added individually was 37%. Highest individual pest loss was stemborer deadhearts at 0.5 t/ha and 9% relative loss followed by weeds below the canopy, brown spot, sheath blight, weeds above the canopy, neck blast, and sheath rot.

An earlier study by Savary et al. (1994) in C. Luzon, Philippines found that weeds above and below the canopy and stemborers were the main contributors to low irrigated rice yields. Stemborer was the only insect group to be associated with high yield loss in the study that measured over 30 crop production variables. Late planting was associated with low fertilizer applications and poor weed control. Surprisingly sheath blight was associated with high yields.

In Madagascar a multiple regression rice production function indicated that regional differences were important, as was quality of irrigation and optimum planting densities at appropriate dates of transplanting (Baumbärtner et al., 1990). Weed control and insecticides contributed positively to yield only when applied in fields with high yield potential. Although the data were limited, fertilization had a positive effect on compensation. In early plantings the relationship between high planting density and yield was positive, but neutral for average planting time and negative for late planting.

Multiple regression studies in India estimated that overall loss at 11% for long duration varieties and 14% for medium duration varieties (Seth et al., 1970). Avoidable loss was only 0.1 t/ha for the wet season and 0.2 t/ha for the dry season. Deadhearts were low, <3% as was whiteheads 5%, with neck blast registering 3–6% incidence.

16.12 Feedback to IPM

16.12.1 Usefulness of Yield Loss Data

Cohen et al. (1998) reviewed the rice crop loss assessment literature over a period of three decades for diseases and insect pests to determine the representativeness of existing data so as to evaluate how it could be extrapolated regionwide. The study focused on five criteria: (1) rice production in tropical Asia, (2) main objective was to measure yield loss, (3) descriptions of experimental and sampling designs provided, (4) techniques used for measuring loss described, and (5) quantitative information on loss provided. Reports were compiled according to rice ecosystem.

Among all of the literature reports, a subset was assembled of studies that were: (1) conducted over more than one year, (2) in more than one location, (3), and the plot size was field level. The main result was that surprisingly few reports met these three criteria. Most were in irrigated rice conducted in one location, in one season, and in plots $< 100\ m^2$. The conclusion of the study team was that it is was difficult to extrapolate such results for even the irrigated rice ecosystem in Asia. The results presented herein would confirm this same conclusion. Given the strict criteria imposed the team such a conclusion is not surprising. For example the main objective of our extensive studies (Litsinger et al., 1987a, 2005) was to use yield loss data to develop improved insect pest control data not to estimate annual production loss for the Philippines as clearly the number of research sites were too few to allow meaningful extrapolation to a national scale. It would be very costly to set up teams to carry out field experiments in all major rice growing areas of a country. To undertake trials on farmers' fields it requires that local people be hired to continuously monitor the studies (Zandstra et al., 1981). Therefore it is not surprising that no studies could be found that would meet this criteria as networks of satellite stations would need to be established to achieve such an objective. It is difficult enough for national programs just to compile data on production let alone yield loss. Yield data is often compiled by interviewing the farmers to record their estimated yield rather than tediously taking yield cuts due to the time and cost involved. In addition it is known that farmers often underestimate their yield when reporting it to a government officer (Litsinger et al., 2008). The reason for under-reporting is for farmers to seem poorer than they are to avoid taxes or to attract government aid.

16.12.2 Rice IPM Program Development

The severe losses from rice pests that threatened food production in Asia in the early 1970s prompted aid organizations to support more effective IPM program development. Smith and Calvert (1978) on contract with USAID outlined four proposals for creation of a new research entity to meet that goal:

1. A developed country-based international plant protection center,
2. US consortium of universities,
3. FAO posting experts in national programs, and
4. Foreign based international plant protection center

A number of international plant protection centers were eventually established in developed countries such as US, France, and UK but their impact was limited to small research projects as the only local linkages were weak research systems. A US consortium of universities did materialize 15 years later (IPM-CRSP), but this was after rice IPM programs were in full swing in many countries. The IPM-CRSP which focused on other crops than rice had more success due to the more lengthy relationships with national programs by lasting over a decade in each country. The role of FAO was not only in posting experts in national programs but also functioning as a facilitating unit based in Asia called the Inter-country Program for Integrated Pest Control in Rice in South and Southeast Asia and now called the FAO Program for Community IPM in Asia (www.communityipm.org and www.farmerfieldschool.info). This was very effective in extending IPM programs. There never was a foreign based international plant protection center, but IRRI, a commodity based center, filled the role in developing many of the appropriate technologies and elucidating the ecological underpinnings of IPM. It provided the strong local research presence needed. IRRI's strengths were in assembling large research teams to undertake action research on key problems. These teams were in turn backed by ample funding and effective support services. Therefore option four above proved to be the most effective mechanism in IPM development.

Mounting a research program to study arthropod ecology including natural enemies is difficult for national programs that lack adequate taxonomic and scientific literature support. IRRI was successful as it had an international rice germplasm bank, an excellent library and bibliographic services, a strong arthropod taxonomic unit with a reference collection of authoritatively identified species, adequate greenhouse and laboratory facilities, ability to hire large numbers of field workers among other needed inputs, and a budget to allow annual travel to international scientific meetings and to national programs. This basic unit in turn attracted scholars, postdocs, and visiting scientists to undertake further indepth studies.

It was soon realized that IPM needs to be seen in the light of Integrated Crop Management due to the potential of modern rices to compensate from insect pest damage and other stresses. The first principle of IPM for irrigated rice advocated in farmer field school training programs is to grow a good crop (Matteson, 2000). The rationale behind this conviction has been to bolster modern rices with greater capacity for pest tolerance. Interpretation of the 'pest pressure-crop tolerance paradox' (Litsinger et al., 2006c) further supports this approach. In Madagascar, farmers were recommended to enhance the quality of agronomic management and to limit insecticide application in their fields that have high yield potential (Baumbärtner et al., 1990). Litsinger et al. (2006c) however recommended to target insecticide use more to crops under multiple stress to get the synergistic yield gain.

Rubia et al. (1996) concluded that enhancing the crop's compensatory attributes may be a better strategy than insecticide application. Litsinger et al. (2005) tested this hypothesis by comparing treatments where 25 kg N/ha (the equivalent cost of one insecticide application) was applied in lieu of insecticide when an action threshold was triggered. The outcome was mixed. There was a significant benefit recorded in the wet season to stemborers and to both whorl maggot and defoliators in the dry season. But there were no significant yield gains with leaffolders in any season. In order for the added nutrients to take their full effect the growing conditions such as solar radiation should not be limiting and of course this is highly variable in the wet season.

Crop management then becomes a two pronged strategy. The first thrust is for the farmer to undertake steps in crop husbandry to increase the crop's inherent yield potential commensurate with the magnitude of the complex of stresses present in the given season and expected weather. This can be best done by aping the practices of the highest yielding farmers in a given season.

The relationship of IPM vis-à-vis crop management practices is complex due to two opposing forces:

(1) On the one hand, the great capacity of high tillering and longer maturing rices that bolster compensation from damage is counterbalanced by
(2) The synergistic effect of multiple stresses in reducing yield, with each pest being just one stress (Litsinger et al., 2006c).

The observation of Viajante and Heinrichs (1987) illustrates this point where they studied the effect of artificial infestation of a defoliator on yield loss in the field with and without wooden frame screen cages. They noticed consistent lower yield losses from the same pest density levels when the plants were not caged over a series of trials. Our interpretation is that solar radiation allowed the crop to compensate from the damage more when no cages were used. On the other hand when cages were used the crop suffered from two stresses – from the defoliator and lack of sunlight. We predict that if they had caged the uninfested check but not the infested treatment that the yield loss would also have been low as both crops would have suffered from a stress. While if they had caged the infested crop but not the uninfested crop that the greatest degree of yield loss would have been measured as the difference between plants which had optimal compensation versus those suffering from two stresses.

It would be a mistake, however, to conclude that because rice can tolerate such high levels of injury that there is no need to apply corrective measures in all rice fields. The compensatory potential is only in effect when the crop is growing under optimal conditions and from farmer surveys we learned this is not happening in two thirds of the farms in any season. Compensation is dependent on several crucial factors, some of which are not under the farmer's influence:

1) Whether the variety is high tillering or not,
2) Maturity class of variety (long maturity allows more compensation),
3) How well the crop is agronomically managed,
4) The weather (cloudy weather lowers the yield potential especially during ripening), and
5) The number and severity of stresses affecting the crop in any growth stage (Litsinger et al., 2006c).

The results of the synergistic yield gain hypothesis have implications for IPM. To obtain optimal yield, the farmer does not have to directly control all of the stresses acting on the crop and would have the choice of correcting those that are least costly or less technically difficult. Research will have to determine which stresses relieve the most compensating capacity in the various stress combinations. It is estimated that half the yield potential of modern rices is based on the degree of management that is given to the crop. This is not true of traditional rices. Being tall, traditional rices have large capacities to store photosynthate that can be used in compensation (Kupkanchanakul and Vergara, 1991) but this is less effective than modern rices that use this mechanism as well as greater tillering ability.

Knowing what stresses are prevalent in the field, the farmer would have options in deploying control measures. As in Montana the deleterious effects of drought could be overcome from farmers adopting disease resistant wheat (Nissen and Juhnke, 1984). But a better tactic may be to improve the crop's ability to compensate by apply more fertilizer or weeding more rather than trying to kill the insect pest with environmentally destabilizing, hazardous insecticides which as applied by farmers have low kill ratios. Thus statements that research has shown that rice crops can tolerate much leaffolder defoliation and insecticide use does not increase yields, therefore insecticide control is unnecessary (Heong, 1998; Teng and Revilla, 1996) becomes conditional. The statement would be more true if the crop were not under stresses but not as true if it were as results (Litsinger et al., 2005) have shown that insecticides, even with their faults often result in significant although marginal yield increases.

On the other hand modern rices to date have not been given sufficient credit for having remarkable compensatory abilities. It is important to note that traditional low tillering rices do not have such an ability. We argue that the compensatory abilities of high yielding varieties are at least as important (if not more important) than genetic insect pest resistance. Luckily modern varieties contain both features where the former has greater importance against chronic pests while genetic resistance targets epidemic pests. We concluded that national rice production is more negatively affected by chronically economically significant insect pests.

In a related matter, if the synergistic yield gain hypothesis were correct, we predict the genetically engineered Bt rice, by effectively controlling lepidopterous insect pests such as stemborers, leaffolders, and defoliators (IRRI, 1996) should result in higher than anticipated yield gains by removing losses caused by not only from key chronic insect pests but also from other stresses. The benefit would perhaps be higher than the yield gain recorded from the insecticide-check method due to the greater killing ability of the bacterium's endotoxin than insecticide sprayed via knapsacks. Thus instead of the crop compensating just from insect pest damage, the effect may be compensation from other stresses as predicted. This hypothesis could be tested in rice environments with Bt rice and the parental non-engineered genotype both protected and unprotected by insecticide producing four treatments. The largest yield gain should come from the comparison of the protected Bt rice vs. unprotected genotype, more so than the yield gain from the protected genotype vs. the unprotected genotype (the conventional insecticide-check comparison). The field results should vary, however, depending on the balance of lepidopterous and non-lepidopterous pests attacking the particular crop.

In addition insect pest crop loss assessment in the light of the findings presented in this review needs to be rethought. Clearly results of trials that measure losses are highly site and time specific, so much so that such results would have little extrapolative value as concluded by Cohen et al. (1998). Also the much used insecticide check method that we believe measures yield gain rather than yield loss needs to be replaced by methods such as genetically designed cultivars or crop modeling where more variables can be included in the assessment as expressed by Baumbärtner et al. (1990) and Pinnschmidt et al. (1995).

16.13 Why Insects are Pests – Breaking of Some Myths

Ecological studies initiated in the 1980s resulted in a clearer understanding of why some rice insects are pests and has led to more effective strategies for their control. This has meant that a number of previously held beliefs to explain pest outbreaks have not stood the test of scientific inquiry. These impressions have been repeated so often that they have come to be taken truths when in fact experimental evidence was lacking. These we term myths and as such they will take a long time to replace with more scientifically sound results. Some of the results of scientific inquiry have several interpretations thus not all researchers agree on the following conclusions. But even while disagreeing these researchers cannot show research data to back up their beliefs.

One of the most prevalent myths is that traditional varieties are more pest resistant than modern rices. Researchers noted correctly that when modern rices were adopted that a number of new pests emerged and many pests became highly abundant (Litsinger, 2008). It was first believed that modern rices such as IR8 were intrinsically more pest susceptible than traditional rices and outbreaks resulted from the wide scale planting of a single susceptible variety. But studies showed that it was not true that modern rices lacked pest resistance as IR8 was resistant to green leafhopper (Heinrichs et al., 1985). Most traditional varieties were later found to be highly susceptible to all common rice insect pests in side by side comparisons and very few have been resistant donors. Outbreaks were shown by research trials to be mainly the result of multiple rice cropping and the use of insecticides (Loevinsohn et al., 1993). As traditional rices were only grown as an annual crop it gave the impression of being resistant due to the lengthy dry season fallow not genetic resistance. The other half of the myth states that the new pest resistant modern rices by being planted uniformly over broad areas increased risk of development of highly virulent insect biotypes such as happened with maize in the US in 1971 with southern corn leaf blight. This indeed did happen at the beginning of the Green Revolution (Gallagher et al., 1994) when few new varieties were available such as IR36 being the most wide scale example which is still widely planted in Asia. It was only natural that farmers wanted to plant the best variety available. Nowadays many local modern rices have been developed by national programs and farmers sow a wider range of varieties. In addition farmers regularly change varieties as measure to prevent such problems.

Initially researchers concluded that systems of modern irrigated culture resulted in lessened arthropod biodiversity compared to natural ecosystems thus had less complex food chains and fewer linkage redundancies and were therefore more susceptible to perturbations. Recent studies in community ecology have indicated that floodwater and canopy invertebrate densities in irrigated rice planted to modern rices equaled those of several natural ecosystems in biodiversity parameters (Schoenly et al., 1998) indicating a rich fauna of beneficial arthropods and are not as tenuous as previously believed and can withstand moderate insecticide usage.

In addition some people concluded that if insect pests were not controlled on modern rices, the damage could become so great that yields would be less than those of traditional varieties. This led to the myth that insecticides were therefore 'required' for high yields. In fact this is not supported by evidence. When modern rices are grown in irrigated culture side by side with traditional ones both without insecticide or fertilizer, yields of the modern rices will be significantly higher (Litsinger, 2008). The misperception came from early trials at IRRI where highly susceptible cultivars were used and insecticide trials registered very high losses. Farmers do not plant such highly susceptible varieties and if they do will quickly change as there are many choices nowadays.

Another myth is that nitrogen fertilizer contributes to many of the pest outbreaks and thus should only be used sparingly. A corollary of this myth is that losses are greater in more vigorous growing crops (Way, 1976). It is true that nitrogen increases pest fecundity and survival leading to higher pest incidence (Litsinger, 1994) but this belief does not take into account crop compensation which enhances the crop's ability to tolerate damage (Litsinger, 1993). The researchers that perpetrated the myth did not integrate yield data into their conclusions, as despite higher pest incidence, one finds yields are also higher and this is what matters to the farmer. Farmers in India who have adopted hybrid rices have noted higher yields despite higher pest incidence and are no longer hesitant to use recommended dosages of inorganic nitrogen along with basal farm yard manure. If nitrogen is used judiciously by splitting applications 3–4 times per crop, the effect on pest buildup is moderated.

When outbreaks first appeared, researchers attributed much of this to changes in the microclimate or weather (Litsinger, 2008). It is true that close spacing increases brown planthopper that could be attributed to the higher humidity for increased egg survival (Dyck et al., 1979), but research has shown that the primary factors spawning outbreaks have been insecticide usage, increase in rice area, and by multiple cropping (Loevinsohn et al., 1993). Climate and weather factors are only secondary factors but they can become important from time to time and be responsible for some of the outbreaks mentioned earlier. For example yellow stemborer suffers high mortality when days reach $> 34°C$ and RH $< 70\%$, as at $> 30°C$ oviposition ceases, and strong winds disrupt dispersal (Catling and Islam, 1999). Similar weather events negatively affect natural enemies which then unleash rapid population increases that can lead to epidemics (Mochida et al., 1987).

The next myth is that planthopper epidemics have been caused by the stimulation of their reproductive capacities by direct exposure to low insecticide dosages. While it is true that greenhouse trials showed that exposure to sublethal dosages of insecticides does stimulate increased fecundity, the magnitude of the effect is not enough to explain the large field populations that developed within the span of a few months (Chelliah et al., 1980). Extensive research has demonstrated that killing of natural enemies by insecticides is by far the most important mechanism (Heinrichs et al., 1982).

A final myth is that new technologies such as modern rices, hybrid rices, or new pest resistant rices such as Bt rice alone will solve the world's food crisis. Indeed these technologies show the potential but as we learned from the Constraints Program at IRRI which identified yield gaps as well as the concept of economic slack where there is a considerable lag phase between researchers developing new technologies and their final adoption by farmers. It was true that farmers readily adopted modern rices but the lag occurred with developing concomitant management practices to obtain the promised high yields. In the US it took farmers two decades to learn how to management the new hybrid maize varieties (Way, 1976). Effective extension systems are needed to assist farmers in learning how to best obtain the promises of modern rice yields (Matteson et al., 1984). The message is that there are few quick and cheap solutions and there is no substitute for more in-depth studies that focus on understanding how the agroecosystem is affected by the changes and can be made more stable by sustainable farm management (Smith, 1972) as well as the development of more effective extension systems to run side by side with new technological developments.

16.14 IPM Tactics

Over the period that rice has been domesticated, a combination of cultural practices and farmer-selected pest-resistant rices and assemblages of natural enemies developed and coevolved in wetland rice, its natural habitat. Although damaged by pests, flooding, and drought traditional crops produced stable yields on which Asian civilizations have depended for at least 7,000 years (Oka, 1988). Unfortunately these traditional systems are low yielding and could not meet the food demands of human population increase. The changes brought by the Green Revolution dramatically changed the way rice is grown. In traditional rice systems most of the farmer management occurred during crop establishment, harvesting, and processing. In the intervening period between transplanting and harvest most management was limited to checking on the water levels and repairing bunds. Nutrient and pest management were almost non-existent because traditional rices did not respond to better husbandry practices.

But modern rices greatly respond to improved management practices, and rice farming now needs to be thought of as a business rather than subsistence agriculture. Before the Green Revolution, IPM had its roots in industrialized societies but soon became the philosophy of choice for managing pests in modern rices in the late 1970s. Rice IPM program development for Asia had its beginning in 1977 funded by USAID in a training course held in Manila, Philippines (BPI, 1978). But IPM is often misunderstood, especially by non-specialists, who think of IPM as a tactic rather than an approach to more sustainable pest control. In IPM jargon, tactics can be thought of as weapons, but strategies are how they are deployed. Furthermore there is a mistaken impression by some that IPM will replace all existing pest control technologies. IPM is a philosophy, a different way in which crop protection is viewed rather than a fixed set of prescriptions.

The IPM concept first began as the integration of biocontrol with chemical control against alfalfa pests in California (Stern et al., 1959), thus the term integrated control was born. It now includes all methods of control including genetic resistance, quarantine, and cultural, mechanical and physical control. IPM began in the domain of entomology but has branched into the other pest control disciplines. Now it is seen as a subset of crop management. Thus the term 'integrated' implies incorporating different control tactics together in a harmonious manner for each recommendation domain (Zandstra et al., 1981); it also advocates integration of the tactics of pest control disciplines, and finally integration into the farming system.

IPM in rice in Asia began with the integration of host plant resistance and chemical control (Pathak and Dyck, 1973). Eventually when the limits of chemical control were realized other tactics were developed. In fact, reduction of chemical control was seen as a necessary step to maintaining the sustainability of genetic resistance particularly in regard to the brown planthopper (Gallagher et al., 1994). Widespread adoption of a single variety resistant to the brown planthopper such as IR36 did not lead to less insecticide usage but rather more directed at chronic pests. Farmers followed the credo 'if a little insecticide works well then more will work better'. The result was resurgence, secondary pest outbreaks, and the evolution of new biotypes, all of which demanded a new IPM strategy (Heinrichs, 1994). Nowadays insecticides are seen in a different light where they play a much more limited role while host plant resistance, natural biocontrol, and cultural control methods form the backbone of most IPM programs. No longer are insecticides considered to be necessary (in the sense that inorganic fertilizers are necessary) to grow modern rices. Ironically it was fear of more outbreaks that led farmers to use more insecticides, which is akin to putting out a fire with kerosene.

Many farmers believe that all arthropods in a rice field are pests and if one takes a few sweeps with an insect net and shows the farmer the contents, his first instinct would be to reach for his sprayer. Only through training will farmers begin to appreciate the importance of the rich beneficial fauna that occurs naturally in their fields, and that by using insecticides indiscriminately on a prophylactic basis this fauna will be depressed robbing farmers of this wealth that Nature provides gratis. It is this fauna which keeps most pests to below economical levels in farmers' fields each season if allowed (Ooi and Shepard, 1994).

The core of IPM is a set of practices that maintain pests below economic damaging levels with husbandry of natural regulating agents and minimal or no use of pesticides. IPM demands an understanding of ecological relationships and that pesticides kill more than pests. Research in the 1980s contributed greatly to understanding the ecological basis of why insect pests had become such problems a decade earlier. This new understanding guides IPM decisions in rice today, which along with new holistic thinking on the mechanisms of compensation give pest managers new insight to develop more effective control strategies.

Before we give examples of these new strategies we review the tools or tactics that are available to pest managers. Farmers are naturally reluctant to adopt technology when they are unsure how it will fit within their farming system. Since it will be virtually impossible for the crop protection specialist to anticipate the full effect of a given technology on an individual farmer's field, a choice or menu of technologies should be on offer from which the farmer can select and with which further on-farm experimentation can be carried out. Technologies must be presented in a form that enables farmers to see how they may fit into his or her farming system. This is a major challenge for adaptive research and demands much improved knowledge of the farmer's decision process (Heong, 1999) and the ability to produce technologies to meet the needs of a range of farmer types (Litsinger et al., 2008). A strategy would also be to train farmers to gather yield loss data in order to build their indigenous technical knowledge base (Kenmore, 1987).

16.14.1 Genetic Resistance

Rice is self fertilized and farmers can harvest seed for the next crop from a standing crop. Man has selected, consciously or unconsciously, the best yielding (adapted) cultivars over the seven millennia of rice domestication. Such selection has produced strains that show high yields even under a multitude of environmental stresses utilizing the mechanisms of genetic resistance and tolerance to pests. Host plant resistance has been the basis of plant protection for centuries. It is also the main means of technology transfer, via improved seeds, to rice farmers all over the world as effective extension services are not needed for this to occur. Although much host plant resistance is of the pedigree single gene type, the recorded insect and disease outbreaks reveal its weakness when used as the sole method of plant protection. Many of the insect pests and diseases that affect modern rices were not important during the era of traditional rice culture so resistance to these organisms is not common.

Genetic resistance is especially valuable in developing countries with small farm sizes, farmers' economic constraints, and lack of technical knowledge that limit the utility of other control methods. Genetic resistance is economical for small-scale farmers as new seed does not have to be purchased each crop. Compared to chemical control, the farmer does not have to develop skills on how to use the control method as it is in the seed and works every day in the field. The large germplasm collection at IRRI and screening programs for pest resistance have allowed the identification a number of genes resistant to four diseases (blast, bacterial blight, tungro, and grassy stunt) and five insect pests (brown and whitebacked planthoppers, green leafhopper, stemborers, and gall midge) (Khush, 1982). These genes have been incorporated into modern rices with high grain quality and early to intermediate duration and are available for breeders to use in national programs throughout Asia. IR36 for example has resistance to all but whitebacked planthopper and sheath blight in the list above. The basis for resistance in the insect pests, with the exception of stemborers, is antibiosis meaning that the insects are killed in the same way as putting insecticide into the rice plant but without the non-target environmental and health problems. The basis of resistance to stemborers is morphological and non-preference but the level of resistance is rated as only moderate (Chaudhary et al., 1984).

The main breeding strategy has been the sequential release of rices with new genes if resistance breaks down. There are greater attempts to place more than one gene in a variety (pyramiding) so that resistance will be that much harder for the pest to overcome. This is the goal for Bt rice as resistance is bound to breakdown otherwise (Ho et al., 2006).

Tolerance, unlike non-preference and antibiosis which interfere with insect behavior and metabolism, provides a plant with the ability to produce satisfactory yield in the presence of pests that would cause loss in a susceptible plant. Tolerant cultivars do not depress or limit pest populations nor do they provide selection pressure that can lead to the development of insect biotypes capable of overcoming resistance. The phenomenon of tolerance is generally cumulative and a result of interacting plant growth responses. These include general vigor, inter- and intra-plant compensatory growth, wound compensation, mechanical strength of tissues and organs, and nutrient and growth regulator partitioning (Velusamy and Heinrichs, 1986). The fact that tolerance is not likely to provide a high level of insect resistance suggests that it should be used in combination with other mechanisms of resistance or IPM tactics.

Although not highly resistant, tolerant varieties have higher decision thresholds than susceptible varieties resulting in a reduction of insecticide usage and enhanced natural enemy activity (Panda and Heinrichs, 1983). Tolerant plants which support large insect populations with little damage or yield loss, have value in preventing selection of new biotypes and in maintaining beneficial natural enemy densities. Tolerance increases yield stability by providing at least a moderate level of resistance when the vertical genes, that provide a high level of resistance through non-preference and antibiosis, are rendered ineffective because of a selection for a biotype with virulent genes. When biotype selection is detected and this first line of defense provided by major genes is removed, the tolerance mechanism becomes a secondary line of defense and will continue to function while preparations can be made to release a new resistant variety.

16.14.2 Cultural Controls

Cultural control in rice is the purposeful manipulation of the agro-ecosystem to suppress insect pest densities (Litsinger, 1994). As such, farmers use crop husbandry practices that have a dual purpose of crop production and insect pest suppression. No matter how the farmer grows his crop, however, certain pests will be favored while others are disfavored. The farmer needs to determine the appropriate balance. Farmers developed these practices mostly by trial and error handed down through generations. The far majority of these practices are more effective if carried out over a large area the size of a village or an irrigation turnout (Litsinger et al., 2008). Practices that are effective on a single field basis are altering the planting method, plant density, water management, and fertilizer usage. Those that are more effective if carried out on an area wide basis are modifying crop rotation, number of crops per year, plant maturity, planting time, synchronous planting, tillage, and crop residue destruction. See Litsinger (1994) for literature citations of cultural control practices stated in the following sections.

16.14.2.1 Single Field Adoption

Transplanting is the preferred sowing method due to its better weed control, but in areas where labor is unreliable, farmers direct seed. Direct seeding and consequent dense seeding favors a number of pests including black bugs (*Scotinophara* spp.), stemborers, and planthoppers, but whorl maggot is virtually suppressed. Ponding attracts the more aquatic species such as caseworm, whorl maggot, black bugs, yellow stemborer, and hispa. Inorganic nitrogen fertilization increases almost all insect pests but particularly brown planthopper and leaffolders, but use of potassium increases the ability of the rice plant to tolerate pests. On the other hand, nitrogen increases the crop's tolerance for insect pest damage.

16.14.2.2 Community Wide Adoption

Early planting is generally an escape mechanism but the effects of planting time are highly site specific as their effect depends on cropping patterns in the surrounding several thousand hectares. A single crop of rice per year ensures the least buildup of insect pests, and rotating a non-rice crop offers pest suppression for the same reason. If double rice cropping is practiced the best suppressive results occur if the dry season crop is planted soon after the wet season one is harvested to create a long dry fallow. Planting more than two rice crops per year, particularly when fields are planted asynchronously, is risking severe insect pest and disease problems because it reduces the pest suppressive effect of a dry fallow (Loevinsohn et al., 1993). Synchronous planting and maintaining a rice free period in the dry season breaks pest cycles and is particularly effective for virus disease control (Litsinger, 2008). Plantings so that fields all mature within a few weeks of each other regardless of plant maturity is an effective method to minimize buildup of stemborers and rice bugs. Thus in order to take advantage of the benefits of synchronous planting and harvest farmers should select varieties of the same maturity class. The consequences of some fields falling out of synchrony are well known to farmers. There are some circumstances where the rice-free fallow has a greater depressing effect on natural enemies, fostering brown planthopper buildup (Litsinger et al., 2008). In such areas farmers should sow brown planthopper resistant rices if available. Tillage and crop residue destruction in the off season aid disease and stemborer control.

16.14.3 Biological and Natural Control

Rice has been domesticated for millennia engendering notable elements of stability, particularly in irrigated culture which is ecologically akin to its original marshland habitat. A rich fauna of biocontrol organisms coevolved which can rapidly colonize a ricefield, thrive in the stable conditions offered by ponded fields, and make a notable impact on most insect pests. To make the most of this natural resource, farmers need to learn to recognize the beneficial effect of the wide array of natural enemies in rice fields and undertake efforts to conserve them. Ecological costs of not doing so include disruption of food web linkages by injudicious insecticide usage that will kill off important natural enemies (Settle et al., 1996; Schoenly et al., 1996). Using food web data and arthropod time-series records from one irrigated field, Cohen et al. (1994) found that insecticides disorganized and destabilized the population and community dynamics of arthropod species in rice agro-ecosystems. One consequence is to trigger outbreaks of primary and secondary pests (Kenmore et al., 1984; Heinrichs, 1994).

Reports from Schoenly et al. (1996) and Settle et al. (1996) show a profound arthropod taxonomic richness in tropical irrigated rice fields. Food webs or the assemblages of natural enemies have been constructed for common rice pests in the Philippines (Jahn et al., 2007). These represent the sum of all the host associations for a pest species and can be presented as records for a season or over all years (Schoenly et al., 1996). Counts of macro-invertebrates alone for Philippine and Indonesian rice fields exceed 600 and 760 taxa, respectively. Significant biocontrol elements of this fauna, such as spiders and hymenopteran parasitoids in Indian irrigated fields number up to 92 and 84 taxa, respectively (Sebastian et al., 2005; Beevi and Lyla, 2000). Like other invertebrate assemblages, rice invertebrate faunas follow the usual distribution pattern of having a few very abundant taxa ($> 5\%$), more taxa of moderate abundance (1–5%), and a large number of rare taxa (Schoenly et al., 1998).

Among the ecological conclusions that have emerged from whole-community studies of rice-invertebrate faunas under pesticide-free conditions are that detritivores and plankton feeders (springtails, midge and mosquito larvae) dominate early crop periods. Their food is the decomposing stubble and roots from the previous crop as well as algal blooms. They provide sustenance for early season generalist predators dominated by spiders. Although there are literally dozens of species of natural enemies in the field at any moment, their number steadily increases with crop age as they colonize from areas outside of each field after land preparation. But there are generally only a few groups that are the most important in a given area, including generalist predators and specialist parasitoids.

A subset of rice pests has specialized in colonizing fields early. These include rice whorl maggot, caseworm, green hairy caterpillar, green semi-looper, rice hispa, armyworms, and cutworms. As natural enemies build up over the crop, these vegetative pests flourish in the absence of effective natural enemy pressure during the first month of the crop in the field.

Spiders are perhaps the largest group of beneficial arthropods whose role in limiting brown planthopper first gave them notoriety by Kenmore et al. (1984) from field studies. Before that studies in temperate climates had concluded that spiders only preyed on nonpest detritus feeders (Yasumatsu and Torri, 1968). Their rich abundance in tropical rice was revealed by Barrion and Litsinger (1984). Katydids and crickets (Canapi et al., 1988; Rubia et al., 1990b) are effective predators particularly of eggs. *Conocephalus longipennis* katydid can for example eat an entire *Scirpophaga* spp. stemborer egg mass, hair mat and all. Aquatic hemiptera in the genera *Microvelia* and *Mesovelia* feed on plant- and leafhoppers that fall on the water surface (Nakasuji and Dyck, 1984). Aquatic predators feed on caseworm larvae (Litsinger et al., 1994).

Cyrtorhinus lividipennis is a noted mirid egg predator of plant- and leafhoppers and also feeds on small nymphs (Heong et al., 1990; Ooi and Shepard, 1994). Its mouthparts penetrate into rice culms where the eggs are inserted by hoppers. Ladybeetles (e.g. *Micraspis, Menochilus, Synharmonia*), staphylinids (e.g. *Paederus fuscipes*), and carabids (e.g. *Ophionea nigrofasciata*) are important against a wide array of pests including planthoppers, leafhoppers, leaffolders, stemborers, and early vegetative lepidopterous defoliators (van den Berg et al., 1992; Ooi and Shepard, 1994).

Of the parasitoids, the egg parasitoids are the most prominent against stemborers (Shepard and Arida, 1986; Litsinger et al., 2006d), planthoppers and leafhoppers (Chandra, 1980), rice bug (Rothschild, 1970b), rice hispa (Prakasa Rao et al., 1971), armyworms (Rothschild, 1969), black bugs (Perez et al., 1989), and gall midge (Hidaka et al., 1988).

Pathogens also play a role in natural pest suppression (Rombach et al., 1994). Epizootics of entomopathogens have been noted for many rice insect pests. Example the fungus *Nomuraea rileyi* regularly suppresses the green hairy caterpillar in the Philippines, while an epidemic of *Zoophthora radicans* was observed on rice leaffolders after a typhoon where only flattened larval bodies adhering to rice leaves provided the evidence of their role. Brown planthopper which appears in dense numbers is particularly prone to a number of fungi such as *Entomophthora* spp., *Beauvaria bassiana*, *Erynia dephacis*, and *Metarrhizium anisopliae*. Armyworms are highly susceptible to nuclear polyhedrosis virus, especially when they aggregate.

General information on beneficial arthropods in rice fields can be sourced from the following references: Shepard et al. (1987), Barrion and Litsinger (1994, 1995). The natural fauna affecting key rice insect pests has been compiled for stemborers (Nickel, 1964; Khan et al., 1991), leaffolders (Khan et al., 1988; Barrion et al., 1991), leafhoppers and planthoppers (Ooi and Shepard, 1994), and rice skipper and greenhorned caterpillar (Litsinger et al., 1997).

There have been but few attempts to introduce natural enemies from one location to another, which is termed classical biocontrol (Ooi and Shepard, 1994). Continuous rice systems or asynchronous planting have been advocated to encourage natural enemies (Settle et al., 1996), however, this increases risk for virus diseases of rice (Koganezawa, 1998). Augmentation by spraying suspensions of pathogens onto rice was extensively tested but met with only limited success (Rombach et al., 1994). One great disadvantage of this method has been low toxicity and low fungal survival in storage as well as in the field after application. Inundative releases of egg parasitoids have been carried out against stemborers with little practical result (Ooi and Shepard, 1994). Consequently conservation of natural enemies is mostly advocated by minimizing insecticide application frequency and selecting materials less toxic to beneficials (Bandong and Litsinger, 1986; Heong, 1998).

One aspect of microbial insect pest control which has made substantial progress has been with *Bacillus thuringiensis* (Bt) which is highly effective against only lepidopterous insect pests. This bacterium occurs naturally but in very low densities as no natural epizootics have been recorded. The toxic crystal (endotoxin) extracted from the bacterium has been shown to have insecticidal properties and is available as a commercial insecticide (Tryon and Litsinger, 1988). A strain of Bt was genetically engineered by insertion of the endotoxin to be part of the rice genome known as Bt rice and has given excellent control of rice stemborers and leaffolders (Theunis et al., 1998, Ho et al., 2006). The endotoxin is carried in the seed just like a resistant gene from a resistant rice plant. Unfortunately policy leaders in a number of countries are skeptical of the safety and ecological consequences of this new form of rice breeding and have not allowed the seed to be tested or sold thus limiting this control option to only a few countries. In the US Bt maize and Bt cotton have been used by farmers for a number of years without any noted problems.

16.14.4 Chemical Control

Chemical control is placed last in the list of IPM tactics on purpose to stress that the central core of IPM is to minimize insecticide usage and spare natural enemies by reviewing other measures first. Beyond risking farmer health, insecticides also increase economic and ecological costs (Pingali and Roger , 1995; Schoenly et al., 1996; Heong and Schoenly, 1998). Chemical control of rice insect pests has been reviewed by Chelliah and Bharathi (1994).

Insecticide usage in the Philippines has declined since hitting its peak in the 1970s during an era of government sponsored credit programs (Bimas in Indonesia and Masagana 99 in the Philippines) designed to encourage farmers to adopt agrochemical inputs. Chemical control still remains as a viable control option to farmers but for only limited use as such a powerful tool can no longer be squandered indiscriminately in the name of increased yield. Safer and more selective materials (e.g. neem, Bt, imidacloprid, buprofezin) are replacing the broad spectrum organochlorine, organo-phosphate and synthetic pyrethroids that dominate the market. Unfortunately farmers prefer them as they are less expensive as their international patents have expired allowing many companies to manufacture them. Competition brings lower pricing however. As an IPM strategy there is a need to avoid excessive use that will inevitably lead to the familiar treadmill characterized by increasing pesticide use to maintain yield stability in the face of developing pesticide resistance, resurgence, and secondary pest outbreaks.

One method to minimize usage is to train farmers to engage in weekly monitoring of their fields for pest and natural enemy population assessment and to use simple guidelines for triggering an insecticide application. In India farmers are asked to place an old rubber bicycle tire in the field on a weekly basis in three locations. No insecticide application is warranted if the total number of stemborer deadhearts and gall midge onion shoots is < 15 or a mean of 5 per tire sample area. Often farmers apply insecticides when no pest is present in a stage that can be controlled.

Stemborer larvae in the stem or pupated leaffolders cannot be killed for example. The determination of accurate guidelines in small farm systems can be complex based on the discussion in this chapter on the push-pull interrelationship that exists between multiple causes of stress and environmental effects on crop compensation. Economic thresholds, or more realistically action thresholds, are best derived from empirical methods. Until crop modeling can incorporate with confidence the many interactions that impact the elucidation of damage functions, the empirically derived action thresholds of Litsinger et al. (2006a–2006c) can be used as a first estimate. Action thresholds should be tested and perfected locally and can be adjusted based on crop vigor, the density and species of natural enemies, farmers' ability to withstand risk, crop maturity class, and the number and type of stresses impinging on the crop at the time.

An important point is that the yield losses determined in the Philippines based on the insecticide check method (Litsinger et al., 1987a, 2005) were equally distributed over the three crop growth stages. If this is the general pattern found elsewhere this does not favor chemical control as the expected gains in any growth stage will be relatively small and in most cases uneconomical to prevent. The extensive yield loss study also found that it was uneconomical to use even one insecticide application in over half of the fields studied. In addition insecticide application technology practiced by farmers produces low kill coefficients. If farmers applied at higher dosages and with greater spray volumes perhaps the kill coefficients would increase but this will take an effective extension program.

Based on the evidence that if a farmer managed his crop well agronomically, it would not be necessary or profitable for him to apply insecticides unless a high insect pest infestation occurred such as an armyworm outbreak, high early vegetative pests, or a mass immigration of planthoppers occur. On the other hand, on a stressed crop caused from either poor management, lack of water, or low solar radiation it may be economically attractive to apply insecticide to benefit from a synergistic yield gain.

16.14.5 Agronomic Practices to Bolster Tolerance

Rice IPM is embedded within the realm of integrated crop management as the healthier the crop the greater the amount of damage it can sustain before economic loss occurs. Some examples of agronomic practices that can fulfill this goal are presented and first include selecting a longer maturing variety (within the range up to 125 days as much longer durations will favor greater stemborer buildup). Farmers should ensure good seed quality with removal of mixtures and undersized seeds as well as seeds infected with fungal diseases. In areas where animals are raised, farmyard manure added to the soil before land preparation ensures good soil texture and slow release and availability of nutrients to plants. Deep plowing should be done every few years to ensure good root development. Thorough land preparation to obtain level fields is important in irrigated rice. Unleveled fields cause not only inefficient use of irrigation water and broadcast nitrogen but poor weed control. Also the crop will not mature evenly which can lead to greater insect problems. Nurseries should be supplied with organic matter to minimize root damage when seedlings are pulled. Transplanting seedlings 3 weeks of age insures good tillering. Maintaining good water control (so as not to pond too deep to impair tillering and root growth but still maintain good weed control) is essential. Remove weeds from both the seedbed as well as the crop before canopy enclosure. Fine tuning the nutrient regime in terms of rates and timing is crucial. All phosphorous and potassium and about one third of nitrogen should be applied basally incorporated under the soil. The IRRI leaf color chart can guide the proper timing of nitrogen before maximum tillering and then a third nitrogen application 5–7 days before panicle initiation. In longer maturing varieties a fourth nitrogen application 5–7 days after flowering is important for even maturity. While it is true that insect pest populations do increase in well fertilized crops, it is also true that yields will be higher despite this.

16.15 Examples of IPM Practices

A few examples are presented to provide insight as to how compensation can be incorporated into IPM recommendations. The first comes from India where patches of severe defoliation appeared 4 w.a.t. from caseworm and rice hispa. The farmer's first reaction was to broadcast Phorate (methadmidophos) granules into standing water. The crop had no signs of foliar diseases, weeds were controlled, but the crop had not yet been fertilized. There were scattered egrets feeding on insects and aquatic life in the nearby rice fields. There was a need to control the defoliators in the most severely infested patches as the plants could be killed and gaps in the rice stand would appear. Methadmidophos is a highly toxic insecticide and would pose a danger not only to the farmer applying it, but also to the egrets that may think the granules were seeds. The farmer was asked if he could fashion an insect net and collect the caseworms and hispa from the patches of damage. He said he did not have the time. It was decided that he could spray a less toxic insecticide such as neem or imidacloprid in the worst damaged areas as it was only necessary to achieve $> 50\%$ control as a young crop still has time to compensate from this degree of defoliation. The farmer was also advised to broadcast 30 kg N/ha to foster compensation.

Another farmer complained of stemborer deadhearts at 6–7 w.a.t. and wanted to spray chlorpyrifos. It is at this stage that the rice plant is most resistant to stemborer entry (Bandong and Litsinger, 2005) thus there is less need to spray at this time as the first instar larvae cannot easily penetrate into the stem. The farmer should bolster the crop's ability to tolerate the few deadhearts that would occur by timing the next nitrogen application at 5–7 days before panicle initiation.

At 8 w.a.t. there was a mean of 10 brown planthoppers and 1 spider per hill. For each predator counted the farmer should deduct 5 planthoppers from the count. This density is very near to action threshold levels therefore the farmer should monitor his field twice a week to see if the predators can stop the buildup before reaching 1–2 per tiller after accounting for predator density. If the threshold is reached, insecticide, as a last resort, should be timed when the population is mostly composed of the 4–5th instar nymphal stage for greatest effect. If adults dominate then the eggs they laid, protected in the stems, would survive the insecticide application. The most appropriate insecticides are buprofezin or imidacloprid which will spare most natural enemies.

At 9 w.a.t. the percentage of leaffolder damaged leaves was rising but otherwise the crop is healthy and without other stresses present. The farmer can raise the action threshold to 15–20% under this condition as the crop can tolerate this level of damage. A lower threshold is used if the crop is under stress from other causes. The actual threshold depends on the risk the farmer is willing to bear as well as his goal of obtaining the either highest profit or highest production. A lower threshold would be in force if production were the goal or if the farmer is risk averse. A final application of nitrogen should also be considered to bolster compensatory capacity.

In the final example a wet season crop planted to an early maturing variety is under stress from a number of causes, e.g., several foliar diseases, weeds, and a gall midge infestation that is rising over 10% damaged tillers. In addition reduced solar radiation will dampen the crop's compensatory capacity along with the short season variety. The farmer should first remove weeds as much as possible as a first priority and then ensure that future nitrogen applications are timely. If gall midge keeps increases, the farmer should apply an insecticide which should give a yield boost not only from suppression of gall midge but also a synergistic yield gain from compensating for the foliar diseases. If gall midge is of a chronic occurrence the farmer should think of selecting a longer maturing variety and preferably one resistant or tolerant to gall midge in his future crops.

16.16 Conclusion

The spectrum of insect pests has changed over the past millennium that yield losses have been recorded in Asia. The earliest epidemics recorded in Japan and Korea on traditional varieties now occur on modern semi-dwarfs in not only temperate Asia but in tropical Asia as well (Litsinger, 2008). The causes in the two regions are different however. In temperate Asia rice planthoppers undergo massive long distance migration and arrive in single cropped rice overwhelming natural enemies, while in tropical Asia multiple rice cropping coupled with indiscriminate insecticide usage can spawn the epidemics which in the latter case also included green leafhoppers and virus diseases. There is some evidence that even in parts of tropical Asia that long distance migration of planthoppers occurs (Kisimoto and Rosenberg, 1994; Riley et al., 1995). Migrations into Central China from Vietnam occur annually and there is evidence that migrations occur from S. India and Sri Lanka up the eastern half of India following the path of the SW monsoon as Chhattisgarh state in India annually records hot spots of brown planthopper in the wet season where in only $<$10% of fields establish a dry season crop. Such populations can be explained only via immigration.

Throughout Asia before high tillering rices were developed, insect pests such as stemborers were chronically abundant on traditional rices. For example Wyatt (1957) stated that 50% of the tillers in Malaysia were normally infested. The factors favoring stemborer incidence on traditional varieties were their long maturation, tall stature, and being thick stemmed. Long maturation meant more stemborer generations developed on the crop. Tall stature meant that longer periods of elongation and hence longer periods of susceptibility occurred. Thick stems favored more species such as the larger bodied *Chilo* and *Sesamia* genera. Modern rices being earlier maturing, shorter stature, and thin stemmed have been less favorable to stemborers thus losses are less. The exception would be the white stemborer *S. innotata* which virtually disappeared from its range when photoperiod insensitive rices were bred allowing multi-rice cropping. Mortality was high during land preparation of the second rice crop for aestivating larvae. But early maturing modern rices, developed in the 1980s, allowed a resurgence of white stemborer throughout its range with devastating effects (Litsinger et al., 2006e). Early maturity meant that the dry season fallow was extended allowing survival of aestivating larvae after the second crop was harvested.

Traditional rices showed a high ability to compensate from defoliation mainly through transport of carbohydrates stored in the stems. Modern rices have demonstrated this ability plus have the capacity of extensive tillering to replace those lost or damaged due to insect pest damage. Both of these processes has meant that the semi-dwarfs have high capacities of damage tolerance, not only from insect pest damage but from other stresses. These qualities have been little appreciated to date but are apparent in all modern rices that have inherited the *indica* genotype, thus the appeals that have been made for rice breeders to breed for new genotypes that have the ability to tolerate more insect damage (Heong, 1999) actually had been answered when IR8 was bred in the early 1960s. All that was lacking was knowledge on how to exploit this trait. There is evidence of some genetic variability in rices with regards to compensatory abilities (Catling and Islam, 1999) but for the most part the high tillering has achieved high levels. Other physiological pathways may also be tapped in new genotypes to build up higher levels.

Yield loss studies have concluded that for farmers to harness modern rices' great capacities for damage compensation, IPM needs to be viewed in the context of integrated crop management as the more fit the crop is to the local conditions the greater will be its ability to tolerate pest damage and stresses in general. Results of yield loss studies revealed instances where very large yield gains occurred in insecticide treated plots which could not be explained by insect pest densities alone. This has led to the hypothesis of synergetic yield gain which is the corollary of synergistic yield loss to explain this phenomenon.

The wide range of yield within a farm community where ten-fold differences among fields are common show that many farmers have not mastered the agronomic practices needed to achieve the yield potential of modern varieties in order to capitalize on the great compensatory capacity. Studies have also shown that the same farmer in one season may reach the high yield potential only to be on the bottom of the yield distribution curve a season or so later. The challenge ahead will be to pull up yields in all seasons. From the results of the yield gap data one takes away the thought that farmers readily adopted modern rices but have had trouble adopting other management practices which continues to this day probably more from the lack of effective extension services than anything else. The more recent data on the wide variability of rice yields in a farm community further supports this conclusion. Modern rices grown in irrigated culture have an advantage over the era when only single crop traditional rice was grown is that the farmer can recoup his production within the next six months rather than having to wait a year for single crop rice culture.

If the synergistic yield gain hypothesis were correct the farmer would have more choices in how to achieve high yields. For example if there were three stresses affecting the crop in the same growth stage, the farmer would only have to resolve two of them and allow the crop to tolerate the third. Farmers could chose to correct the easiest to control stresses at great savings. In order to capitalize on the yield compensatory strengths of modern rices, the farmer needs to master agronomic management more effectively and to time his planting to receive the greatest incidence of solar radiation. Growing longer maturing rices is one key to achieving higher yields. Yield loss studies showed that insecticide application with a knapsack sprayer produces marginal returns at best as spray coverage is not adequate to realize the high kill ratios necessary to benefit from this technology. The farmer is better off using the money he would have spent on insecticides for use in other stress reduction methods and allow the crop to compensate.

Yield losses have been found to be highly variable by culture, location, season, and field. This is hardly surprising given the high field to field variability documented in this review as well as the revelation that even the same farmer in the same field experiences this same degree of variability as the farmer community as a whole crop to crop. Part of the reason for the variability is the propensity of farmers to change management practices season to season, variability in insect pest infestations season to season, variability in crop stresses season to season, and the variability of weather season to season. These factors are especially dynamic with regard to modern rices which have a high capacity of compensation but which outcome is highly influenced by the factors just described.

All methods developed to assess yield loss to date are flawed to varying degrees. Plot size is important regarding all methods as many trials have been conducted on areas that are too small to accurately measure yield and to take into account the hill to hill interactions between infested and uninfested plants. Extrapolating yields taken on a few hills to a hectare run risks of small errors being grossly magnified. Few studies to date have been repeated in more than one year or in a sufficiently large number of fields to be representative of a farm community or in enough areas to be representative of a region of a country. There is also difficulty in determining loss caused by one pest species while keeping other pests neutralized.

The insecticide check method which has been the most used has limitations, the most significant as illuminated in this review as it probably measures yield gain from compensatory suppression of a host of stresses rather than yield loss caused by insects alone. It also has problems with usage of phytotonic or phytotoxic chemicals or other materials that affect other pest groups such as diseases and nematodes, the difficulty of achieving > 90% pest control, and the difficulty of controlling insecticide drift. If the synergistic yield gain hypothesis were true then the effect of carbofuran would even be more insidious in that it would have allowed for even more compensation to occur. Damage simulation always begs the question of whether the method used accurately mimics that of the pest. Artificial infestation often uses cages which interfere with the natural growth of a crop mainly by shading. The yield potential comparison method is in question of whether the potential has been accurately determined. Modeling still is in its infancy with regard to discovering a pest's influence on plant physiological processes and accounting for the effects of the multitude of environmental interactions. It will require continual field validation during its elaboration.

As a result, more than one method should be employed as a cross check in crop loss assessment. Modeling needs to be validated to field situations. Some of the methods with the least problems were the artificial infestation of yellow stemborer eggs practiced by Bandong and Litsinger (2005). The caging was limited to only one week and the plot size was 25 hills, allowing for inter-hill competition to occur normally. Artificial defoliation or detillering with scissors showed the power of compensation while modeling has revealed its numerous physiological pathways. Potentially the most realistic would be developing designer variants of the same genotype having Bt genes and possibly other attributes that affected only certain pest guilds. Thus these genotypes could be grown on large plots under a variety of management situations to test these factors under realistic conditions.

The far majority of crop loss assessments have occurred on irrigated rice with only limited data from the other rainfed cultures. The conclusion of Cohen et al. (1998) rings true that very little of the voluminous data that exists on yield loss can challenge that produced by Cramer (1967) despite the fact that he used data from insecticide trials which are probably not representative as researchers conducting such trials generally time their plantings for the highest field densities.

The remarks of Kenmore (1987) that farmers stand to gain the most from the knowledge of crop loss assessments but now are the least likely to learn of any results ring true. As farmers need local prediction of crop losses, this information should be most efficiently and effectively collected by the farm community. The suggested method to achieve this end would be for farmers to develop their own database of yields from each field in the community each season. They then could compare each crop to the yield potential determined by the database by taking accurate yield cuts as well as gathering data on input usage and crop stresses that are at least semi-quantified. Farmers would convene after each season and discuss their yields as well as management practices of those attaining the highest yields that season so that the low yielders could learn of management practices they should adopt the next crop. Through such an iterative approach, yields of the whole farm community could be gauged against the historical yield potential and farmers would have a basis from which to work to make improvements season to season. Policy makers (through local extension agents) could tap such databases each season by a simple survey of the farm communities to get regional and national crop loss assessment data.

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Chapter 17
Changing Trends in Cotton Pest Management

K.R. Kranthi and D.A. Russell

Abstract The cotton crop sustains more insects than any other crop grown commercially world-wide. Any single insecticidal intervention to control a particular pest invariably sets up a chain reaction causing short-term imbalances in the ecosystem, mostly in favour of the pest in the long run. Thus over the years, insecticide use was establishing undesirable ecological and economic consequences for cotton cultivators and administrators in many countries. Individual insecticide molecules when first introduced have always been impressive in their rapid efficacy in controlling target insect pests. As long the target pests are effectively controlled with the pesticide, cultivators do not care for the naturally occurring predators and parasites in their ecosystems. Unfortunately almost all the insecticides have inadvertent adverse effects on naturally occurring beneficial insects. However, phytophagous target pests usually develop resistance much faster than entomophages, thereby causing pest populations to survive the pesticide, increase in numbers in the absence of natural control, and so generate outbreaks. The cotton crop has been subjected to more pesticide exposure than any other crop, in all cotton growing countries of the world. Intense insecticide use has resulted in insect resistance to insecticides, pesticide residues, and the resurgence of minor pests causing immense problems to cultivators. With the most reliable tools turning redundant, pest management experts started exploring the utility of naturally occurring pest control components as alternatives to replace the chemical insecticides. Thus, Integrated Pest Management (IPM) programs began to take shape as 'intelligent selection and use of pest management tactics which results in favorable ecological, sociological and environmental consequences' as defined by Rabb (1972). Insecticide Resistance Management (IRM) strategies have strengthened pest management systems by identifying appropriate insecticides, rates and timings so as to delay resistance, ensure effective control of target pests, and conserve naturally occurring biological control for enhanced sustainability of ecosystems. With the recent introduction of Bt-cotton, novel eco-friendly pesticides and IRM strategies, coupled with the trends in technology

K.R. Kranthi (✉)
Crop Protection Division, Central Institute for Cotton Research, PB. No. 2. Shankarnagar PO, Nagpur-440 010, India
e-mail: krkranthi@satyam.net.in

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dissemination through area-wide farmer participatory approaches and farmer field schools, IPM programs all over the world have improved their sustainability and economic success.

Keywords IPM · IRM · Bt-cotton · *Helicoverpa armigera* · Insecticide resistance

17.1 Introduction

Cotton pest management has always been an immensely challenging task for entomologists all over the world. Around 1,326 species of insects have been reported on cotton worldwide (Matthews and Tunstall, 1994). World wide, the cotton crop suffers severe economic damage from a range of insect pests, most importantly the bollworms, *Helicoverpa armigera, Heliothis virescens, Helicoverpa zea, Pectinophora gossypiella, Earias vittella, Earias insulana, Diparopsis* sp; the leaf feeding lepidopteran species, *Spodoptera, Bucculatrix thurberiella, Alabama argillacea, Sylepta derogata, Anomis flava*; hemipterous bugs, *Lygus* sp *Dysdercus* sp, mirids and pentatomid bugs and sucking pests such as jassids, whiteflies, thrips and aphids. Several species apart from these, particularly weevils, rootworms, stem borers, termites, cut worms etc. are also known to cause significant damage in many countries. Conventional insect pest control strategies rely heavily on insecticides. It is estimated that cotton cultivation consumes at least 10% of all insecticides used globally. Pesticides worth US $600 million are used annually in India for pest management, of which, nearly 50% of the total insecticides used are applied on the cotton crop alone, although it occupies only 5% of the total cropping area in the country (Ghosh, 2001). Over the past two decades, the perplexities in pest management have intensified with more and more insect species developing resistance to over-used insecticides. Insecticide resistance rendered insecticides ineffective, thus increasing the need for repeated applications, wastage of resources and consequent environmental pollution. Various efforts have been made all over the world to devise region-specific integrated pest management (IPM) systems. However, poor efficacy of insecticides due to insecticide resistance in insects, and performance inconsistencies of biopesticides and biological control have been making IPM unsustainable. The introduction of insect resistant GM (genetically modified) cotton, especially Bt-cotton, represents the latest of the various methods being deployed to fight the insect pest menace in cotton.

17.2 Historical Perspective of Cotton IPM

Cotton being a commercial crop has always been subjected to intense human interventions to ensure maximum profitability. Though a number of insect pests have been known to cause severe crop losses, the cotton bollworm *Helicoverpa armigera* has been the main focus of attention in the old world because of its propensity to cause sustainable losses to a range of crops. It has been recorded from 182 plant species including cotton, chickpea, pigeon pea, peas, cowpea, sunflower, sorghum, groundnut, field beans, tomato, tobacco, maize (Gowda, 2005) in addition to wheat, okra, castor and a wide range of field vegetables. It was found to cause yield losses of up to US$ 290–350 million in India annually (King, 1994). It is estimated that out of the insecticides worth US$ 480 million used in agriculture in India, nearly 50% is used for cotton crop protection, of which 75% is targeted against *H. armigera*. There have been several estimates of crop losses in various parts of the world. Fitt (1994) reported cotton crop loss of 7.7% in Queensland, Australia despite an expenditure of US $ 4.2 million for its control. *H. armigera* alone was estimated to cause losses of over $US900 million in chickpea and pigeon pea world-wide (Reed and Lateef, 1990), with over $300 million loss in those crops in India alone (Sharma, 2001). Several efforts have been made all over the world to minimize crop losses due to major pests of cotton with focus on sustainable control of the bollworms. Insecticide use ranks the most significant amongst such interventions. Over the past five decades cotton cultivators had to rely on the conventional groups of insecticides such as organochlorines (DDT, BHC), cyclodienes (aldrin, dieldrin, endosulfan), organophosphates (monocrotophos, quinalphos, chlorpyriphos, profenophos, dimethoate, phosalone, metasystox, acephate, phorate, methyl parathion etc.), carbamates (carbosulfan, carbaryl, thiodicarb, methomyl) pyrethroids (cypermethrin, deltamethrin, fenvalerate, λ-cyhalothrin, etc.) and formamidines (chlordimeform and amitraz). Many materials have been used for *H. armigera* control over the years. Not all are equally effective, many have impacts on others insects in the pest and beneficial complex and many are to a greater or lesser extent harmful to human health.

In the late 1990s four chemical classes dominated cotton crop protection in Asia. The synthetic pyrethroids (cypermethrin etc), the organophosphates (quinalphos, phoxim etc), a single cyclodiene (endosulfan) and the carbamates (esp. methomyl). These individual chemicals have been used as representatives of their classes in many of the studies reported here. Toxicity and range of efficacy varies between chemicals but those of the same class are generally (but not always) metabolized and resisted by the same mechanisms in insects (see below).

Information from the 557 significant, peer reviewed, published reports on pesticide performance, were summarised to give a score for efficacy (out of 6) (A), a score for harmful impact on beneficial insects (out of 4.5) (B) and a score for mammalian toxicity (5 is the least toxic) (C). These have been combined as an Overall Score (= A − B + C). The higher the Overall Score, the more suitable the insecticide is for cotton bollworm a control (Table 17.1).

This table can be used to make decisions on which insecticide to use (in conjunction with the information below on resistance management strategies and taking into account other pest species present). Several insecticides obtain high Overall Scores indicating that they would be good all-round choice products for *Helicoverpa* control.

Mixtures of insecticide with two or more active ingredients are widely used in Asian pest control programs. Where different insect pests are being targeted simultaneously (e.g. sucking pests and lepidopterans) this may sometimes be justified. However, the use of mixtures for the control of caterpillars especially *H. armigera*, and particularly in China, is more problematic. Wu and Yang, writing in Russell and

Table 17.1 Insecticide performance and Overall Score of suitability for *H. armigera* control (in the absence of resistance) (from Russell and Kranthi, 2006)

Insecticide	Control efficacy A	Impact on natural enemies B	WHO mammal toxicity class C	Overall score A − B + C
NPV products (Bio)	4.4	1	5	8.40
Bt products (Bio)	4	2.2	5	6.80
azadirachtin (Bot)	4	2	4	6.00
thiodicarb (Carb)	6	2.5	2	5.50
fluvalinate (Pyr)	6	2.8	2	5.20
fenpropathrin (Pyr)	6	3.8	2	4.20
chlorpyrifos (OP)	6	3.9	2	4.10
bifenthrin (Pyr)	6	4	2	4.00
cyfluthrin (Pyr)	6	4	2	4.00
endosulfan (OC)	5.2	3.5	2	3.70
fenvalerate (Pyr)	5.2	4	2	3.20
deltamethrin (Pyr)	5.2	4.2	2	3.00
flucythrinate (Pyr)	6	4	1	3.00
cypermethrin (Pyr)	5.2	4.3	2	2.90
profenofos (OP)	5.4	4.5	2	2.90
malathion (OP)	4	4.3	3	2.70
methomyl (Carb)	6	4.3	1	2.70
quinalphos (OP)	4.8	4.4	2	2.40
monocrotophos (OP)	5.2	4.1	1	2.10
carbaryl (Carb)	4	3.9	2	2.10
BHC (OC)	4	4.1	2	1.90
triazophos (OP)	4.4	4	1	1.40
acephate (OP)	2	3.7	3	1.30
Lambda-cyhalothrin (Pyr)	4	4.7	2	1.30
carbofuran (Carb)	2	3.8	1	−0.80
parathion-methyl (OP)	2	4.3	1	−1.30

Kranthi (2006) came to the following conclusions on the commonly used insecticide mixtures in Asia. Few mixtures produce more mortality than the most effective component of the mixture on its own. Where resistance to pyrethroids is metabolically mediated some mixtures (esp those containing certain phosphorothionate organophosphates) can undermine the resistance and restore the efficacy of the pyrethroids but this effect is short lived. Relatively slow development of resistance to a mixture does not mean slow development of resistance to each component in the mixture. The commonly used binary mixtures of pyrethroid + organophosphate select intensely for metabolic mechanisms, especially oxidases, in *H. armigera*. The employment of mixtures in controlling *H. armigera* can result in the simultaneous enhancement of multiple resistance mechanisms and significant cross resistance to other compounds.

Mixtures may still be cost-effective for controlling insect pest complex in cotton, however rational use of mixture as insecticide resistance management strategy should be treated cautiously. Development of an anti-resistance mixture should be based on a full understanding of the genetic basis and mechanisms of resistance to each component in the mixture. In West Africa, use of Pyrethroid/OP mixtures from the beginning seemed to result in suppressing the development of esteratic resistance to some extent, though oxidative resistance gradually developed in *H. armigera* (Martin et al., 2003). But in most cotton areas of China, Indian and Pakistan, both pyrethroids and OPs have been widely used and already have resistance problems. Employment of Pyrethroid/OP mixtures for resistance management in *H. armigera* is unlikely to be helpful in the long term in this situation.

All these insecticides disrupt naturally occurring beneficial insect populations to variable extents. History shows that excessive and indiscriminate insecticide use representing an 'exploitation phase' was invariably followed by 'crisis' and 'disaster' phases in cotton, thereby leading to problems of insecticide resistance, pest resurgence, accumulation of harmful residues and toxicity to non-target organisms. Subsequently non-insecticidal alternative methods of eco-friendly pest management have been developed. Cotton IPM programs have been built around cultural control, biological control and biopesticide interventions in many parts of the world. Appropriate application technology can make a great deal of difference to the efficacy of all chemicals applied (Sohi et al., 2004).

17.2.1 Cotton Pest Control 1960–1980

The pest spectrum on cotton before 1980 comprised mainly the pink bollworm, spotted bollworm and *Spodoptera litura*. The American bollworm *Helicoverpa armigera* was mentioned but was 'not a regular or a serious pest' of cotton in India (Nair, 1981). Standard recommendations for sucking pest control included carbofuran granules, dimethoate and metasystox. Bollworms and other lepidopteran insects were controlled with methyl parathion dust, quinalphos and chlorpyriphos. During the late 1970s, *Spodoptera litura* was found to exhibit resistance to several conventional insecticides recommended for its control (Ramakrishnan et al., 1984). The synthetic pyrethroids were introduced into India and several other countries in 1980 to control the major pests of cotton, especially the leafworm, *Spodoptera litura*.

17.2.2 Cotton Pest Control from 1980 to 1990

From 1980 to 1985, synthetic pyrethroids, which were found to be highly effective on a wide range of insect pests at low dose application per unit area, occupied center stage. But their utility started to diminish from 1986 to 1987 when insecticide resistance was recognised as a major contributory factor to pest control difficulties or failures. Problems were especially acute in 1987 in the coastal belt of Andhra Pradesh. It is not known if the introduction and widespread use of synthetic pyrethroids was the main cause, but within the subsequent 2–3 years, *H. armigera* and the whitefly, *Bemisia tabaci* (Gemm.) emerged as the major pests in place of the earlier species. The American bollworm *Helicoverpa armigera* was found to survive and cause extensive damage to cotton crop despite repeated applications of insecticides, even up to 30 sprays in a cotton season. The pest later caused heavy economic losses to other crops such as chickpea and pigeonpea and was found to withstand sustained insecticide pressure. High levels of resistance to synthetic pyrethroids were subsequently confirmed by Dhingra et al. (1988) and McCaffery et al. (1989) as a major cause of control failures. Cotton yield worth US $100 million was lost to this insect pest in Andhra Pradesh alone, which led to a severe crisis in the state.

17.2.3 IPM from 1990 to 2000

This decade was most difficult so far for cotton pest management. By the mid 1990s Indian cotton farmers were spending >43% of the variable costs of cotton production on insecticides, around 80% of that being for bollworm control and in particular *Helicoverpa* control (ICAC, 1998a,b). Insecticide use on cotton was 50% of all insecticide use in the country and it was increasing at c.7% per annum. Many, perhaps even most, cotton production was being rendered uneconomic. The reasons for the very rapid increase in the importance of *H. armigera* as a cotton pest are unknown but by the end of the decade it was the major cotton pest. In 1998–1999 14.6% of Indian cotton production was lost to insect (mainly bollworm) damage. The Green Revolution had increased the area of more susceptible *H. armigera* hosts and the intensification of cropping patterns meant that these hosts were available to *H. armigera* all year round. Upland cotton (*Gossypium hirsutum*), which is a better host for *H. armigera* than desi cottons (*G. arboretum and G. herbaceum*) had been introduced in the early 1970s and it spread rapidly.

The excessive use of insecticides, especially synthetic pyrethroids, led to further and worse problems of insecticide resistance in *Helicoverpa armigera* and *Spodoptera litura*, which further necessitated the repeated application of insecticides. The first few reports related to high levels of *H. armigera* resistance to pyrethroids and DDT. Mehrotra and Phokela (1992); Armes et al. (1992), (1996); Sekhar et al. (1996) reported high levels of pyrethroid resistance in several cotton and pulse growing regions of the country. Subsequent studies (Armes et al., 1992, 1996; Kranthi et al., 2001a,b, 2002a,b) showed that resistance to pyrethroids was ubiquitous and resistance in *H. armigera* to conventional insecticides such as methomyl, endosulfan and quinalphos was increasing in India. Due to unsatisfactory insect control on account of insecticide resistance, farmers were forced to spray repeatedly, most often with mixtures. By 1992, *H. armigera* resistance to insecticides had emerged as a great challenge to cotton pest management in Asia and Australia. Similar problems were being experienced in the Americas with other heliothine species. Subsequently, a number of IPM programs were initiated across the world in cotton growing countries to ensure effective bollworm management. IPM recommendations were based on calender applications of biopesticides/bioagents interspersed with need-based application of insecticides. A typical IPM program recommendation in India at the time might include an initial application of organophosphate insecticides against sucking pests followed by fortnightly 4–5 serial releases of *Trichogramma* egg cards, 6–7 neem based formulation sprays, 5–6 HaNPV sprays and 4–5 periodical releases of a few other biocontrol agents such as *Chrysoperla carnea and Habrobracon hebator*. Other standard recommendations were, installation of bird perches, pheromone traps and intercropping with cowpea, black gram etc. or trap crops such as marigold. In some parts of the world, where commercial formulations were available, the recommendations also included entomopathogenic nematodes, *Verticillium lecani, Metarhizium anisopliae, Beauvaria bassiana*, and *Bacillus thuringiensis*. In addition pheromones were also included for pest monitoring and in some cases for mating disruption.

To a certain extent the biological interventions were found useful in many situations in many countries. But, despite enormous governmental support and intensive scientific effort, cultivators did not adopt IPM methods wholeheartedly. Some of the major reasons were poor efficacy, non-availability and lack of cost-effectiveness of the non-insecticidal alternative components. In general, IPM came to be associated only with methods that deployed intensive biological control and bio-pesticide based techniques, as a result of which many campaigns promoted IPM as a set of strategies with minimum or zero-pesticide approaches. However, with experience based on ground realities, there was a gradual shift in the pest management perspectives and extension approaches. With the non-availability of good quality biopesticides and biological control organisms, coupled with sub-optimal efficacy under field conditions, cotton cultivators had to depend on insecticides. Since insect resistance to insecticides had emerged as a major threat to pest control programs, thereby rendering insect pest control ineffective, inefficient and unsustainable, IPM packages were refined to include IRM (Insecticide Resistance Management) as a major component. IRM was most relevant to the management of crises caused by insect resistance to insecticides. Therefore specific IRM programs were designed for regions affected by severe resistance problems. Clearly IPM was seen as a proactive method with emphasis on biopesticide and biological control interventions, whereas IRM was meant to overcome the existing 'resistance' crisis through specific strategies to ensure efficient pest control with what insecticides were used and mitigate the problem of resistance. It was also being increasingly felt that implementation of the IPM or IRM programs in individual fields or a few villages, especially in developing countries, was not making a significant impact on the pest damage and regular outbreaks. Therefore 'large-scale farmer participation' was sought as a sustainable remedy to combat the menace of recalcitrant problems such as the bollworms. It was clear that extension efforts with 'IPM-demonstrations' in progressive farmer field conditions to popularize the technology were not achieving the desired results, mainly because IPM was a package of strategies that involved a series of processes and not a product in itself, unlike a pesticide or a new variety. The knowledge base required to utilise the elements of the IPM package with optimal timing was considerable and largely lacking in either farmers or the overstretched extension staff. This led to the initiation of different extension approaches such as 'area-wide farmer participatory', 'whole-village participation' and 'season-long implementation through farmer field schools'. The methods were found very useful in enhancing the knowledge levels of farmers on sustainable eco-friendly pest management systems. The IPM/IRM strategies were successful in reducing insecticide applications, enhancing yields and ensuring sustainable eco-friendly cotton pest management, Governments, especially in India, wholeheartedly supported the initiatives. Because of the extensive efforts of many Governments, IPM/IRM became commonly recognized terms for cotton cultivators all over the world. The details of these practices are described in Sections 17.4 and 17.5. By the late nineties insect resistant GM (genetically modified) Bt-cotton was introduced for bollworm control in major cotton growing countries such as the USA, Australia, China. Bt-cotton was introduced in India in 2002. The technology was so potent that within 3–4 years of its introduction, the area under Bt-cotton increased to more than 70% in these countries. Thereafter there were changes in the cropping patterns, pest spectrums and the associated parasite, predator complex, thus altering IPM perspectives significantly.

17.2.4 IPM from 2000 to 2007

Cotton pest management underwent a radical change after 2000 all over the world. With the introduction of novel eco-friendly insecticides that were highly effective on bollworms, *Helicoverpa armigera* and other bollworms were no longer being perceived as intractable problems. Apart from the introduction of Cry toxins in the form of transgenic Bt-cotton technology, chemicals such as spinosad, indoxacarb, emamectin benzoate, novaluron and lufenuron ensured effective control of *H. armigera* while being less toxic to beneficial insects in the cotton ecosystem. Interestingly, *H. armigera* infestation reduced significantly in cotton ecosystems from 2000, to the point of effective non-existence in some parts of India. It is not clear whether it was the introduction of Bt-cotton or the change in insecticide use pattern in Asia, notably the decrease in pyrethroids, coupled with increase in the new chemistries which impose fitness problems in residual surviving populations, which caused the change, but *H. armigera* populations rarely exceeded economic threshold levels in Asia, particularly in majority of the cotton growing regions of India. Additionally, the chloronicotinyls (imidacloprid, acetamiprid and thiomethoxam) and the insect growth regulator diafenthiuron, which are selectively more effective on the sucking pests and less toxic to beneficial insects as compared to the conventional insecticides added to sustainable pest management, reducing the selection pressure from bollworm insecticides early in the season. However, it must be remembered that overuse of any of these molecules with scant regard for the principles of insecticide resistance management can lead to the development of pest resistance to the insecticides. The chloronicotinyl insecticides have been used to treat seeds since 1998; preventing sucking pest damage on seedlings up to 50–60 days after sowing. However, recent observations during the 2004–2006 cropping seasons showed that the benefit of seed treatment was now short lived and rarely extended beyond 20–30 days after sowing. In some cases sucking pests such as jassids continued their damage despite seed treatment. After the introduction of Bt-cotton, with the consequent reduction in insecticide sprays, especially during the flowering and boll formation phases, some minor pests (*Spodoptera litura*, mealy bugs, mirid bugs, thrips, jassids, weevils etc), which are not susceptible to Cry1Ac, showed resurgence in many parts of the world. Resistance management strategies have been revised from time to time in light of the introduction of Bt cotton and new insecticides. Primarily the resistance management principles involved in the strategies have been based on use of a 'refuge' areas under non-Bt cotton and a rational and sensible sequence of insecticides which are effective on the target species, cause minimal disturbance to beneficial fauna and minimize selection pressure, combined with the rotation of insecticide groups which to which the pests have unrelated resistance mechanisms (i.e. which are not cross-resisted).

17.3 Natural Enemies in the Cotton Ecosystem

Cotton is an annual crop, hence it does not provide a sustainable niche for the long term establishment of natural enemies. For biological control interventions to be effective, continuous releases are required, which is neither possible nor economically feasible. In practice there has been almost no establishment of introduced natural enemies into cotton ecosystems worldwide (Russell, 2004). Moreover, cotton has an indeterminate growth habit which provides a continuous source of food for a wide range of insect pests throughout the season, necessitating insecticide use, since inundative bio-agent releases seldom help in preventing the pest from reaching economic action thresholds. Because of this reliance on chemicals to control a range of insect pests, cotton has not been a favourable environment for conservation of even naturally occurring beneficial organisms. Further, any minor damage to cotton squares results in flaring-up and shedding. Flowers and young bolls are also readily shed due to insect feeding, making protection of the fruiting bodies in their early stages a very important determinant of final yields. Biological control, being generally slow-acting in nature does not prevent larvae from damaging squares or flowers, resulting in losses to fruiting bodies. In the majority of the cotton cultivating countries the market availability of bio-control agents has been very poor, as has their quality, and the production of bio-control agents has been very cumbersome and uneconomical. Over the past decade, results with commercial (as opposed to experimental) releases of bio-control agents in cotton have not been consistent and, despite the claims of being economic feasible, have not been popular with farmers. The efficacy that can be at best described as marginal and inconsistent, has not been enough to convince farmers to undertake their sustained use.

Amongst the many sucking insect pests that attack the cotton crop in its initial stages, jassids, *Amrasca devastans* (Distant)., aphids, *Aphis gossypii* (Glover)., whiteflies, *Bemisia tabaci* (Gennadius), thrips *Thrips tabaci* (Lindermann) and mites *Tetranychus macfarlenai* (Baker and Pritchard) are economically the most important. Aphelinid parasitoids, *Encarsia formosa* (Gahan) and *Eretmocerus mundus* (Mercet) and predators such as *Chrysoperla carnea* (Stephens) and *Geocoris ochropterus* (Fieber), *Chilomenes sexmaculatus* (Fabricius), *Scolothrips indicus* (Priesner) and *Scymnus* sps. can keep sucking pest populations under economic threshold levels if not disrupted with broad-spectrum insecticides.

There are several naturally occurring biological control factors that keep bollworm populations under check. Some of the important naturally occurring parasitoids on *H. armigera* are *Trichogramma chilonis* (Ishii), *Chelonus curvimaculatus* (Cameron), *Campoletis chloridae* (Uchida), *Palexorista laxa* (Curran), *Eucarcelia illota* (C.) and *Goniopthalmus halli* (Mesnil). Some major predators include *Geocoris ochropterus* (Fabricius), *Coranus spiniscutis* (Reuter), *Chrysoperla carnea* (Stephens), *Orius* spp., *Polistes* spp., *Chilomenes sexmaculatus* (Fabricius) and spiders (*Oxyopes* spp., *Clubiona* spp and *Thomisus* spp.). The pink bollworm, *Pectinophora gossypiella* (Saunders) is parasitized by *Apanteles angalati* (Mues.)., *Chelonus* spp. and *Camptothlipsis* spp. Some important parasitoids of the spotted bollworm, *Earias vittella* (Fabricius) and the spiny bollworm, *Earias insulana* (Boisduval) are *Trichogramma chilonis* (Ishii), *Apanteles angalati* (Mues.) and *Rogas aligarhensis* (Q.). Predation by *Coranus spiniscutis* (Reuter) and *Chrysoperla carnea* (Stephens) is also common in many ecosystems.

There are three main leaf eating lepidopteran species that are considered important, the cotton leafworm, *Spodoptera litura* (Fab.), cotton semilooper, *Anomis flava* (Fabricius) and leaf folder, *Syllepte derogata* (Fab.). Several parasitoids have been observed to reduce their populations. These include *Trichogramma chilonis* (Ishii), *Glyptapanteles phytometrae* (Wilkinson), *Palexorista* spp., *Sysiropa formosa* (Mensil) and *Charops bicolor* (Czepligeti). Amongst the several parasitoids of the leaf folders, the most important ones are, *Apanteles significans* (Walker), *Phanerotoma syleptae* (Zettel), *Elasmus* spp., *Eurytoma syleptae* (Ferriere) and *Xanthopimpla punctata* (Fabricius).

In almost all cotton growing countries, Chrysoperla lacewings *Coccinella* and *Orius* species, nabid bugs and spiders consistently predate the eggs of a number of pests. In Paraguay, *Bracon* sp and *Catolaccus* sp. provide significant parasitism of the boll weevil (Gallo, 2000, Stadler, 2001). In Uzbekistan *Chrysopa carnea* and *Coccinella septempunctata* contribute to effective control of early season sucking pests (Jones et al., 2000). Moawad and Gerling (2000) showed very significant mortality of whitefly from parasitoids in Egypt and Israel. First instar larvae hatching from egg masses of the cotton leafworm, *Spodoptera littoralis* in Egypt, are heavily preyed upon by *Vespa/Vespula* wasps provisioning nests close to the cotton fields. Van den Berg et al. (1993), showed that *Pheidole* ants frequently caused high mortality in *H. armigera* in Kenya. However, in spite of the evidence for the role of all these natural enemies in reducing pest populations, the action of *Solanopsis* fire ants on boll weevils in Texas is almost the sole example of demonstrated irreplaceable mortality caused by a key predator (Fillman and Sterling, 1983, Sterling, 1984).

Major parasites and predators which are regularly observed in the cotton ecosystem in India include *Chrysoperla* spp. *Cheilomenes* spp. *Apanteles* spp. *Campoletis chloridae, Microchilonus* spp. and several tachinid flies and ichneumonids. The egg larval parasitoid *Microchilonus curvimaculatus* and larval parasitoid *Campoletis*, have been recorded as regular mortality causing factors in larvae collected from cotton fields in many countries, epecially on pigeonpea. The predator lacewing *Chrysopa* populations coincide mostly with the peak flowering period of cotton while the ladybird beetles *Cheilomenes* spp., which are regular predators of soft bodied insects such as aphids, occur early in the season. If they are to be conserved, it is essential to avoid the use of broad spectrum organophosphates during their occurrence. As the above paragraphs show, there is wide range of beneficial fauna in the cotton ecosystem, which can help in pest management if they are not disturbed or destroyed. Since a level of natural control exists in the ecosystem without the need for human intervention, it is important, where practical and feasible, to design strategies aimed at conserving their populations with a judicious and sensible use of selective insecticides. Kranthi et al. (2005) observed that avoidance of organophosphate insecticides for the first three months helps in build-up of entomophage populations such as *Chrysoperla, Campoletis chloridae, Microchilonis curvimaculatus* and tachinids, which contribute to the management of *H. armigera*.

17.4 IPM Components

17.4.1 Use of Sex Pheromones

Pheromones are chemicals, which are released externally by insects to elicit specific responses from individuals of the same species. Sex pheromones can be extremely valuable components for detection, population monitoring, mass trapping, mating disruption and lure and kill. In cotton pest management, so far, only monitoring and mating disruption have been found feasible, with most of the success reported only for the pink bollworm. The value of pheromones in controlling *P. gossypiella* is now well established and they have been widely used in countries like Egypt (Critchley et al., 1991) and Pakistan. Surprisingly, the major success in Egypt, where over 95% of the total cotton crop was protected from pink bollworm by the use of slow release pheromones for mating disruption by 1996 was not maintained. Neighbouring Israel, however, continues to use the pheromone with considerable success (Niv, 2000). Chamberlain et al. (1992) showed successful mating disruption with *Earias* pheromone (using the common components of the sex pheromones of *E. insulana* (Boisduval) and *E. vitella* (F.)). But the high costs of production of the unstable diene pheromone made the technology unviable. In India, traps baited with lures have been shown to be important decision making tools in determining effective control action (Dhawan and Sidhu, 1984). Surulivelu (1985) showed that pheromone treatment using hand application of hollow fibre gossyplure dispensers reduced larval infestation. The *Helicoverpa* pheromones have been mostly considered for detection and population monitoring. However, a consistent relationship between trap catches and field infestation has been elusive (Leonard et al., 1989). Mating disruption using *H. armigera* pheromone has been attempted in many countries over hundreds of hectares. Mating suppression within fields was demonstrated but the mobility of the species resulted in no significant reduction in oviposition in the area (Sohi et al., 1998, Chamberlain et al., 2000, Sundaramurthy, 2003).

Attacticides were developed using a combination of pheromone and cypermethrin and demonstrated successfully for the control of *P. gossypiella* (Patil et al., 2003) and *S. littoralis* (Downham et al., 1991). The boll weevil *A. grandis* was successfully controlled in Paraguay, Columbia, Ceara in North-east Brazil, Argentine and the state of Mato Grosso in Brazil and other regions in South America using pheromone in an attracticide mode, originally developed by USDA and licensed to a private company (Plato et al., 2000).

17.4.2 Microbial Control

The use of biological pesticides such as entomopathogenic nematodes, nuclear polyhedrosis virus (NPV), *Bacillus thuringiensis* (Bt), *Verticillium lecani, Metarhizium anisopliae*, and *Beauvaria bassiana* in cotton IPM has been restricted by their relatively short field life. Although several microbial pesticides have been commercialised, they constitute less than 1% of the world pesticide market (Powell and Rhodes, 1994). Apart from the short field life, there have been problems in efficient production of good quality products. The production and market costs are high for both NPV and Bt. Of the biopesticide market, perhaps 10% is for microbials derived from the family Baculoviridae, the nuclear polyhedrosis viruses (NPVs) and the granulosus viruses (GVs). Commercial baculovirus strains have been developed against *Spodoptera exigua*, (W Europe, C America, SE Asia), *S. littoralis* (Africa), *S. litura* F. (China), *S. frugiperda* (S America), *Helicoverpa armigera* (CIS countries, China, SE Asia, Australasia), *Heliothis* sp (N America) and *Trichoplusia ni* (Central America) (Entwhistle, 1998). *Spodoptera exigua* NPV was successful in Thailand, while *H. Armigera* NPV was recommended in IPM programs in Thailand at 1.3 to 2×10^{12} OB/ha (Ketunuti and Prathomrut, 1989) and in Indonesia (Ruchijat and Sukmaraganda, 1992). *S. littoralis* NPV at 1×10^{12} OB/ha was successful in Egypt (Jones, 1994) and was commercialised there by Calliope SA. *Spodoptera litura* control, has been successfully achieved with NPV in India (Jayraj et al., 1981) but its use has not spread significantly. When exposed in the open to direct solar radiation, half lives of the NPVs of *Heliothis* spp. and *Spodoptera littoralis* (Boisduval) were less than one day or even only a few hours (in the USA) and less than one hour (in Egypt), respectively (Ignoffo and Couch, 1981; Jones, 1988). The average half-life of *Heliothis zea* (Boddie) NPV on the upper surface of *Gossypium hirsutum* was 13 hours and three quarter-life was 41 hours (Entwistle and Evans, 1985). Inactivation of the NPV also takes place on the alkaline leaf surface of cotton (Jones, 1988) resulting in reduced efficacy. Yearian and Phillips (1983) reviewed the field efficacy of sprayed *B.t.* and the *Heliothis* Baculovirus in Arkansas for several years and concluded that neither microbial product provided adequate control of *Heliothis* spp. in cotton. The control of *Helicoverpa* with NPV in India was reported to be inconsistent (Jayraj et al., 1981).

Sprayed *Bacillus thuringiensis* Berliner (commercial strain B.t. var. Kurstaki-HD-1) has been an important component of IPM programs the world over for the past 20 years. However, its field performance in cotton on *Heliothis* spp. has been far from satisfactory right from its introduction. Repeated field trials in the Delta and RioGrande Valley of Texas in the 1970s showed that *B.t.* failed to provide satisfactory commercial control (Allen, 1983) as *Heliothis* spp. feed only sparingly on the foliage and moved rapidly on to squares and bolls where they feed internally thus escaping the toxins. The use of fungus for *Helicoverpa* control is yet to be demonstrated convincingly in any part of the world and is perceived to be extremely dependent on the narrow requirement of relative humidity and weather conditions at the time of use.

Microbial control is slow in action and allows the larval damage to continue for the full period of infectivity with the exception of *Bacillus thuringiensis*, which is comparatively faster. Farmers find it unrealistic to tolerate the continuous damage to squares, which results in shedding and reduction in yields. Due to the unreliable performance, the commercial products have not been popular with the cotton farmer and do not even command 1% of the total market. The technology is, however, valuable and needs to be fine-tuned to the point at which mass production costs are low and efficacy is rapid and reliable before being popularised.

17.4.3 Inundative Releases of Parasites and Predators

Augmentative and inundative control by release of a limited range of biological agents has been attempted in many countries. A number of countries have attempted augmentative biological releases for bollworm control mostly with *Trichogramma*, with variable success. The species depends on the region of the world e.g. *T. pretiousum* Riley in the New World, *T. pintoi* Voegele in Uzbekistan, *T. chilonis* Ishii in India. Reports of satisfactory control using *Trichogramma* have been primarily from the former USSR, China and Mexico although it is not clear on which crops were these used. In 1992 in Uzbekistan, 4,000 Kg of *Trichogramma pintoi* Voegele and smaller quantities of *Bracon hebator* Say were applied to cotton fields for control of *H. armigera*, contributing to the decline in the insecticide use from 60,000 tonnes in 1975 to 2,000 tonnes in 1992 (Matthews, 1993). A total of 8 million hectares were reported to have been covered by *Trichogramma* releases in USSR and 20 million hectares in China (King et al., 1985). *Chrysopa/Chrysoperla* lacewings, especially *C. carnea* (Stephens) and *Chrysoperla externa* (Hagen) but also *Chrysoperla chaquensis* (Navas) in Argentine (Polak et al., 2000), and parasitoids, such as *Bracon hebetor* Say, have been mass-reared for release in some areas, notably China and Uzbekistan. In the USA, a number of on-station trials have been conducted but the technology was not adopted in IPM programs in Texas and Arkansas (Cate, 1985) as it was not cost effective. In India trials on research stations were reported promising (Dhandapani et al., 1992) but records of field successes are rare. Inadequate control with *Trichogramma* was reported from Queensland in Australia (Twine and Loyd, 1984) and hence its use was not encouraged in cotton IPM programs. The reasons for the popularity of *Trichogramma* in the USSR and a few other countries is presumed to be due to the lower production cost (or indeed non-calculated costs in the command economies) in these countries as well as other factors such as lower pest densities and clear spring emergence of the caterpillar pests where winters are severe, as in Uzbekistan (King et al., 1985). Some of the major reasons for the low control efficacy in situations where the benefical insects are mass produced away from the fields, appear to be the generally poor searching ability of the wasps, negligible recovery, and weak adaptability to temperature. Control is grossly inadequate when oviposition by *Helicoverpa* is high and continuous throughout the reproductive phase of the crop, which is usually the case in cotton growing areas of India. Inundative releases of *Trichogramma* at economically acceptable levels are not able to sufficiently reduce pest pressure where such persistent egg loads are delivered by moths each night throughout the season especially as efficacy is highly dependent on the time of release and prevailing weather conditions. Where detailed examinations have been done of the actual mortality of pests resulting from *Trichogramma* releases, the results have generally been disappointing, to the extent that even major programs like that in the southern USA have been abandoned (King et al., 1985). Jones et al. (2000) found searching ability and heat tolerance to be major problems with factory reared *T. pintoi* in Uzbekistan and similar problems are evident in India. Rameis and Shanower (1996) reviewed the status on the considerable body of work on parasites and predators of *H. armigera* in India and concluded that the impact of classical or augmentative releases on pest numbers was very modest.

17.4.4 Botanical Biopesticides

As many as 2,121 plant species have been reported to possess pest control properties. Of these, 1,005 plants are bio-insecticides and 384 have antifeedant properties (Puri, 1998). India has an estimated 18 million neem trees with a potential of production of 0.7 million tonnes of fruit (Narwal et al., 1997). With good research and high production standards and careful planning these can help in an ecologically sound pest management. Most of the commercial neem formulations have a strength of 0.03–0.3% of Azadirachtin. Used at the recommended rates these were found to be significantly inferior in efficacy when compared to 5% neem seed kernel suspensions. Field trials with neem formulations in cotton have not shown satisfactory control, and it has been seen that for a reasonable field efficacy even with seed kernel extracts, it is necessary to use repeated applications due to the low toxicity and rapid biodegradability of neem. Botanicals in general are rapidly inactivated by UV light, temperature, leaf surface pH conditions and have a delayed action and hence are not favoured by farmers. Research gaps in areas such as efficacy, shelf life, field stability and formulation, still persist and need to be addressed before the full potential of botanicals is realised for effective pest management.

17.4.5 Host Plant Resistance

Host plant resistance strengthens IPM in a sustainable manner. Several efforts have been made to identify pest resistant genotypes that could be used in plant breeding programs to develop multi-adversity resistant cultivars. Both morphological and biochemical mechanisms in *Gossypium* spp. have been found to mediate resistance against jassids, whiteflies and the bollworm. Pubescent genes H1 and H2 were used to provide jassid resistance to cultivars in India. However extreme pubescence has been reported to have an adverse effect on agronomic traits (Uthamasamy, 1995). Biochemical features such as high levels of gossypol, phenol, tannin and heliocides in squares and bolls have been found to impact host plant resistance to bollworm significantly. While these features have been commercially exploited to a certain extent in the genotypes of the US (Jenkins, 1995), its utilization in the Indian context has been limited.

Whitefly resistant varieties Kanchana, LK 861 and Supriya and the jassid resistant varieties, DHY286, Mahalakshmi, MCU15, Krishna, Sujatha were developed in India. Composite crossing F_1s and subsequent inter-mating of selected plants was utilized for developing Abhaditha – a bollworm resistant variety (Kadapa, 1990). Sahana, a bollworm tolerant cultivar, is a cross between JK 97 and JK 44 and was released in 2001 from Dharwad in India. In the US, multiple disease resistance and multi-adversity resistance approaches have been adopted in the recent years. Tamcot CAMD-E was the first upland cultivar with significant resistance to six plant pathogens and four insect pests. The MAR 7 and MAR 8 germplasm have the highest levels of resistance to insect pests (aphids, thrips, flea hopper, boll weevil, tobacco bud worm, bollworm and whitefly) (El-Zik and Thaxton, 2001). In Pakistan, the main focus has been on developing early maturing insect resistant cultivars for pest resistance. CRIS 342 and CRIS 355, which are of short duration of 110 and 120 days respectively, escape late season whitefly and bollworm attack. CRIS 7A is resistant to jassids. CRIS 310 is an early maturing cultivar tolerant to pink bollworm, and whitefly and is also resistant to boll rot (Soomoro, 1998). Insect pest resistant varieties can offer significant advantage in pest management programs by reducing the need for pesticide applications but this has not been widely and effectively taken into account in cultivar breeding programs in India.

17.4.6 Other Strategies

Cropping systems that encourage sustenance, survival and multiplication of beneficial arthropods into cotton fields have been integrated into IPM programs in many countries. Intercropping with sorghum was found to enhance spider and predatory ant populations in South Africa (Mamogobo et al., 2003). Alfalfa (*Medicago sativa L.*) was reported to act as a good nursery crop for ladybirds (*Coccinella septempunctata, Propylea quatrodecimpunctata (L)* and *Hyppodama variagata* (Goeze)), chrysopids and other beneficials (Lin et al., 2003). Strategies such as intercropping with blackgram or soybean, or cowpea as bund crops have been demonstrated to be useful in supporting natural enemy populations (Rao et al., 1994) and are encouraged wherever farmers find them practical. Several other ideas such as erecting bird perches or use of light traps are not supported by convincing data and it is not clear so far if any studies have been conducted to clarify the selectivity these mortality factors on the natural enemies as opposed to the insect pests. Birds are effective predators of insects which occur on foliage such as most beneficial insects and spiders, while many major insect pests of cotton are either internal plant tissue feeders or feed on the undersides of leaves.

Many other general strategies such as the destruction of crop residues to prevent carry over of pest populations (esp. of pink bollworm and *Dysdercus* species) and summer ploughing to destroy resting stage insect populations (esp. bollworms) are recommended in many countries to minimise pest attacks and carry-over of pest populations between seasons.

17.4.7 Economic Threshold Levels

IPM interventions are optimized only when the need for the intervention is justified based on the economic threshold levels (ETL) of the pest. ETLs depend on pest numbers of a particular stage in either a unit area or on a specified number of plants or plant parts. Identifying these threshold levels requires a background understanding of the relationships between the pests, their natural enemies and the crop damage which may result from particular pest populations at particular stages of crop growth. These then need to be translated into a practicable scouting system for identifying when these pest pressures are exceeded. This is a difficult requirement to place on frequently illiterate farmers. Pegboards, using match sticks to track the numbers of key pests in a limited number of scouted plants (often c.25 to the acre) were originally developed in Zimabwe in the 1960s (Matthews and Tunstall, 1968). These are currently in use in Zambia, South Africa and Uganda (Sekamatte et al., 2003). However, counting insects relative ETLs remains a problem, particularly in small-scale farming systems. Several studies have been conducted on sampling methods to define the optimum number of plants required to unambiguously determine ETLs for *H. armigera* (Silvie et al., 2000, Traore et al., 2000, Goze et al., 2000). Sampling methods for aphids were worked out by many research groups (Mazza et al., 2000, Sekamatte et al., 2003, Goze and Deguine, 2000) with a consensus for ETLs based on damage to the top 4–6 leaves, rather than aphid numbers, which did not actually correlate with the level of damage. Similarly, lygus bug sampling was found to be more reliable when damaged plants/25 plants were considered rather than counting the number of bugs per plant (Sekamatte et al., 2003). Generally sampling is carried out in a criss-cross diagonal, or zig-zag manner to ensure a fair representation of the plants sampled from a plot. The IPM programs in India recommend interventions at ETLs based on damage symptoms of grades 1–4 for sucking pests and 50–100% affected plants (plants with any flared-up squares or damaged bolls) for bollworms, with the higher threshold applying later in the season.

17.5 Insecticide Resistance and its Management

Cotton insect pests, exposed to repeated application of toxic insecticides of a number of types over many years, have been amongst the most important pests to develop resistance, which has reduced the efficacy of the sprayed insecticides. Although *H. armigera* resistance to insecticides has been a significant concern for well over two decades since 1985, insecticide resistance in sucking pests of cotton has also been found to threaten sustainable pest management.

17.5.1 Insecticide Resistance in Sucking Pests

Resistance to organophosphates in aphids, *Aphis gossypii*, was first reported by Kung et al. (1961). Aphids have ben reported to be resistant to endosulfan, cypermethrin, deltamethrin and fenvalerate (Villatte et al., 1999, Wei et al., 1988, Zhang et al., 1997, Ahmad et al., 1999, Herron et al., 2001, Delorme et al., 1997), monocrotophos and dimethoate (Deguine, 1996, Nibouche et al., 2002), and carbamates (Furk et al., 1980, Bobert et al., 1994). Leaf hoppers, *Empoasca devastans* are reported to have developed resistance to endosulfan, monocrotophos, cypermethrin, phosphamidon, dimethoate, methyl demeton and acephate (Santhini and Uthamasamy, 1997, Challam and Subbaratnam, 1999 and Jeyapradeepa, 2000). By 1985, aphids in China had evolved resistance of 126 fold for deltamethrin and 412 fold for Fenvalerate (Wei et al., 1988). High levels of resistance were detected in cotton aphids from Xinjang (766 fold) and Shandong (1,835 fold) during 1995–1996 (Cheng et al., 1997). The aphid population of western Australia displayed extreme resistance leading to control failure with a serious impact on cotton industries reported by Herron et al. (2001). A resistance factor of 1,350 was observed (Delorme et al., 1997) for primicarb in *A. gossypii* populations in southern France. In laboratory toxicity studies, aphids revealed resistance to monocrotophos and dimethoate in Cameroon since 1993, according to Deguine (1996). The resistance ratio in thirteen population of aphids from Hawaii ranged from 96 to 2,116 as reported by Bobert et al. (1994). Dittrich and Ernast (1983) showed that Sudanese field strains of *B. tabaci* were highly resistant to dimethoate and monocrotophos. Cahill et al. (1996) reported resistance to monocrotophos and other organophosphate insecticides in *B. tabaci* strains from USA, central America, Europe, Pakistan, Sudan and Israel. Resistance to promising insecticides introduced for control of *B.tabaci* such as buprofezin and imidacloprid has already been detected in localized areas (Cahill et al., 1996). However, high resistance levels to monocrotophos during 1992–1996 were lowered considerably by 2000 when the use of the product for whitefly control in Pakistan was reduced (Ahmad et al., 2002). The cotton leafhopper *Amrasca devastans* was found to have developed resistance to the recommended organophosphate insecticides, metasystox, diamethoate and phosphamidon in India (Santhini and Uthamasamy, 1997, Challam and Subbaratnam, 1999, Challam et al., 2001, Praveen, 2003). The whitefly *Bemisia tabaci* was found resistant to BHC, endosulfan, diamethoate, phosalone, acephate, monocrotophos, quinalphos and carbaryl (Prasad et al., 1993). Field strains of *B. tabaci* collected from 22 cotton growing district across India exhibited high level of resistance to methomyl and monocrotophos and moderate resistance to cypermethrin (Kranthi et al., 2002a).

17.5.2 Insecticide Resistance in Lepidoptera

Helicoverpa armigera is the major old world lepidopterous pest of cotton and the one in which insecticide resistance has been most problematic. A global history of insecticide resistance in *H. armigera* is given in Kranthi et al. (2005). The first reports of resistance to pyrethroids in *H. armigera* in India were in the late 1980s (McCaffery et al., 1989), only 6–7 years after their initial introduction. China, India and Pakistan have been monitoring resistance of *H. armigera* to the common insecticides since the late 1980s (Armes et al. (1996) for India, Shen and Wu (1995) and Tan (1999) for China and Ahmad et al. (1999) for Pakistan) using discriminating dose assays for the chemicals common in their regions. Cypermethrin was used as an example pyrethroid; quinalphos (phoxim in China) as an example organophosphate; endosulfan as the only widely used cyclodiene and methomyl as an example carbamate. India has the most comprehensive set of data, collected from at least four sites (and often more) across the country since 1992. India and China have used topical assays on 3rd instar larvae while Pakistan has used the leaf dip method (IRAC Method No 7). The data is voluminous. Results naturally vary with the area of the country and the history of insecticide use in each area. The International Cotton Advisory Committee held a Regional Consultation on Insecticide Resistance Management in Cotton, in Multan, Pakistan in 1999 (ICAC-CCRI, 1999). Resistance survey results since then have largely re-enforced the earlier findings with only relatively minor changes. Details for Pakistan are in Arif et al. (2004); for India in Kranthi et al. (2002a, b and 2005). A regional summary results of the recent work were presented at the 3rd World Cotton Conference (Regupathy et al., 2004).

Until the late 1980s, resistance to organophosphates was almost negligible with the highest resistance factors of 9-fold to quinalphos, and 3-fold to monocrotophos in *H. armigera* in India (McCaffery et al., 1989; Armes et al., 1992). Later, Armes et al. (1996) reported the absence of resistance to monocrotophos, but observed resistance levels of up to 59-fold to quinalphos and >30-fold to methomyl in *H. armigera* field strains in India. Kranthi et al. (2001a) reported high levels of *H. armigera* resistance to Monocrotophos (65-fold); Chlorpyrifos (82-fold); Quinalphos (15-fold) and Methomyl (22-fold). In China, *H. armigera* strains which were susceptible to monocrotophos until 1993 (Wu et al., 1995) exhibited higher levels of resistance in 1995 (Wu et al., 1996). High levels of >300-fold resistance to methomyl and >200-fold to monocrotophos were reported from China (Cheng and Lieu, 1996, Ren et al., 2002) and 720-fold resistance to monocrotophos in Pakistan (Ahmad et al., 1995). Resistance levels to endosulfan have generally varied at moderate levels of 4 to 37-fold in India (Armes et al., 1996, McCaffery et al., 1989, Kranthi et al., 2001a).

H. armigera resistance to cypermethrin was first reported in Thailand (McCaffery et al., 1988). Subsequent reports include, resistance levels of 25–205-fold to five pyrethroids in Pakistan (Ahmad et al., 1997), 17-fold to cypermethrin in Turkey (Ernst and Dittrich, 1992), 1,361-fold to fenvalerate and an amazing 56,911-fold to deltamethrin in China (Shen et al., 1993, Cheng and Lieu, 1996), 6-fold to fenvalerate in Australia (Gunning, 1993) and 189-fold to deltamethrin in South Africa (Martin et al., 2003). In India, reports (Dhingra et al., 1988; McCaffery et al., 1989) on *H. armigera* development of resistance to pyrethroids, attributed field control failures to resistance. Subsequently, high levels of pyrethroid resistance were reported in several cotton and pulse growing regions of the country (Mehrotra and Phokela, 1992; Armes et al., 1992, 1996; Sekhar et al., 1996). Based on a survey conducted during 1991–95, it was concluded that resistance to pyrethroids was ubiquitous across the Indian sub-continent (Armes et al., 1996). A follow up survey (Kranthi et al., 2001a,b, 2002a,b) showed that insect resistance to insecticides was indeed a critical problem in several parts of the country. A very brief summary of the regional resistance to the commonly used chemicals is shown in Table 17.2.

In summary we could say that the synthetic pyrethroids are highly resisted, and that cypermethrin and fenvalerate in particular have lost most of their usefulness (with resistance frequencies (RFs) frequently in the hundreds and often in the thousands). Resistance to organophosphates and carbamates have remained moderate (RF <30 generally), with endosulfan resistance generally low to moderate, especially early in the cotton season. Full or almost full susceptibility is limited to the newer and less used materials (often more expensive). There is no reason to think that they will not be resisted in their turn as they are more widely used. These levels of resistance are maintained by selection with the insecticides. Where, as in Pakistan, certain insecticides have been strongly discouraged for use on cotton, resistance to these materials has fallen quickly.

Table 17.2 Typical resistance levels to widely used chemicals in various *H. armigera* populations in India (I), China (C), and Pakistan (P) (from Russell and Kranthi, 2005)

Chemical	Resistance level*				
	Susceptible	Low	Medium	High	Very high
Pyrethroids					
Cypermethrin					I, C, P
Fenvalerate				I	I, C, P
Deltamethrin			P	I	I
Lambda cyhalothrin			P	I	I,P
Bifenthrin			P	P	
Beta Cyfluthrin				I	
Organophosphates					
Quinalphos			I		
Phoxim		P, C	C		
Chlorpyrifos		P	I		
Profenophos		I, P			
Monocrotophos		P	I		
Cyclodiene					
Endosulfan		P	I		
Carbamate					
Methomyl	C	I,P			
Thiodicarb	P		I		
Organotin					
Indoxacarb	P				
Fungally derived					
Spinosad	I, C, P				

* *Susceptible* – RF<3; *Low* – no field effects; *Medium* – some reduction of field efficiency but chemical still useful; *High* – chemical compromised for field use; *Very High* – high larval survival at the field rate, chemical not useful.

The major types of resistance likely to be important in *H. armigera* were known from earlier work with this species (McCaffery, 1999) and other insects. As in other insects, metabolic mechanisms of detoxification of insecticides before they reach their target sites in the insect are very important. Esterases, mixed function oxidases and glutathion-S-transferases were known to be implicated. In many insects, the target site for the insecticide within the insect has also mutated in such a way as to reduce the binding affinity of the chemical. It was also known that evolved alteration to the cuticle of the insect could prevent or slow the passage of insecticide, allowing the pest more time to detoxify any product with did penetrate. However, the importance and ubiquity of the various mechanisms in different populations within Asia was not known. It was expected that the patterns would reflect the historical use of various materials in different orders in different areas, which would have been selecting for different mechanisms. Intensive work in India, China, Pakistan and the UK from 1993 to 2005 clarified the situation. In India the situation for pyrethroids is given in Kranthi et al. (2001a) and for organophosphates and carbamates in Kranthi et al. (2001b). Recent results on enzymatic detoxification of pyrethroids are reported in Yang et al. (2004, 2005) and Chen et al. (2005). Table 17.3 summarises what is now known of the distribution and importance of the three major types of mechanisms of insecticide resistance in *H. armigera* in Asia.

It is now clear that amongst metabolic resistance mechanisms, GSTs play only a minor role (RF<10). Oxidases are very important in pyrethroid resistance. Esterases are less important in pyrethroid resistance but are involved with OP/carbamate/endosulfan resistance). The rdl '(dieldrin resistance) 'mutation' is ubiquitous in *H. armigera*, but although it is likely to confer background tolerance to endosulfan it doesn't currently appear to account for variation in endosulfan resistance between field populations. Insensitive forms of acetylcholine esterase (at various levels in different populations) also appear ubiquitous in field populations, conferring basal resistance to OPs and carbamates but perhaps is not the primary cause of variations in response between strains. Evidence for knockdown resistance to pyrethroids (kdr) is strong in heavily sprayed populations in India although it does not seem to be attributable to any of the known mutations. Penetration reduction is present in China and Pakistan and probably India. It may well have a multiplicative effect on the impact of metabolic mechanisms.

Table 17.3 Distribution and relative importance of resistance mechanisms in Asian *H.*armigera (from Russell and Kranthi, 2005)

Mechanisms	Metabolic			Target Site			Penetration Reduction
	Oxidases	Esterases	GSTs	Ache	Nerve Insens	rdl	
Chemicals Affected	Pyreth.	OP/Carb Endo/Pyreth	Pyr	OP/Carb	Pyreth	Endo	Pyrethroid (others?)
India	* **	**	*	*	**	*	**?**
China	* * *	**	*	*	*	*	*
Pakistan	**	**	*	*	*	*	*

In general, reports of *P. gossypiella* resistance to insecticides have been rare. For example, Tang et al. (1988) could not find any evidence of insecticide resistance in *P. gossypiella* in China. However, resistance to azinphosmethyl and permethrin was reported from strains collected in Arizona and California (Osman et al., 1991). Resistance in *E. vittella* was > 70-fold to monocrotophos in Sriganganagar and Sirsa strains of north India (Kranthi et al., 2002a). Resistance in *Spodoptera litura* to endosulfan, carbaryl and malathion was reported in field strains from Haryana (Verma et al., 1971), West Bengal (Mukherjee and Shrivastava, 1970) and Andhra Pradesh (Ramakrishnan et al., 1984). Armes et al. (1996) reported resistance levels of up to 13-fold to quinalphos, 362-fold to monocrotophos and 19-fold to methomyl, in Indian strains of *S. litura*.

17.5.3 Resistance Management

Globally, all insecticide resistance management (IRM) strategies have been designed with emphasis on efficient use of insecticides to conserve the ecosystem for better pest management. In essence, all IRM strategies aim at optimising the use of insecticides in a manner that maximizes their efficacy, minimizes intensity of selection pressure, and mitigates the adverse effect on ecosystems and the environment. The tactics of enhancing efficacy include transient measures such as either the use of synergists or mixtures; or use of the least resisted conventional insecticides or new chemistries; or targeting vulnerable stages of the pest. Strategies to minimize selection pressure include either rotation of insecticide groups over space and or time, or use of alternative options such as bio-pesticides or ecosystem management or biological control or reduce application frequency. Currently, many countries have devised IRM strategies that combine the best of pragmatic resistant management theories amalgamated with conventional IPM tactics to forge sustainable methods of pest management (Russell, 2004).

IRM research and programs in India were strongly supported by the Indian Council of Agricultural Research, Dept. for International Development, UK, the Common Fund for Commodities, Netherlands and the International Cotton Advisory Committee, Washington. The Ministry of Agriculture, Government of India has been the major supporter of the field program. The IRM strategies have now been implemented through area-wide farmer participatory programs for a decade from 1996 to 2007 and so provide an instructive example. The Indian IPM/IRM strategies are designed to reduce the dependence on insecticides and are based on the use of a rational and sensible sequence of insecticides that are effective on the target species, cause the least disturbance to beneficial fauna and minimize selection pressure. The strategies include, cultivation of sucking pest tolerant genotypes and chemical seed treatment to help in delaying the first spray, thereby conserving the initial build-up of natural enemies (Kairon and Kranthi, 1998). After the introduction of Bt cotton, the strategies were revised to further minimise insecticide spray applications so as to move towards eco-friendly systems of pest management. Avoidance of organophosphates (especially, monocrotophos, methyl demeton, phosphomidan, and acephate) as sprays is important and *Trichogramma* releases can be helpful. Since chloronicotinyl insecticides are used as seed treatments, any further use either as sprays or through stem application is discouraged, to minimize selection pressure. Sucking pest control is carried out either with neem oil sprays, soil application of acephate or with dimethoate as a stem application to control aphids, jassids, thrips, mirid bugs and mealy bugs. Initial infestation of whiteflies, *Spodoptera* and *H. armigera* at 60–90 days after sowing (DAS), are managed with either neem oil + neem seed extracts, NPV or endosulfan. For bollworm control, with what is now known of cross resistances, it has been possible to suggest which materials can be used with confidence next to each other in chemical use rotations in Asia. Given that the inheritance patterns and effective dominance of these mechanisms have been worked out (especially for India (Russell and Kranthi, 2005)), these sequences may now be proposed with some confidence (Table 17.4). The number of different resistance groups is smaller than might have been hoped, limiting the scope for rotations.

Table 17.4 Insecticides which can be rotated in an IRM strategy for *H. armigera* control in India (from Russell and Kranthi, 2006)

	Major mechanisms of resistance	Minor mechanisms of resistance	Potential Rotation groups
Pyrethroids	Oxidase	Esterase Nerve insensitivity Penetration	• Most pyrethroids • Bifenthrin and similar structures
Organo-phosphates	Insensitive Ache	Esterase	• Phosphatic–(monocrotophos) • Phosphothioronate (quinalphos, phoxim and most others)
Carbamates	Esterase	Insensitive Ache	• Methomyl/carbaryl • Thiodicarb
Endosulfan	Esterase (sequestration)	Rdl	• Endosulfan

17.5.4 Indian IRM Field Program

As described above, it was clear from the early 1990s that there was significant resistance by cotton bollworm to all the major classes of insecticide in use at the time (Armes et al. (1995, 1996), Kranthi et al. (2001a,b, 2002a,b)). Between 1993 and 1996, experiments on an increasing scale had shown that insecticide use on cotton was not well targeted, either in time of application or in the materials used. Small scale trials showed that insecticide use could be cut dramatically and less toxic materials used while enhancing yields by using appropriate rotations. Rational insecticide use on over-threshold pests and active ingredient rotations were integrated into an IPM strategy which was then implemented on a village level. By

1999 the program had demonstrated strong insecticide use reductions and yield and profit increases with 10–150 farmers in villages in the states of Tamil Nadu and Andhra Pradesh in the south, Maharashtra in central India and Punjab in the north (Russell et al., 2000a,b, Kranthi et al., 2000). The number of insecticide applications fell by 44–95% except in the Punjab where bollworm numbers were very high, and above scouting thresholds for much of the season. Nonetheless, because of the rationalization of materials and quantities of insecticide used and the reduction of the use of expensive mixtures, even the Punjab farmers showed strong reduction in the costs of production and a 50% yield increase with significant income increases compared with their neighbours. The work had also shown that this rationalization of spraying had reduced the impact on bollworm parasitoids by 65–82% (depending on the species), on predators by 63–78% and reduced the health implications of spraying for farmers by 76%. This scale of operations – 21 villages and 255 farms in four states, was about as far as research funds could take the demonstration of the benefits of improved insecticide use.

Early in the program it was appreciated that working with single farmers was not going to produce significant impacts, especially as peer pressure in the villages was a major determinant of spraying behavior. The unit of adoption of these practices was the therefore the village. Areas were adopted in response to requests from farming communities in difficulties over pest control (responding to newspaper adverts). This ensured that the issue was important to the community and demonstrated commitment. Initially the village would propose a small number of farmers who agreed to work with the program throughout the season. The profile of the project remained highly visible to all the farmers in the village though regular meetings with research and extension staff throughout the season, including a direct comparison of costs and benefits at the end of the harvest. The constant presence of a junior IPM facilitator in each of these villages helped enormously to build farmer confidence in the program.

This success prompted the Indian Council for Agricultural Research to continue the program in 2000 and 2001 in the four cotton states of Haryana, Maharashtra, Andhra Pradesh and Tamil Nadu. Some 3,000 farmers were enrolled in this program in 2001–2002. The state average insecticide use for participators was reduced by 17–60%, average yields were increased and profitability was increased for participators by over 50% in all states.

A national IRM program in cotton from 2002 to 2007 under the Govt of India's Cotton Technology Mission Program, picked up these relatively modest scale results. The Govt. of India provided roughly $0.4 million in program funds each year to 2005 and $0.8 million from 2006, allowing the system to expand to all 11 major cotton states, and a much larger number of growers. State co-ordinators are responsible for the management of district co-ordinating scientists who each have two junior scientists to run the resistance monitoring laboratory and train and support the team of field workers who provide supporting information and training, but no inputs, to farmers. Currently there are close to 1,000 field workers; usually farmer's sons from the villages, but in some instances final year undergraduate students from the Agricultural Universities undertaking their obligatory farm residence program. The field workers are employed for the four month cotton season and each is responsible for training and working with the farmers in one village.

Each district in which the program is working (currently 28 districts) has a simple resistance monitoring laboratory using topical assays, to which larvae are brought regularly throughout the season. The results are provided to the district and state co-ordinators, providing them with local data on which to base changes in recommendations if these are necessary. The program provides mobility and technical support to the state and district co-ordinators and pays the salaries and operating expenses of the junior scientists and field workers.

The technical program is deliberately kept extremely simple in order to facilitate its understanding by farmers and to make it possible for the information to pass from farmer to farmer without errors and confusion creeping in (Kranthi et al., 2005). Decisions are made entirely on recent visible damage. Villages are visited before cotton planting and the rationale for practices of the program are clarified with farmers. These are repeated in farmer meetings across the season. Farmers are supported in pest and beneficial insect identification and scout their fields weekly. The farmer walks diagonally across the field taking 20 plants per field (<1 acre (0.42 ha)) at random for examination. Intervention thresholds are:

Sucking pests: 10 plants with symptoms of sucking pest damage curling the top leaves

Bollworms: 60–90 days – 50% of plants with one or more flared squares
90–120 days – >90% of plants with one or more flared squares

Simple insecticide use recommendations (Table 17.5) have been used very widely over a number of years with great financial success by over 200,000 farmers now. They use only readily available and moderately inexpensive materials.

Research had shown insecticides in the four groups not to be cross-resistant. Endosulfan was least resisted by *H. armigera* early in the season and relatively less harmful to beneficials than most broad-spectrum cotton insecticides. Spinosad and indoxacarb were highly efficient on pyrethroid-resistant *H. armigera*, the OPs (esp chlorpyrifos) and the carbamates were effective against the full mid-late season complex by which time the natural enemy population has declined, even the absence of insecticide spraying. Pyrethroids are reserved for late season use if required. In practice this is often only for control of pink bollworm (*Pectinophora gossypiella*) against which they remain effective, if indeed they are needed at all.

A fuller (and more complex) series of recommendations is now being promoted in situations where farmer resources and local extension capacity permits it (Box 1).

Table 17.5 Simple IRM Program Recommendations for Central India 2002–2005

Sucking pests	Bollworm window 1	Bollworm window 2	Bollworm window 3	Bollworm window 4
0–60 days* Zero Sprays	60–90 days Endosulfan (Neem/HaNPV)	90–105 days Spinosad/ Indoxacarb	105–120 days Organophosphate/ Carbamate	120–140 days Pyrethroid

* Days after planting.

Note: Windows 2 and 3 are commonly run together, using only OP/carbamates, by the more resource-poor growers.

Box 1 Indian IRM Program Recommendations for 2005–2006 onwards

A. Early sucking pests: NO SPRAY up to 60 DAS

1. Cultivation of sucking pest tolerant genotypes.
2. Insecticide seed treatment if genotype not sucking pest tolerant.
3. Avoidance of broad-spectrum organophosphates.
   Emergency : IT* based spray of diafenthiuron (POLO) against jassids or whitefly or aphids.

B. Window 1: 60–75 DAS: Initial bollworm infestation: Mostly eggs and young larvae: biological and biopesticides window

4. Soft chemistry biopesticides such as *Bacillus thuringiensis* or HaNPV or Neem-based insecticides to help conservation of natural enemies.
5. No spraying against the cotton leaf folder, *Sylepta derogata* and cotton semi-looper, *Anomis flava*. The larvae cause negligible damage to cotton but serve as hosts for parasitoids such as *Trichogramma* spp., *Apanteles* spp and *Sysiropa formosa*, that also parasitise *H. armigera*.
   Aditional practices where possible:

   – Release of Trichogramma egg parasitoids at 70 DAS

   Emergency: IT based spray 50% plants showing flared up squares: Endosulfan may be used if none of the biological control or biopesticides alternatives are available.

C. Window 2: 75–90 DAS: Bollworm infestation: Mostly younger larvae: Bioselective and least resisted insecticides.

6. IT based spray: 50% plants showing flared up squares: Use of Novaluron (Rimon) or Lufenuron (Match) or Endosulfan (Spinosad in north India).

D. Window 3: Mid bollworm: 90–110 DAS Bio-selective and least resisted insecticides.

7. IT based spray: 90–100% plants showing flared up squares: Spinosad and Indoxacarb.

E. Window 4: peak bollworm: 110–140 DAS: Conventional insecticides.

8. IT based spray: 90–100% plants showing flared up squares: Organophosphates or carbamates can be used as effective larvicides.

F. Window 5: Pink bollworm: >140 DAS: Pyrethroids.

9. IT based spray: Eight pink bollworm moths per trap per night for 3 consecutive nights: Pyrethroids.

* IT – Scouting Intervention Threshold exceeded

In 2003–2004, data was collected from 5,372 'core' farmers out of the >18,000 direct participators in 331 villages (there were, in all >50,000 formal and informal participants in the program). All states showed spray use reductions, with an average across the states of 50% (dropping from 10.3 to 5.1 applications), yield increases averaging 24%, and consequently net profit increases averaging $US 107/ha or an increase of 74% when compared with non-participators in nearby villages (Kranthi et al., 2004a,b, Russell, 2004). In 2004–2005 the overall yield increase as a result of the IRM program (data from every field in every district – not an estimate from a sample) was 11%, with a value of $7.37 million ($124/ha) and the insecticide use reduction compared with the same fields in the previous year was 46% (from a mean of 8.93 applications to 4.8 applications) with a saving of $4.08 million ($69/ha). This gave a net benefit from insecticide use reductions and yield increases of $193/ha. The program has continued to expand in scale, with corresponding benefits as shown in Table 17.6.

The cost of delivering the program was $US3.9/ha in 2006–2007. This program has now been running in various forms for 11 years and the Govt of India

Table 17.6 Benefits of the IRM village program in India over the last three seasons

	No of villages	No of farmers	% Reduction in no. of insecticides	Yield increase	Profit increase $US/ha	Total benefit to participating farmers $US million	Benefit to Cost ratio
2004–2005	444	20,525	−46%	11%	$193	$11.5 million	28 : 1
2005–2006	565	46,400	−48%	12%	$183	$24.6 million	32 : 1
2006–2007	1,062	72,783	−52%	10–15%	$174	$33 million	44 : 1

is committed to expanding support until at least 2011. Experience has shown the value of the following key components:

- Good underpinning science, continually updated.
- Extension workers in the villages for the whole season in early years
- No reliance on ‘experts’ for decision making – the farmer must make all decisions
- Very simple practical recommendations at the field level – they must be able to pass from farmer to farmer without significant loss of accuracy
- No recommendation of inputs which are marginal, expensive or difficult to obtain and use
- No provision of free physical inputs to growers
- Creating a positive enabling environment by working with farmers in village groups rather than as individuals

Continuous application of the evolving program has been going on for longest in the Wardha district of Maharashtra, where a cluster of villages has been part of the program since 1997. Resistance values for the major insecticide groups are given below in Table 17.7 and has declined to effective susceptability in all cases.

On a larger scale, the insecticide resistance monitoring results from the 26 laboratories of the IRM network and on populations monitored from CICR Nagpur, are showing significant shifts in resistance nationally which parallel a decline in the use of multiple, sequential applications of pyrethroids, partly due to their declining efficacy, but also in response to a growing national awareness of the phenomena of insecticide resistance and the practices which minimise its impact.

Table 17.7 *H. armigera* resistance frequencies 1999–2004 in the IRM district of Wardha, Maharashtra, India (figures are resistance ratios)

	1997 Status	1997 RR	1998 RR	1999 RR	2000 RR	2001 RR	2002 RR	2003 RR	2004 RR
Pyrethroid *(Cypermethrin)*	Medium	96	7	10	6	7	9	3	5
Cyclodiene (*Endosulfan)*	Medium	29	35	7	5	3	2	1	1
OP: *(Qunialphos)*	Low	2	3	1	1	1	1	1	1
Carbamate *(Methomyl)*	None	1	1	1	1	1	1	1	1

RR – multiple of dose killing 50% of a susceptible population which is required to kill 50% of the current population.

17.6 Implementation of IPM

IPM programs vary greatly across the world depending on the land holdings, farming systems and extension institutions. While in the developed countries, private consultants play a major role, in less developed and developing countries where the farming units average one hectare or less, IPM is promoted by Government institutions, cooperative companies, ginneries, pesticide dealers, universities and agricultural organizations. The World Bank (1990) defined IPM as *'Putting in place by the farmer of the most effective mixture of tactics, allowing control of pests while keeping in mind the productivity of the fields, the role of beneficial organisms and safety considerations'*. The Inter-Agency Task Force of FAO, World Bank, UNDP and UNEP reviewed the constraints to IPM implementation (NRI, 1992). The Task Force initiated the formation of the Global IPM facility in 1994. This was a major step forward in establishing IPM as the preferred route to pest management. Important aims were to encourage farmer participation, encourage supportive national policies, finance pilot programs and to support the planning and development of national IPM programs. All these areas have been strongly promoted over more than a decade and, through the generation of a more enabling climate, have arguably had more of an impact on global IPM adoption in cotton than have individual technologies, with the possible exception of the spread of transgenic Bt cotton since 1996. It is anticipated that over the next few years, new technologies such as Bt-cotton and modern chemistries such as insect growth regulators, avermectins such as abamectin and emamectin, spinosad, indoxacarb, chlorfenapyr etc. if used properly may assist in the decline in resistance to the conventional insecticides, thereby enhancing the spectrum of available pesticides, so as to facilitate efficient and economical IRM-compatible pest management strategies. However, the overuse of these technologies may again lead to insect resistance, thereby diminishing their utility. Resistance reduces the effective window for insecticides to achieve economic control of *Helicoverpa armigera*, hence, the choice of effective insecticide is imperative if pest control has to be efficient. Keeping in view the existing information on cotton pest management, window strategies as described above in detail for India have been developed for cotton pest management, usually with specific emphasis on the management of insecticide resistance in bollworms. These IPM/IRM strategies aim to at least slow down the resistance treadmill, thereby extending the usefulness of available chemicals (Sawicki and Denholm, 1987).

17.6.1 IPM/IRM in the USA and Australia

In the developed countries such as the USA and Australia, where the average land holding per farmer is more than 800 ha, private consultants provide pest management expertise. The IPM strategies are devised by technical experts from scientific organizations and are implemented by the private consultants. In South America, large cotton companies oversee the cotton pest management programs. The first successful example of formulating and implimenting IRM guidelines, came from Australia in 1983. The strategies were carefully incorporated into IPM methods so as to ensure that unnecessary selection pressure by chemical groups was avoided. The strategies have been refined continuously each year with scientific expertise from the CSIRO and other institutions. The recent recommendations incorporate soft chemistries to minimize adverse effects on beneficial fauna and set up a three window rotational approach for insecticide use on *H. armigera*. Soft chemistries such as endosulfan, methoxyfenozide, Bt, NPV and amitraz are permissible through the first two windows, with Bt, NPV and amitraz extending until the end of third window. Spinosad is used from 10th December onwards and avermectins, emamectin and abamectin are used from 15th November until the end of the 2nd window. Indoxacarb is permissible from 20th December until the end of February (mid point of 3rd window). Other insecticides such as chlofenapyr, pyrethroids (with or without PBO), organophosphates (chlorpyriphos and profenophos) extend through the 2nd and 3rd windows. Carbamates (thiodicarb and methomyl) are used exclusively in the 3rd Window.

17.6.2 IPM/IRM in Africa

IPM strategies have been refined in African countries, to ensure that IRM principles were incorporated (Ochou and Martin, 2003). In West Africa, Government or semi-government cotton companies provide technical expertise, arrange for reliable inputs such as seeds, pesticides, fertilizers etc., and supply them to cultivators depending on the need. In east and central African countries such as Zambia and Uganda, ginneries and Government cotton companies have recently emerged as the main source of expert technical advise and input provision to farmers co-operative organisations (Burgess, 2001, Jarvis, 2001). In the African countries, there is a move towards 'liberalisation' of the production channels under pressure from the IMF/World Bank structural Adjustment Programs, as a result of which West Africa for example, is moving towards multiple private company (or grower co-operative) cotton companies. Staff of the Ministry of Agriculture manages IPM in Egypt. Single varieties are grown in particular governorates and 'engineers' of the Ministry of Agriculture supervise pest management programs. Thus the extension systems organize area-wide IPM implementation to ensure long-term impact. West Africa appeared to avoid pyrethroid resistance for many years, perhaps because the pyrethroid/organophosphate mixtures used prevented the selection of esterase-based metabolic detoxification resistance through the impact on esterases of the OP component of the mixtures (Martin et al., 2002). Problems were first identified in 1996 (Vassal et al., 1997) with a 20–100 fold resistance identified across the region by 1998. The West African pyrethroid resistance action network (PR-PRAO) quickly suggested the replacement of the first two calendar sprays of the OP/pyrethroid mixtures by endosulfan. This was widely implemented across W.Africa, from the 1998 season in the north of the region and 1999 in the south (Ochou and Martin, 2003). *Helicoverpa armigera* declined rapidly in importance in cotton across the region the following year and remained low thereafter (Ochou and Martin, 2003). *Helicoverpa armigera* is notoriously variable in pest pressure, but this is probably a rare example of successful regional co-operation, combined with the benefits of a bulk pesticide purchase and provision system by a well organised cotton company sector. A three window strategy is now being proposed (Ochou and Martin, 2003) with spinosad for the first two sprays as it has a better profile against *Earias* and phytophagus mites and the beneficial coccinellids. This would be followed by two sprays of the tradition OP/pyrethroid mixtures for control of mites and the endocarpic bollworms.

A final two applications of indoxacarb would be made in the late season when cotton stainers are of greater importance.

17.6.3 IPM/IRM in Asia

IPM programs in India and Pakistan are implemented mainly by the Agricultural extension systems. In India, state agricultural departments were expected to play a major role in popularizing the IPM concepts and implementing them. However, IPM was not adopted on a large scale owing to difficulties in timely availability of biological inputs and their effectiveness in pest control. Small-scale farming systems such as those in Pakistan and India comprise land holdings, which are less than 1–2 hectares per farmer and are not input-intensive. Extension efforts in such countries are immensely challenging. Farmers generally obtain guidance and pest management inputs from an extremely extensive, unlicensed, pesticide dealer network, moderated by technical advice from the Agricultural Universities and the government cotton research institutions. In China, the extension system is active with state extension employees and licensed input dealers delivering technical advice. Resistance Management programs in countries such as China, USA, Israel (Horowitz et al., 2000) and India (Kranthi et al., 2002b) followed the Australian window strategy in principle but modified it to suit their local needs. Invariably, all the australasian strategies restrict the use of pyrethroids to the later part of the cotton season to coincide either with the 2nd or 3rd window. Some countries recommend the use of synergists such as chlordimeform, PBO or organophospates to be used with pyrethroids to enhance its efficacy on resistant larvae. The Indian system is discussed in detail in Section 17.4.

17.6.4 Farmer Field Schools

The Farmer Field School (FFS) approach was originally initiated for rice pest management in Asia and found to be very successful (Pontius et al., 2002). The FFS training is carried out season-long through facilitators who themselves have passed through a more intensive season-long Training of Trainers (TOT) or Training of Facilitators (TOF) course. Farmers are encouraged to take an ecosystem approach to pest management decisions; considering the time of season, presence of beneficials organisms, weather, risk of damage and other factors rather than using rigid numerical intervention thresholds. The concept has been particularly promoted by the Global IPM Facility based at FAO in Rome, which has managed a number of the FFS projects. The earliest such wide-spread program in cotton was the Asia Development Bank-funded program in China, India and Pakistan in cotton in 1994–1996 (organised by the IPM Facility and facilitated by CAB International). In India FFS were run in 5 states. Yield increases were said to range from 21 to 27% and pesticide reduction from 30 to 50% (Dhaliwal et al., 1998). In many areas, however, the simultaneous rice FFS achieved 100% pesticide use reductions, as had been seen in Indonesia. This points to the general experience that there is a requirement for targeted pesticide interventions in cotton IPM. Pilot and full cotton FFS programs have been carried out in several countries such as Vietnam, Zimbabwe, Uganda Mali, Senegal and Burkina Faso, with variable success. Farmer field school programs in cotton with a funding of US $12 million were initiated by the FAO Global IPM Facility, to cover Bangladesh, China, India, Pakistan, the Philippines and Vietnam; countries which together produce over 40% of the world's cotton (Eveleens, 2000). China in particular is continuing to pursue the widespread use of FFS as a major farmer education system. As the scale of operations rises and the number of trainers increases, the average costs of delivering FFS fall dramatically.

17.7 Insect Resistant GM (Genetically Modified) Crops and IPM

17.7.1 Genes for Pest Management

Several genes coding for insecticidal toxins have been isolated and are being used to develop insect resistant transgenic crops. Currently, four GM crops (cotton, maize, potato and tomato) incorporating nine Cry (crystal) toxin genes (*cry1Ab, cry1Ac, cry1F, cry34Ab, cry35Av cry3A, cry3B, cry2Ab, cry9C*) and *vip-3A* gene isolated from *Bacillus thuringiensis* and one protease inhibitor gene are under commercial cultivation in 22 countries. The Bt-cotton technology was first commercialized in 1996 in the USA. It was released in China and Australia in 1997 and became popular. Later it was released in Mexico, Colombia, Indonesia, Argentina, South Africa, and India and is continuing to spread. The Bt-cotton adoption rate has been very high in most countries. An estimated 70–80% of the crop area in Australia, US, Mexico, China and India is currently under Bt cotton and is rapidly increasing in several other countries. Currently more than 14.0 million hectares are under Bt cotton in the world. Recently, Bt-cotton with Cry2Ab and Cry1F have been released in the US for commercial cultivation.

In addition protease inhibitor genes from legumes and also insects themselves, have been used to generate insect pest resistant transgenic cotton. These govern the expression in the plants of proteins that inhibit midgut proteases in lepidopteran larvae. Cotton transgenic plants resistant to *H. armigera* have been developed using the cowpea trypsin inhibitor gene in China. Both groups, the 'Bt toxins' and the 'protease inhibitors' used thus far, are extremely specific in their target range and have been conclusively demonstrated to be safe to the environment. In India, eleven crops (cotton, corn, brinjal, cabbage, cauliflower, ground nut, mustard, okra, pigeonpea, rice and tomato) have been genetically transformed for enhanced resistance to insects and viruses and are in various stages of testing. Seven Cry (crystal) genes (c*ry1Aa, cry1Ab, cry1Ac, cry1F, cry1B,cry1C, cry2Ab*) and the *vip-3A* gene from *Bacillus thuringiensis* were used for insect resistance in nine crops. Over 406 genes of the 179 holotypes that encode the Cry toxins have now been sequenced enabling the toxins to be assigned to more than 50 groups on the basis of sequence similarities. There are several other microbial sources that have been used to isolate insecticidal genes. Genes from *Xenorhabdus* and *Photorhabdus* are being actively considered for the development of transgenic crops. Amongst animal sources, anti-chymotrypsin, anti-elastase, chitinase, cholesterol oxidase and anti-trypsin were isolated from the tobacco hornworm, *Manduca sexta* and used to develop transgenic crops (cotton, tobacco, potato and alfalfa) resistant to sucking pests and lepidopteran insects. Trypsin inhibitors and spleen inhibitors have been isolated from cattle and used to develop insect resistant transgenic petunia, potato, tobacco, white clover and lettuce. Protease inhibitors from plants (soybean, barley, cowpea, squash, mustard, rice, potato, tomato) have been used to develop transgenic crops (oilseed, rape, poplar, potato, tobacco, apple, lettuce, rice, strawberry, sunflower, sweet potato, tomato, Arabidopsis, Petunia, birch, alfalfa, nightshade) resistant to Homoptera, Lepidoptera, Coleoptera and Orthoptera. Similarly amylase inhibitor genes from beans and cereals were used to develop transgenic beans, peas and tomato crops resistant to beetles and caterpillars. Lectins from peas, wheat and rice were used to develop insect resistant grapevine, oilseed rape, potato, rice, sweet potato, sugarcane, sunflower, tobacco, tomato. Other genes include chitinases, peroxidase and tryptophan decarboxylase from various plant sources to develop insect resistant crops such as potato, sweet gum, tobacco, tomato and oilseed rape.

17.7.2 Impact of Bt-Cotton on Pests and Non-Target Beneficial Insects

The Cry1Ac-based Bt-cotton is mainly toxic to the bollworms (cotton bollworm, pink bollworm and spotted bollworm), semiloopers and hairy caterpillars. Bt-cotton expressing Cry1Ac has been reported to be safe to all other non-target organisms such as beneficial insects, birds, fish, animals and human beings. Laboratory and field studies carried out all over the world have shown that the Cry1Ac protein deployed in Bt-cotton did not have any significant direct effect on any of the non-target beneficial insects. Dong et al. (2003) reported only minor effects on some life table parameters in laboratory feeding studies with lacewings and predatory beetles and none with predatory bugs and spiders. There was some evidence of a reduction in numbers of predators and parasitoids which specialise on the Bt-controlled bollworms, but also of increases in numbers and diversity of generalist predators such as spiders. Generally the decreases in the parasitoid and predator populations were associated with decrease in the densities of the pest populations on account of Bt-cotton. Any effects could be assigned to the decrease in prey quality – for example with stunted *Spodoptera litura* caterpillars which had fed on Bt cotton. In the field situation, partial life studies broadly confirmed this finding. There was no increase in green vegetable bug numbers, aphid or whitefly numbers on Bt cotton. In general, such adverse effects as have been measured are very small when compared with the side effects of the spraying of conventional insecticides. However, unsprayed Bt cotton in the Americas has been reported to sustain 4 times more attack from tarnished bugs, 2.4 times more with boll weevil, 2.8 times more with stink bugs and *Spodoptera*. Due to these changes in pest complex, farmers sprayed 3–5 times on Bt-cotton as compared to 6–8 times on non-Bt cottons. In general, a reduction of 40–60% in spraying the total pest complex seems generally to be obtained from Bt cotton, with a much higher percentage for the sprays specifically directed against bollworms.

17.7.3 Efficacy of Bt-Cotton

In India Bt-cotton varieties recorded significantly lesser boll and locule damage compared to non-Bt and check hybrids, indicating higher tolerance to bollworm damage. Bambawale et al. (2003) reported a 50% overall reduction in the *H. armigera* larval population in Bt-cotton compared to the non-Bt cotton. Further, the locule damage caused by pink bollworm was found to be 58% less in Bt-cotton. Udikere et al. (2003) also showed that Bt-cotton hybrids were able to reduce larval populations of *H. armigera* up to 40%, spotted bollworm (*Earias vittella*) up to 30–40% and pink bollworm (*Pectinophora gossypiella*) up to 60–80% in south India. Reports (Qaim and Zilberman, 2003; Barwale et al., 2004; Bennet et al., 2004, Morse et al., 2005) showed that yields increased substantially by adopting Bt-cotton and farmers in India were able to reduce insecticide use by at least 2–3 applications. However, the benefits of Bt-cotton have been higher in countries where bollworm infestation was high; where insecticide use had previously been inefficient or where other strategies were in place to control the rest of the pest complex. Insecticide use on Bt-cotton varieties was reduced by up to 14 applications in China (Pray et al., 2002), 7 in South Africa and 5–6 in Indonesia and Australia (James, 2002).

17.7.4 Resistance Management Strategies for Bt-Cotton

Bt-cotton transgenic plants can impose a continuous selection pressure on *H. armigera*, eventually resulting in the development of resistance. Transgenic plants expose insects to toxins continually, even at times when they are not causing economic damage (Mallet and Porter, 1992). Development of insect resistance to a toxin is due to progressive selection and sequential propagation of individuals of a population, surviving the toxicant. Continuous selection pressure with the toxicant eventually leads to an increase in numbers of tolerant/resistant individuals in populations. After the introduction and large scale cultivation of Bt transgenic cotton it is reasonably certain that *H. armigera* and other species will respond to the intense selection pressure through a decline in their susceptibility to Cry1Ac, the transgene protein most frequently used against them. Xu et al. (2005) demonstrated at least one molecular mechanism (truncated cadherin target molecule) for *H. armigera* in China. Hence it is important to develop strategies to retard the rate of resistance development. Resistance management approaches generally rely on conserving susceptibility by minimizing toxin exposure and/or removing resistant hetrozygous resistant (RS) and homozygous resistant (RR) genotypes by using either high dose of the same toxin or by using other unrelated toxins. In India the planting of 20% of a farmer's area with a sprayed refuge of non-Bt cotton with Bt-cotton has been recommended by the Genetic Engineering Approval Committee (GEAC). A stochastic model 'Bt-Adapt' developed at CICR, Nagpur (Kranthi and Kranthi, 2004) showed that the 20% refuge crop would not offer a significant advantage in delaying resistance development. Using the model it was inferred that one of the most important strategies in Bt resistance management would be to reduce the surviving population of *H. armigera* on Bt-cotton through alternative pest management practices. The extent of reduction in the surviving population, which represents resistant genotypes, would determine the longevity of the technology utilisation. Effective strategies would include the use of alternate genes such as the Cry2Ab which is combined with Cry1Ac in Bollgard-II, which do not share common resistance mechanisms with Cry1Ac. If practicable, efficacy would be further enhanced if these genes could be used in rotations, alternation or mixtures. Removal of the resistance gene-bearing caterpillars by eco-friendly methods such as cultural control or handpicking of surviving bollworms in Bt cotton fields would help enormously. Biopesticides that are neem based or HaNPV would be useful to manage younger larvae on the 60–90 day old crop. Alternatively, conventional insecticides such as endosulfan, thiodicarb, quinalphos and chlorpyriphos, or new molecules such as spinosad, emamectin benzoate, novaluron or indoxacarb could be used, especially on the 90 and 120 days old crop to reduce populations of resistant genotypes. It seems sensible to avoid the use of Bt-based biopesticides on top of Bt cotton as that may contribute to the selection of a broad-spectrum resistance to several useful Bt genes of potential future interest.

17.8 Conclusion

For several years IPM has been a continuous struggle all over the world to obtain sustainability of the pest management based on biological control and biopesticides. The main constraints have been the sub-optimal efficacy levels, poor quality and non-availability of the recommended inputs. Since, over the years, a wide range of insecticide groups have been introduced with varying levels of toxicity to target pests and beneficial insects in the cotton ecosystem, sustainable methods have been evolved allowing informed choice of selective pesticides to simultaneously minimise insecticide use, reduce selection pressure, delay resistance and ensure the safety of naturally occurring biological control while reducing target pest populations. The recent introduction of genetically modified (GM) insect resistant crops such as Bt-cotton (*Bacillus thuringiensis* based GM cotton) and biologically derived novel pesticides such as spinosad and emamectin benzoate, have strengthened eco-friendly approaches to pest management. The principles of appropriate management of insecticides in such a way as to minimise their use while maximising the benefits of any necessary interventions are now much more widely adopted. The old adage *'the right dose of the right chemical at the right time'*, is being much more closely and intelligently respected after the success of the national IRM programs in countries like India. Now, after many years, cotton pest management appears to be moving closer to a sustainable set of strategies. With extension strategies having been strengthened through area-wide farmer participatory methods and farmer field school approaches, IPM has become more practical, user friendly and adaptable to the variable challenges of small-scale farming systems.

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Chapter 18
Non Pesticidal Management: Learning from Experiences

G.V. Ramanjaneyulu, M.S. Chari, T.A.V.S. Raghunath, Zakir Hussain and Kavitha Kuruganti

Abstract Pests and pesticides contribute to the major economic and ecological problems affecting the farmers, crops and their living environment. Two decades of experience in Andhra Pradesh on Non Pesticidal Management shows that pest is a symptom of ecological disturbance rather than a cause and can be affectively managed by using local resources and timely action. The emerging new paradigm of sustainable agriculture shows that the new knowledge synthesized from traditional practices supplemented with modern science can bring in ecological and economic benefits to the farmers. The small success from few villages could be scaled up into more than 1.5 million ha in three years. The costs of cultivations could be brought down significantly without reduction in yield. The institutional base of Community Based Organizations like Federations of Women Self Help Groups provides a good platform for scaling up such ecological farming practices. This experience also shows how the grass root extension system when managed by the community can bring in change and help the farming community to come out of the crisis.

Keywords Non pesticidal management · Pesticides · Natural enemies · Community based organizations · Sustainable agriculture · Local resources

18.1 Introduction

Farming in India evolved over centuries of farmers' innovations in identifying locally suitable cropping patterns and production practices. The crisis of food production and geo-political considerations during 1960s created conditions in many developing countries particularly in India to strive for food self-reliance. The country has chosen the path of using high yielding varieties (more appropriately high input responsive varieties) and chemicals which brought about what is popularly known as the Green Revolution. This continued as a quest for modernization

G.V. Ramanjaneyulu (✉)
Centre for Sustainable Agriculture, 12–13–45, Street No.1, Tarnaka Secunderabad-500 015, India,
Website: http://www.csa-india.org, http://www.indiagminfo.org
e-mail: gvramanjaneyulu@gmail.com

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of agriculture which promoted the use of more and more of high yielding varieties/hybrids, chemical pesticides and fertilizers across crops and situations displacing farmers' knowledge, own seeds and practices. The country could become self reliant for a while, farmers lost self reliance in the process due to excessive dependency on external inputs and are caught in serious ecological and economic crisis. This crisis is manifesting itself in the form of migration, indebtedness and in extreme cases as farmers' suicides.

In midst of the deep crisis in agriculture farmers and various organizations associated with farmers are trying innovative approaches to sustain agriculture. One such initiative is the "Non Pesticide Management" of crop pests to reduce the costs of cultivation by adopting a set of practices based on farmers' knowledge supplemented by modern science which makes best use of local resources and natural processes by the farmers and women self help groups in Andhra Pradesh. During *kharif 2007* (*kharif* season is synonymous with the wet season, covering the crop growing period April/May through September/October), more than 350 thousand farmers from 1800 villages in eighteen districts of the state are practicing NPM in more than 280 thousand ha in various crops. Sixteen of these districts are part of the 32 districts with serious agrarian crisis identified by the Government of India. The savings (on chemical pesticides) in costs of cultivation on pest management ranged from Rs. 600 to 6000 (US $ 15–150) per ha without affecting the yields. The savings on the health costs are also substantial. Non Pesticidal Management is one of the components of the "Community Managed Sustainable Agriculture" program with technical support from Centre for Sustainable Agriculture and its partner NGOs and financial and administrative support from the Society for Elimination of Rural Poverty, Government of Andhra Pradesh and implemented by Federations of Women Self Help Groups.

18.2 Pests, Pesticides and the Distress

The problems of pests and pesticides in farming are well documented. Among the production inputs in agriculture chemicals especially pesticides occupy major share of costs in crops like cotton, chillies, paddy etc. The pest resistance and resurgence due to abuse of pesticides propelled mainly by a lack of awareness, regulation of pesticide marketing extended on credit with high interests by "all-in-one dealers" (money lenders cum dealers of seeds/fertilizers/pesticides) and lack of market support ended up pushing hapless farmers into a vicious debt trap from which suicides were sought as a way out. The same pesticides which were promoted to solve the farmers' problems were consumed by these farmers to kill themselves.

18.2.1 The Dominant Paradigm

The dominant paradigm of pest management largely depends on use of chemical pesticides. The recommended schedules of the chemical pesticides are based on the studies conducted by the Pesticide Companies and Agriculture Research Institutes. The pesticides and the pesticide recommendations need to be registered with the Central Insecticides Board (CIB). Most of the chemical pesticides are used to kill the pest when it is in the most damaging stage of its life cycle. Farmers are suggested to spray their fields when the insects are in damaging proportions (Economic Threshold Level). The regular use of pesticides creates pressure and result in the development of genetic resistance in the insects and makes the sprays more and more ineffective. All these make the farmer to increase the pesticide doses or go for newer pesticides frequently pushing the farmers into a vicious cycle of pesticides, increasing costs, ill health and debt.

18.2.2 Pesticide Induced Pest Problems

Nearly from the beginning of the Green Revolution increases in insect populations following insecticide applications were detected. In rice insecticide induced increases in populations of plant sucking insects are among the first reliable symptoms of an intensification syndrome that destabilizes production (Kenmore, 1997). The Pesticides often induce pest outbreaks by killing beneficial insects, reducing natural pest control, and resulting in explosive outbreaks of pest species which are either resistant, or physically invulnerable to pesticides. For example, brown plant hopper eggs are laid within the rice stalk and shielded from spray; after spraying, they hatch into a field free of their natural enemies and reproduce explosively without predation (Kenmore, 1980). Systemic pesticides can kill the early "neutral" insects which lure the first generation of beneficials, and kill the beneficials as well (Mangan and Mangan, 1998). Similarly mealy bug and other sucking pests are increasingly becoming a problem in the cotton growing areas of Gujarat and Punjab. This ecological disturbance results in pest shifts as is seen widely today.

18.2.3 Pesticide Resistance

Pesticide resistance which is heritable and results in significant decrease in the sensitivity of a pest population to a pesticide reduces the field performance of pesticides. The percentage of resistant insects in a population continues to multiply while susceptible ones are eliminated by the insecticide (IRAC, 2007). How quickly resistance develops depends on several factors, including how quickly the insects reproduce, the migration and host range of the pest, the crop protection product's persistence and specificity, and the rate, timing and number of applications made. Based on their observations about resistance, farmers use either more concentration of the chemical (higher dose) or more sprays of the same or different chemicals mixed or at short intervals which is often termed as "indiscriminate" use while 'recommendations' ignore the problem (Table 18.1).

Table 18.1 Pesticide recommendations in chillies in 2000 and 2006 against *Helicoverpa*

Pesticide	First report of resistance*	Recommendation in 2000**	Recommendation in 2006**
Quinolphos	2001	2.5 ml/lit	2 ml/litre
Chlorpyriphos	2002	2.5 ml/lit	3 ml/litre

*Fakruddin et al., 2002, Kranthi et al., 2001a,b
**Vyavasaya Panchangam, 2001 and 2006 published by ANGRAU

18.2.4 Pesticide Poisoning

Pesticide poisoning is a significant problem in India. Pesticide poisoning to human beings through exposure to the toxic fumes while spraying is a lesser known and lesser acknowledged aspect of pesticide abuse in places like Warangal in Andhra Pradesh (Kavitha, 2005a,b; Mancini et al., 2005), Tanjavur in Tamil Nadu (Chitra et al., 2006) or Batinda in Punjab (Mathur et al., 2005). There is no systematic documentation of such cases during hospitalization, often they are combined with the ingestion cases. The numbers of deaths that happen prior to hospitalization and not reported are substantially high. The socio economic and environmental conditions in which the agriculture workers and small and marginal farmers work do not permit them to adopt the so called "safe use practices" often promoted by industry or agriculture scientists (Kavitha, 2005b).

There are also several reports on the chronic effects of the chemical pesticides on the farmers (Mathur et al., 2005), growth and development of children (Kavitha, 2005a, Timothy et al., 2005) and women's reproductive health.

18.2.5 Pesticides and Ecological Impacts

The chemical pesticides leave larger ecological foot prints in manufacturing (e.g. Bhopal gas tragedy), storage, transport and usage polluting the soils, water and air. Some amounts of pesticides used in crop production appear as residues in the produce. These residues in food, soil and water enter into the food chain and cause serious health problems to human beings and other living beings (Karanth, 2002, Kavitha et al., 2007). The pesticide residues are even noticed in human milk (Down to Earth, 1997). Studies show that the pesticide residues in soil can kill the soil microbes there by effect the soil fertility. Common pesticides block the chemical signals that allow nitrogen-fixing bacteria to function. Over time, soils surrounding treated plants can become low in nitrogen compounds, so more fertilizer is needed to produce the same yield (Fox et al., 2007).

18.2.6 Pesticide Regulation

In India, the production and use of pesticides are regulated by a few laws which mainly lay down the institutional mechanisms by which such regulation would take place – in addition to procedures for registration, licensing, quality regulation etc., these laws also try to lay down standards in the form of Maximum Residue Limits, Average Daily Intake levels etc. Through these mechanisms, chemicals are sought to be introduced into farmers' fields and agricultural crop production without jeopardizing the environment or consumer health. In spite of these regulatory systems, a number of pesticides banned across the world for their toxicity and residual problem are still produced and used in India.

The pesticides and pesticide recommendations to control specific pests on crops are to be registered with Central Insecticide Board and Registration Committee (CIBRC). While farmers are blamed for "indiscriminate use of pesticides", studies by Centre for Sustainable Agriculture show that indiscriminate recommendations are made by Agriculture Universities and Departments of Agriculture and Horticulture violating the registration rules. Pesticides are usually registered for one or two crops and one or two pests but sold, recommended and used for other crops and pests as well. (Kavitha et al., 2007). For example, acephate is registered for use only on cotton and safflower in the country. It is not registered for use on chillies, brinjal, cabbage, cauliflower, apple, castor, mango, tomato, potato, grapes, okra, onion, mustard, paddy and many other crops where it is being used extensively now. Further, it is also being recommended by the NARS for use in other crops even without registering the recommendations with CIBRC. Acephate is being recommended for the control of sap sucking pests in most crops. Further, MRLs have been set only for safflower seed and cotton seed for this pesticide. (Website Department of Horticulture, Govt. of AP http://www.aphorticulture.com, Vyavasaya Panchangam 2006–2007, ANGRAU, Central Insecticides Board & Registration Committee's website www.cibrc.nic.in)

18.3 Managing the Problem: Integrated Pest Management

The attempts to overcome the serious economical and ecological problems of the chemical pesticides have given rise to alternative systems to manage pests and pesticides.

18.3.1 Integrated Pest Management

In an attempt to slow the development of pest resistance, improve the financial basis for agricultural production, and improve the health of the farming population, systems of Integrated Pesticide Management have been introduced around the world. IPM is an ecological approach to plant protection, which encourages the use of fewer pesticide applications.

The field experiences gave rise to several paradigms of IPM which agriculturists presently adhere to. The most up-to-date paradigm of IPM is ecology based approach which is promoted by the FAO world wide in the form of Farmers Field

Schools (FFS). Through interactive learning and field-experimentation, FFS programs teach farmers how to experiment and problem-solve independently, with the expectation that they will thus require fewer extension services and will be able to adapt the technologies to their own specific environmental and cultural needs (Vasquez-Caicedo et al., 2000). Extension agents, who are viewed as facilitators rather than instructors, conduct learning activities in the field on relevant agricultural practices. In the FFS, a method called "agro-ecosystem analysis" is used to assess all beneficials, pests, neutral insects and diseases, and then determine if any intervention like a pesticide spray is needed. Economic Threshold Levels are discussed in the FFS, but crop protection decisions are based on conserving beneficial insects/spiders.

The Indonesian tropical wet rice ecosystem the IPM field school experience (Kenmore, 1980, 1996; Way and Heong, 1994; Settle et al., 1996) shows that:

- Beneficial insects/spiders comprise the majority of species in healthy ecosystems. 64% of all species identified were predators (306 species) and parasitoids (187 species); neutrals (insect detritivores, plankton feeders) comprise 19% (Settle et al., 1996) and rice pests constitute only 17% of species.
- Beneficials are extremely effective in controlling major rice pests; very substantial reduction of pesticide applications does not threaten rice yield.
- Contrary to previous understanding, beneficials typically enter the tropical wet rice ecosystem before pests, and feed on detritivores and other "neutral" insects, e.g., Springtails (*Collembola*) and Midge larvae (*Chironomidae*) already present in the rice paddy. Beneficials are therefore present from the start of the crop season and effective in pest control from an earlier stage than had previously been assumed (Settle et al., 1996; Wu et al., 1994)

The learnings from IPM projects and FFS experiences worldwide should have led to research on the complex interaction between crop ecology, agronomic practices, insect biology, and climate change to develop effective methods to manage disease and insect control strategies. Similarly the farmers' knowledge on using the local resources could have been captured and the principles could have been standardized. But FFS mostly remained as a paradigm shift in agricultural extension: the training program that utilizes participatory methods "to help farmers develop their analytical skills, critical thinking, and creativity, and help them learn to make better decisions." The agriculture research and extension system worldwide still continue to believe in chemical pesticide based pest management in agriculture.

The effectiveness of the IPM-FFS could have been enhanced by broadening the focus from a single crop to a broader systems approach, to address other matters, such as water management, crop rotation, crop diversification and marketing (Mancini et al., 2005).

Though FFS is seen as a knowledge intensive process, main focus was on taking external institutional knowledge to farmers. Proper space was not provided for traditional knowledge and practices or grass root innovations by farmers. In a study by Mancini (2006) evaluating the cotton IPM-FFS in Andhra Pradesh, farmers reported that their confidence in implementing the new management practices was not strong enough to translate into a change in behavior. This supports the argument that an effective, empowering learning process is based on experience, rather than on simple information and technology transfer (Lightfoot et al., 2001).

Pesticide industry is aware of the growing pest resistance towards their pesticides. Many of the pesticides become useless as the pests develop resistance and loose their market before they can recover the costs involved in developing the product leaving aside the profits. This situation has forced the pesticide industry to come up with their paradigm of IPM called "Insecticide Resistance Management" (IRM) which is a proactive pesticide resistance-management strategy to avoid the repeated use of a particular pesticide, or pesticides, that have a similar site of action, in the same field, by rotating pesticides with different sites of action. This approach will slow the development of one important type of resistance, target-site resistance, without resorting to increased rates and frequency of application and will prolong the useful life of pesticides. This resistance-management strategy considers cross-resistance between pesticides with different modes of action resulting from the development of other types of resistance (e.g., enhanced metabolism, reduced penetration, or behavior changes) (PMRA, 1999).

Though pesticide industry states that it fully supports a policy of restricted pesticide use within an IPM program, it perceives a clear need for pesticides in most situations. Furthermore, its practice of paying pesticide salespeople on a commission basis, with increased sales being rewarded with increased earnings, is unlikely in practice to encourage a limited use of pesticides (Konradsen et al., 2003).

Right from the time of the Rio Earth conference, India has been highlighting this IPM policy in all its official documents. The ICAR had also established a National Centre for Integrated Pest Management in 1998. In India a total of 9,111 Farmers' Field Schools (FFSs) have been conducted by the Central Integrated Pest Management Centres under the Directorate of Plant Protection, Quarantine & Storage from 1994–1995 to 2004–2005 wherein 37,281 Agricultural Extension Officers and 275,056 farmers have been trained in IPM. Similar trainings have also been provided under various crop production programs of the Government of India and the State Governments (Reports of Government of India available on http://www.agricoop.nic.in).

IPM is sought to be made an inherent component of various schemes namely, Technology Mission on Cotton (TMC), Technology Mission on Oilseeds and Pulses (TMOP), Technology Mission on Integrated Horticultural Development for North East India, Jammu & Kashmir, Himachal Pradesh, Uttarakhand, Technology Mission on Coconut Development etc, besides the scheme "Strengthening and Modernization of Pest Management" approach in India being implemented by the Directorate of PPQ&S [Plant Protection, Quarantine & Storage].

The problems with chemical pesticides also prompted the research systems and industry to look for alternatives. Several schemes and projects have been initiated to research, produce and market biopesticides and biocontrol agents which are recommended as non chemical approaches to pest management.

Today, there is much data generated by the agriculture research establishment in India to show that non-chemical IPM practices across crops have yielded better results in terms of pest control and economics for farmers. However, the field level use of pesticides has not changed much. The official establishment usually claims that pesticide consumption in the country has come down because of the promotion and deployment of IPM practices on the ground by the agriculture research and extension departments (as was informed to the Joint Parliamentary Committee in 2003). However, the actual progress of IPM on the ground has been quite dismal and small.

Further, the government often fails to take into account the fact that even if pesticide consumption has decreased in terms of quantities due to a shift to consumption of low-volume, high-concentration, high-value pesticides, the real picture in terms of number of sprays and costs involved is still the same for the farmers.

The Integrated Pest Management (IPM) initiatives which have come up as alternative though largely debates about the effects of pesticide on human health and on environment still believe that pesticides are inevitable, at least as a last resort and suggests safe and "intelligent use." On the other hand, replacing chemical products by biological products by itself may not solve the problem of pest management with restoration of ecological balance.

While the inevitability of pesticides in agriculture is promoted by the industry as well as the public research and extension bodies. There are successful experiences emerging from farmers' innovations that call for a complete paradigm shift in pest management.

18.4 Shifting Paradigms: Non Pesticidal Management

The ecological and economical problems of pests and pesticides in agriculture gave rise to several eco-friendly innovative approaches which do not rely on the use of chemical pesticides. These initiatives involved rediscovering traditional practices and contemporary grass root innovations supplemented by strong scientific analysis mainly supported by non-formal institutions like NGOs. Such innovations have begun to play an important role in development sector. This trend has important implications both for policy and practice. One such initiative by Centre for World Solidarity and Centre for Sustainable Agriculture, Hyderabad was Non Pesticidal Management.

The "Non Pesticidal Management" which emanates from collaborative work of public institutions, civil society organizations and Farmers in Andhra Pradesh shows how diverse players join hands to work in generating new knowledge and practice, can evolve more sustainable models of development.

Red Hairy Caterpillar (*Amsacia albistriga*) Management (1989–93):

During late eighties, red hairy caterpillar (RHC) was a major pest in the dryland areas of Telangana region of Andhara Pradesh. The pest attacks crops like castor, groundnut, sesame, sorghum and pigeon pea in the early stages and causes extensive damage in dry land areas. This forces farmers to go for 2–3 resowings or late sowing which affect the yield. The problem of crop failure due to delayed and uncertain rainfall was compounded by the damage caused by RCH. Resowings were happening in more than 30% area.

Discussions with several voluntary agencies, farmers from different regions and few scientists from the subject area established that:

1. This pest infests crops only on light red soils
2. There is only one generation of moths that lay eggs producing the caterpillars which later hibernate in the soils. Adult moths appear in waves at the onset of the monsoon. Controlling the pest necessiated the destruction of the early emergence moths.
3. The caterpillars are also attracted to some wild non-economical plants such as calatropis, wild castor, yellow cucumber.
4. The later instars of larvae had dense red hairs all over the body, which prevents pesticides from reaching the body of the insects as a result any pesticide sprayed will not cause the mortality of the insect.

Package of practices were evolved based on the insect behavior, which can manage the RHC before it reaches damaging stages and proportions. Deep summer ploughing exposes the resting pupae, adults of RHC. These insects are attracted to light-community bonfires. Bonfires were used to attract the insects and kill them. Alternatively light traps (eletric bulbs or solar light) were also used. Trenches around the field to trap migrating larvae by use of calatropis and jatropha cuttings were found to be effective. Neem sprays on the early instar larvae was found to be effective.

During 1989–1993 the program covered 18,260 ha in 95 villages across 12 districts of AP involving 21 voluntary organizations in two phases.

RHC could be effectively managed in dryland crops like castor, groundnut, sesame, sorghum and pigeonpea. Farmers could avoid late sowing and only 4% farmers went for re-sowing in areas where RHC management was followed. After the initial success of these methods, it evolved into a Red Hairy Catepillar Management Program with coordinated of Centre for World Solidarity (CWS), ICAR Zonal Coordinating Unit, Directorate of Oilseeds Research and Department of Agriculture, and the program is still continuing. The CWS sustainable agriculture desk later on evolved into Centre for Sustainable Agriculture which is now engaged in large scale promotion of NPM approach.

Source: Qayum. M.A. and Sanghi. N.K. (1993) Red Hairy Caterpillar Management through Group Action and NPM Methods published by ASW and Oxfam(India) Trust.

Pest is not a problem but a symptom. Disturbance in the ecological balance among different components of crop ecosystem makes certain insects reach pest status. From this perspective evolved the Non Pesticidal Management which is an "ecological approach to pest management using knowledge and skill based practices to prevent insects from reaching damaging stages and damaging proportions by making best use of local resources, natural processes and community action."

Non Pesticidal Management is mainly based on:

- Understanding crop ecosystem and suitably modifying it by adopting suitable cropping systems and crop production practices. The type of pests and their behavior differs with crop ecosystems. Similarly the natural enemies' composition also varies with the cropping systems.
- Understanding insect biology and behavior and adopting suitable preventive measures to reduce the pest numbers.
- Building farmers knowledge and skills in making the best use of local resources and natural processes and community action. Natural ecological balance which ensures that pests do not reach a critical number in the field that endangers the yield. Nature can restore such a balance if it is not too much meddled with. Hence no chemical pesticides/pesticide are applied to the crops. For an effective communication to farmers about the concept effectively, and to differentiate from Integrated Pest Management which believes that chemical pesticides can be safely used and are essential as lost resort it is termed as "Non Pesticidal Management" (Ramanjaneyulu et al., 2004).

18.4.1 The Approaches: Basic Set of Practices Followed

18.4.1.1 Growing Healthy Plants

Good Quality Seed

Selection and use of good quality seed which is locally adopted either from traditional farmers' varieties or improved varieties released by the public sector institutions is important. Farmers are suggested to make their decision based on a seed matrix regarding suitability of the different varieties into their cropping patterns, based on the soil types, reaction to insect pests and diseases and their consumption preference. They maintain the seed in their seed banks. This ensures farmers to go for timely sowing with the seeds of their choice. In rainfed areas timely sowing is one critical factor which affects the health and productivity of the crop. The seed is treated with concoctions depending on the problem for example cow urine, ash and asafetida concoction provides protection against several seed borne diseases

In NPM –main emphasis is to prevent insect from reaching damaging stage and proportions. If the pest reaches damaging stage, reactive inputs locally made with local resources are used. In IPM chemical pesticides are integral part.

like rice blast, or *beejamrut* to induce microbial activity in the soil and kill any seed borne pathogens. Similarly in crops like brinjal where there is a practices of dipping of seedlings in milk and dipping fingers in milk before transplanting each seedling was observed to prevent viral infections. Several such practices are documented and tested by the farmers. Non Pesticidal Management involves adoption of various practices which prevents insects from reaching to damaging stage and proportions (Fig. 18.1).

Reduce Stress

The pest and disease susceptibility increases with abiotic stress. Practices like mulching will improve the soil moisture availability.

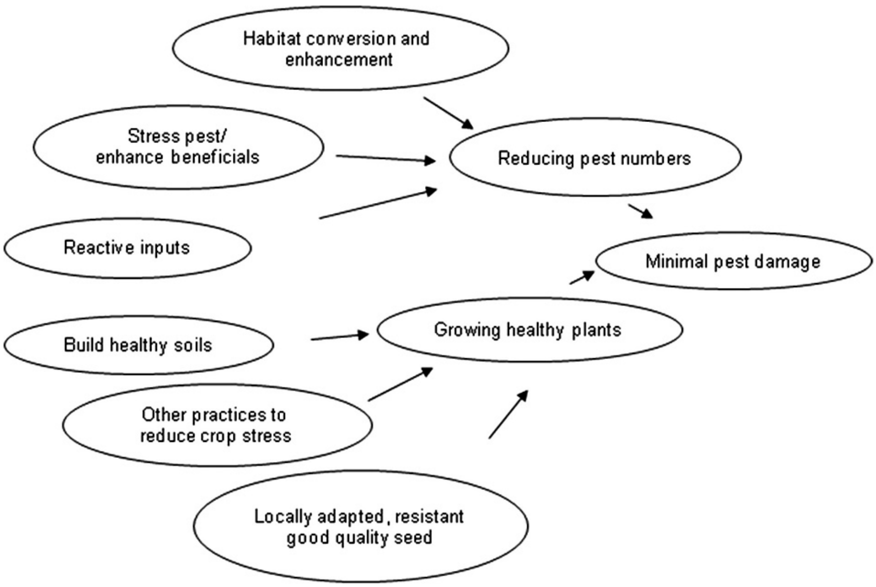

Fig. 18.1 Schematic representation of non pesticidal management

Build Healthy Soils

Healthy soils give healthy crop. Chemical fertilizers especially nitrogenous fertilizer makes the plants succulent and increases the sucking pests like brown plant hopper in rice. Production practices, such as putting on crop residues or other biomass as surface mulch, using compost and green manures, intercropping of legumes in cropping systems, and biocontrol of insect pests and diseases, all help to enhance yields and sustain soil fertility and health (Rupela et al., 2007).

18.4.2 Enhancing the Habitat

18.4.2.1 Crop Diversity

Crop diversity is another critical factor which reduces the pest problems. Traditionally farmers have evolved mixed cropping systems, intercropping and crop rotation systems. These systems will create a better environment for nutrient recycling and healthy ecosystems. On the contrary the monoculture of crops and varieties lead to nutrient mining and insect pest and disease buildup. Under NPM farmers adopt mixed and intercropping systems with proper crop rotations.

18.4.2.2 Trap and Border Crops

Many sucking pests fly from neighboring farmers' fields. In crops like chillies, groundnut, cotton, sunflower where thrips are a major problem, sowing thick border rows of tall growing plants like sorghum or maize will prevent insects from reaching the crop. Farmers adopt marigold as a trap crop for the gram pod borer and it reduces the pest load on pigeonpea. The flowers that have been oviposited by the female moths of *Helicoverpa* can be picked out and destroyed (KVK DDS, 2003) (Table 18.2).

Table 18.2 Trap crops used for pest management

Crops	Pests	Trap crops
Cotton, groundnut	Spodoptera	Castor, sunflower
Cotton, Chickpea, pigeonpea	Helicoverpa	Marigold
Cotton	Spotted bollworm	Okra

Source: KVK DDS, 2003

18.4.2.3 Other Agronomic Practices

Several **c**rop specific agronomic practices like alley ways in rice to allow enough light to reach the bottom of the plant are documented by the farmers and suggested by the scientists (*Vyavasaya Panchangam*, 2007).

18.4.3 Understanding Insect Biology and Behavior

18.4.3.1 Life Cycle

In most of the insects which completely undergo complete metamorphosis, in the four stages of the life cycle, insects damage the crop only in larval stage and in at least two of the stages are immobile [egg and pupa]. Every insect has different behavior and different weaknesses in each of the stage. They can be easily managed if one can understand the lifecycle and their biology. The different stages in the insect life cycle are morphologically different and relating between one stage and other is difficult unless one studies/observes the life cycle (Fig. 18.2).

Adult stage: Adults of red hairy caterpillars are attracted to light-community bonfires or light traps (electric bulbs or solar light). These can be used to attract and kill them. Similarly adult insects of *Spodoptera* and *Helicoverpa* can be attracted by using pheromone traps. Normally pheromone traps are used to monitor the insect population based on which pest management practices are taken up. The Natural Resources Institute, UK in collaboration with the Tamil Nadu Agriculture University, the Gujarat Agriculture University, the Centre for World Solidarity, the Asian Vegetable Research and Development Centre has evolved mass trapping method to control brinjal fruit and shoot borer and demonstrated it on a large scale (http://www.nri.org, GAU, 2003) The adults of sucking pests can be attracted using yellow and white sticky boards.

Egg stage: Some insects like *Spodoptera* lay eggs in masses which can be identified and removed before hatching. Insects also have preference for ovi-position. *Spodoptera* prefers to lay eggs on castor leaves if available. Hence growing castor plants as trap crop is adopted. By observing the castor leaves farmers can easily estimate the *Spodoptera* incidence. *Helicoverpa* lays eggs singly, but has a preference towards okra, marigold (mostly towards plants with yellow flowers) (Fig. 18.3). Hence marigold is used as a trap crop where ever *Helicoverpa* is a major problem. Rice stem borer lays eggs on the tip of the leaves in nurseries; farmers remove these tips before transplanting (*Vyavasaya Panchangam*, 2007).

Pupal stage: The larvae of red hairy caterpillar burrow and pupate in the soil. Deep summer ploughing, which is a traditional practice in rainfed areas expose these larvae to hot sun which kills them. The larvae of stem borers in crops like paddy and sorghum pupate in the stubbles. So farmers are advised to cut the crop to ground level and clear the stubbles.

18.4.3.2 Biology

The larva of red hairy caterpillar (*Amsacta albistriga*) has a dense body hair over the body hence no pesticide reaches it when sprayed. Therefore, it needs to be controlled in other stages of its life cycle (see box). For any safe and economic method of

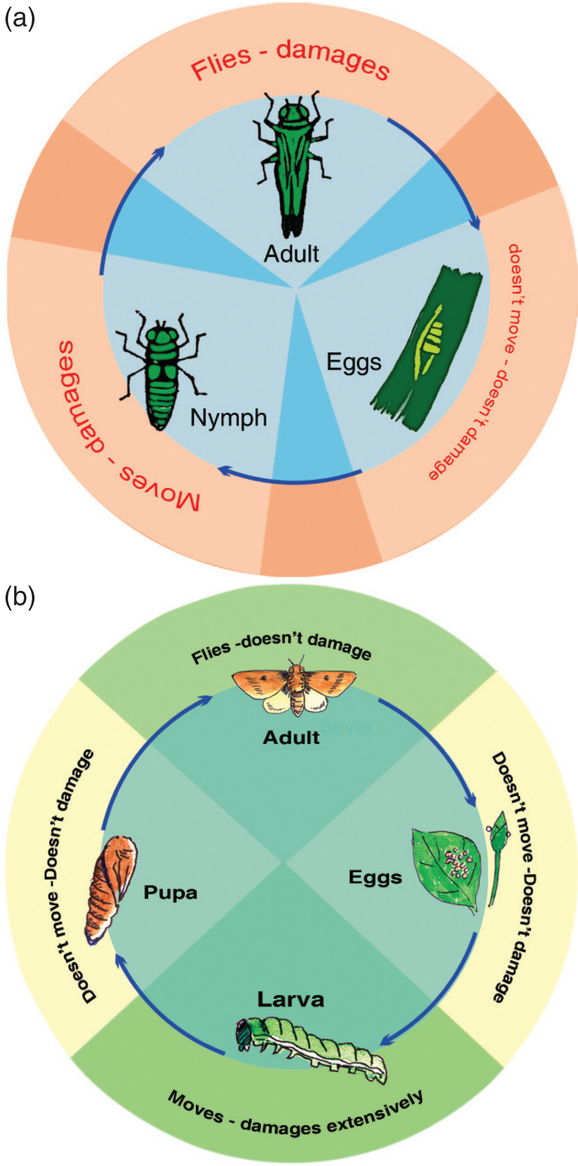

Fig. 18.2 Typical life cycle of insects (a) 3 stages (b) 4 stages

pest management one must understand how the pest live and die, where does it come from and when, where and how does it damage the crop. Knowledge of these biological attributes of pest will help farmers to use NPM methods successfully on a sustainable basis (GAU, 2003).

Traditional Technology with a Modern Twist http://www.icrisat.org

Farmers in south India used indigenous methods like shaking the plants to manage the pod borer (*Helicoverpa armigera*) in pigeonpea until chemical insecticides were introduced in the early 1970s. After crop pollination and pod set, when 1–2 larvae per plant are noticed, three farmers enter the field, one to hold/drag a polyethylene sheet on the ground, while the other two shake the plants. This gentle shaking can dislodge most of the caterpillars from the plants. These dislodged larvae are collected in a sack and destroyed.

During 1998–1999 season, this technology was evaluated in a research watershed (15 ha) at ICRISAT-Patancheru with support from IFAD and in collaboration with ICAR, ANGRAU, MAU, and NGOs under the coordination of CWS.

The results showed 85% reduction in insect population while the larval population in the adjacent, chemically sprayed plots remained high throughout the cropping period. This cost of this practice is just Rs. 280 (US $6) per hectare to have 7 people to shake pigeonpea planes, and collect larvae; while each chemical spray costs Rs. 500–700 (US $11–16) per hectare. This technology, initiated at a few locations during 1997, rapidly spread to more than 100 villages involving several thousand farmers in three states of southern India within two years.

Later, the larvae collected by shaking the plants were used for the multiplication of the Nuclear Polyhedrosis Virus (NPV), a biopesticide that kill *Helicoverpa*.

This project proposal by ICRISAT and CWS had won the World Bank's Development Marketplace Award for 2005.

18.4.4 Understanding Crop Ecosystem

The pest complex and the natural enemy complex are based on the crop ecosystem. The pest complex of cotton is completely different from that of sorghum. The pest complex in wet rice ecosystem differs from the pest complex in dry rice. Decision about any pest management intervention should take into account the crop ecosystem which includes cropping pattern, pest-predator population, stage of the crop etc. Similarly the management practices followed in one crop can not be adopted in all other crops. For example: to manage *Helicoverpa* in pigeonpea, the farmers in Andhra Pradesh and Gulbarga shake the plants and falling insects are collected over a sheet and killed (see box). Similarly in paddy there is a practice of pulling rope over the standing crop to control leaf folder.

(a)
(b)


Fig. 18.3 Egg laying behavior of (a) *Spodoptera litura* (egg mass) (b) *Helicoverpa armigera* (single egg)

18.4.5 Reactive Sprays

Insect population may reach pest status if the preventive steps are not taken in time, changes in weather conditions and insects coming from neighboring farmers fields. In these situations based on the field observations farmers can take up spraying botanical extracts and natural preparations (Green sprays) instead of chemical pesticides. There are wide ranges of these preparations which are evolved by the farmers (CSA, 2007).

Based on the process of making, these sprays can be classified into four categories

18.4.5.1 Aqueous or Solvent Extracts

Extracts are made by dissolving the required material in water (aqueous) or other liquids (solvent). For example, neem seed kernal extract is prepared by dissolving crushed neem seed kernal in water. For extracting "Allenin" from garlic, kerosene is

Fig. 18.4 Shaking method in pigeonpea for removing pests

used as a solvent. After extraction this solution is mixed with chilli extract and used against sucking pests (Prakash and Rao 1997, Vijayalakshmi et al., 1999, Prasad and Rao 2006).

18.4.5.2 Decoctions

For example, plants like tobacco, *Nux Vomica* contain volatile compounds which can be extracted by boiling them in water to get the decoction. Several decoctions are used in pest management (Prakash and Rao, 1997, Vijayalakshmi et al., 1999, Prasad and Rao, 2007).

18.4.5.3 Concoctions

Concoctions are mixtures. For example, five leaves mixture which is a aqueous extract of any five latex producing leaves is used to control pests in Tamil Nadu and other parts of south India (Prakash and Rao, 1997, Vijayalakshmi et al., 1999, Prasad and Rao, 2007).

18.4.5.4 Fermented Products

Products made by fermenting the different botanicals with animal dung and urine. These products have rich microbial cultures which help in providing plant nutrients in addition to acting as pest repellents and pest control sprays. For example cow dung urine-asafetida solution is used to manage rice blast (Prakash and Rao, 1997, Vijayalakshmi et al., 1999, Prasad and Rao, 2007).

The Evolution of Dialogue on Non Pesticidal Management

In 1988, ASW and EZE organized People's Science Conference at Bangalore to promote concept of substituting synthetic chemical pesticides by a non-pesticide approach based on locally available resources. This led to a collaborative program for non pesticidal approach for controlling RHC in 1989 with Zonal Coordinator, Transfer of Technology (ToT) Unit, ICAR, Hyderabad; Department of Agriculture, ASW/CWS; OXF AM; and village based voluntary organizations as partners.

In 1994, CWS organized a workshop in collaboration with National Academy of Agriculture Research Management (NAARM), Hyderabad to bring together initiatives working in NPM across the country. This worshop evolved a joint strategy paper on NPM.

In 1998, CWS organized second National Worshop on Non Pesticidal Management in collaboration with MANAGE in Hyderbad. The workshop which was attended by eminent scientists and civil society organizations called for expansion and popularizing the concept and practices.

In 2004, Punukula, a small village in Khammam district of Andha Pradesh which used to spend about Rs. 4 million annually on chemical pesticides to grow crops like cotton and chillies declared itself as a pesticide free after five years of NPM work. Centre for Sustainable Agriculture was formed to promote sustainable models in agriculture.

In 2005, in the context of serious crisis in agriculture and farmers suicides, NPM got the attention of the Society for Elimination of Rural Poverty, Government of Andhra Pradesh which works with Federations of Women Self Help Groups and began scaling up by adopting an institutional approach across the state.

During *kharif* 2007, more than 350 thousand farmers from 1800 villages in eighteen districts of the state adopted NPM in more than 280 thousand ha in various crops. The success of the program in reducing the costs of cultivation and increasing the net incomes of the farmers has received Prime Minister's attention and was selected for a support under 11th Five Year Plan under National Agriculture Development Project to cover one million farmers cultivating one million ha in over 5000 villages.

In September 2007, CSA and WASSAN (sister organizations of CWS engaged in promotion of NPM) have organized a National Workshop on 'Redesigning support systems for rainfed farming' in collaboration with Rainfed Farming Authority and ICAR in New Delhi. The nationwide experiences of public sector and civil society organizations on local resource based, sustainable models in agriculture were discussed and urged the government to redesign the support systems to help promotion of such practices.

(Based on the internal documents, proceedings of workshops organized by CWS in 1994 and 1998, Ramanjaneyulu et al. (2004))

Transgenic Insect Resistant Crops: Not a solution Either

As the problems of chemical pesticides are becoming evident, the industry has come out with yet another technological fix in the form of insect resistant genitically engineered crops like Bt cotton. The results of the last seven years (2002–2008) of commercial cultivation of the Bt cotton in india, especially in Andhra Pradesh clearly shows devastating effects such technologies can have in the farming communities. This comes from the fact that the seed is four times the price of conventional seeds and Bt crops often are not even completely resistant (http://www.indiagminfo.org). In addition other sucking pests will affect the crop and chemicals are needed again. The first three commercial Bt hybrids released in Andhra Pradesh were withdrawn from commercial cultivation (GEAC, 2005).

It should be added that studies have assessed the variabity of Bt toxin production under carefully controlled conditions, rather than the real life conditions of farmer's fields.Under real life condition toxin product of the crop is extremely uneven (Kranthi et al., 2005).

Transgenitic Bt plants, which produce their own insecticidal toxins, have the similar effects like chemical pesticides. However, unlike topical sprays, which become inactive after a short period of time, transgenetic Bt plants are engineered to maintain constant levels of the Bt toxin for an extended period, regardless of whether the pest population is at economically damaging levels. The selection pressure with transgenic Bt crops will therefore be much more intense (Ramanjaneyulu and Kavitha, 2006).

Today the experience of Bt cotton in several areas specially dryland regions is well known. The sucking pests are on increase. The newer questions like toxicity to smaller ruminants and soil microbes, are raised by several scientists across the world and the farmers are complaining on this issue.

The Economic Analysis of NPM and Bt Cotton

A study was taken up by Central Research Institute of Dryland Agriculture (CRIDA) to compare the performance of NPM in Bt and non-Bt cotton. The study showed that NPM in non-Bt cotton is more economical compared to Bt cotton with or without pestcide use (Prasad and Rao 2006) (Table 18.3).

Table 18.3 Comparative economics of Bt cotton vs Non-Bt cotton with NPM

Strategy	Genotype	No. of chemical sprays	Cost of cultivation ($ US/ha)	Yield (kg/ha)	Gross returns ($ US/ha)	Net returns ($ US/ha)
NPM	Non-Bt	0	407.75	2222.5	1127.5	719.50
NPM	Bt	0	388.89	2220.0	1091.81	702.92
Control	Non-Bt	5.0	409.69	2087.5	1031.25	621.56
Control	Bt	3.8	452.19	2242.5	1111.63	659.44

Source: (Prasad and Rao, 2006)

18.5 Successful Case Studies

18.5.1 Punukula: The Pesticide Free Village

Punukula a small quite village in Khammam district in Andhra Pradesh (AP) created waves by local Panchayat (local self government body) formally declaring itself pesticide-free in 2003. Farmers here gave up using chemical pesticides even for crops such as cotton, chilli and paddy – all known to use notoriously high quantities of pesticides.

From 1986 onwards the State witnessed farmers' suicides due to indebtedness. During 1997–1998 several farmers committed suicides after the cotton crop failed in Telangana region. An estimated 1,200 suicide deaths were reported between June and August 2004. One of the reasons for the rise in suicides has been the crushing burden of debt; many farmers buy expensive seeds and pesticides and when the crops fail, their own survival becomes difficult. Against this scenario the pesticide-free status of the predominantly tribal village of Punukula gains significance.

The Punukula farmers claim that they are able to save up to $ 75,000 every year on agricultural inputs by adopting Non Pesticidal Management approach towards pest management. There is a total of 240 ha of farmland; and on every hectare, they have been able to save at least $ 300 per season, as they do not have to buy expensive pesticides.

Farmers learned using pesticides from the farmers who brought cotton crop to Punukula from Guntur districts about 15 years ago. Initially, the pesticides worked well and several pesticide shops were opened in the nearby town of Palvancha. Pesticide dealers also gave local farmers the latest pesticides on credit. But gradually, the pests became resistant to these pesticides. Monocrotophos, methyl parathion, chlorpyriphos, endosulfan and synthetic pyrethroids... nothing seemed to work. The pests would only come back in greater numbers. Pretty soon, the cotton crop needed greater quantities of pesticides, which meant a higher investment.

In addition to supplying seeds, fertilisers and pesticides, the dealers also lent money to the hapless farmers at high interest rates.

But when yields started reducing – due to pests – and debts increased, some farmers in Punukula committed suicide. The high use of pesticides also posed health-related problems. Women, who did most of the pesticide spraying work, complained of skin problems, blurred vision and body ache.

In 1999, the Socio-Economic and Cultural Upliftment in Rural Environment (SECURE), a local NGO, stepped in and suggested that the farmers try out non pesticidal approaches for pest management. Technical and financial support for this project initially came from the Centre for World Solidarity (CWS) and later from the Centre for Sustainable Agriculture (CSA), both based in Hyderabad. However, the determination and support of five self-help groups (SHGs) run by the village women contributed towards making this shift to ecological methods possible.

SECURE initially began work with 20 farmers, including a few women. Earla Dhanamma, whose husband Nagabhushanam represented the interests of several pesticide companies, also joined in. The farmers were sceptical in the beginning.

Table 18.4 Economics of NPM in Cotton Punukula village (Kharif, 2001–2002)

Particulars	NPM	Conventional*
Avg. Yield (kg/ha)	1575	1450
Cost of plant protection ($ US/ha)	107.50	214.88
Net income ($ US/ha)	85.50	–130

* Conventional pesticide used cotton from neighboring village
(On 6.4 ha, with 8 farmers in Punukula)
Source: Ramanajaneyulu and Zakir Hussain (2007)

But the method of preventing pest attacks by understanding the pests' life cycles did appear both simple and affordable. Instead of chemical sprays, the farmers began preparing sprays made with local and inexpensive material such as neem seed powder and green chilli-garlic extract. The farmers also used pheromone traps to attract moths and destroyed them before they started mating. Some farmers also used 'crop traps' along with the cotton crop they would grow another crop (marigold or castor) that attracted the pests more.

In just one season, the positive results began to show. Useful insects such as spiders, wasps and beetles – which feed on cotton pests – returned to the fields once the chemical pesticides were stopped. In the next season, many other farmers came forward to try out the new approach. However, there were several men in the village who found it easier to buy a container of chemical pesticide from a pesticide dealer than go through the trouble of preparing extracts to control pest population (Table 18.4).

But the women's SHGs prevented these men from going back to pesticide shops. Others also realised that pesticides meant higher debts as well as high medical costs. The women even took on the additional work of preparing the anti-pest sprays from neem and chilli-garlic paste. They also ensured that no one brought pesticides in their village.

By 2003, most farmers in this 200-household village had stopped using harmful chemical pesticides. Pesticide dealers stopped coming to the village as sales dropped dramatically. Besides covering 160-odd ha of cotton, the new method was also used in fields growing chilli and paddy. No pesticides were sprayed in 240 acres (96 ha) of farmland during the 2003 *kharif* season. Even during the first crop season of 2004, no pesticides were required.

In August 2004, the women's groups also bought a neem seed crushing machine (extracts for the sprays are prepared from the powder) with support from SECURE and CWS/CSA.

Today, Punukula has become a role model for other villagers who are inspired and impressed by its healthy crops. Around Punukula many villages are inspired to give up chemical pesticide usage.

Punukula farmers now have the money to invest in house repair, livestock and purchase of land. Most of the farmers reported higher income, enabling them to repay old debts. The villagers now firmly believe that the way to get rid of pests is to rid their farming of pesticides.

For the agricultural laborers also, things have improved on many fronts. There was a wage increase from 75 cents to one dollar during the corresponding period [when NPM was practiced]. They do not have to be exposed to deadly pesticides now, nor incur medical care expenses for treatment of pesticides-related illnesses. Some point out that there is even more work for the labourers – in the collection of neem seed, in making powders and pastes of various materials and so on. Farmers are even leasing in land and putting all lands under crop cultivation these days – this implies greater employment potential for the agricultural workers in the village.

Source: (http://www.thehindubusinessline.com/life/2004/10/08/stories/2004100800030200.htm)

18.5.2 Enabavi: A Whole Village Shows the Way

Enabavi is probably the first modern-day organic farming village in Andhra Pradesh. The entire village, in each acre of its land, on every crop grown here, has shunned the use of chemicals in agriculture. They neither use chemical fertilizers nor chemical pesticides in their farming. This in itself meant a tremendous saving for the village in monetary terms. This small village in Lingala Ghanpur of Warangal district shows the way out of agricultural distress that almost all farmers find themselves in today.

Warangal district presents a classic paradox of an agriculturally developed district [with most area occupied by commercial crops] showing the worst manifestation of the distress of farmers – that of the highest number of suicides in the state in the past decade or so. It is a district where farmers' frustration with lack of support systems manifested itself in almost a spontaneous and well-planned agitations of unorganized farmers. Farmers in this district are known to have resorted to violence to end their problems, including resorting to a violent end to their own lives.

Enabavi is a small village which showed the resolve of a strong community which decided to take control of its agriculture into its own hands. With just 45 households in the village belonging mostly to the backward castes, the village started shifting to non-chemical farming about five years ago. Then in 2005–2006, the entire land of 113 ha was converted to organic farming. This is not organic farming as you would normally expect. No expensive external certification here. It is a model of "declared organic farming". Though there are no formal participatory guarantee systems established in the village in this alternative model of organic farming, there is strong social regulation within the community to ensure that there are no "erring farmers". The elders in the village take the youth along with them. They also have started investing in teaching their school-going children the knowledge and skills of non-chemical farming. Special training sessions have been organized by CROPS to rope in children into this new system of cultivation in the village.

The farmers here grow their food crops of paddy, pulses, millets etc., mostly for household consumption. In addition, they also grow crops like cotton, chilli, tobacco and vegetables for the market. Their average spending on chemical fertilizers and pesticides across crops used to be around US $ 220/ha, whereas it was around US $ 31.25/ha for seeds. This more often meant credit from the input dealers, who would also double up as traders for the produce. These traders would dictate the price for the produce in addition to charging interest for the inputs supplied. Now, all this has changed.

The process of change began with a program that CWS had initiated to control the dreaded red hairy caterpillar, in the late 1990s. This was followed by converting all crops to the NPM. Later, some farmers came forward to shift from chemical fertilizers to other methods of soil productivity management. They started looking for other options like tank silt application, poultry manure application, vermicompost, farm yard manure etc. CROPS stepped in at this point of time and subsidized the costs up to 50% for tank silt application and setting up vermicompost units. The farmers set up their units at their fields and started following various ecological practices being recommended to them. They also started to depend on their own seed for many crops, except for crops like cotton. They set up farmers' self help groups for men and women separately and started thrift activities too.

Today, Enabavi has many valuable lessons to teach to other farmers, not just on how to take up sustainable farming. They also have lessons to share on social regulation, learning from each other, the benefits of conviction born out of experience and most importantly, the way out of agricultural distress by taking control over one's own farming.

18.6 NPM Scaling up with SERP

Society for Elimination of Rural Poverty (SERP) is a registered society under Department of Rural Development implementing the largest poverty alleviation project in the state of Andhra Pradesh. The project understands that sustainable poverty eradication requires the recognition of the poor as active partners in the processes of social change; therefore, all project interventions are demand based and are in response to the proposals conceived and planned by the poor.

SERP works towards empowering the poor to overcome all social, economic, cultural and psychological barriers through self managed institutions of the poor. The project reaches the rural poor families through social mobilization processes and formation of SHGs, federation of these into Village Organizations at village level and Mandal Samakhyas at the mandal level. The project envisages that with proper capacity building the poor women's federations would begin to function as self managed and self reliant people's organizations. The poor have started to demonstrate that they can shape their own destinies when adequate knowledge, skills and resource support is accessible to them.

In this context SERP initiated the work on agriculture based livelihood, supporting them to adopt sustainable agriculture practices to reduce the costs of cultivations. Learning from the experiences of villages like Punukula, SERP initiated scaling up of NPM in collaboration with a consortium of Non Governmental Organizations and technical support provided by the Centre for Sustainable Agriculture (CSA).

18.6.1 Critical Issues in Scaling Up

While the sustainable models in agriculture like NPM are established on smaller scale scaling up these experiences poses a real challenge in terms of:

- relevance of small experiences for a wider application,
- availability of resources locally,
- farmers willingness to adopt these practices,
- lack of institutional and support systems,
- supplementing farmers' knowledge and enhancing the skills,
- reducing the time of transformation,
- reaching to larger areas with minimal expenditure, and
- establishing extension system which give community a central stage.

18.6.2 Process of NPM Scaling Up

In December, 2005, a small pilot project was launched in Kosigi Mandal (Blocks in Andhra Pradesh) as a livelihood intervention with the help of WASSAN. Farmers were trained systematically and technical support provided in the form of coordinators who were accountable to the Women SHGs. In 90 ha, average savings of US $ 75/ha on pigeon pea the total savings were US $ 6875 (WASSAN, 2006).

18.6.2.1 Grounding the Work 2005–2006

Based on the experiences drawn from the pilot program for 2005–2006 was initiated by establishing clear institutional system and a community managed extension system in nine districts of AP. Five villages were grouped into a cluster and were provided with a cluster activist. Each village has a practicing farmer selected as village activist who coordinates the village level capacity building programs in the form of Farmer Field Schools. All over nine districts 12,000 farmers with 10,000 ha in both *kharif* and *rabi* (It is synonymous with the dry season, covering the crop growing period October/November through March/April) adopted Non Pesticidal Management. Sixty-two Federations of Women SHGs (Mandal Mahila Samakyas or MMS), 150 Cluster activists and 450 village activists are involved in managing the program. Each MMS entered into an agreement. This clearly established that a paradigm shift in understanding pest management both at farmers' level and extension system level can effectively tackle the pest problem and also give ample benefits to farmers in terms of savings on input costs, health costs etc. Better quality products from such production systems also fetch a better price to farmers and are highly preferred by discerning consumers (refer http://www.downtoearth.org.in/default20060531.htm). Also, the NPM intervention for the first time shifted the control in terms of production back to the farmer (Sopan, 2006).

Awareness was created through state level campaign about the ill affects of pesticides and the potential alternatives. Communication material was developed and distributed for use.

18.6.2.2 Case of NPM in Rice in Kurnool Dist (2005–2006)

During *kharif* 2005, NPM in paddy was taken up in 6 villages of 2 mandals in Kurnool district. It was successfully implemented by 57 farmers in 28.4 ha. On an average there was a saving of $ 125/ha in cost of plant protection compared to conventionally grown rice crop. In yields, NPM farmers got additional yield of around 937.5 kg/ha, which may be attributed to increased number of natural enemy populations in the rice ecosystem that has happened due to continuous monitoring and timely interventions. In monetary terms, a net extra benefit of $ 290/ha was made by NPM farmers compared to non NPM farmers (Table 18.5).

Table 18.5 Economics of NPM v/s conventional Paddy in Kurnool dist (2005–2006)

SI. No	Village	Farmers		Area (ha)		Costs of plant protection ($ US/ha)		Yield (kg/ha)	
		NPM	Con	NPM	Con	NPM	Con	NPM	Conventional
1	Arlagadda	16	15	8.4	12.0	10.00	63.13	5683	5613
2	Durvesi	5	15	5.2	59.4	12.26	77.92	6187	6550
3	Bhupanapadu	4	5	1.6	2.0	11.00	50.00	5625	5887
4	Alamuru	17	23	7.6	10.0	12.00	81.00	5545	5380
5	Konidedu	6	9	2.4	3.8	13.00	57.00	6405	5012
6	Panyam	5	9	2.0	3.6	18.12	67.00	6450	4813
	Total								

(Source: Annual Report, NPM, 2005–2006)

Each participating farmer on an average saved up to US $ 160–310/ha (average across crops and across districts) on pest management expenses. With more area and more farmers coming into the program the saving will be higher. The ecological and other benefits would be enormous.

Nearly 30 neem seed powder units were established with SHGs along with 15 NPV units as village enterprises.

The benefits are not only seen in the areas of high pesticide use but also in areas of low pesticide use. The crops could be saved from the insect pests and diseases thus instilling new interest in the farmers.

The experiences during 2005–2006 clearly showed the benefit of moving towards non-chemical approaches in agriculture, and farmers were enthused by these approaches (Tables 18.6 and 18.7). SERP has organized a state level mela at Krishi Vigyan Kendra (KVK), Banaganpalli along with scientists from Agricultural University, ICAR institutions and KVKs.

Table 18.6 Economics of NPM across crops (2005–2006)

Crop	Cost of Plant protection ($ US/ha)		Saving ($ US/ha)
	Conventional	NPM	
Cotton	315	63	252
Chillies	940	125	815
Pigeon pea	94	20	74
Groundnut	94	20	74
Castor	125	25	100
Paddy	125	15	110

Source: (Annual reports of NPM, 2005–2006)

Table 18.7 Reduction in costs of pest management in Ananthapur, 2005–2006

S.NO	Village	No. of. Farmers	NPM area (in ha) (2005–2006)	2003–2004 Pesticide usage (in lit)	Value of pesticides ($ US)	Value of NPM extracts ($ US)	Total saving ($ US)
1	Chinnajalalapuram	39	73	7,000	13,500	1365	12,135
2	Madirepalli	36	56	5,000	10,000	1112	8,888
3	Guruguntla	36	42	4,687	16,400	910	15,490
	Total	111	171	16,687	39,900	3,387	36,513

Source: (Annual Report, NPM, 2005–2006)

18.6.3 Moving to Community Managed Sustainable Agriculture

The successful grounding of NPM during 2005–2006 has given important learning on how any ecologically sound and economically benefiting technology can be scaled up by providing proper institutional support. In 2006–2007, higher number of farmers in the same villages and more villages in the same districts and few newer districts joined the program. The program covered 1250 villages in 17 districts covering wide variety of crops from groundnut, rice, chillies and cotton. Program expanded to districts like Guntur where the pesticide problem is serious and north coastal Andhra Pradesh where the productivity of crops in general is low. The program is implemented in Adilabad, Ananthapur, Chittor, Guntur, Kadapa, Karimnagar, Khammam, Kurnool, Mahaboobnagar, Medak, Nalgonda, Nellore, Ranga Reddy, Srikakulam, Visakhapatnam, Vijayanagaram and Warangal. Program covered more than 80,000 farmers cultivating about 80,000 ha. In addition to pest management, initiations on soil productivity management and seed management have begun on a small scale. Agriculture credit from formal banks was mobilised in 3 districts to the tune of US $ 150 million.

In addition to the NPM, efforts were initiated to establish seed networks so that farmers produce and share their seed. Seed banks have been established in 100 villages where farmers could retain, replace, reuse and revive seed, and are managed by the community. The pilot in Ananthapur has shown good results. Efforts are also on to develop non-chemical soil productivity improvement practices based on the experiences of the villages like "Yenabavi" in Warangal which became the first organic village in the state.

In 2006–2007, while the institutional systems were further strengthened; focus was also given to specific commodities like rice and groundnut in Kurnool district, pigeon pea in Mahaboobnagar district, cotton in Warangal and Khammam and chillies in Guntur district (Table 18.8). The marketing links were established. The NPM products were in demand and could command premium in the market. The local processing and marketing of the commodities have also brought in additional benefits to the farmers.

Table 18.8 Savings on pesticides during 2006–2007

S.NO	CROP	Area (ha)	Avg. Savings/ha ($ US/ha)	Total Savings (Million $ US)
1	Cotton	16,170	312	5.05
2	Paddy	20,112	63	1.27
3	Pigeon pea	9,732	75	0.73
4	Groundnut	9,200	50	0.46
5	Chillies	1500	937	1.41
6	Others	10,400	63	0.66
	TOTAL	67,114		9.56

Source: (Annual Report NPM, CSA 2006–2007)

This scalingup experience in Andhra Pradesh has broken the myth that pesticides are inevitable in agriculture and also provided important lessons on the paradigm shift in technology, institutional systems and support systems required for sustaining agriculture especially of small and marginal farmers.

In 2007–2008, the program was further expanded to cover 1,800 villages in 18 districts. There are more than 350,000 participating farmers cultivating 280,000 ha. In the villages which are in second year, works on soil productivity management with local resources and local seed management have been planned.

- Special focus on certain commodities to deal with post harvest management to increase the value of the commodities. In 2007–2008, village level quality control centers were initiated in chilli producing villages.
- The marketing Community Resource Persons working with women SHGs were also trained in NPM and in 50 clusters (250 villages) they started motivating farmers to adopt NPM practices.
- Best performing villages are identified as resource villages and best practicing farmers are identified as community resource persons who will help in further scaling up of the program.
- Community Seed Banks where farmers produce, save, share and use their own quality seed would be established in 70 villages.

- Program will also be integrated with other ongoing programs like National Rural Employment Guarantee Program (NREGP) to provide further employment opportunities to the agriculture workers.
- Total program expenditure is about US $ 11/ha.

The state government has proposed to scale up NPM into organic farming in 5000 villages over next five years covering 10 million ha with an outlay of US $ 45.5 million. The proposal has been accepted under Additional Central Assistance from Prime Minister's package for distress states called *Rastriya Krishi Vikas Yojana*.

18.7 Conclusions

The pests and pesticides have seriously affected the farm based livelihoods in rural areas. The last three years experience shows that moving towards local resource based sustainable agriculture as the only way to sustain the livelihoods of small and marginal farmers and community based organizations like federations of women self help groups form an excellent institutional platform for scaling up such models. To sustain agriculture and agriculture based livelihoods, this calls for a complete paradigm shift in the way agricultural practices are understood, developed, promoted and supported. The new paradigm is based on the local resource based technologies and a community managed extension systems.

Abbreviations

CIBRC	Central Insecticide Board and Registration Committee
CSA	Centre for Sustainable Agriculture
CWS	Centre for World Solidarity
ETL	Economic Threshold Level
FAO	Food and Agriculture Organisation
FFS	Farmer Field Schools
IARI	Indian Agriculture Research Institute
ICAR	Indian Council for Agriculture Research
IPM	Integrated Pest Management
KVK	Krishi Vigyan Kendra (Farm Science Centres)
MMS	Mandal Mahila Samakya (Federation of Women Self Help Groups)
NPM	Non Pesticidal Management
RHC	Red Hairy Caterpillar
RMG	Rytu Mitra Group (Farmers group)
SERP	Society for Elimination of Rural Poverty
SHGs	Self Help Groups
TMC	Technology Mission on Cotton
TMOP	Technology Mission on Oilseeds and Pulses
WASSAN	Watershed Support Services and Activities Network

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Chapter 19
IPM Programs in Vegetable Crops in Australia and USA: Current Status and Emerging Trends

Nancy A. Schellhorn, Teresia W. Nyoike and Oscar E. Liburd

Abstract Integrated Pest Management (IPM) in vegetable crops is limited in the breadth and depth of information available. However, as with any IPM program the cornerstone practices involve regular monitoring, and knowledge of key components in the field and greenhouse that will guide sound decisions. We focus on current IPM programs in high value vegetable crops grown in Australia and the USA, and use case studies in Brassica vegetable and tomato systems to show specific tactics and tools used to evaluate the level of success achieved and the evidence for impact. We show that the drivers, which cause change from a single, usually chemical control tactic to a more integrated system relate to a crisis that cause crop loss or restricted market access and includes insecticide resistance, insecticide residues above the maximum allowable limit, or withdrawal of insecticides from lucrative international market. However, market demand and drivers aligned with growers' experiences and values may be more important in the future. Although the current 'Best Practice IPM' in Australia and the USA in vegetable systems includes: (1) routine crop monitoring, (2) using soft chemistries (where impact on beneficials is known) and (3) some monitoring of beneficial insects, IPM could be expanded and have greater integration with cultural control. We conclude by highlighting new advances and emerging trends and making suggestions on how to increase the adoption of IPM.

Keywords Vegetable IPM · Cultural control · Living mulches · Cover crops · Revegetation by design

19.1 Introduction

In vegetable systems in Australia (AUS) and the United States of America (USA), pest management tactics are many and varied including: biological, cultural, physical/mechanical, genetic and chemical. Integrating pest control tactics in such a way

N.A. Schellhorn (✉)
Commonwealth Scientific & Industrial Research Organization (CSIRO) Entomology, Indooroopilly, Queensland, Australia 4068
e-mail: nancy.schellhorn@csiro.au

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as to maximise the total benefits and minimise the harmful side effects that can arise from the exclusive use of chemical pesticides is known as Integrated Pest Management or IPM (Kogan, 1998; Finch and Collier, 2000). The cornerstone practices of integrated pest managers are monitoring crops regularly, and knowledge of key components in the field that will guide sound decisions including: accurate pest and natural enemy identification; monitoring pests, natural enemies and crop phenology, understanding of pests lifecycle; biology and ecology; examining the effects of pest damage on crop quality and market value; and knowing the effects of control measures on both the pests and natural enemies.

IPM has a long history primarily with focus on invertebrate pests, particularly for alfalfa (Lucerne), apple, cotton, and soybean (Kogan, 1998). IPM in vegetable crops is more recent and limited in the breadth and depth of information available. The wide diversity of vegetables and the system specific knowledge required for IPM has meant that developing the tools for the IPM tool-box has been slow and adoption even slower.

There are several drivers, which cause change from a single, usually chemical control tactic to a more integrated system (Quinby et al., 2006). Generally, these drivers relate to a crisis that cause crop loss or restricted market access and includes insecticide resistance, insecticide residues above the maximum allowable limit, or withdrawal of insecticides from lucrative international markets. An incursion of an exotic pest can also be a strong driver because often it can only be controlled by a broad-spectrum insecticide, in turn causing secondary pest outbreaks. Other drivers include those aligned with farmers' experiences and values such as participating in successful commercial IPM demonstrations, producing crops in a community that is positive about IPM (McDougall, 2007), concern for the health and safety for themself and their family, environmental stewardship, and pressure from new close neighbours as a result of urban sprawl.

Market demand for IPM labelled produce, domestically and internationally, may in the future be a strong driver for change. However, in Australia this has not yet been successful. Major supermarket chains are not interested in differentiating produce based on quality and safety issues. From their prospective, all the vegetables available on their shelves meet quality and assurance guidelines; therefore all produce they sell is high quality and safe. Furthermore, consumers are not knowledgeable with regards to IPM, and as yet there is no officially recognised certification process for IPM produced vegetables. This is in contrast to organic produce (grown in the absence of conventional pesticides and fertilizers) which is certified as 'organic' by the United States Department of Agriculture (USDA) and by seven different certifying bodies in Australia. In the USA and Australia, there are a few instances where growers are labelling foods as IPM, which means products were produced with limited pesticides. However there is no indication if consumers preferentially purchase IPM labelled produce. Finally, in the USA, there are drivers directed towards the development and implementation of IPM programs through legislative government funding from United States Department of Agriculture (USDA) and Environmental Protection Agency (EPA). This is largely the result of phasing out of many conventional insecticides (chlorinated-hydrocarbons, organophosphates and carbamates), hence a significant amount of funding through the USDA and EPA, which has facilitated research and extension at many land-grant institutions throughout the USA.

The best examples of IPM programs in vegetables in Australia include Brassica vegetables (broccoli, cauliflower and Brussels sprouts and very limited in Chinese Brassicas), potato, sweet corn, and processing tomatoes (McDougall, 2007). The drivers are: (1) the development of insecticide resistance in diamondback moth, *Plutella xylostella* (L.) (Lepidoptera: Plutellidae), in Brassica vegetables, and corn ear worm, *Heliothis armigera* (Hübner) (Lepidoptera: Noctuidae), in sweet corn and tomatoes; and (2) the withdrawal of organochlorine insecticides to control pests in potatoes, thus causing high dependence on organophosphate and synthetic pyrethroid insecticides (Horne et al., 1999). The indirect driver for sweet corn IPM was the restriction of sweet corn into the SE Asian market. This was due to the increasing presence of *H. armigera* as a result of insecticide control failures (McDougall, 2007). Although fresh tomato and capsicum growers have only recently begun adopting IPM, the key driver has been western flower thrips, *Franklinella occidentalis* (Pergande) (Thysanoptera: Thripidae) and the disease they vector, tomato spotted wilt virus. While the vegetable crops listed above have taken a more traditional approach to developing practices and tools of IPM, the crisis in the tomato and capsicum crops has lead to an innovative cultural control method using Australian native plants (see below).

The best examples of IPM programs in vegetables in the USA include Brassica vegetables (cauliflower, broccoli, cabbage, brussels sprouts, kale, collards, and kohlrabi) (Phillips and Rix, 1993) and fresh tomatoes. Broccoli and cabbage are the most economically important Brassica crops. Similar to Australia, the direct drivers are the development of insecticide resistance in diamondback moth, *Plutella xylostella*, and the cabbage maggot *Delia radicum* (L.) (Diptera: Anthomyiida) in brassica vegetables, and western flower thrips and leafminers (*Liriomyza* spp.) (Diptera: Agromyzidae) in tomatoes. A 'Do Nothing' strategy (Pedigo and Rice, 2006) allows natural populations of *Orius insidiosus* (Say) (Hemiptera: Anthocoridae) to build-up, which regulate western flower thrips and ultimately suppress tomato spotted wilt virus in tomatoes.

Here we focus on current IPM programs in high value vegetable crops grown in Australia and the USA. We provide general examples of IPM tactics, use case studies to show specific tactics and tools, and evaluate the level of success achieved and the evidence for impact. We highlight innovation, new advances and emerging trends and conclude with suggestions to remedy the criticisms about lack of adoption of IPM.

19.2 IPM Tactics

19.2.1 General Examples

There are numerous publications in the peer-reviewed scientific and gray literature on the principals, tools and tactics of IPM (Stern et al., 1959; Pedigo, 1995; Cuperus et al., 2000) but relatively few for vegetable crops. However the general tactics are the same; IPM programs must ultimately be considered in the context of basic ecological principles within the surrounding environment. Management strategies that can be employed include: biological, cultural, physical / mechanical, genetic and chemical control. Biological control of insect pests is the control or regulation of pest populations by natural enemies (DeBach and Rosen, 1991). Cultural control of insect pests include any modification in the way a crop is produced that results in lower pest populations or damage (Pedigo, 1995). This includes changes in practices and changes in surrounding areas of production (Schellhorn et al., 2000). Examples include a diverse set of practices: sanitation; destruction of alternate habitats and hosts used by pests; tillage; water management; plant density; crop rotation and fallow; crop planting date; trap cropping; vegetational diversity; fertilizer use; and harvest time. There are many aspects of physical / mechanical control considered under the category of cultural control. However, a few are not and they include: traps, bands, barriers such as screens, trenches, and shields, and extraction (vacuuming) (Oseto, 2000). All of these have been evaluated for decades and there are excellent reviews of recent papers in the literature. A less frequently studied factor is how cultural practices can also be used to affect natural enemies of insect pests (Schellhorn et al., 2000).

Genetic control includes host plant resistance and genetically modified organisms (GMOs). Host plant resistance is defined as the heritable qualities possessed by the plant, which influence the ultimate degree of damage caused by the pest (Cuperus et al., 2000: after Painter, 1951). Genetically modified (GM) vegetable plants have been altered using genetic engineering techniques for herbicide tolerance, and pest and disease resistance. Chemicals have been used to kill insect pests for centuries and information on the history, groups, and ecologically based use of chemical insecticides is available in numerous publications; hence not covered here.

Regardless of the breadth of approaches, in Australia and the USA, information on sustainable non-chemical control strategies for managing key insect pests in vegetable systems is very limited. The conventional strategy of using broad-spectrum pesticides remains a very popular tactic. Unfortunately, as many farmers have learned, this method of managing key pest populations is unsustainable and very expensive. In addition, it has tremendous negative impacts on non-target organisms and the environment. Below we show case systems that integrate sustainable strategies with IPM techniques, including monitoring protocols, decision support tools, biological control, cultural control and the use of reduced-risk or bio-rational pesticides.

19.2.1.1 Australian Case Studies

Vegetable production in Australia is worth approximately $2.3 billion AUD annually and divided 60:40 fresh and processing (see McDougall, 2007). Queensland and New South Wales account for the largest areas of vegetable production, but Victoria returns the greatest value for its vegetable production output. In 1996 a National Vegetable levy (0.5% of the gross sale value at first point of sale) was introduced to fund research and development for all vegetable crops; with some vegetable sectors having independent arrangements. Since the levy was introduced $43 million AUD has been spent on crop protection projects with $7 million AUD on IPM specific projects (McDougall, 2007). The vegetable sectors that have had the most effort in IPM research include Brassica vegetables, sweet corn, lettuce, tomatoes (processing and fresh), capsicum and English and sweet potatoes. Brassica vegetables, fresh tomato and capsicum case studies are highlighted below.

Brassica Vegetable IPM

In Australia, there are ca. 1400 growers producing 226,400 tonnes of Brassica vegetables with a gross value of $166 million AUD annually. Globally, diamondback moth (DBM) is the most destructive pest of Brassica vegetables, and is the main pest for southern Australia; the location where $>50\%$ of production takes place. Damage is caused by larvae tunnelling into the heads of cabbage and Brussels sprouts and by larval and pupal contamination inside cauliflower and broccoli florets.

For the past 50 years the principal control tactic for DBM has been the use of synthetic insecticides. However, DBM is difficult to control with insecticides because it has a fast development time, overlapping generations, continually available host-plants, feeds on the undersides of leaves avoiding spray deposits and develops resistance to chemicals rapidly. As proof, synthetic pyrethroid (SP) and organophosphate (OP) resistance developed throughout the 1980's and 1990's (Altmann, 1988; Baker and Kovalski, 1999), and it became necessary to spray more frequently to achieve control of DBM or to institute a regional crop production break in some production zones (Deuter, 1989). Despite the increased spraying, and production break, crop losses due to DBM attack continued, often on a larger scale than previously experienced (Baker, 2007).

As stated by Baker (2007), in the late 1990s two important developments occurred in Australia that have been instrumental in driving the development of IPM tools for the control of DBM. Firstly, a national industry-levy funded project to advance the integrated management of DBM in Brassica vegetables was initiated. A national project has continued in various forms over the past 10 years. Secondly, five new DBM insecticides were sequentially registered for use in Brassica vegetable crops. These insecticides each have different modes of action and metabolism, and several are relatively safe to natural enemies. These developments provided a unique opportunity to: improve DBM management, limit the further development of insecticide resistance, and develop IPM approach for all pests in Brassica vegetables. Single pest control is often rightly criticised, however in the Brassica system DBM is the catalyst for changing from chemical pest management to IPM. This creates an opportunity to integrate pest control tactics within and across Brassica pests.

Practices and Tools

Throughout the past 10 years of the national project considerable effort has been made to instil sound IPM practices among growers and emphasise the importance of monitoring crop health regularly. Workshops have been conducted and educational material generated to teach accurate pest and natural enemy identification;

understanding of pest lifecycle, biology and ecology; understanding the effects of pest damage on crop quality and market value; and knowing the effects of control measures on both the pests and natural enemies.

A range of decisions support tools have been developed to assist growers with the sustainable use of chemical insecticides including resistance management and insecticide spray decisions. The 'two-window' insecticide rotation strategy is a nationally organised, regionally focused insecticide rotation plan developed to delay resistance (Fig. 19.1; Baker, 2000). The idea is that all growers in a region may use a selection of chemicals during a specified 5 months period, and then switch to another selection of chemicals for the remaining 7 months of the year. The computer assisted dynamic-binominal *DBM Sampling Plan* has been developed to assist growers with spray decisions (Hamilton et al., 2004). This was the first plan to formally incorporate crop growth stage, destination markets and parasitism of DBM into action thresholds (Fig. 19.2; Hamilton et al., 2004; 2006). A DBM temperature development calculator has been developed to be used in conjunction with the sampling plan. For example, a 'no-spray' decision, combined with the observation of a few eggs may cause alarm. However this information plus weather forecast can be entered into the *DBM Development Calculator* to get an idea as to how many days before the eggs become larvae, hence better targeting of sprays – particularly biologicals that require larvae to feed on the plant material to ingest the chemical. Of course, any spray decision must be made where the impact on natural enemies (often called beneficial insects in Australia) is known. Therefore, the *Beneficial Insect Disruption* chart can be used to make an informed decision about chemical pest control with the least amount of disruption to beneficial insects. All of these decision support tools are available on the web at http://www.dpi.vic.gov.au (Click on: Agriculture & Food → Horticulture → Plant diseases & Pests → DBM sampling plan).

Science Supporting Brassica Vegetable IPM

In Australia, there has been extensive scientific investment in the basic understanding of DBM and its natural enemies in an attempt to develop control tactics other than insecticides and achieve better integrated pest control, eventually across pest species. Host-plant resistance was evaluated for broccoli and cabbage cultivars for DBM resistance to oviposition and larval development (Hamilton et al., 2005). The only difference in oviposition preference was between cabbage cultivars. Unfortunately, the varieties that were least attractive for oviposition were most suitable for larval development.

Some Brassica vegetables have been genetically modified to include the insecticidal protein, *Bacillus thurigensis* (*Bt*) (Shelton et al., 2002; Cao et al., 2005). However, to date no GM vegetables are grown commercially nor have they been trialled in the Australian environment (record of the Office of the Gene Technology Regulator www.ogtr.gov.au). Plant host location and oviposition by DBM, cabbage white butterfly *Pieris rapae* (L.) (Lepidoptera: Pieridae) and aphids *Brevicoryne brassicae* (L.) (Hemiptera: Aphidide) in a diversified cropping system was evaluated by Broad et al. (2008a; b). They found DBM host finding and oviposition and alate

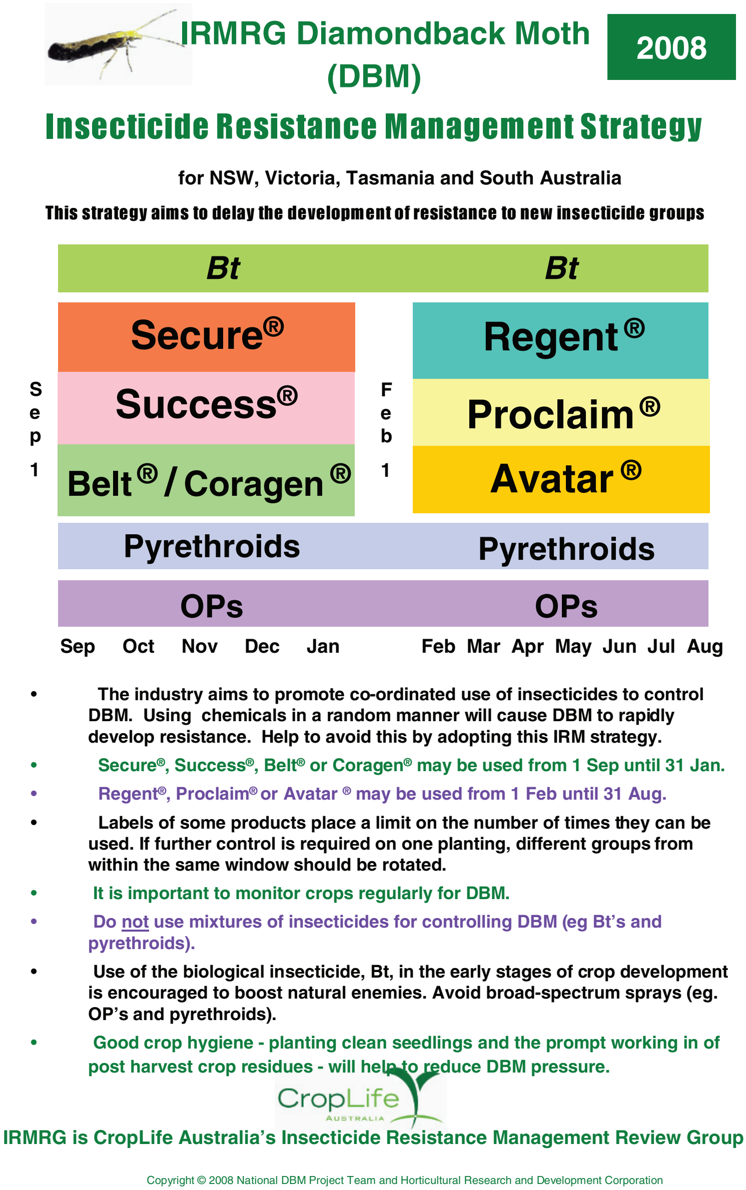

Fig. 19.1 'Two-window' insecticide resistance management rotation strategy developed by G. Baker and R. Roush (Baker, 2000)

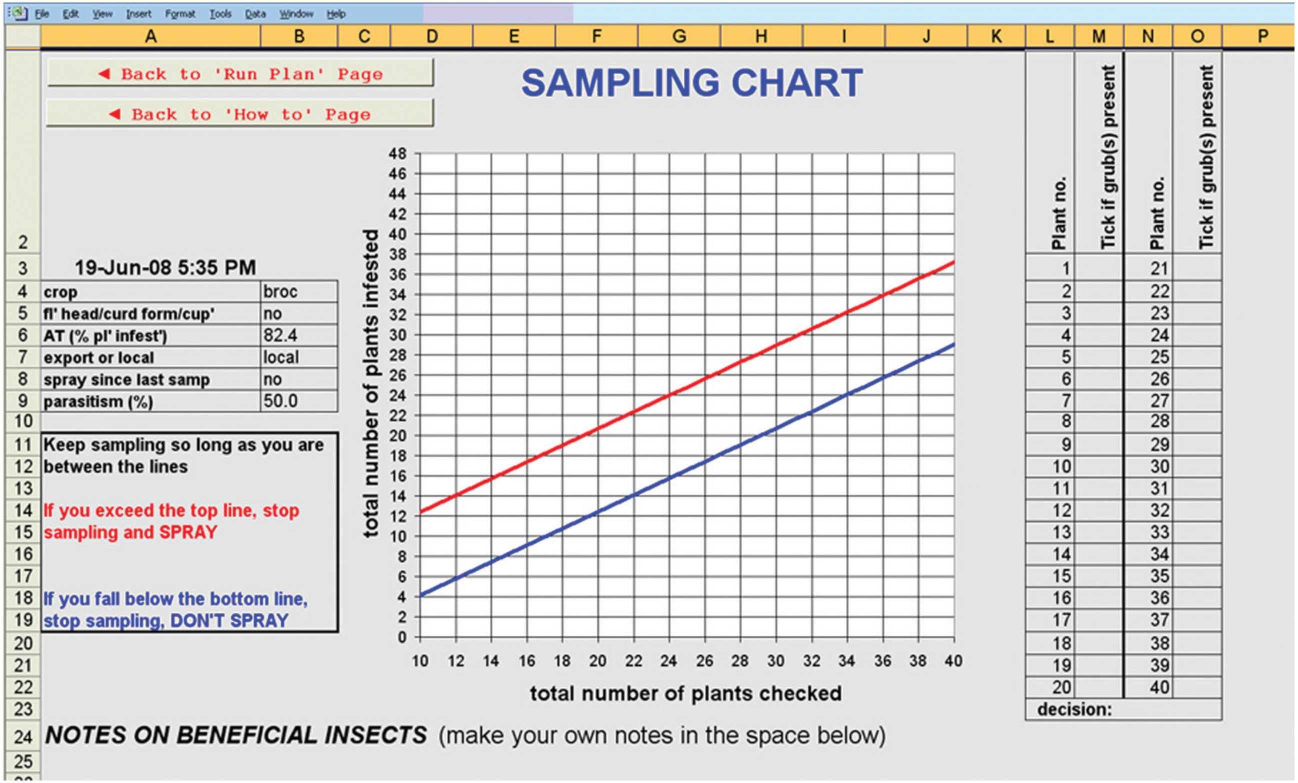

Fig. 19.2 Computer-assisted dynamic sampling plan for DBM. The upper left hand corner details the factors that were considered to generate this plan. The crop is broccoli, the floret is not showing nor will it in 5–7 days, market destination is domestic, the crop has not received a spray of insecticide other than a biological for the past week, and there is information on parasitism levels, which is 50%. The plan is printed and taken to the field to sample and record information. The details are described in Hamilton et al. (2004)

Fig. 19.3 Broccoli monoculture planted in a cereal rye (*Secale cereale*) cover crop (after Broad et al., 2008a; 2008b)

aphid host finding was disrupted when broccoli was planted into a cover crop of cereal rye *Secale cereale* (L.) (Poacea) that had been killed and rolled flat (Fig. 19.3). The cabbage white butterfly, did not respond similarly, but is well controlled by *Bt* sprays and several species of natural enemies.

There are many natural enemies (predators, parasitoids and diseases) of DBM found throughout the Mediterranean, temperate and sub-tropical regions of Australia where Brassica vegetables are grown (Kent, 1996). However, the parasitic hymenoptera *Diadegma semiclausum* (Héllen) (Hymenoptera: Ichneumonidae) is the most abundant parasitoid and causes significant mortality to DBM (Furlong et al., 2004a; Wang et al., 2004); so significant that it is worth factoring this mortality into decision making for pest control. For example, once parasitism levels are known this value is entered into the interactive program and the pest threshold is adjusted accordingly (Hamilton et al., 2004). In-field detection of parasitism will speed up this process. Potential field-based methods have been developed (Li et al., 2007), but not commercialized. Furthermore, in a detailed experimental approach, Furlong et al. (2004b) showed that natural enemy impact was greatest from farms adopting IPM and poorest from farms adopting conventional spray practices. Given *D. semiclausums*' potential as a natural control agent of DBM, several studies have focused on how cultural practices can be used to increase their abundance, longevity and fecundity. Studies have demonstrated in the lab and field enclosures that host finding, oviposition and longevity is improved when *D. semiclausum* female wasps are provided with a carbohydrate source such as nectar of flowering plants (Thompson, 2002). These findings are similar to results of others in Europe (Winkler et al., 2006) and the USA (Lee and Heimpel, 2008). *D. semiclausum* has also been shown to be highly vagile and moves readily from a refuge of flowering plants throughout the Brassica vegetable crop (Schellhorn et al., 2008a).

DBM egg, larval and pupal mortality from predators is thought to be important (Furlong et al., 2004a; Wang et al., 2004). However it is more difficult to know which predators are responsible, hence which cultural controls are best to increase their abundance and predation. Similar to the work by Symondson (2002), recent Australian studies have developed DNA probes to identify the remains of Brassica vegetable pests in the guts of predators (Hosseini, 2007). Results from this study clearly show that predators are eating several pests of Brassica vegetables.

19.2.1.2 Revegetation by Design

In vegetable systems numerous species of weeds are known to harbour pests and diseases of vegetable crops. Controlling the weeds can often be costly, short-term and cause environmental problems such as erosion, excessive dust, and changes in soil moisture. There is incentive for controlling weeds in crops because they can compete directly with the crop, but there is less incentive for controlling weeds along drainage ditches, fence rows, and land surrounding fields. In Australia, more and more tomato, capsicum and lettuce production is moving from the field to hydroponic containment facilities, which vary tremendously in their degree of openness to the environment. This change has resulted in more unmanaged weedy land on-farms and a reservoir for thrips pests (Western Flower *F. occidentalis*, tomato *F. schultzei* (Trybom), and onion *Thrips tabaci* (Lindeman)) and the disease that they vector such as tomato spotted wilt virus (Wood et al. submitted).

Revegetation by Design involves the integration of Australian native vegetation with vegetable production systems, with a focus on replacing weeds that host insect pests and diseases with native plants that do not, ultimately manipulating vegetation to disadvantage pests and disease at a farm scale. The native plants chosen must meet a range of criteria to be suitable for revegetation and the primary criteria include those plants that: (1) are not the host plants for vegetable pests and diseases (eg. pests and diseases cannot develop and populations cannot increase on these plants), (2) provide habitat for a range of natural enemies of pests so that they are available for early colonisation into the crop, (3) are compatible with agronomic practices in that they are low growing so as not to get in the way of machinery or containment facilities, and (4) native to the region. The secondary criteria are that the native plants: (1) provide an additional source of income for the farm such as native bush tucker, native cut flowers, and native seed for the revegetation industry. The outcome of Revegetation by Design is for long-term cost savings for weed, pest and disease control.

The list of plants trialled can be found in the Revegetation by Design Guidebook (Taverner et al., 2006). Thus far, the results show that there are several native plants that meet the criteria listed above (Wood et al. submitted), particularly in not being a good host for thrips or the virus they vector (Taverner and Wood, 2006). However, these native plants are quite good for hosting a very diverse array of parasitic hymenoptera, which quickly colonise newly planted single species stands of native plants (Stephens et al., 2006).

Replacing weeds with particular species of native plants has the potential to improve pest control for two main reasons. Firstly, many Australian native plants are not likely to be host plants for these exotic pests, hence pest populations cannot develop on them. This is particularly true for the Australian plants in the specious Myrtaceae family. All major vegetable crops, of which there are ca. 56, except one, Warrigal greens (in the Aizoaceae plant family) are exotic and >60% of their insect pests are exotic. The most difficult pests to control and most frequently sprayed are exotics (Schellhorn, 2008). Secondly, native plants can provide habitat (eg. shelter, alternative food and alternative prey) for natural enemies of vegetable insect pests as demonstrated by Stephens et al. (2006). Immature stages of insect predators were also present, suggesting that some species of native plants may be providing habitat for natural enemy population growth (Schellhorn et al., 2008b). This may allow for the build up of natural enemy populations close to the crop resulting in more individuals colonising the crop earlier. However, demonstrating that on-farm vegetation manipulation disadvantages the pest resulting in lower pest populations and lower pest control costs still needs rigorous testing. The work to date both in Australia and overseas certainly suggest that the Revegetation by Design approach is a promising and an important component of IPM.

19.2.1.3 USA Case Studies

Fresh market vegetable production for 24 selected crops in 2007 was estimated at 494 million hundredweight in the USA (U.S. Department of Agriculture, 2007). At least 0.80 million ha valued at 10.9 billion US dollars were harvested during 2007. California is the leading fresh market producer, accounting for 46% of the harvested area, 50% of production, and 54% of the total US vegetable value. Other leading producers contributing to the value of US vegetables are Florida (11.9% on 70,324 ha), Arizona (8.3% on 54,081 ha), Georgia (5.3% on 60,980 ha) and New York (3.5% on 33,244 ha) (U.S. Department of Agriculture, 2007).

In open field production most of the vegetables are grown on raised soil beds with drip lines covered with polythene plastics. The soil is fumigated before planting with the now restricted soil fumigant; methyl bromide to kill soil pathogens and weeds. Different colors of polythene are used ranging from white, black, and aluminimized mulch (UV-reflective). In the spring, use of black mulch is more popular in order to increase the soil temperature, and in the fall white or white-on-black is used to keep the temperature low. UV reflective mulch is mostly used in the production of tomatoes and squash despite their cost. It has several benefits including pests' reduction (whiteflies and thrips) compared to plants grown on bare soil, (Csizinszky et al., 1997; Stavisky et al., 2002) hence increased yields.

Brassica Vegetable IPM

Broccoli is by far the most valuable Brassica crop with 90% of production in California. However, Arizona and Texas have a significant acreage of this crop.

Cabbage is more widely distributed in production throughout the United States with New York and California the major producers, followed by Florida, Georgia, North Carolina, Texas and Wisconsin. In 2007, total hectares harvested with cabbage in USA were 30,204 valued at $ 413,199,000 USD. New York State was the leading cabbage producer with 5,143 ha valued at $101,190,000 USD and California ranks second with 6,000 ha valued at $85,944,000 USD (U.S. Department of Agriculture, 2007).

Similar to Australia, the evolution of IPM in Brassica vegetables has evolved as a mechanism to control the diamondback moth [DBM] and for the same reasons; development of resistance to many insecticides (Talekar and Shelton, 1993). By the 1980s DBM had developed resistance to organophosphates and carbamates, later to the *kurstaki* strain of *Bacillus thuringiensis* in the early 1990s (Anonymous, 1999). Several parasitoids have been introduced into the system for managing DBM and other key pests. Although *Trichogramma pretiosum* attack DBM eggs, and the ichneumonid wasp *Diadegma insularis*, attack the larvae, none of the parasitoids can give effective control in the field. The reduce-risk naturalyte insecticide, Spinosad is now used heavily in broccoli in California for DBM control. Spinosad is fairly compatible with some of the parasitoid in the system. Other serious pests of Brassicas include cabbage maggot, cabbage aphid, turnip aphid, cabbage seedpod weevil, loopers and cutworms.

The cabbage maggot, *Delia radicum*, is also considered a major pest, which has driven IPM adoption in brassicae particularly in the northeastern states. The management of cabbage maggot is facilitated with a rigorous monitoring program using yellow sticky cards (Finch, 1990) or periodic inspection of known numbers of Brassica plants selected randomly. A preventative strategy involves dipping the roots of transplants into a reduced-risk insecticide or application of a soil drench at the time of transplanting seedlings. Some cultural techniques have been developed, involving the use of soil barriers to control cabbage maggot (Hoffmann et al., 2001 and references within). The cabbage aphid, *Brevicoryne brassicae* is a major pest to all Brassica crops throughout California and Arizona. Cultural control tactics involving the use of living mulches have been used to suppress aphid populations, with some levels of success. Some of the newer reduced-risk neonicotinoid insecticides have also been used to manage cabbage aphid populations. Biological control agents such as the parasitoid, *Diaeretiella rapae* (McIntosh) (Hymonoptera: Braconidae) can help to regulate aphid populations but cannot control large infestations.

Science Supporting Brassica Vegetable IPM

The Science supporting the adoption of Brassica IPM involve frequent monitoring of Brassica plants for pests and beneficials, development of action thresholds for DBM and cabbage maggot, alternation of chemical classes to avoid resistance build-up and introduction of newer soft chemistries. In addition, allowing time-lapse between growing seasons (one brassica-free season).

Tomato IPM

In 2007, the USA fresh market field tomatoes harvested area was estimated to be 48,653 ha valued at $1.3 billion USD. The leading fresh market tomato state was Florida [15,428 ha, total value of $464,241,000 USD] and California with [16,734 ha, total value of $392,370,000 USD] in second place (U.S. Department of Agriculture, 2007). Glasshouse tomato production was estimated at 259 ha with Colorado being the leading producer with 38 ha valued at $34,220,000 USD and California in second place with 27 ha valued at $ 20,244,000 USD (U.S. Department of Agriculture, 2003). Although IPM programs have been developed in several parts of USA, below we case study those for field crops from California and Florida.

In Florida, in the late 1970s important development occurred, which resulted in a successful IPM program for tomatoes. The over-use of insecticides (34 sprays in a 90-day season) on tomatoes in an attempt to control secondary pests (such as leafminers, *Liriomyza* spp.) lead to the development of resistance in the leafminer population (Bloem and Mizell, 2004). This outbreak of leafminers led to interdisciplinary collaboration of major departments within the University of Florida such as plant pathology, entomology, horticulture and nematology. The resulting effect was the development of an aggressive program involving regular scouting and the development of action thresholds. This was coupled with the introduction of reflective mulch for reducing thrips and whiteflies, ultimately reducing virus transmission. In addition, the use of selective insecticides conserved key natural enemies, which regulate armyworm populations. One of the major achievements was the dramatic increase in yields from 32,490 to 41,117 kg per ha in 8 years from 1988–1989 to 1996–1997 growing season. Up to 50% of the growers would routinely scout for pests in the field before any pesticide application and this has led to an 82% reduction in the overall pesticide use including insecticides (Bloem and Mizell, 2004). Pesticide applications are guided by the scouting information that is collected biweekly, which has enabled growers to detect outbreaks of new and uncommon pests and diseases leading to early interventions. The shift towards the use of reduced-risk insecticides is quite evident in Florida. Other factors that led to the implementation of IPM included loss of farmland to urbanization and to diseases including late blight and bacterial spot.

Practices and Tools

Crop monitoring for pests and natural enemies has lead to the greatest advancements in tomato IPM (Fig. 19.4). Sampling procedures designed to estimate the population of pests (disease, weeds and insects) and their natural enemies (Bird, 2003) are part of a decision support system. For example, in Florida sampling one ha of tomato production is used to make pest control decisions. Six plants are sampled twice a week, randomly by selecting a new sample area each time to avoid bias (Schuster et al., 1996). Depending on the crop phenology a decision is made whether to inspect the entire plant or 3 leaflets on the plant stratum. In the case of aphids, whiteflies,

Fig. 19.4 Crop monitoring for key pests in tomatoes in north-central Florida, USA (Photo by: David Schuster, Gulf Coast REC, Wimauma, Florida, USA)

and leafminer larvae, the entire plant is inspected if the plant has 0–2 true leaves. If the plant has more than 2 true leaves the terminal 3 leaflets of the 3rd and 7th leaf from top are examined (Schuster et al., 1996). This procedure takes into account the vertical distribution of the pests' such as leafminer larvae and whitefly nymphs. Leafminer larvae and the sessile nymphs of whiteflies occur mostly on leaves 6 to 10 counting from the top. Yellow sticky traps are sometimes used to estimate the densities of leafminer and silverleaf whitefly adults. Silverleaf whitefly adults can also be determined by foliar counts. This entails turning over the leaf and counting the adult whiteflies encountered.

When sampling for armyworms and fruitworms, the whole plant is usually inspected at pre- and post bloom focusing mostly on the damaged leaves. Tomato pinworm larvae are counted on the leaves and after fruit set, 10 fruits per sample are inspected. Flower thrips and other pests are inspected at bloom, where 15 flowers are sampled by gently tapping them onto the hand.

Although economic thresholds have been established for various pests in tomatoes, their use is complicated by other factors. In Florida a set threshold has not been used in certain management practices because market values and weather variability is constantly changing and are unpredictable. However, the set values are used as an indicator for pest numbers that are likely to cause measurable damage on the plants. Economic thresholds need to be dynamic and reflect changes in input cost, market destinations and current market price.

19.2.1.4 Science Supporting Tomato IPM

The science that supported the development of tomato IPM involves: the breeding of virus-resistant varieties, and more frequent scouting and evaluation of reduced-risk or softer chemistries for controlling key pests, the development of action threshold and conservation of natural enemies. Also, the implementation of UV-reflective mulches as preventative measures against thrips and whiteflies.

19.3 Advances

In addition to some of the advances highlighted above, advances that promise to contribute to greater integration of control tactics, less reliance on insecticides and ultimately reduced pest problems are occurring at the plant, field, farm and landscape scale.

19.3.1 Plant and Field Scale

The key advances for the future at the plant and field scale include: (1) continued selection of varieties for pest resistance; (2) the ability to quantify mortality from generalist predators and parasitoids and incorporate this information into sampling plans and pest control decision making; (3) further development of biorationals / biopesticides; and (4) development of practices that increase sustainability and reduce fertilizer, pesticide and fuel inputs, for example living mulches and cover crops. Host plant resistance continues to be a promising area and important starting point for any IPM program. The first challenge is identifying the mechanism to resistance, once this is achieved making sure that the trait does not reduce quality linked to consumer preference (e.g. taste). Much effort has been given to developing host plant resistance in Brassica vegetables (Eigenbrode and Shelton, 1992; Hamilton et al., 2005). However, the cultivars with greatest resistance are often the least preferred by consumers. This has also been seen recently with lettuce in Australia and the selection of lettuce varieties resistant to lettuce aphid (personal communication Sandra McDougal).

Natural regulation by predators and parasitoids is estimated to provide 5–10 times more control of pest species than synthetic pesticides (Olfert et al., 2002). However, it is difficult to quantify the mortality that they cause and make pest control decisions accordingly. In vegetable systems around the world the same groups of natural enemies are a fundamental part of IPM and include predatory Hymenoptera (ants and wasps), Coleoptera (carabid, coccinellid, and staphylinid beetles), Heteroptera (pirate, assassin, and ambush bugs), Neuroptera (lacewings), Diptera (syrphid and chamaemyiid flies), as well as mites and spiders (Olfert et al., 2002). As more work demonstrates the importance of mortality from naturally occurring parasitoids and predators, better ways of including that information into pest control decision making will follow (Hamilton et al., 2004; 2006). The challenge will be including parameters for other pests as well, and integrating biological control agents with insecticide use.

Biopesticides / biorationals offer greater opportunity to integrate chemical control with natural enemies of pests. These are microbial pesticides (derived from viruses, bacteria, fungi or nematodes); or pesticides derived from plants and/or various new types of formulations particle film barriers, spinosad, and compounds such as pheromones. Most of these compounds have low non-target impact and degrade into non-toxic components (National Agriculture Information Service, 2006). Successful examples include the use of a virus biopesticide Gemstar® to control tomato bud worm in Australia, and Natralite® and several *Bt* products to control DBM in Brassica vegetable systems around the world.

Living mulches and cover crops are a means to reduce inputs. Living mulches are alive and maintained throughout the growing season and have been shown to cause a significant reduction in key pests in vegetables (Hooks et al., 1998; Frank and Liburd, 2005; Liburd et al., 2008; Nyoike et al., 2008). The subsequent benefit of pests' reduction has resulted in lower incidences of insect-transmitted virus in these crops. Cover crops are grown to cover the bare soil and can be planted into (Broad et al., 2008a; Broad et al., 2008b) or used during the off-season periods and become green manure when they are plowed back into the soil to improve soil nutrient quality (Bugg et al., 1991). They also suppress weeds and nematode populations (Abawi and Widmer, 2000), which will become increasingly important with the incremental phase out of the heavily used soil fumigant methyl bromide.

19.3.2 Farm and Landscape Scale

The key advances for the future at the farm and landscape scale include: (1) on-farm vegetation manipulation to reduce pests and increase natural enemies; and (2) area-wide management for pests and their natural enemies including what makes for pest suppressive landscapes. There is wider recognition that insect pest problems need to be considered beyond the crop boundary. Although information is limiting for horticultural crops, in grain landscapes there is evidence actions undertaken on individual farms have an impact both on their neighbours and regionally. The culmination of these actions can lead to changes in population dynamics of pests, natural enemies and pollinators (Schellhorn et al., 2008b). Such evidence suggests that growers may benefit by implementing area-wide pest management s trategies on a landscape scale in collaboration with growers of other crops that also host the major pest species. Furthermore, studies are demonstrating the crucial role of non-crop habitats in agricultural landscapes (Bianchi et al., 2006). In the USA, native remnant hedge rows and woodland edges and grasslands provide habitat for natural enemies (Marino and Landis, 1996; Menalled et al., 2003; Fiedler et al., 2008). At a more local scale, on-farm planting of native vegetation (particularly replacing weeds known to host pests) has promise for reducing pests (Wood et al., submitted) and increasing their enemies (Stephens et al., 2006). Further, studies have attempted to remedy the ephemeral agricultural landscapes by manipulating habitat within and adjacent to fields; thereby focussing on tactics such as flower strips or field margins to enhance natural enemies in adjacent crops (e.g. Dennis and Fry, 1992; Baggen and Gurr, 1998; Tylianakis et al., 2004; Schellhorn et al., 2008a).

19.4 Impact

Several projects have assessed the awareness, adoption and potential impacts of IPM in vegetable crops (Horne et al., 1999; Baker, 2007; McDougall, 2007; Page and Horne, 2007). Despite millions of dollars being spent over the last 10 plus years in vegetable IPM, the same legitimate concerns exists for most IPM programs. These include (a) in most cases the rate of adoption has been slow; (b) many programs rely principally on the timely application of pesticides as the principal management tactic; and (c) majority of programs focus on a single pest or pests within a category with little consideration of multiple pests interactions and control (Kogan, 1998).

19.4.1 Adoption in Australia

In Australia the current rate of awareness and adoption varies among vegetable sector and geographic region. The potato sector is the exception rather than the rule for IPM awareness and adoption. In surveys sent to 2000 potato growers, Horne et al. (1999) showed that IPM awareness ranged between 35 and 60%. Adoption was assessed by asking if growers practiced IPM and by asking how much of the crop was treated with insecticide. The response to the first question ranged between 15–30%, and the second question was 35–83%. Adoption was highest (up to 100%) in districts where advice was given in person by crop advisors. The most recent survey of IPM awareness and adoption across vegetable sectors indicates that 28% of growers practice IPM (Page and Horne, 2007). The criteria to support the claim was that growers knew what beneficial insects they had and the impact of the insecticides on these species.

A tremendous amount of educational material has been produced to assist with awareness and adoption of IPM. For Brassica vegetables, potatoes, tomatoes and lettuce the materials range from comprehensive to introductory and include materials like: CD-ROM on Integrated Pest Management for Brassica (Institute for Horticultural Development, 2002), DVDs on resistance management, web-based tool kits (http://www.dpi.vic.gov.au Click on: Agriculture & Food → Horticulture → Plant diseases & Pests → DBM sampling plan), comprehensive handbooks and regular newsletters, which include reminders about the importance of IRM (insecticide resistance management) and preliminary research findings (Baker, 2007; McDougall, 2007). In surveys, growers have indicated that this material has been important for increasing awareness of IPM (Baker, 2007). However, surveys have consistently shown that the highest levels of adoption have occurred where information on IPM has been presented to growers, in person (McDougall, 2007; Page and Horne, 2007) and often by someone with whom they have regular contact (Horne et al., 1999). For growers not using IPM, the major factor was that current pesticide approach still worked; not because growers believed that IPM was too expensive, complicated or too few selective chemicals (Page and Horne, 2007). This suggests that for Australian vegetable growers, the reason for not adopting IPM is lack of motivation, not lack of information (Page and Horne, 2007).

19.4.2 Adoption in USA

It is very difficult to measure adoption rates of vegetable IPM in the USA since no comprehensive studies have been conducted. However, over twenty companies are now demanding IPM-grown vegetables with the ultimate goal of promoting environmental stewardship. Many growers are aware of IPM but because they are not sure of the economics and benefits of this program they are cautious to adopt IPM practices. The future for IPM looks very promising and Federal Government is making the resources available to fund large-scale demonstration projects, which they hope will increase the adoption rates.

Implementation of IPM in vegetable production among other crops is of national interest in the USA. United States Department of Agriculture (USDA) through Cooperative State Research, Education and Extension Service (CSREES) provides several funding programs aimed at developing safe and effective IPM programs that reduce environmental and human health risks and increase farm returns http://www.csrees.usda.gov/integratedpestmanagement. Part of the focus of CSREES extension is to help growers and other pest managers gain confidence in alternative pest management strategies as they are demonstrated and evaluated in production and other systems. Also supported by CSREES is the four regional IPM Centers (north central, north eastern, southern and western) website. The website provides a link to each of the four Regional IPM Centers and complete list of the crop profiles http://www.ipmcenters.org/cropprofiles/index. Crop profiles provide information on production and pest management compiled by each state. Also available to USA growers is extension publications in all the States that can be downloaded and printed for free.

19.5 Synthesis

The current ‘Best Practice IPM’ in Australia and in the USA includes: (1) routine crop monitoring, (2) using soft chemistries (where impact on beneficials is known) and (3) some monitoring of pests and beneficial insects (McDougall, 2007). IPM could be expanded and integrated with cultural control tactics, however such examples are limited.

IPM technologies are still being developed and efforts are being made to apply them to numerous vegetable crops and integrated across pest species. Funding organizations such as USDA-CSREES and Horticulture Australia Limited (the funding organization for vegetable R&D) continue to fund research and extension programs in IPM through land-grant Universities in USA and Universities, state and commonwealth research institutions in Australia.

Integrated pest management has made growers and to some extent consumers aware of the benefits of adopting the programs, which reshaped pest management from solely relying on chemical control to integration of other factors such as biological and cultural control. However, the greatest challenges for increasing adoption of IPM include demonstrating: (1) IPM from planting to harvest, and (2) tools and tactics that motivate growers to change from a solely chemical control system to a sustainable integrated strategy. Arguably the most successful IPM programs in the world are the Farmer Field Schools (FFS) (Pontius et al., 2002), where group based in-field learning is used to promote IPM. These programs have trained over 2 million farmers, and achieved tremendous success (Pontius et al., 2002). The small scale FFS-like programs in Australia have clearly shown a benefit (Page and Horne, 2007). It will be important to have these programs supported by grower groups, funding bodies and government. Furthermore, as long as the sole reliance on chemicals works, motivation for change will have to come from drivers that increase profit margin (eg. either lower costs, increase yields or increase value of farm gate sales), change growers' quality of life (e.g. halve the time applying insecticides such as GM cotton has done for Australian cotton growers) or are legislated. The involvement of farmer groups will allow integration of sustainable practices that enable growers to make decisions and better understand some of the ecological and economical factors involved.

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Chapter 20
Integrated Pest Management in Fruits – Theory and Practice

Donn T. Johnson

Abstract Pest management practices used in several deciduous fruit crops are discussed. The chapter begins by noting the geographic origin and approximate date of domestication of several fruit crops and the need for more fruit breeding programs to identify and incorporate insect resistant genes into more fruit cultivars. It is assumed that fruit production probably began as small plantings where growers selected for the more pest resistant plants and later used earth-based insecticides like lead arsenate or oils to manage pest populations. After WWII, synthetic broad spectrum insecticides were developed followed by fairly rapid development of pesticide resistant insect populations. Broad spectrum pesticides eliminated many natural enemies and caused outbreaks of secondary pests like spider mites. In the last 30 years, pest management programs have become more knowledge-based and scouting intensive. More programs attempt to conserve natural enemies, delay development of pesticide resistance and be more environmentally sound (low-risk). This chapter conveys several categories of knowledge used in fruit pest management programs: fruit pest and crop agroecology; overwintering habitats; edge effect behavior; host preference; lists host resistant cultivars; shows how to derive lower and upper developmental thresholds, thermal constants, daily and cumulative degree-days (DD) after a biofix date; lists available DD models for several fruit pests; identifies two online DD calculators; lists general pest scouting guidelines and suggestions for maintaining visual and odor-based traps; and lists recommended economic thresholds for fruit pests. The next section presents four cases to illustrate various sampling programs and tactics used to manage fruit pests: (1) use of resistant rootstocks against grape phylloxera; (2) mite management program that integrates use of selective pesticides against key pests to ensure conservation of spider mite natural enemies, use of binomial or sequential sampling programs to predict the probability of biological control of spider mites, and a dynamic economic threshold for making management decisions; (3) areawide pheromone-based mating disruption

D.T. Johnson (✉)
Department of Entomology, Agriculture Experiment Station, University of Arkansas, Fayetteville, Arkansas 72701; USA
e-mail: dtjohnso@uark.edu
FAX: 479-575-2452

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of codling moths in Washington coupled with scouting to identify the need for supplemental application of low-risk insecticides; and (4) plum curculio DD model and sampling program to aid spray timing and the potential for using perimeter trees baited with aggregation pheromone and kairomone to focus plum curculio fruit damage and reduce insecticide usage. The chapter ends by identifying that recent laws and increased input costs, especially petroleum-based inputs, are causing a shift to more environmentally low-risk and sustainable fruit pest management tactics.

Keywords Deciduous fruit · Geographic origin · Degree-days · Biofix, scouting · Sampling · Economic threshold · Grape phylloxera · Resistant rootstock · Spider mite · Secondary pest · Selective pesticide · Natural enemy · Conservation · Mite sampling · Biological control · Plum curculio · Edge effect · Bait tree · Codling moth · Mating disruption · areawide · Low-risk · Sustainable

20.1 Introduction

Legislation, high input costs, and the appearance of insecticide resistant pest populations in temperate fruits are shifting fruit pest management programs toward more environmentally low-risk practices that make fruit production more sustainable. These programs integrate knowledge of crop and pest biology and ecology with site selection, host plant resistance, scouting, and making management decisions based on economic thresholds that prevent secondary pest outbreaks and avoid or delay development of insecticide resistance. Pest management programs have been developed for a spectrum of growers from individual grower to many growers (areawide). There is also renewed interest in evaluating fruit germplasm for insect resistance and using these genes in fruit breeding. This chapter will review the geographic origins of deciduous fruit and major pests, theory of integrated fruit pest management and give examples of some of the current management tactics available to fruit growers.

20.1.1 Origins of Deciduous Fruit

Fruits have been domesticated in various parts of the world over several millennia. Grape vines were domesticated as early as 6,000 B.C. (McGovern, 2003) and blueberries as late as the 20th century (Galletta and Ballington, 1996).

The Old World grape, *Vitis vinifera* L., originated between the Black and Caspian seas (Reisch and Pratt, 1996) with the first grape wine jars found in Godin Tepe, Iran dated ca. 3000–6000 B.C. (McGovern, 2003). Most of the 14,000 cultivars grown today were bred from *V. vinifera*. In the early 1800s, American cultivars were developed that were cold hardy from the native American fox grape, *V. labrusca* L., and heat resistant from the muscadine, *V. rotundifolia* Michx. These cultivars only constitute 8% of the world grape production (Reisch and Pratt, 1996).

As early as 3,000 B.C., the Greeks and Romans cultivated apple which was presumed to be the interspecific hybrid called *Malus x domestica* Borkh. Apple is thought to have originated from Alma-Ata (Father of Apples), Kazakhstan (Janick et al., 1996).

Peaches, *Prunus persica* (L.) Batsch, originated in China and were introduced to the Mediterranean area between 400 and 300 B.C. (Scoryza and Sherman, 1996).

Brambles include raspberries and blackberries that are in the genus *Rubus* (Tourn.) L. The Greeks used the European raspberry, *R. idaeus* subsp. *vulgatus* Arrhen for medicine since the first century and for fruit since the fourth century A.D. The North American red raspberry, *R. idaeus* subsp. *strigosus* Michx., was crossed with the European subspecies in the early eighteenth century. Blackberries include four *Rubus* subgenera (*Eubatus*, *Caesii*, *Suberecti, Coryfolii*), but were not domesticated until the nineteenth century because extensive wild plantings with edible fruit occurred in most parts of Europe, Asia and North America (Daubeny, 1996).

Vaccinium fruit crops (blueberries, cranberries) were recently domesticated. Cranberries, *Vaccinium macrocarpon* Aiton, were first developed in Massachusetts USA in 1816. Blueberry, *V. corybosum* L., production began in New Jersey USA in 1916, but commercial production now occurs in Europe, New Zealand and Australia (Galletta and Ballington, 1996).

Currently, there are 1,000 or more accessions or plants of different genera of deciduous fruit in the United States National Plant Germplasm System (Data from GRIN database 2008) (Table 20.1). However, resistant species or cultivars have been identified for only a few deciduous fruit pests (Table 20.2). This fact points to the need to increase research and breeding efforts to identify insect and disease resistant germplasm for use in pest management.

Table 20.1 Fruit genera with more than 1000 accessions or plants in the plant germplasm collections and their location in the United States National Plant Germplasm System (Data from GRIN database 2008)

Genus	Number of accessions (origin)	Location of holdings
Fragaria (strawberry)	1810 (1001 = USA, 361 = Chile)	Corvallis, OR
Malus (apple)	3548	Geneva, NY
Prunus (cherry, peach, plum)	1727	Davis, CA
Pyrus (pear)	2379 (937 = USA, 181 = France, 118 = China)	Corvallis, OR
Rubus (blackberry, raspberry)	2276 (1141 = USA, 180 = China, 137 = UK)	Corvallis, OR
Vaccinium (blueberry)	1682 (1210 = USA, 167 = Russian Federation)	Corvallis, OR
Vitis (grape)	2831	Davis, CA
Vitis (grape, muscadine)	1204 (mostly North America)	Geneva, NY

Table 20.2 Germplasm resistant to fruit pests

Pest	Resistant germplasm	Reference
Apple maggot, *Rhagoletis pomonella* (Walsh)	**Species:** crab apple *Malus baccata, M. sikkimensis, M. toringoides* **Crab apple cultivars:** Dupont Flowering, Henrietta Crosby, Almey, Seedling of Geneva, Morden 455	Neilson (1967); Pree (1977)
Root form of grape phylloxera, *Daktulosphaira vitifoliae* (Fitch)	**Species:** *Vitis aestivalis, V. berlandieri, V. cordifolia, V. rupestris, V. solonis* **Rootstocks:** *'99 R', '110 R', '1103P', '140R', '1616 C, '44–53 M', 'Gravesac', 'Gloire de Montpelier','Saint George' '101–14', 'Schwarzmann', '3309'*	Stevenson (1978); Pongrácz (1983)
Rosy apple aphid, *Dysaphis plantaginea* (Passerini)	**Species:** *M. robusta*	Alston and Briggs (1970)
Woolly apple aphid, *Eriosoma lanigerum* (Hausmann)	**Species:** *Malus halliana, M. hupehensis, M. tschonoskii, M. glaucescens* **Apple cultivars:** Northern Spy, Winter Majetin, Irish Peach, Cliff's Seedling[1], John Sharp[1], Mona Hay[1], Ivory's Double Vigour, Kola, Redflesh (limited testing found other cultivars lightly infested) **Rootstocks:** M 793[2], MM 102[2], MM 104, MM 106, MM 109, MM 111, CG 202[2], CG 210, Robusta 5	Anonymous (1905); Cummins et al. (1981); Knight et al. (1962)

[1] Cliff's Seedling, John Sharp and Mona Hay derived resistance to woolly apple aphid from Northern Spy parentage.
[2] M = Merton, MM = Malling-Merton and CG = Cornell-Geneva rootstock series from Northern Spy parentage.

20.1.2 Origins of Deciduous Fruit Pests

Many of the current fruit pests and diseases were introduced into new areas by traders and immigrants as they transported host fruit products and plant materials around the world (Table 20.3). Some introduced fruits became a host to native insect species in the United States. For example: the plum curculio, *Conotrachelus nenuphar* (Herbst), shifted from wild hawthorns (*Crataegus* spp.), American plum and crab apple species to apple, cherry, blueberry, huckleberry, grape, peach and persimmon (Quaintance and Jenne, 1912; Snapp, 1930; Chapman, 1938; Bobb, 1952). The apple maggot, *Rhagoletis pomonella* (Walsh), shifted from wild hawthorns (*Crataegus* spp.) to apple (Feder and Bush, 1989).

20.1.3 History of Fruit Pest Management

Fruit pest management has gone through several phases since fruit domestication. For centuries, it is assumed that fruits were probably grown in small plantings and

Table 20.3 Geographic origin of key and indirect pests of deciduous fruits

Pest	Origin	Reference
Apple maggot *Rhagoletis pomonella* (Walsh)	Eastern USA	Walsh (1867)
Codling moth,*Cydia pomonella* (L.)	Europe	Chapman (1973)
Japanese beetle, *Popillia japonica* Newman	Japan	Hadley (1940)
Oriental fruit moth, *Grapholita molesta* (Busck)	Japan	Chapman (1973)
Plum curculio, *Conotrachelus nenuphar* (Herbst)	Eastern USA	Chapman (1938)
Grape berry moth, *Enodopiza viteana* (Clemens)	Eastern USA	Slingerland and Crosby (1914)
San Jose scale, *Quadraspidiotus perniciosus* (Comstock)	East Asia	Despeissis (1903)
Grape phylloxera, *Daktulosphaira vitifoliae* (Fitch)	Eastern USA	Galet (1982)
Woolly apple aphid, *Eriosoma lanigerum* (Hausmann)	Eastern USA	Marlatt (1897)

even harvested from the wild in the case of blackberries and blueberries. Over the years, growers continued to propagate and cultivate the healthiest plants that survived their climate and best avoided damage by various pest and disease complexes.

For centuries, world trade by land and sea introduced consumers and growers to new fruit cultivars and exotic fruit species. As a result, there has been increased demand for locally grown and exotic fruit crops often resulting in larger acreage plantings of specific cultivars. Currently, fruit plantings around the world consist of less diverse germplasm than in past centuries (Campbell, 1961).

Pest management practices began to change in the 1800s. The introduction of the grape disease, powdery mildew, and the grape root pest, grape phylloxera, on American vines shipped to Europe in the late 1850s and 1860s caused major vine death in Europe. Eventually Bordeaux mixture was identified as a means to prevent damage by powdery mildew and phylloxera-resistant rootstocks were developed. These efforts lead to the discovery of and confirmed insecticidal efficacy against phylloxera of soil injections of carbon disulfide (Ordish, 1987).

Slingerland and Crosby (1914) reported that codling moth, *Cydia pomonella* (L.), San Jose scale, *Quadraspidiotus perniciosus* (Comstock), peachtree borers, *Synanthedon exitiosa* (Say), grape insects and plum curculio, *Conotrachelus nenuphar* (Herbst), annually destroyed 40–60 percent of the deciduous fruit crops in the United States resulting in loss of $66,000,000 in both yield and use of repressive measures. It was recommended that growers augment the natural checks of each fruit insect pest population (temperature, drought, wet, parasites, predaceous enemies, fungus and bacterial diseases) with clean farming practices that included maintaining healthy trees and reducing overwintering sites, e.g., cultivate orchard ground cover, use crop rotation in strawberries, remove accumulations of dead leaves in and around planting, and remove stone piles. Recommendations for applying the few insecticides available at the time were to be timed against younger, more susceptible insect stages and ensure thorough coverage. In the early 1900s, the New York spray schedule included a mixture of lime-sulfur and arsenate of lead sprayed at the following phenological steps: dormant against San Jose scale, blister mite, *Eriophyes* sp., and tufted apple bud moth, *Platynota idaeusalis* (Walker); pink against tufted apple bud-moth, *Platynota idaeusalis* (Walker), and case-bearers; petal fall and three weeks later against codling moth, and the last week of July against second brood codling moth (Slingerland and Crosby, 1914).

From the late 1800s to 1945, the main insecticidal compounds included: oils, soaps and resins (natural and petroleum-based); plant-derived poisons (nicotine, pyrethrin, rotenone, sabadilla); and inorganic compounds (boiling water washes, carbon disulphide, arsenic, sulfur, lime, gas lime, lead arsenic). An artifact of research on human neurotoxins for weapons in WWII was the finding that many of these compounds proved to be excellent insecticides (Marlatt, 1897; Pedigo, 2002).

Following the introduction of DDT in 1945, azinphos-methyl, carbaryl and phosmet were some of the major insecticides recommended for pest management in fruit crops. The organophosphates were the most widely used class of insecticides in pome fruit orchards in the United States (Beers and Brunner, 1991; NASS, 1998). The passing of the United States Food Quality and Protection Act (FQPA) of 1996 called for less exposure of the public and the environment to compounds like chlorinated hydrocarbons, organophosphates and carbamate insecticides. Similar laws were approved in other countries and these governments began to provide more research and extension funds to develop and implement alternative fruit pest management tactics. These alternative tactics were designed to reduce environmental risk, cause less worker health problems and be more sustainable than the many high-risk, petroleum-based synthetic insecticides that FQPA had targeted for cancellation by EPA. These alternative pest management programs were to include multiple tactics that would reduce key pests below economic injury levels (EIL), conserve natural enemies and significantly delay development of insecticide resistance in insect and mite pest populations.

Since 1989 there have been numerous changes in the availability, allowed usage and efficacy of broad spectrum insecticides and miticides. Organophosphate insecticides were considered high-risk for environmental contamination and harm of non-target organisms, especially humans. Since the passing of FQPA in 1996, EPA cancelled use or the manufacturer did not re-register ethyl parathion, methyl parathion, methoxychlor and phosphamidon. After 1998, restrictions were set on the amount of azinphos-methyl allowed per acre, whereas chlorpyrifos and formetanate hydrochloride uses were restricted to pre-bloom and to the bloom period, respectively (Brunner et al., 2003).

By the early 1990s, resistance to organophosphate insecticides, especially azinphos-methyl, was reported in key pest populations of codling moth and leafrollers in fruit plantings in the western United States. Many secondary pests, such as aphids, leafhoppers, and leafminers, were also reported as resistant to organophosphate and carbamate insecticides (Varela et al., 1993; Knight et al., 1994 and

Dunley et al., 2006). Resistance to azinphos-methyl and cross-resistance between azinphos-methyl and the insect growth regulators tebufenozide and methoxyfenozide were found in populations of leafrollers, *Choristoneura rosaceana* (Harris) and *Pandemis pyrusana* Kearfott, collected from commercial orchards (Dunley et al., 2006).

20.1.3.1 Toxicity of Pesticides to Natural Enemies

Continued use of broad-spectrum insecticides prevents implementation of biological control for many secondary pests because most biological control agents are killed (Croft and Brown, 1975; Croft, 1990). However, the important phytoseiid predatory mites have developed resistance to some of the long-used organophosphate insecticides azinphos-methyl, endosulfan, malathion, and phosmet. Predatory insects are moderately to seriously impacted by many broad spectrum insecticides in the following classes: organophosphate (except phosmet), carbamate, pyrethroid, neonicotinoid, and pyridazinone. The insecticides considered highly to moderately toxic to predatory mites include: carbaryl, chlorpyrifos, diazinon, esfenvalerate, methomyl, oxamyl, and permethrin. Miticides only slightly toxic to predatory mites include bifenazate, clofentezine, etoxazole, fenbutatin-oxide, propargite and oil, but others that are highly toxic include the carbamates: oxamyl, formetanate hydrochloride, and dicofol. The pyrethroids aggravate and induce outbreaks of mites, woolly apple aphids, *Eriosoma lanigerum* (Hausmann), San Jose scales and Comstock mealybugs, *Pseudococcus comstocki* (Kuwana) (Croft, 1975; Mahr, 2008; Walgenbach, 2008). A good secondary pest management program is sustained by using these known selective pesticides that do not disrupt natural enemies.

20.1.3.2 Economic Induced Shift of Tactics

A series of events caused insecticide prices to increase significantly after 1996. First, many of the cheaper but high-risk compounds were cancelled. Second, new formulations and classes of insecticides cost more to develop and register since FQPA became law. Third, oil and transportation costs began to increase significantly after 2007 when world demand for oil first exceeded apparent supply. As a result, growers became more receptive to implementing pest monitoring programs. This included using decision-making protocols to justify and aid timing for applying synthetic insecticides and to consider using non-insecticide tactics, especially pheromone-based mating disruption.

Newer classes of pesticides tend to be safer to humans and the environment and are usually more selective which results in less impact on natural enemies (Brunner et al., 2003). Replacing conventional control tactics (use of neuroactive insecticides, primarily organophosphates) with safer and less disruptive controls requires a combination of tactics. The most promising tactics include mating disruption, granulosis virus, insect growth regulators, sterile insect release, and cultural practices (http://ipmnet.org/CodlingMoth/bionomics/about.html).

20.2 Theory

20.2.1 Foundation of Pest Management

Effective use of pest management tactics from individual plantings to areawide management programs requires a thorough foundation and knowledge of: insect biology and behavior as affected by habitat and edge effects; relationship of crop phenology to pest biology; effects of temperature on development as represented by degree-day (DD) models; pest scouting methods; economic thresholds and decision-making protocols that justify use of a control tactic(s) and aid timing of tactic.

20.2.2 Habitat and Edge Effects

Fruits are perennial crops where climate and site selection affect overwintering survival and the potential risk for damage by certain fruit pest species. Snow cover during low winter temperatures was reported to increase pupal survival of grape berry moth, *Endopiza viteana* (Clemens), and strongly influenced the risk of infestations by grape berry moth. Also, grape berry moth pupae survived best in groundcover debris in the woods or hedgerows than in the vineyard with less debris. The overwintered adults emerge in the spring and disperse from woodlots to lay eggs on perimeter vines. First generation grape berry moth larvae damaged more fruit clusters in the perimeter vines than the more interior rows = "edge effect". It was reported that as the percentage of the vineyard perimeter bordered by woodlots or hedgerows increased from 0 to 25%, 25 to 50% and >50% the classification of the vineyard risk potential for damage by grape berry moth increased from low to medium to high risk, respectively (Martinson et al., 1991). Johnson et al. (1988) recommended that the best location to place sex pheromone traps for monitoring flight of first generation grape berry moths was from a tree limb in the edge of woodlot adjacent to the vineyard (Table 20.5). In contrast, it was recommended to monitor moth flight of later generations in traps placed inside the vineyard.

A similarly strong edge effect behavior was reported as overwintered plum curculio adults emerge from woodlots and disperse to edge of tree fruit plantings. Fruit damage was higher in the orchard perimeter adjacent to woods in the spring than in either the perimeter adjacent to open fields or in the orchard interior. Damage did increase inside the orchard during the summer generation in the southern United States. Therefore, it was recommended to tether gray pyramid traps to perimeter orchard trees to monitor plum curculio adult movement to the orchard in the spring (Table 20.5) (Johnson et al., 2002a; Johnson et al., 2002b).

Codling moth fruit damage in an orchard treated with 1000 Isomate-C dispensers per hectare disrupted mating inside the orchard but perimeter trees often had higher fruit damage than did interior trees due to dispersal of gravid females from outside the orchard (Gutt and Brunner, 1998).

Edge effect feeding behavior of these three species and probably others allow growers to make spot or perimeter applications of insecticides versus full planting applications.

20.2.3 Crop Phenology and Pest Biology

All fruit pest and disease management guides have the pest and disease management recommendations arranged chronologically by plant phenological stages. For example, the phenological stages of apple are dormant, silver tip, green tip to 1/2″ green, tight cluster to pink, bloom, petal fall, and then a periodic series of cover sprays through to harvest (Walgenbach, 2008).

20.2.4 Developmental Degree-Day (DD) Models

Plant and arthropod development occurs between two temperature thresholds, a lower developmental threshold (LDT) and an upper developmental threshold (UDT). Species-specific LDT and UDT values for many of the deciduous fruit pests are listed in Table 20.4. The LTD for fruit insects ranges from 6.1°C (43°F) for the orange tortrix, *Argyrotaenia citrana* (Fernald) (Bettiga et al., 1992) to 13.9°C (57°F) for the pink bollworm, *Pectinophora gossypiella* (Saunders) (Beasley and Adams, 1996). The UDT is an estimated temperature where development rate approaches zero as temperature is increased. This UDT ranges from 25.6°C (78°F) for the orange tortrix (Bettiga et al., 1992) to 34°C (93°F) for the grape berry moth (Tobin et al., 2001).

20.2.4.1 Deriving LDT and UDT

Species-specific values for LDT and UDT are derived as follows. Experimentally, 30 or more eggs, larvae or pupae are exposed together as a cohort to one of four or more constant temperatures in an environmental cabinet with a summer photoperiod (>12 h light). The number of days to development to the next stage are recorded for each insect and averaged for each cohort. The developmental rate (v) for a growth stage = 1 divided by the number of days to complete stage development. Figure 20.1 includes a hypothetical set of data plotted as developmental rate (v) versus the corresponding constant temperature (t). A linear regression can be calculated from these data points to derive an equation of the line ($v = a + bt$), where a = intercept of the y-axis when t = 0, and b = slope of line. The fit of this predicted line to these hypothetical data is noted by the square of the correlation coefficient ($R^2 = 0.992$). The LDT = t, given that the developmental rate v = 0. Therefore, the LDT can be derived by solving for $t_{(v=0)}$ in equation 1. In this example, the y-intercept = –0.0104 and the slope = 0.0014, therefore,

Table 20.4 Predictive models based on lower (LDT) and upper (UDT) developmental temperature thresholds (°C) and cumulative degree-day (Σ DD °C) after biofix for fruit pests

Pest	LDT	UDT	Σ DD °C (DD °F) After biofix[1]	Reference
Apple maggot, *Rhagoletis pomonella* (Walsh)	6.4	–	Fly emergence by 627 (1129) after March 1	Reissig et al. (1979)
Tufted apple bud moth, *Platynota idaeusalis* (Walker)	7.2	32.8	Hatch by 292 (525.6) after 1st trap catch	Hogmire (1995)
Oriental fruit moth, *Grapholita molesta* (Busck)	7.2	32.2	Hatch from 222 (400) to 389 (700) after 1st trap catch	Croft et al. (1980)
Grape berry moth, *Endopiza viteana* (Clemens)	8.4	34	50% egg hatch at 264 (475) after January 1	Tobin et al. (2001, 2003)
Codling moth, *Cydia pomonella* (L.)	10	31.1	Hatch from 138 (250)[2] to 444 (800) after 1st trap catch	Pitcairn et al. (1992)
Plum curculio, *Conotrachelus nenuphar* (Herbst)	10	–	Adult disperse from 95% petal fall until 189 DD (340)	Reissig et al. (1998)
San Jose scale, *Quadraspidiotus perniciosus* (Comstock)	10.6	32.2	Crawlers from 222 (400) to 389 (700) since 1st trap catch	Jorgensen et al. (1981)

[1] Biofix is first date after which traps have sustained catch on two successive nights.
[2] Biofix is first date after which traps have sustained catch on two successive nights and when sunset temperatures are above 16.7°C which allows egg laying.

$$\text{LTD} = t_{(v=0)} = -(\text{y intercept})/\text{slope} = -(-0.0104)/(0.0014) = 7.3°\text{C}(45.1°\text{F}) \quad (20.1)$$

20.2.4.2 Deriving the Thermal Constant (TC)

The inverse of the slope of the linear equation gives the thermal constant (TC) as a cumulative number of degree-days (DD) or physiological developmental time units required to complete a given growth stage (Baskerville and Emin, 1969). Equation (2) calculates TC from data used in Fig. 20.1:

$$\text{TC} = 1/\text{slope} = 1/0.00142 = 704\text{DD}°\text{C}(1,267\ \text{DD}°\text{F}) \quad (20.2)$$

The thermal constant for the complete life cycle of a given species is the sum of the stage-specific cumulative DD values = preovipositon period + egg + larva or nymph + pupa. Values in Celsius DD are noted throughout this text and are 5/9 that of the value for Fahrenheit DD noted in parentheses.

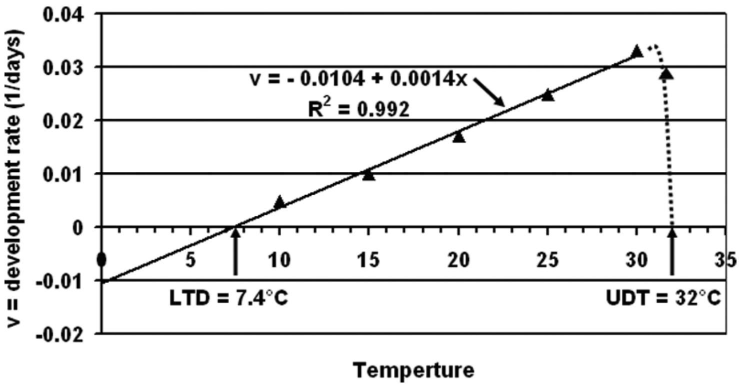

Fig. 20.1 The lower developmental threshold (LDT) is derived from the equation of the line for the linear set of values (R^2 = square of the correlation coefficient) given that the developmental rate v = 0, then the solution for x = − (y-axis intercept where x = 0)/slope = 0.0104/0.0014 = 7.4°C. The thermal constant for duration of life cycle (or stage) = 1/slope = 1/0.0014 = 704 degree-days. The upper developmental threshold (UDT) is estimated to be 32°C where v is presumed to decrease to 0

20.2.4.3 Biofix and Cumulative DD

Pest managers should begin to accumulate daily DD after a biofix date or biological event. After a given number of DD, the sampling program is initiated to estimate the pest population. When the sample count exceeds the economic threshold then a decision is made to use an insecticide or other management tactic. For example, begin to accumulate DD after January 1 in Pennsylvania for grape berry moth and begin treatment by 264 DD. In the case for codling moth, the biofix was when trap catch of codling moths occurred on three successive nights when sunset temperatures were above 16.7°C (62°F), a requirement for flight and egg laying, and begin treatment by 138 DD (Pitcairn et al., 1992) (Tables. 20.4 and 20.5).

20.2.4.4 Estimating Daily Degree-Days

Several methods are available to estimate daily growing DD values, where max = daily maximum temperature; and min = daily minimum temperature. Degree-day calculations and accumulations are based on the area under the diurnal temperature curve and between the LDT and UDT. The inclusion of UDT in the DD calculation method with either a "horizontal cutoff" or a "vertical cutoff" is critical in geographic regions where summer maximum temperatures often exceed the UDT. This prevents over-estimation of cumulative DD.

Hourly temperature data recorded by electronic weather loggers in the field can be used to calculate the most accurate estimates of daily DD. Logger software programs can record temperature data in different increments per day, calculate degree-hrs between LDT and UDT, accumulate degree-hrs for day and divide by this daily value by the number of records per day to give cumulative daily DD. The other calculation methods use daily max and min temperatures from the simplest to

Table 20.5 Sampling methods and economic thresholds for pests of apple (Agnello et al., 1993; Hogmire, 1995), blackberry (Johnson, 1985; McKern et al., 2007), grape (Johnson et al., 1988; Tobin et al., 2001, 2003) and peach (Horton and Johnson, 2005)

Species:	Economic threshold
All Fruit: Climbing cutworms (many spp.), or Grape flea beetle (grapes only), *Altica chalybea* Illiger	From bud swell to 1-inch growth, check buds for presence of flea beetles or chewing damage (hollowed out); treat if >2% bud damage or flea beetles present
Japanese beetle, *Popillia japonica* Newman	Pheromone trap can be set out by June 1 to note first adults, then twice weekly inspect susceptible cultivars, treat if foliage injury extends further down than the top 3rd of canopy
Grape: Grape Berry Moth, *Endopiza viteana* (Clemens)	By bud break, place 3 pheromone traps at 2 m height on limb along woodlot perimeter next to vineyard, check for 1st catch (biofix), treat perimeter vines at 264 DD°C after biofix and then weekly check 300 clusters in perimeter for damage; treat if >1% new cluster damage; after first flight move traps into vineyard and monitor weekly
Apple and Peach: San Jose scale, *Quadraspidiotus perniciosus* (Comstock)	Place pheromone trap by April 1, check twice weekly, note 1st male catch (biofix); 175 DD°C after biofix begin weekly inspection of double-stick tape wrapped around scale-infested limbs for yellow crawlers and apply insecticide to only infested trees while crawlers are detected
Oriental fruit moth, *Grapholita molesta* (Busck)	By pink peach bloom, place 3 pheromone traps in interior trees (30 m apart), weekly check for 1st catch (biofix), 222 DD°C after biofix inspect terminals of 10 trees for flagging and treat during hatch period (Table 20.4) if >5 moths caught per trap per week or see new terminal flagging
Plum curculio, *Conotrachelus nenuphar* (Herbst)	When 2 days in spring >21.1°C, tether 4 gray Tedders traps to individual perimeter apple or peach trees adjacent to woods, check traps weekly and inspect 30 fruit on 10 trees in perimeter for new damage; treat if traps exceed 0.05 adults per trap per day or >1% new feeding damage
Apple: Rosy apple aphid, *Dysaphis plantaginea* (Passerini)	Apple at pink, check 10 fruit clusters from interior canopy in 10 trees of susceptible cultivars ('Rome', 'Yorking', 'golden Delicious', or 'Stayman'), treat if >3 infested clusters
Codling moth, *Cydia pomonella* (L.)	Place 3 pheromone trap per block by bloom, weekly check traps for 1st catch (biofix), 138 DD°C after biofix make weekly inspections of 100 fruit for new entries; treat at 138 DD°C or if >1% fruit damage during hatch period (Table 20.4), and repeat treatment in 14 days if ET >5 moths per trap per week since the last treatment
Spotted tentiform leafminer, *Phyllonorycter blancardella* (F.)	Sequential sampling at pink or at petal fall, count number of eggs or mines on 2nd, 3rd and 4th leaves in cluster of 3 fruit clusters per tree on every other tree from 2 to 7 trees, treat if count is above ET on chart (Agnello et al., 1993)

Table 20.5 (continued)

Tufted apple bud moth, *Platynota idaeusalis* (Walker)	Place 2 pheromone traps per block by petal fall, after 1st sustained catch (biofix), accumulate catch for 3 to 4 (if cool) weeks, see Fig. 11.1 in Hogmire (1995) for damage potential relative to cumulative trap catch
Apple maggot, *Rhagoletis pomonella* (Walsh)	Mid June, place 3 red sticky sphere baited with apple volatile lures and ammonium acetate (attract flies mating and egg laying) 2 m height in trees 1 or 2 rows from edge closest to woods or abandoned orchard, remove leaves around trap to increase insect view and access, check weekly, treat if >5 flies per trap and reapply 14 days later if >5 more flies per trap
European red mite, *Panonychus ulmi* (Koch)	Sequentially inspect 20 to 100 leaves weekly. For New York, ET >2.5, 5 or 7.5 mites per leaf for June, July and early August, respectively (Agnello et al., 1993), see Fig. 20.3 (Hogmire, 1995) for ET as function of crop load and time of season
Woolly apple aphid, *Eriosoma lanigerum* (Hausmann)	3 weeks post-bloom, check weekly 5 pruning cuts on each of 10 trees; ET >50% infested pruning cuts
Blackberry: Rednecked cane borer (RNCB), *Agrilus ruficollis* (F.)	Late April, check several hundred floricanes for galls; remove galled canes if <5% galled canes; if >5% of floricanes with RNCB galls, weekly from early May to early June walk through gall-infested planting and note presence of adults; treat if adults present; or weekly cut off at ground and split 10 galled floricanes to check for newly eclosed adults in pith or empty tunnels (adults newly emerged), treat primocanes weekly in evening during adult emergence period
Raspberry crown borer (RCB), *Pennisetia marginata* (Harris)	Weekly in September (North USA) or October (Southern USA), cut off dead floricanes at ground to assess percent with RCB tunnels; check underside of leaves of new blackberry terminals for presence of round, brown eggs; If recent >5% of floricanes with RCB tunneling present apply insecticide drench to crowns after hatch in fall

most complex methods: growing DD; single triangle; double triangle; single sine; double sine; and Huber's method that is a single sine method with a horizontal cut-off (Source is online: http://www.ipm.ucdavis.edu/WEATHER/ddconcepts.html). Equation 20.3 is the simplest calculation for a growing DD usually used by growers:

$$DD = (\max + \min)/2) - LDT = (95 + 75)/2 - 50 = 35 \text{ or } (80 + 60)/2 - 50 = 20 \quad (20.3)$$

20.2.4.5 Validating Degree-Day Models

A DD model must be run and validated for each species using natural temperature and photoperiod conditions in several sites within a climatic region over several years. Once the model is validated, it can be demonstrated and recommended for use by growers. Several online locations provide phenology models and DD calculators.

20.2.4.6 Online Degree-Day Calculators

There are DD calculators available online that can access either archived or real-time weather data for a specific state or county or allow uploading a max/min temperature data file using a specific format. Two online interactive sites with DD calculator programs that allow you to use your site-specific temperature data are:

1. University of California Agriculture and Natural Resources Statewide IPM Program has an online series called "How to manage pests" which includes sections titled: "Degree-Days" that explains how DD can be calculated; "Run Models and Calculate Degree-Days" for an array of fruit and vegetable pests at: http://www.ipm.ucdavis.edu/WEATHER/ddretrieve.html
2. IPM Weather Data, Degree-Days, and Plant Disease Risk Models for agricultural and pest management decision making in the US. Integrated Plant Protection Center at Oregon State University and the IPM Centers - PNW Coalition has instructions for calculating site-specific cumulative DD and has a cumulative DD map calculator program for state and regions in United States at: http://pnwpest.org/wea/weaexp.html#CALCS and calculator at: http://ippc2.orst.edu/cgi-bin/ddmodel.pl?clm.

20.2.5 Pest Scouting

Pest management decisions to use a tactic should be based on sample estimates of both the density of the pest and its natural enemies in blocks most susceptible to pests. For example, if the estimated natural enemy population is large enough that biological control of the pest is probable; this eliminates the need for an insecticide application. If the natural enemy population is too low to achieve biological control, then either purchase and release more natural enemies into planting (many suppliers of natural enemies) or sample again to note if and when pest population exceeds the ET. Also, sample after treatment to confirm efficacy of tactic or detect insecticide resistance in pest population (Beers et al., 1993).

20.2.6 Sampling Programs

A sampling program consists of a sampling method that describes how to identify the pest species, the pest stage to be sampled, timing and frequency of sampling, sample size = the number of sampling units (individual leaf, terminal, fruit, or trap on which insects are counted), and the spatial pattern for collecting sampling units (Table 20.5).

20.2.6.1 Sampling Methods

A scout can use one of many sampling methods including: visual inspection of terminals, fruits, leaves, limbs, trunks or roots; jar limbs; collect and brush leaves; or check for insects captured on attractive visual or odor-based traps.

20.2.6.2 General Scouting Guidelines (Ciborowski, 2007)

- Weekly scouting data form (in back of most fruit pest management guides)
- Divide orchard into 4–6 hectare (10–15 acre) blocks based on pest pressure history
- Sample block consists of cultivars similar in susceptibility, age, size and spacing
- Each pest requires a specific sampling protocol where sampling can occur weekly or is based on specific cumulative DD period after a biofix
- Randomly select crop plants, leaves, or fruit within a scouting block using a predetermined pattern, e.g., transect of every other plant, diagonal, v-shape or perimeter row
- At least 2 traps per planting if 4 hectares (10 acres) or less or one trap per each 4–6 hectare block

20.2.6.3 Maintenance of Visual or Odor-based Traps

- Store pheromone or odor attractant dispensers in freezer or refrigerator
- Wear plastic gloves to handle visual traps or pheromone or odor dispensers to minimize hand contamination with sticky material or odor attractant
- Secure pheromone or odor dispenser with a paper clip or wire to trap and not on sticky liner to ensure lure does not get blown out
- Attach or replace different attractant dispensers on separate weeks so you reduce cross contamination of dispensers in order to prevent multiple species captures per trap
- Set traps out one week before the expected first emergence of the pest
- Set traps at height that captures the most insects, e.g., top of tree for codling moth or knee high for tarnished plant bug or Japanese beetle or eye-level for most other species
- Set traps at correct location in or around the fruit planting, e.g., for first generation grape berry moths, hang pheromone traps from tree limb along wooded edge adjacent to vineyard and then move traps into vineyard interior just before flight of second generation moths
- Remove leaves around trap to increase access by pest and scout
- Record Global Positioning System (GPS) coordinates for latitude and longitude to pinpoint geographic location of trap to within 3 meter accuracy (Wide Area Augmentation System or WAAS) and/or place light colored flagging near trap to assist scout in relocating traps
- Record trap catches at time interval recommended by sampling protocol, e.g., usually sample weekly but may need to sample daily or twice weekly when establishing biofix date (1st catch)
- When trap catch is lower than expected, check for corresponding low temperatures or rainfall during known flight period, e.g., codling moth flight and egg laying only occurs on evenings when dusk temperature exceeds 16.7°C (62°F)
- Replace sticky liner as it looses tackiness due to many captured insects, wing scales or dust
- Replace lure or attractant dispenser as recommended by supplier

20.2.7 Economic Thresholds in Fruit

Pest management decision making uses the weekly scouting report of the average number of pests per sample and percentage damage to determine if and when the pest population exceeds the economic threshold (Table 20.5). If the pest population exceeds the economic threshold, the grower makes a decision as to the most appropriate, available or economical tactic to employ that will reduce the pest population and delay or prevent it reaching the economic injury level.

20.3 Management Tactics

All six categories of management tactics listed by Pedigo (2002) have been implemented in various fruit pest management programs: (1) Biological control; (2) Host plant resistance; (3) Cultural or modify effective environment (exclude pests, eliminate alternate hosts, site selection, sanitation, pruning, proper fertilization, rotation, ripen during pest-free dates, trap crops, ground cover for beneficials); (4) Exclude pests via fruit bagging or netting or green houses; (5) Reduce reproductive potential (mating disruption and sterile-insect technique); and (6) Insecticides, insect growth regulators (IGR), and biopesticides (earth-derived toxins, soaps, oils, sulfur, diatomaceous earth, kaolin clay, microbials).

Four cases will be presented to illustrate various sampling programs and tactics used to manage fruit pests: (1) host plant resistance of grape phylloxera; (2) integrated mite management in apple; (3) codling moth areawide mating disruption program; and (4) plum curculio management.

20.3.1 Host Plant Resistance

Fruit are high-value crops with a low economic injury level for pests so the best method of combating insect pests is to grow resistant plants (Luginbill, 1969). Myers et al. (2007) hypothesized that researchers should direct evaluations of the fruit crop germplasm for insect resistance to the more monophagous and limited oligophagous pest species because finding host plant resistance appears to be unlikely for the more polyphagous pest species like plum curculio. Many fruit crops in their native habitat are presumed to have extensive genetic defenses against local pests. However, as many of these fruit crops were introduced into other parts of the world, they were attacked by new diseases and insects (Janick et al., 1996). Painter (1951) composed an international bibliography on insect resistance in apples, grapes (especially grape phylloxera), raspberries and strawberries. Only a few fruit insect pests have been reported to kill extensive monocultures of a specific fruit, e.g., woolly apple aphid and grape phylloxera.

20.3.1.1 Evaluating Fruit Germplasm for Pest Resistance

The shift toward sustainable agriculture means that pest-resistant germplasm will be more important in the future. Table 20.2 contains a partial list of known fruit germplasm (species, rootstocks or cultivars) that exhibit resistance to specific fruit pests. From 1980 to 2004, the USDA-ARS, National Germplasm Resources Laboratory in Beltsville, MD identified gaps in the United States national germplasm collections, and prioritized and funded 37 exploration/exchange projects for fruit and vegetable crops (Forsline and Hummer, 2007). Recently, the Grapevine Crop Germplasm Committee stressed the need to increase efforts to characterize the resistance and horticultural traits of grape species world-wide (NPGS, 2001). It wasn't until 1989, that a group of scientists began collecting the first cuttings and seeds in Kazakhstan and Kyrgyzstan from 24 crop species including wild apple, pears, hawthorn, hops, walnuts, pistachios and grapes. Many of these cuttings and 18,000 apple seeds were planted by scientists around the world and are being evaluated for horticultural attributes and will contain disease and insect resistance genes of use in future fruit breeding programs (Adams, 1994). Some accessions planted at the USDA Plant Genetic Resources Unit in Geneva, NY show resistance to feeding by oriental fruit moth, *Grapholita molesta* (Busck), codling moth, and apple maggot (Myers et al., 2007).

20.3.1.2 Grape Phylloxera Problem

Grape phylloxera is native to the southwestern and southeastern United States on American *Vitis* (Downie et al., 2000). The foliar form of grape phylloxera feeds on the upper surface of susceptible grape leaves causing galls to form and reduce yields. The root form feeds on roots causing susceptible roots and rootlets to swell into tuberosities and clubbed nodosities and allow entry of pathogen that kill vines (Flaherty et al., 1992; Granett et al., 2001).

In Virginia United States, colonists could not grow French *V. vinifera* vines due to susceptibility to grape phylloxera and powdery mildew (Reisch and Pratt, 1996). They did cultivate and improve upon native bunch grape *Vitis* species in the cooler parts of eastern and western United States (Unwin, 1991) and the muscadine grape cultivars derived from *V. rotundifolia* that grow in the warmer southeastern United States.

20.3.1.3 Resolving the Grape Phylloxera Problem

In 1845, powdery mildew began infecting and reducing production of very susceptible *V. vinifera* vines throughout Europe, Greece, Turkey, Algeria and Hungary (Ordish, 1987; Unwin, 1991). By the 1860s, American vines with resistance to powdery mildew were being imported to and distributed throughout Europe and inadvertently introduced grape phylloxera and downy mildew, *Plasmopara viticola* (Berk. & M.A. Curtis) Berl & De Toni.

By 1868, a connection was made between grape phylloxera on vine roots and the destruction of southern French vineyards (Bazille et al., 1868). Phylloxera spread to other wine producing regions of the world about the same time (Galet, 1982). Phylloxera was identified in California in 1873 (Ordish, 1987) but spread slower than in France because California vineyard producing areas were too dry for the winged form (Hutchinson, 1984).

A search for a solution to the grape phylloxera was being conducted in the 1870s. In 1872, Laliman noted that grape phylloxera did not kill roots of *V. aestivalis* and proposed grafting susceptible *V. vinifera* cultivars onto rootstocks from *Vitis* species indigenous to North America (Table 20.2). From 1870 to 1910, a French Commission selected, bred and evaluated phylloxera-resistant rootstocks which ensured the future culture of *V. vinifera* (Pongrácz, 1983). In 1877, the Commission began testing 317 suggested remedies for grape phylloxera. Flooding an infested vineyard to a depth of 10 cm for 40 days in autumn or winter successfully eradicated phylloxera (Ordish, 1987; Lachiver, 1988) as did carbon disulfide injected into the soil around roots of vines (Ordish, 1987). By 1881, the International Phylloxera Congress in Bordeaux France agreed that grafting of phylloxera-susceptible French vine scions onto phylloxera-resistant American rootstocks was the preferred tactic against phylloxera (Fitz-James, 1889). Widespread adoption of rootstocks occurred after the publication of a booklet in 1882 that recommended and described how to use American vines as rootstocks (Stevenson, 1978). Replanting French vineyards with phylloxera-resistant grafted vines occurred from the 1890s to 1920 which realized an increase from 13.5 hectoliters in 1880 to 38.6 hectoliters by 1920 (Lachiver, 1988).

The French developed AXR#1 in 1905. But its resistance to GP failed in Sicily by 1908 (De Grully and Ravaz, 1909; Grimaldi, 1909) and it was discarded in favor of other more resistant rootstocks in Europe by WWI (Boubals, 1970). In 1938, the California industry adopted AXR#1 because of its adaptability to soils of the region (Jacob, 1938; Lider, 1958). In the 1970s, 75% of the plantings in Napa and Sonoma Counties were on AXR#1, but phylloxera capable of damaging AXR#1 was discovered in 1983 (Granett et al., 1985). This biotype B caused a billion dollar replanting of scion grafted on phylloxera-resistant rootstock with no *V. vinifera* parentage (Granett et al., 2001).

20.3.2 Integrated Mite Management in Apple

There are several components of a successful integrated mite management program that leads to biological control of spider mites in apples (Beers et al., 1993; Croft, 1975; Nyrop and Binns, 1992; Agnello et al., 1999): (1) delayed dormant oil applications kill overwintering European red mite eggs and delay the buildup of pest mites; (2) use selective pesticides that conserve predators; (3) use a sampling program to estimate numbers of both mite predators and pest mites; and (4) a decision-making index that estimates the probability for biological control or the need for either partial or full strength miticide.

20.3.2.1 Mite Damage and Mite Predators

The European red mite, *Panonychus ulmi* (Koch), twospotted spider mite, *Tetranychus urticae* Koch, (both spider mites) and apple rust mite, *Aculus schlechtendali* (Nalepa), are secondary pests that build up to outbreak levels after pesticides disrupt mite predators including: Phytoseiid mites: *Neoseiulus fallacis* (Garman) (=*Ambyleius fallacis*) or *Typhlodromus pyri,* and the black lady beetle, *Stethorus punctum* (Leconte). Fruit trees can tolerate 15–20 spider mites per leaf or 200 rust mites per leaf feeding for a maximum of 10–14 days before causing significant foliar bronzing due to loss of photosynthetic activity. This foliar damage leads to loss in fruit size, color, fruit drop and poor fruit set in subsequent years (Croft, 1975).

20.3.2.2 Cumulative Mite Days

The quantification of mite feeding or leaf bronzing over time is represented by cumulative mite days. This value is calculated by taking the average number of mites per leaf from one sample date to the next and multiplying it by the number of days between these samples. Repeat these calculations for each subsequent sample date and keep a running accumulation of mite days for the season. It has been noted that higher mite numbers can be tolerated as the season progresses. This is why the ET values increase monthly. For example: the monthly ET values for New York are: 2.5 mites per leaf for June 1–30; 5 mites per leaf for July 1–31; and 7.5 mites per leaf for August 1–15 (Agnello et al., 1999).

20.3.2.3 Mite Predators

The mite predator, *T. pyri*, is by far the most reliable and effective mite predator. Adult *T. pyri* overwinter in the canopy under the bark and feed all during the season on pollen or fungal spores or apple rust mites when pest mite populations are low. Since *T. pyri* is always in the tree canopy, it is susceptible to early season toxic pesticides which do not affect *N. fallacis* or *S. punctum* that disperse to the canopy in late spring. If *T. pyri* is not present in particular block, they can be introduced in early season after petal fall (May- June) from shoots or blossom clusters cut from identified 'donor' sites (Breth et al., 1998).

Adult predatory mites, *N. fallacis*, overwinter on the trunk or in groundcover. In early spring *N. fallacis* feed on twospotted spider mites in the groundcover and then disperse into tree canopy later in the spring when there are more than one spider mite per leaf or apple rust mites are present (Johnson and Croft, 1981). If not present in the orchard, *N. fallacis* can be purchased from one of several suppliers and released into the orchard (Aselage, and Johnson, 2008).

Adult predatory lady beetles, *S. punctum*, disperse to fruit leaves to feed on spider mites and lay eggs so larvae can continue to feed on mites (Croft, 1975).

20.3.2.4 Stethorus Sampling

Stethorus sampling involves counting the number of adults and larvae observed during a timed 3-minute search around the periphery of mite-infested trees. For example: 25 *Stethorus* adults or larvae per 3 min. canopy inspection divided by 10 mites per leaf = predator-to-prey ratio of 2.5. Biological control is likely with a predator-to-prey ratio >2.5. Note, *S. punctum* larvae must almost always be present in canopy if this predator is to control mites (Hogmire, 1995).

20.3.2.5 Mite Sampling

It can occur after the scout has estimated the number of *Stethorus* per 3-min. visual count. Estimating the number of European red mites and predatory mites per leaf involves randomly selecting 5–10 leaves from 5 to 10 trees throughout a block of susceptible cultivars ('Red Delicious', 'Northern Spy', 'Golden Delicious', 'Yorking'). The most accurate mite counting method is to use a mite brushing machine to brush mites from 100 leaves onto a grid. A stereomicroscope is used to count the actual number of spider mites and predatory mites and calculate the number of each per leaf. Although mite brushing is accurate, it is very time consuming so two, presence-absence sampling methods were designed: binomial and sequential sampling.

20.3.2.6 Binomial Mite Sampling

This method uses a hand lens or visor lens to aid in counting both the number of leaves with pest and/or predatory mites present out of 100 leaves. Table 20.6 is used to convert percent of mite-infested leaves to an estimate of the number of mites per leaf (Beers et al., 1993).

20.3.2.7 Sequential Mite Sampling

Sequential mite sampling method starts by selecting a random tree in a mite susceptible block and to collect 5 middle-aged leaves from the middle of fruit clusters or shoot leaves from each quadrant of the tree canopy. The scout counts only the number of infested leaves out of 20 that have one or more moving European red

Table 20.6 Relationship between percentage European red mite-infested leaves and estimated number of mites per leaf (Walgenbach, 2008)

% Mite-Infested leaves (>1 mite/leaf)	Estimated No. mites per leaf	% Mite-Infested leaves (>1 mite/leaf)	Estimated No. mites per leaf
40	0.7	70	2.6
45	0.9	75	3.4
50	1.1	80	4.7
55	1.3	85	6.8
60	1.6	90	11.4
65	2.0	95	26.4

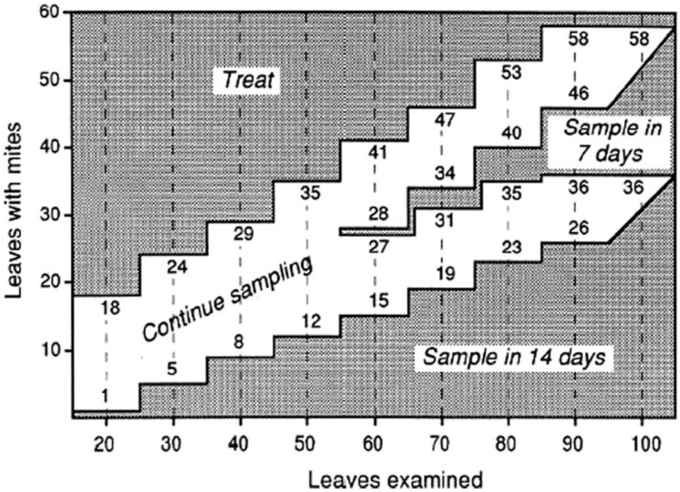

Fig. 20.2 Sequential mite sampling chart for June 1–30 in New York when economic threshold = 2.5 mites per leaf (reprinted with permission, Agnello et al., 1999)

mites or twospotted spider mites. After each set of 20 leaves, the scout refers to the decision chart (Fig. 20.2) developed by Nyrop and Binns (1992), Breth et al. (1998), and Agnello et al. (1999). One of four decisions is usually made before the scout inspects all 100 leaves thus saving scouting time:

- Count is in zone of chart (Fig. 20.2) labeled "Treat " because mites >ET; or
- Count is in zone of chart labeled "Continue sampling"; or
- Count is in zone of chart labeled "Sample in 7 days" where mites <ET; or
- Count is in zone of chart labeled "Sample in 14 days" where mites <<ET.

20.3.2.8 Dynamic ET for Apple

Hogmire (1995) and Krawczyk et al. (2008) described the following steps for selecting a more dynamic economic threshold for mites as a function of crop load and time of season (Fig. 20.3): (1) determine the number of mites per leaf based on percent mite-infested leaves; (2) estimate the projected number of bushels per acre for the affected block; and (3) select the threshold line on the graph for the appropriate time of the growing season. If the mites per leaf exceed the economic threshold for a certain time of season, then estimate the mite predator population and decide if the predator-to-mite ratio will ensure biological control or need a miticide application. If no action is taken, the orchard should be checked again in 5–7 days.

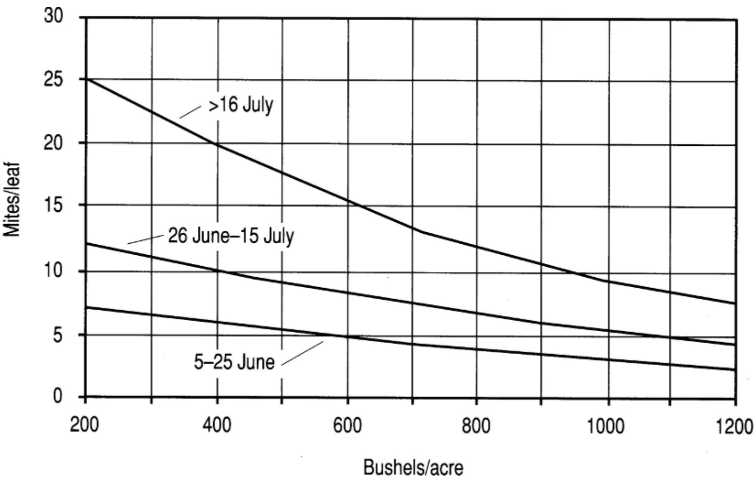

Fig. 20.3 Determination of economic threshold in mites per apple leaf as a function of expected crop load in bushels per acre and one of three time periods (reprinted with permission, Hogmire, 1995)

20.3.2.9 Probability of Biological Control

Croft (1975) developed a decision-making index for estimating probability for biological control of spider mites by *N. fallacis* (also works for *T. pyri*) where:

- Predator-to-prey ratio of at least 1:10 allows scout to recommend to grower to wait one week and resample to ensure that biological control is achieved (increasing predator-to-prey ratio);
- If bronzing appears and there are >0.08 but <1 *N. fallacis* per leaf then apply reduced rate of miticide;
- Only use full strength miticide when there is less than 0.08 *N. fallacis* per leaf.

20.3.3 Codling Moth

Codling moth is a key pest of 160,000 ha of apple worldwide in Asia, Australia, North and South America, South Africa, North-central Mexico and New Zealand (Witzgall et al., 2008). The potential for crop loss to the codling moth makes it the most important pest of pome fruits. When uncontrolled, the codling moth is capable of annually destroying 80% or more of an apple crop and 40–60% of a pear crop. Sauphanor et al. (1998) noted that delaying resistance development by the usual implementation of a program rotating insecticide applications with different modes of action was presumed to be ineffective for French codling moth populations due to simultaneous resistance development to diflubenzuron, deltamethrin, and phosalone and azinphos-methyl. Thus, researchers were motivated to develop alternative control tactics such as microbiological insecticides and/or mating disruption.

Protection of apples from codling moth requires identifying its biofix (Table 20.4). At 139 DD (250 DD°F) and again from 333 to 389 DD (600–700 DD°F) after biofix or first flight for each generation, apply a spray of insecticide or granulosis virus to prevent fruit damage. For all generations, if high levels of moths are being caught in traps, do not wait until 111–139 DD (200–250 DD°F) to treat, but apply the first spray at the beginning of egg hatch or 56 DD (100 DD°F), especially if using kaolin clay or an insect growth regular (IGR) (methoxyfenozide) and reapply as needed. Using a reduced-risk material such as the IGRs or organically acceptable alternatives (oil, spinosad, or codling moth granulovirus) may be sufficient for control of low populations.

20.3.3.1 Codling Moth Areawide Mating Disruption

In 1995, the USDA implemented the areawide pest management initiative. The goal was to achieve systematic reduction of target key pest(s) to predetermined levels through the use of uniformly applied pest mitigation measures over large geographical areas clearly defined by biologically-based criteria (Coppedge et al., 1993). This approach was expected to be a more permanent pest management approach than a reactive field-by-field approach for several reasons: (1) field-by-field populations may rebound due to emigration (Knipling, 1979); (2) pests do not honor property lines; (3) cost of control is lowered if addressed on a larger scale; (4) reduce pest population below the economic threshold over a large area; (5) local eradication is possible for a short time; (6) reduce pesticide use and increase worker safety; and (7) adjacent small and large plantings using same treatment will enjoy same advantages (Calkins, 1998).

Mating disruption has been used commercially since 1991 (Brunner et al., 2003). Codling moth mating disruption was used in a few thousand treated acres in Washington in 1992. Variable results were noted in early attempts to use mating disruption in small orchards surrounded by conventionally sprayed orchards (Beers et al., 1993). Larger orchards had codling moth damage in the perimeter on uphill sides (due to uneven distribution of pheromone plume), and near overwintering sites such as piles of harvest bins, prop poles and brush (Calkins, 1998). These findings and availability of other alternative tactics (cited above), all led to the initiation of the areawide codling moth management program (CMAP) which transitioned to "Areawide II".

CMAP had funding for five sites in three states (Washington-3, Oregon-1 and California-(1) from 1994 to 1999 with 68 participants encompassing 3,000 acres (Calkins, 1998, Thomson et al., 2001). As positive results were reported, other growers requested to participate in the CMAP program. By 2001, mating disruption use increased to about 90,000 acres in Washington (Alway, 2002).

Brunner (2002) noted that mating disruption treatments to manage codling moth should not be considered as a "stand-alone" approach. He proposed the following CMAP best management recommendations for using pheromones against codling moth: 1) When starting out, use mating disruption at full rate of 500–1000 dispensers per hectare (200–400 per acre). Reduce rate of dispensers only after codling moth populations and damage have been reduced. Reduced rates of pheromones are effective against low-pressure codling moth situations. Even in these situations, supplemental insecticides might be needed if monitoring shows more codling moth activity than expected. (2) If codling moth pressure is moderate to high you should use full rates of hand-applied dispensers and plan to use supplemental insecticides. Take care to place the dispensers in the proper locations for optimum impact (upper two feet of the tree canopy). (3) Distribute the dispensers uniformly unless using aerosol emitter devices. (4) Use pheromones on as large an area as possible. Avoid treating small irregular blocks unless they are part of a larger project. It is better to cooperate with neighbors to establish an areawide project. (5) Supplement pheromone treatments with insecticides as needed based on monitoring information, especially against the first generation. (6) Establish a good monitoring program. Use high-load type lures and possibly DA lures (pear essence attracts both males and females and can be used to assess mating of females). Decide on a standard trap type and stick with it. Place traps in the upper canopy, not near a dispenser. Use one trap every 2–3 acres unless experience allows you to reduce this density.

Calkins (1998) stressed that with widespread participation in the CMAP the cost of the mating disruption program was less than the conventionally sprayed orchards. In 2000, 92% of growers were using economic thresholds, 76% using alternate row spraying, 81% using biological control, 89% using reduced chemical rates, 93% using pheromone traps coupled with degree-day models and 71% following an integrated mite management program (Brunner et al., 2003). As a result of the successful development of codling moth mating disruption, organic fruit growers finally had a viable means of controlling this pest.

20.3.4 Plum Curculio Management

Plum curculio is a key pest of pome and stone fruit that hinders sustainable fruit production east of the Rocky Mountains in the United States (Myers et al., 2007). Larval feeding causes either fruit drop (Levine and Hall, 1977) or severe scarring (Quaintance and Jenne, 1912). In the fall, the adults can overwinter in weedy orchards but most move outside of mowed orchards to overwintering habitats in adjacent hedgerows or woodlots where there is more weed and leaf litter (Chapman, 1938; LaFleur et al., 1987; Piñero et al., 2001; Johnson et al., 2002a; Leskey and Wright, 2004).

The plum curculio causes damage to fruit on host plants of six genera in the family Rosaceae, the genus of highbush blueberries in the family Ericaceae (Polavarapu et al., 2004) and the genus of muscadine grapes in the family Vitaceae (Jenkins et al., 2006). Myers et al. (2007) found little resistance to plum curculio in the exotic and domestic *Malus* germplasm collection evaluated in Geneva, NY (Table 20.1).

Not all fruit crop species are similarly attractive to plum curculio adults. Leskey and Wright (2007) reported that Japanese plum, *Prunus salicina* Lindl., was 1.5

times more preferred by plum curculio than the other seven fruit tree species: apple, *Malus domestica* Borkh., pear, *Pyrus communis* (L.), peach, *P. persica* (L.), apricot, *P. armeniaca* L., tart cherry, *P. cerasus* L., sweet cherry, *P. avium* (L.), Japanese plum, and European plum, *P. domestica* L. Plum curculio males were reported to produce grandisoic acid, an aggregation pheromone that attracts both sexes (Eller and Bartelt, 1996). Several plum volatiles were found to be attractive to plum curculio (Leskey et al., 2001), especially benzaldehyde which synergized plum curculio attraction to grandisoic acid (Piñero et al., 2001).

20.3.5 Scouting for Plum Curculio

Monitoring and management systems have been developed to improve timing of control tactics against plum curculio. Wylie (1951) first used limb jarring of peaches to determine the location and relative abundance of plum curculio adults in fruit orchards. However, jarring was labor intensive and difficult to achieve accurate counts due to variations in tree shapes, height, time of day, and weather conditions. For apple, it was once recommended to make a full block insecticide application at petal fall to prevent damage from the overwintered immigrating population. Johnson et al. (2002a) developed a monitoring program based on weekly inspections of four Tedders traps (Tedders and Wood, 1994) (gray pyramid traps with boll weevil funnel capture arena) or screen circle traps (Mulder et al., 1997) tied to perimeter peach trees adjacent to woodlots and 300 fruit for new feeding damage. These traps were much more likely to capture plum curculio adults than did limb jarring trees. The recommended economic threshold was 0.05 plum curculio adults per Tedders trap per day or 1% new fruit damage (Table 20.5). For apple in New York, Reissig et al. (1998) recommended insecticidal protection for 188 DD (base 10°C) after petal fall. In Arkansas, peach trees were protected against the first generation of plum curculio with one or two full block insecticide applications timed from shuck split until >80% of the plum curculio population had immigrated to the orchard which occurred by 222 DD (base 10°C) accumulated after temperatures first exceeded 21°C for 2 d after 15 March (Johnson, 1996).

20.3.5.1 Reduced Spray Program for Plum Curculio

Recently, reduced spray programs have been developed against the plum curculio. In Canada, Chouinard et al. (1992) and Vincent et al. (1997) achieved similar levels of plum curculio fruit damage with petal fall insecticide treatments restricted to the perimeter row as achieved by full orchard insecticide sprays. Perimeter apple trap-trees baited with benzaldehyde and grandisoic acid were shown to provide a means to monitor initiation of overwintered plum curculio immigration into the orchard and more easily detect fruit feeding and egg laying (Piñero and Prokopy, 2003, Prokopy et al., 2003; Prokopy et al., 2004). Aselage, and Johnson (2008) found that plum curculio adults were attracted to and caused significantly more damage (11–17% damage) in baited perimeter trees (8 benzaldehyde and 2 grandisoic acid lures) than adjacent trees (3.6–5.2% damage). In apple blocks under low to moderate plum curculio pressure, $<1.8\%$ of fruit on interior trees were damaged by plum curculio in blocks receiving full perimeter insecticide sprays versus $<2.5\%$ damaged fruit in blocks with insecticide applied only to four perimeter baited trees (4 benzaldehyde and 1 grandisoic acid lures) (Leskey et al., 2008).

A bait tree plum curculio management approach may become even more effective. This approach could use trees baited with the more attractive host volatiles of the Japanese plum (as yet to be identified) (Leskey and Wright, 2007) or plant Japanese plum trees every fifth tree in the perimeter of apple or peach blocks. These baited trees or plum trees would attract plum curculio adults away from adjacent apple or peach trees and would be the only trees treated with insecticide. Another option may be to apply a soil drench of entomopathogenic nematodes to baited trees or plum trees in perimeter to control the plum curculio larvae as they pupate in the soil (Shapiro-Ilan et al., 2008).

20.4 Conclusions

Since the 1970s, many advances have occurred in fruit pest management practices that have lead to more sustainable programs. The areawide pest management programs are showing that mating disruption can be integrated with scouting and low-risk pesticides to reduce secondary pest outbreaks. This approach has significantly reduced usage of synthetic insecticides, conserved natural enemies, delayed development of resistance to synthetic insecticides or biopesticides and still produced high quality fruit. These advancements have allowed many growers to adopt an organic pest management program using more earth-derived biopesticides.

However, the potential for fruit pest attack is high because many of the present fruit cultivars were derived from a narrow genetic base, with limited pest resistance genes, and deployed in extensive monocultures in regions around the world. The genetic diversity of domestic cultivars of apple has eroded from 7,000 commercial cultivars available from 1804 to 1904 to the present commercial cultivars being based on sports of two cultivars: 'Delicious' and 'Golden Delicious' (Janick et al., 1996). In 2000, 98% of the grapes grown in the world are *V. vinifera* cultivars (FAO Statistical Service) of which few possess resistance genes to defend against various grape pests around the world. There may be many sources of disease and pest resistance yet to be identified among the various fruit crop germplasm. Once resistant genes are identified, breeders should make crosses and have researchers worldwide evaluate regional adaptability and promote consumer acceptance of these new fruit cultivars in order to promote more local and regionally sustainable fruit production.

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Chapter 21
Bio-Intensive Integrated Pest Management in Fruit Crop Ecosystem

Virender Kaul, Uma Shankar and M.K. Khushu

Abstract This chapter deals with integrated pest management practices used in fruit crops. The chapter begins with a historical overview of integrated pest management in fruit crops. Pest management practices began to change in the 1800s. From the late 1800s to 1940s, the main insecticidal compounds used were oils, soaps and resins, plant-derived poisons and inorganic compounds. After 1940s synthetic broad spectrum insecticides were developed. Repeated application of these pesticides led to the development of resistance in insect pests. This resistance paved way for increased application of pesticides and to the collapse of the agricultural systems characterized by highly resistant pests, with no natural enemies left to control them. This chapter throws light on the knowledge of biointensive pest management used in managing fruit pests. The prerequisites of BIPM like survey and surveillance, proper and accurate identification, sampling and pest forecasting, field monitoring and scouting, threshold level determination have been discussed. Further, the tactics such as cultural, mechanical, physical, and biological and role of host plant resistance in BIPM have also been included in the chapter. The next section presents the key pests of mango, citrus, litchi, guava, olive, apple, pear, peach and the IPM strategies used to manage these. The chapter ends by listing the measures for adoption of biointensive pest management programs and identifying future thrust areas.

Keywords Biointensive pest management · Survey · Surveillance · Sampling · Pest forecasting · Field monitoring · Scouting · Economic threshold level · Mango · Citrus · Litchi · Guava · Olive · Apple · Pear · Peach · Adoption

V. Kaul (✉)
Division of Entomology, Sher-e-Kashmir University of Agricultural Sciences and Technology of Jammu, Chatha, Jammu-180009, India
e-mail: kaulvirender@yahoo.com

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21.1 Integrated Pest Management: An Overview

It is a well known fact that agricultural pests cause substantial crop losses throughout the world. In the past farmers had to manage this problem to secure their basic subsistence needs, and as a response, the farmers practiced and developed cultural and mechanical pest control based on trial and error. Over a period of time, these practices have become a part of their production management system. One of the first documented examples of farmers' awareness of biological pest control is the manipulation and placing of predatory ants, *Oecophylla smaragdina* (Fabricius) by Chinese citrus growers in mandarin orange trees to control leaf feeding insect. They also used bamboo bridges to help the ants cross between trees (McCook, 1882, in DeBach, 1964). The first known chemical control dates back to 2,500 years. Pest management practices began to change in the 1800s. From the late 1800s to 1940s, the main insecticidal compounds used were oils, soaps and resins, plant-derived poisons and inorganic compounds. The chemical age began in the 1940s with the discovery of dichloro diphenyl trichloroethane (insecticide), ferbam (fungicide), and 2, 4-D (herbicide) (Arneson and Losey, 1997). In 1940s and 1950s, pesticides were thought to be the final word in pest control and their introduction contributed substantially to raising agricultural productivity in many regions of the world. Since then, pesticides have become an integral component of many intensive agricultural systems. At that time, the growing concerns and deleterious effects caused by pesticides to the environment, human health, and wildlife were pointed out by Rachel Carson in her book *Silent Spring* in 1962.

Repeated applications of pesticides lead to resistance in the pest (Adams, 1990; Beaument, 1993). This resistance results in the increased application of pesticides and to the collapse of the agricultural systems characterized by highly resistant pests, with no natural enemies left to control them. Pesticides have been found to cause: acute and chronic human health problems, contamination of groundwater, surface water, atmospheric contamination, and negative effects on non-target organisms (Howard et al., 1991; Mullen, 1995). Although developing countries account for a relatively small portion of the total pesticide used each year, they have the highest rates of pesticide poisoning of humans (Adams, 1990; Beaument, 1993). Concerns about the negative effects of pesticides led to research and promotion of alternative pest control practices – Integrated Pest Control or simply IPC. This new concept called Integrated Pest Control (IPC) and later Integrated Pest Management (IPM) was stimulated by symposia organized by the Food and Agriculture Organization (FAO) of the United Nations in 1966 and the International Organization for Biological Control (IOBC) in 1967. Later the concepts of economic threshold level (ETL) and economic injury level (EIL) came into shape to take up decisive control measures and replaced the term control with management. Bajwa and Kogan (1998) have documented around 70 definitions of IPM for the period 1950–1998 as cited by different authors. IPM made a paradigm shift in the philosophy of pest control, from pest eradication to pest management. Instead of single tactic control, emphasis was placed on the use of a combination of available tactics in a compatible manner aimed at providing cheap, long term sustainability with minimum of harmful side effects (Dent, 2000). Consequently, a more integrated approach to pest control was advocated to consider the ecological factors such as natural mortality which may keep insect pest populations below economic damage levels.

IPM is a complex system approach that comprises of judicious use of cultural, physical, mechanical, biological, host plant resistance, regulatory and chemical methods. Agenda 21 of the United Nations Conference on Environment and Development (UNCED) at Rio de Janeiro in June 1992 identified IPM in agriculture as one of the requirements for promoting sustainable agriculture and rural development.

Norton and Mullen (1994) defined IPM as an approach to making pest management decisions with increased information and multiple tactics to manage pest populations in an economically efficient and ecologically sound manner.

21.2 Bio-intensive Integrated Pest Management (BIPM)

The success of biological pest control in India dates back to early 1762, when Indian bird, Mynah was shipped to Mauritius for the control of red locust, *Nomadacris septemfaciata* Serv. Biological control utilizing a population of natural enemies to seasonally or permanently suppress pests is not a new concept. The cottony cushion scale, which nearly destroyed the citrus industry of California, was controlled by introduced predatory insects from Australia in the 1880s. Similarly, certain introductions of exotic natural enemies in India made around early 20th century gave success in many areas such as the suppression of wolly aphid of apple, *Eriosoma lanigerum* (Hausm.) by the North American hymenopterous parasites, *Aphelinus mali* (Hald.) in 1937 and of the polyphagous fluted scale *Icerya purchasi* Mask by Australian lady bird beetle predator *Rodolia cardinalis* (Muls) obtained from the USA in 1929 and from Egypt in 1930.

Classical biological control involves the deliberate introduction and establishment of natural enemies into the areas where they did not previously occur, and has been employed largely against pests of exotic origin. For example *Rodolia cardinalis* was used against *Icerya purchasi* in India, which gave a spectacular control. Besides this, fortuitous biological control is the accidental movement of exotic natural enemy to new area which eventually results in suppression of pest population. Chalcid parasik, *Aphytis lepidosaphes* (Compere) indigenous to the area of China has spread to California and other countries along with the import of citrus planting material became a major factor in controlling purple scale of citrus *Lepidosaphes beckii* (Newman). Currently, the term Bio-intensive Integrated Pest Management (BIPM) is used to lay major emphasis on conservation and enhancement of natural enemies and utilization of all compatible methods for achieving effective, economical and safe pest control/suppression. These methods are the most appropriate in horticulture and in protected cultivation. Some of the promising biocontrol agents used for horticultural ecosystem include *Trichogrammatid* egg parasitoid alone or in combination with *Bacillus thurigiensis* var. kurstaki or baculoviruses for management of lepidopterans; coccinellid beetles for management of mealy bugs and scale insects; lacebugs for aphids and soft bodied insects; parasitoid and predators for san jose scale and wolly aphis on apple, phytoseiid mites for tetranychid mites; entomopathogenic nematodes for soil borne pests and entomofungal pathogens for several hoppers and mites. In addition, exotic bioagents have been introduced for the menagement of accidently introduced exotic pests.

BIPM is the recent trend to reduce the pesticide pressure and to enhance the farmers' interest to fetch higher remuneration for their produce. BIPM also opens new horizons to opt for a better choice, as biological control and use of bio rational products, which are less toxic and only affect the target pest. It also includes biopesticides derived from microbials, parasitoids, predators, botanicals and all conventional non-chemical methods of pest management. It refers to the more dynamic and ecologically informed approach to IPM that considers the farm as a vital part of an agro-ecosystem. BIPM approach is a biological form of agriculture in which a small area is intensively cultivated, using natural ingredients to rebuild and revitalize the soil health. Initially, it is more labor intensive than conventional approaches, therefore, it is better suited to the small farm areas. It lays emphasis on the use of predominantly indigenous or region specific cultivars, crop diversity, good soil health and water conditions which results in little or no pest problem.

Consumers Union of the United States Department of Agriculture defines biointensive IPM as, "A systems approach to pest management based on an understanding of pest ecology. It begins with steps to accurately diagnose the nature and source of pest problems, and then relies on a range of preventive tactics and biological controls to keep pest populations within acceptable limits. Reduced-risk pesticides are used if other tactics have not been adequately effective, as a last resort, and with care to minimize risks."

21.3 Pre-requisites of Bio-intensive Management System

21.3.1 Collection of Base Line Data Through Survey and Surveillance

The base line data or information is quite necessary to understand the real picture or status of farmers' perception about the biologically intensive pest management. The baseline survey serves to identify farmers' pest perceptions, pest management practices and decision making process, basic socio-economic characteristics, and other information.

21.3.2 Proper and Accurate Identification of Major Fruit Pests

Correct identification of the insect pests or diseases is essential to pest control in a fruit tree ecosystem. It is important to know all the stages of a pest, such as, eggs, larvae, where they pupate, and the adult's appearance, as well as the type of damage to the fruit or tree. An incorrect diagnosis can lead to unnecessary sprays and wastage of money. Many insects found in the orchard are not pests, but only incidental visitors, while others are beneficial (natural enemies), acting as biological controls for pests. Identification or diagnosis is the process of recognizing the damage or injuries from its symptoms whether the injuries/damage is caused by the physical environment, or by an insect. The diagnostic process comprises looking at the entire plant as well as its separate parts, carefully analyzing the observations, and attempting to understand why injuries or damage has occurred. Before deciding to take pest control decision, insect types prevailing in the field, their mode of feeding or damage habits should be considered.

21.3.3 Sampling and Pest Forecasting

Sampling population estimates of insect pests are the fundamental activities in ecology and primary basis of integrated pest management (Pedigo, 2001). A full treatment of the methods of selecting the optimum size sampling unit is given by Cochran (1977). But as population density is always fluctuating, too much stress should not be placed on a precise determination of sample unit. The total number of samples to be taken depends on the degree of precision required. Sampling techniques should be standardized for trees in orchards and taken from different corners, all peripheries, diagonally, zig-zag diagonally etc. Sampling in fruit tree ecosystem is relatively more complex phenomenon than annual crop plants because of wide variety of habitat prevalent in the tree ecosystem (Hare, 1994). Sampling techniques for insect pests in mango and citrus trees are better described by Smith et al. (1997). Sampling and monitoring methods for tropical fruits are well established for some direct pests namely fruit fly and fruit borers as well as, for indirect pests like banana weevil, leaf miner, mites (Keenan, 1997) and for defoliators. Beers et al. (1994) developed the sampling methods for insect pests and beneficial arthropods in apple ecosystem. A sequential sampling plan for monitoring mango hopper populations has been developed in India. To assess mite densities in the field, the relationship between bud proliferation and mite densities could be used to determine action levels. The spatial distribution of *Rastrococcus invadens* (Williams) a polyphagous mealybug infesting leaves, flowers and fruits was studied by Boavida et al. (1992), who developed binomial sampling plans for estimating population levels. The sampling methodology and action levels against important pests of mango have been devised on 3,170.60 hectares area in semi-arid regions of Brazil (Haji et al., 2004).

21.3.3.1 Pest Forecasting in Fruit Crops

Disease and pest outbreaks occur as a result of congenial weather conditions, which facilitate their uninterrupted multiplication. The weather and climate greatly influence the quantity and quality of food provided by the host plants and the associated species of pest. The impact of various weather components on insect pests and diseases is location and crop specific. Day and night temperature greater than 35°C and 23°C, respectively, in conjunction with humidity in the range of 50–80 percent and vapour pressure between 20–24 mm of Hg were found conducive for mango hopper breeding and thereby, helpful in increasing population buildup in subsequent months (Pandey et al., 2003). Traditionally, majority of the fruit growers are using a calendar or a phenological schedule to determine the pest events and time of pest control in their orchards. The calendar method is grossly inaccurate since pest development may not occur at the same calendar dates each year. On the other hand, the phenological method while more accurate, assumes incorrectly that pest populations peak at the same stage of host development every year. A more scientific and accurate method of forecasting pest development and orchard events is degree-day accumulations. A degree-day (DD) concept is said to be the indicator of insect pest development as many growing season-emergent insect pests have their development driven by temperature. Like crops, there are a number of baselines and thresholds for degree-day accumulation for pest development. The occurrence of insect pest/disease in time and space can be predicted in advance with reasonable accuracy on the basis of relevant weather variables (Huda and Luck, 2008).

Presently, automatic weather stations are being used to record the microclimate of the orchards at different time intervals depending upon the requirement. Data recorded by the weather station can be periodically downloaded (once or twice per week) directly to a disc or to a computer hard drive. A computer software program makes the calculation of degree days and disease forecasting. Various agencies have developed software programs that will run several disease models like apple scab, fire blight, and powdery mildew using weather data of a specific field. The weather information at micro level will not only help in forewarning of insect pests and diseases, but it will also help to find suitable time for application as the deposition and retention of pesticide spray droplets/dust particles on the tree canopy are dependent on weather conditions prevailing in orchard at the time of application. Forewarning of incidence of tea mosquito bug, *Helopeltis antonii* (Sign.) in cashew can be made one month in advance on the basis of prevailing weather which can be used for decision making in IPM (Prasada Rao and Beevi, 2008).

21.3.4 Field Monitoring and Scouting of Pest Population

Field monitoring is the prerequisite against the fluctuating trends of many insect pests and allows the growers to take decisions on insect pests control interventions (Barnes, 1990). Monitoring procedure requires survey and surveillance, and injury caused by insect pests. To monitor the initial development of pest complexes in endemic areas, survey routes have to be identified, and the state extension functionaries have to concentrate their efforts at village level to initiate field scouting by farmers. Therefore, for field scouting farmers should be mobilized to observe the insect pest and disease occurrence at regular intervals. The plant protection measures are required to be taken, based on field scouting, only when insect pests and diseases cross ETL. It should be undertaken once in a week by growers to workout economic threshold level (ETL). The sampling intensity and knowledge of action thresholds is valuable information in order to provide high quality mango fruits (Pena, 2004). Field monitoring of insect pests and beneficial organisms is needed to design, evaluate and proper execution of IPM practices. Undertake roving survey at every 10 km distance at 7–10 days intervals (depending upon pest population). Keep the record of incidence of major insect pests and diseases on fruit trees and all other host plants of the locality. Observe at each spot 20 trees at random and 5 samples in each tree. Record the population of all insect pests on 3 leaves of new shoots of these plants. Also keep the record of population potential of different biocontrol fauna. Agro ecosystem analysis (AESA) is an approach, which can be gainfully employed by extension functionaries and farmers to analyze field situations with regard to insect pests, natural enemies or bio-agents, soil conditions, plant health, the influence of climatic factors and their interrelationship for growing healthy crop. Such a critical analysis of the field situations will help in taking appropriate decision on management practices.

21.3.5 Threshold Level Determination

Economic threshold for temperate fruits have been postulated by Hoyt and Burts (1974). There are insufficient data available on ecological consequences of arthropods of tropical fruits. The meager information available is mere approximation. This factor together with the lack of sampling techniques suggests that little efforts have been focused on determining economic threshold levels. Consequently, pesticides continue to be widely applied as prophylactic measures. When spray is necessary as a control tactic, consider all the monitoring information and other factors such as tree stage, fruit age, pest stages, climatic factors, fruit variety, etc for taking the right decision. The density of a pest, given all these factors, that will result in an economic loss of the crop, which outweighs the cost of the control measure, is termed the economic injury level (EIL). EIL have been scientifically determined for only some pests, thus for many pests and fruit varieties thresholds have been devised by the scientists based on experience, level of aversion to perceived risk of crop loss, etc. Action threshold is the point at which control action should be taken to prevent unacceptable damage to the agro-ecosystem. A low level of insect pest damage can perhaps be ignored if the loss will not justify the cost of control. The economical, ecological and aesthetic values or social importance of the crops grown are the prime factors which need to be considered for taking the control decisions. Control of mango fruit pests by chemicals alone has been complicated by development of pest resistance and resurgence and elevation of minor pests to major pest status (Cunningham, 1984). The foundation of integrated pest management as presented by Flint and van den Bosch (1981) is based on sampling, economic thresholds, and natural mortality in agroecosystems. Whalon and Croft (1984) have also determined the action threshold against apple pests in North America and observed that they vary across the country due to differences in sampling system, pest status, market parameters, management options, time of yearly control, orchard history and human factors etc.

21.3.6 Proper Record Keeping

Record keeping is simply a systematic way to learn from past experience. A variety of software programs are now available to help fruit growers keep track record and access data on their farm's inputs and outputs. Monitoring process goes simultaneously with record keeping and forms the ready reckoner tool of the farm. Records should not only provide information about when and where pest problems have occurred, but should also incorporate information about cultural practices (proper time of irrigation, timely application of fertilization, weeding operations, training and pruning etc.) and their effect on insect pest and their natural enemy populations. The effects of abiotic factors, especially weather, on biotic factors like insect pest and their natural enemy complexes should also be noted for future insect pest forecasting. Systematic recording of data in the field is time consuming but necessary for clarity in review and interpretation of the results. If field counts are considered impractical and some form of rating scale is employed (e.g., trace, low, medium, high, very high), the assignment of numerical values from 1 to 5 is acceptable. Organization of the data in summary form following field sampling allows for identification review and assessment of individual orchard situations. Information gathered during the monitoring process aids in planning future pest management strategies.

21.4 Tactics of Bio-intensive Integrated Pest Management

Tactics commonly adopted for the control of fruit pests are classified into curative and preventive methods. These methods include cultural, mechanical and physical, chemotherapeutic, regulatory, biological, plant resistance and genetic to check the increase in pest population.

21.4.1 Cultural Approaches in BIPM

Clean culture and ploughing creates condition unfavourable for insect pest development and eliminates the weeds and other secondary hosts of some pests. They have been proved useful in controlling the dormant stages of pests either by burying them deep in the soil or exposing them to inclement weather conditions. They are found promising in controlling scales and mealy bugs on citrus, guava and mango, thrips and shot hole borer on grapes, fruit sucking moths on citrus, San Jose scale on apple and peach leaf curl aphid on peach. Plant density alters the micro climate habitat for the pest populations build up e.g. aphids on peach as close plantations develops canopy favourable for multiplication of aphids in shady humid climate, mango hoppers, scales, mealy bugs, citrus white flies and balack fly on mango and citrus trees, respectively. Pruning is used to maintain maximum yield of high quality fruit as well as maintaining the tree vigour, size and shape. In addition, sound orchard practices like weed management, pruning management, and sanitation help to reduce the pest infestation pressure. These practices also increase the number of beneficial arthropod species to survive in deciduous fruit orchard e.g. decreasing status of phytophagous mites in pome fruits. Planting cover crops/trap crops like legumes and alfa-alfa between trees at critical times are useful for increasing habitat diversity and refuge management to sustain the beneficial and natural enemies for many ecosystems to work upon the aphid and mite pests. However, Hansen and Amstrong in 1990 observed that orchard sanitation did not reduce infestation of mango stone weevil in Hawaii. Untreated and neglected fruit trees are the major source to harbour the fruit flies population. Hoyt and Burts (1974) revealed that cultural practices generally do not offer a direct benefit to reduce pest but when used properly they can enhance natural enemy's activity to a certain degree that is important in integrated pest control programs. Removal of related host plant for polypahgous pests is also beneficial cultural practice to reduce the pest incidence.

21.4.2 Mechanical and Physical Control

Removal or destruction generally involves the removal or destruction of pests mostly by using manual labour. At small scale, it is very effective and profitable especially to home fruit growers. Collection and destruction of insect stages is a predominating and effective method in checking the outbreak of many pests. Bagging the fruits like pomegranate and citrus with butter paper or cloth material immediately after fruit formation prevents the damage of butterfly and fruit sucking moths, respectively. Slippery alkathene sheet or sticky band, encircling the trunks of trees is used to prevent certain stages of insects from climbing to the foliage from the ground. This method is widely used to suppress the creeping up of mealy bug to the tree trunks of mango orchard (Singh et al., 2001). Physical removal of certain insect pest species by using physical factors like heat, cold, sound, radiation etc. also proved promising by using artificial or natural sources.

21.4.3 Role of Host Plant Resistance (HPR) in BIPM

Despite the great achievement in host plant resistance in field crops, these aspects have gained little attention in the fruit tree crops. Barring the historical examples of plant resistance in apple variety, Winter Majetin against wooly apple aphid (*Eriosoma lanigerum*) and wild American grapes (*Viteus viniferata*) against *Phylloxera vitifolia*, much has not been achieved in fruit crops and these two examples are still legendary in fruit pest management. An overview of host plant resistance of fruit crops in India (Sharma, 2006; Sharma and Singh, 2006) shows that certain information based on the insect damage is available in citrus, mango, apple, guava, peach, plum, banana, grapes, date palm, ber, sapota etc. but little efforts have been made to incorporate the resistant/tolerant germplasm in breeding program. Most of the commercial mango varieties are susceptible to fly attack; however, infestation is quite low in Langra, Dashehari and Bombay Green varieties (Jothi et al. 1994). Angeles (1991) reported that *Mangifera altissima* does not seem to be affected by mango pests, *i.e.*, leafhoppers, tip borers and seed borers, in the Philippines (Table 21.1).

Table 21.1 Resistant/tolerant stock of different fruit crops against different insect and mite pests in India

Fruit crop	Resistant/tolerant stock	Insect/mite pest
Citrus	Redblush, Foster, Marsh seedless, Fallglo, Nova mandarin, Star ruby	Whitefly, *Dialeurodes citri* Ashmed
	Cleopatra, Rubidoux, Orange Michal, Coorgcitron, Deshndo, Nagpur mandarin, Gal-gal,Kagzi lime	Psylla, *Diaphorina citri* Kuwayama
	Jatti Khatti, Citrumelo, Carrizo, Troyer, Orage-Michal, Coorg citron, Deshndo, Eureka lemon, Savage, Sacaton, Rangatra L.J.	Leaf-miner, *Phyllonistis citrella* Stainton
	Citron, Redblush, Marsh seedless	Lemon caterpillar, *Papilio demoleus* Linnaeus
	Nagpur mandarin, Ikeda Unshiu, Long sportvalencia, Campbel valencia, Washington Naval	Aphids, *Toxoptera aurantii* Boyer de Fonscombe, *Aphis gossypii* Glover
	Washington Naval, Hazara, Jenru tenga	Scales, *Aonidiella aurantii* Maskell, *Coccus hesperidium* Linnaeus
	Chakotra, Blood red, Kagzi lime, Malta, Mosambi, Kinnow, Galgal, Sweet lime, Etrong citron, Coorg, Wilking, Sylhet,Valencia champman	Mites, Eutetranychus orientalis Klein, Panonychus citri McGreger
Guava	Nasik, China Surkha, Behat Coconut, Pear shaped, Red flesh, Smooth Green hybrid	Fruit fly, *Bactrocera zonatus* Saunders, *Bactrocera dorsalis* Hendel
	Red flush	Shoot borer, *Indrabela tetraonis* Moore
	Bangalore Round, Bapatala, AC 10, Seedless	Tea mosquito bug,
Mango	Pulhora, Kala Hapus, Keshar Basti, Annanas, Baneshan Bangalora, Chinnarasam and Khander	Leaf Hoppers, *Amritodes atkinsoni* Lthiery
	Annanas, Anain, Delicious, Gulabkhas, KO7, KO11, Maharaja of Mysore, Salem, Banglora, Vellakachi	Gall insect, Procontarinia matteriana Kieff & Cecec
	Toranjo, Monteiro, Manjurad	Fruit fly, *Bactrocera dorsalis* Hendel
	Deshi Malgoba, Alam Baneshan	Leaf gall midge. *Dasyneura mangiferae* Felt
	Mohandas, Malgoa, Pulliadi	Mites, *Aceria mangiferae* Sayed
Apple	Malling Merton series(MM)	Woolly apple aphid, *Eriosoma lanigerum* Haussmann
Peach	Stark Early Giant, Early White Giant and Flavour Crest	Peach leaf curling aphid, *Brachycaudus helichrysi* Kaltenback

Source: (Sharma, 2006; Sharma and Singh, 2006)

21.4.4 Potential of Biological Control Agents in BIPM

The biological pest control is not only an important tool for sustainable agriculture but also is environmental friendly and safe for human beings. In this process natural enemies (parasitoids, predators, fungi, bacteria, nematodes, viruses etc.) are introduced, multiplied by artificial means instead of leaving it to nature to control the pests. Biocontrol is a slow process that takes some time to achieve the desired pest control. Unlike chemical pesticides bioagents are not commercially available in India even after more than 55 years of biocontrol research, except few parasitoids (*Bracon brevicornis, Leptomastix dactylopii, Parasierola nephantidis, Trichogramma* spp.) and predators (*Chilocorus nigritus, Crytolaemus montrouzieri, Pharoscymnus horni* and *Scymnus* spp) used against pests of fruits like guava, grapes, citrus, mango etc. Conservation of biological control agents has received considerable attention in the recent past. Bentley and O'Neil (1997) reported that four types of biological control namely (1) natural, (2) conservation, (3) augmentation, and (4) importation. Importation biological control is a cost-effective alternative to chemical control for basic food crops of resource poor farmers. Augmentation has some technical concerns, but is generally environmentally sound and viable alternative to chemicals, and offers employment generation. Conservation can help empower farmers to preserve native species, while saving labor and money and reducing chemical insecticide pressure on ecosystem. The successes in classical biological control have provided the background and encouragement for efforts in the manipulation of natural enemies. Such manipulations include conservation, augmentation, habitat management and genetic manipulation. In fruit crops, several predators and parasitoids of different insect pests have been identified and appear to be ideal for the control of insect pests. But there are few instances where the biocontrol agents are being used to reduce the pest population below the economic injury level. Except few instances where they are used directly for the immediate control of pest species e.g. predatory coccinellid, *Cryptolaemus montrouzieri* has been used against mealy bugs on citrus and guava. Among different bioagents, parasitoids have received increasingly more attention than predatory insects. Hitherto many entomophagous spiders, mites, fungi, bacteria, protozoans, virus, nematodes and other vertebrates have been found to play a significant role in balancing the pest population of the fruit crops. Some promising bioagents of different insect pests are listed in Table 21.2.

21.4.5 Autocidal Approaches or Genetic Approach

The reduction of insect population by using substances that cause sterility by altering sexual behavior or otherwise disrupt the normal reproduction in insects is found effective in many insect pests. Male sterility has successfully been used on oriental fruit fly, melon fruit fly and codling moth. It involves the artificial rearing, sterilization with direct application of γ- radiation or by using some chemosterilents like TEPA, METEPA and apholate and releasing otherwise healthy male insects in

Table 21.2 Some promising bioagents of different pests in India

Natural enemies	Pest species
Predators	
Rodolia cardinalis	Cottony cushion scale (*Icerya purchasi* Maskell) Citrus mealy bug (*Planococcus citri* Risso)
Platymeris laevicollis	Rhinoceros beetle (*Oryctes rhinoceros* Linnaeus)
Cryptolaemus montrouzieri	Mealy bug (*Ferrisia virgata* Cockerell, *Planococcus citri, Maconellicocus hirsutus* Green)
Mallada boninensis	Citrus blackfly (*Aleurocanthus woglumi* Ashby), Mango hopper, *Amritodes atkinsoni* Lethierry
Cryptolaemus nigritus	Citrus red scale (*Aonidiella aurantii* Maskell)
Parasitoids	
Aphelinus mali	Wooly apple aphid (*Eriosoma lanigreum* Hausmann)
Encarsia perniciosi	San jose scale (*Quadraspidiotus perniciosus* Comstock)
Trichogramma cacoecia and *T. embryphagum*	Apple codling moth (*Cydia pomonella* Linnaeus)
Tetrastichus radiatus	Citrus psylla (*Diaphorina citri*)
Leptomastix dactylopi	Mealy bugs (*Planococcus citri*)
Fungus	
Verticillium laccani	Mango hoppers (*Amritodes atkinsoni*)

Source: Singh et al. (2001)

numbers that will compete with natural males. The female thus mated with such sterile males, produce unfertilized and non viable eggs and ultimately the suppression of insect population. No work on autocidal control on fruit crops is done in India.Using of sex attractants or pheromones are also found effective in monitoring the pest populations of codling moth and Mediterranean fruit fly. The use of sterile insect techniques (SIT) against fruit fly has significantly reduced insecticides usage on grapes and codling moth and other pests are being considered for control by this unique method (Barnes and Eyles, 2000).

21.4.6 Novel Approach

Insecticide resistance in key pests will continue to be a major impetus for adopting novel insecticides. Narrow spectrum insect growth regulator (IGR) and less hazardous encapsulated pesticides formulations form the part of control and resistance pest management program particularly codling moth (Blomefield, 1997). Low volume bait spray against fruit fly precludes the necessity for full cover sparys which have greater negative impact on natural enemies (Barnes, 1999). A major advantage of these new products is that they act on insect's biological processes such as moulting. Many also have greater selectivity to target specific species, so they are less likely to harm natural enemies when compared with the broader spectrum organophosphate, carbamate, neonicotinoid and pyrethroid insecticides. Such novel insecticides currently in use include targeting lepidopteran pests, sucking insects, dipteran, leafminers and insect growth regulator that control a wide range of insects. One negative aspect of these insecticides is that because of their narrower range of activity, controlling only a limited number of insect pests, growers may need to apply additional pesticides for secondary pest groups that have poor biological control, increasing the total number of treatments per hectare and total pest control costs.

21.4.7 Pheromones and Trapping Devices

Pheromomne based mating disruption program are quite effective and economical to control codling moth and oriental fruit fly, respectively (Barnes and Blomefield, 1997). So far, only feeding and sex attractants are devised against fruit flies. Few traps are species specific like weevils (Gold et al., 2003) and lepidopterans (Bailey et al., 1988). Certain pests require positioning of various kinds of traps like, pheromones, yellow pan and sticky traps to monitor the initial pest build-up. Florescent lights placed around stone fruit orchard repel nocturnal invasions of fruit piercing moth (Whitehead and Rust, 1972). While the concept needs to be popularized amongst farming community, the government agencies need to take greater initiatives for pest monitoring through specific pheromone trapping methods as per following details.

21.4.7.1 Pheromone Trap Monitoring

Use Pheromone traps for monitoring of fruit flies, leaf miner and mealy bug. Install pheromone traps at distance of 50 meter @ five traps per hectare for each insect pest. Use specific lure for each insect pest species and change it after every 20 days. Trapped moths should be removed daily.

21.4.7.2 Yellow Pan/Sticky Traps

Set up yellow pan sticky traps for monitoring whitefly @ 10 yellow pans/sticky trap per ha. Locally available empty yellow palmolive tins coated with grease/vasline/castor oil on outer surface may also be used.

21.4.7.3 Light Trap

Yellow color traps reflecting light at the wave length of 550 nano meter may be installed and operated for 2 hours in the evening for the monitoring of black fly. Florescent lights placed around stone fruit crops repel nocturnal insects like fruit piercing moth (Whitehead and Rust, 1972).

21.4.8 Blending of Selective, Safer and Eco-friendly Insecticides

In the United States, approximately 500,000 tons of 600 different types of pesticides are used annually at a cost of $4.1 billion, including application costs. It has been estimated that losses to pests would increase by 10% if no pesticides were used at all and specific crop losses would range from zero to nearly 100% (Pimental et al., 1992). Measurable benefits of pesticide use have included a reduction in costs to farmers and processors as well as lower relative prices and increased food quality for consumers (Lichtenberg et al., 1990). Several insecticides have been adequately tested in the orchards but many of them are either too expensive or too toxic for orchard spraying due to involvement of many interactive factors, including man and beneficial
organisms.

Little efforts have been made on determining the ETL on fruit tree crops (Table 21.3) and there is a need to develop the strategies to avoid the insecticide residues on fruits. Moreover, to obtain high efficacy with minimum risk of insecticide residues on fruits, the following factors must be taken into consideration:

- Right stage, site and activity period of the pest.
- Proper selection of insecticide, dosage and application equipment.
- Coverage of the tree canopy.

Table 21.3 Economic threshold levels of different insect and mite pests

Sl. No.	Insect pests	Economic threshold levels
1	Green citrus aphid, *Aphis spiraecola* Patch	5–10% infested shoots
2	Melon Aphid, *Aphis gossypii* Glover	25% infested shoots
3	Black citrus aphid, *Toxoptera aurantii* Bayer de Fonscolombe	25% infested shoots
4	Citrus whiteflies, *Dialeurodes citri* Ashmed	5–10 nymphs/leaf on mandarin
5	Citrus blackflies, *Aleurocanthus spp*. Ashby	First colonies occurrence
6	Bayberry whitefly, *Parabemisia myricae* Kuwana	First colonies occurrence
7	Citrus mealy bug, *Planococcus citri* Risso	5–10% infested fruits
8	Black olive scale, *Saissetia oleae* (soft scale) Bernard	3–5 nymphs/leaf
9	California red scale, *Aonidiella aurantii* (armoured scale) Maskell	3–5 nymphs/leaf
10	Citrus flower moth, *Prays citri* (flower moth) Milliere	50% infested flowers
11	Mediterranean fruit fly, *Ceratitis capitata* Wiedmann	20 adults/trap/week (Clementine)
12	Citrus bud mite, *Eriophyes sheldoni* Ewig	50–70% infested buds
13	Pink citrus rust mite, *Aculops pelekassi* McGregor	2–3% infested fruits
14	*Panonychus citri*	3 specimens/leaf or 50% infested leaves
15	Two spotted spider mite, *Tetranychus urticae* Koch	2% infested fruits or 10% infested leaves
16	Banana stem weevil, *Odoiporus longicollis* Oliver	5% infested plants
17	Banana root weevil, *Cosmopolites sordidus* Germer	4 weevils/trap

Source: DPPQS (2001).

21.5 Key Pests in Major Fruit Ecosystem

21.5.1 Mango

Mango (*Mangifera indica*), is infested by more than 492 species of insects and mites. About 45 percent of these have been reported from India. Mango is usually attacked by four to five key pests damaging the crop to a considerable extent causing severe losses which includes fruit flies, stone weevils, mango hoppers, mealy bugs, scale insects and tree shoot borers, and several secondary pests that can become serious pests as a result of certain aberration in cultural practices or because of indiscriminate and excessive use of insecticides against a key pest. Mohyuddin and Mahmood (1993) reported that scale insects (secondary pest) became serious pests owing to non judicious use of insecticides against fruit flies. Similarly, mites, *Oligonychus* spp. are secondary pests of mango, which can become serious pest due to human intervention. Occasional or incidental pests also cause economic damage only in localized areas at certain times. Worldwide lists of pests of mango have also been documented by de Laroussilhe (1980); Tandon and Verghese (1985) and Veerish (1989). Lists of mango pests with special reference to details of life histories and control of mango pests are also discussed by Golez (1991); Morin (1967) and Murray (1991).

Most of the mango producing countries are located in fruit fly infested areas, and growers suffer significant direct and indirect economic losses resulting from fruit fly damage (Aluja, 1994; Drew and Hancock, 1994; Hill, 1975; Singh, 1991). Attacked fruits usually show signs of oviposition punctures and ripe fruits with high sugar content exude a sugary liquid. On an average, 36–40% fruits of mango have been observed to be damaged by *B. dorsalis* and *B. zonata* (Syed et al., 1970; Hill, 1975 and Mohyuddin and Mahmood, 1993). The Mediterranean fruit fly, *Ceratitis capitata* (Wiedemann), is a common polyphagous pest in mango growing areas of Hawaii, Israel, Australia, Spain, Mexico, and South America (Galan-Sauco, 1990; Morin, 1967). Of all the mango pests, hoppers are considered as the most serious and widespread pest throughout the Indian subcontinent. Large number of nymphs and adults of *Idioscopus clypealis* and *I. niveosparsus* suck and puncture the sap from tender parts, thereby reducing the vigour of the plants and particularly destroying the inflorescence and causing fruit drop. Heavy puncturing and continuous draining of the sap encourages development of sooty mould *Maliola mangiferae* and *Capnodium mangiferae* on leaves and inflorescence. The extent of damage depends upon the critical crop stage and hopper population. Mango mealy bugs (*Drosicha mangiferae, Drosicha stebbingi* and *Rastrococcus iceryoides*), the polyphagous pests of mango in India are recorded as serious pests from Asia on several host crops (Tandon and Verghese 1985). Nymphs and adult female bugs are flat, oval and waxy white which suck sap from inflorescence, tender leaves, shoots and adversely affect the fruit set and causes fruit drop. Three species of stone weevil, namely, *Sternochetus mangiferae, S. gravis* and *S. frigidus* have been reported infesting the mango trees and the extent of damage in susceptible varieties like Neelum, Totapuri and Banganpalli can be up to 60–65% (Tandon and Verghese 1985).

IPM Strategies:

1. Deep ploughing of orchard immediately after harvest or during summer months to expose eggs and pupae of mealy bugs, inflorescence midge and fruit fly to natural enemies and sun heat.
2. Heavy irrigation of orchard in October also helps in destruction of eggs of mealy bugs, diapauses pupae of midge and fruit fly.
3. Avoid dense planting, keep orchard clean by regular ploughing, removal of weeds and prune the over crowded and overlapping branches in December for control of hoppers.
4. Raking of soil around the tree trunk and mixing with methyl parathion 2% dust @ 250 g per tree for controlling early instar nymphs of mealy bugs in the month of November–December.
5. Collection and destruction of stone weevil infested fallen fruits and stones help in reduction and carry over of infestation.
6. After mud plastering 25 cm wide, 400 gauge alkathene (polythene) sheet should be fastened to the tree trunk about 30 cm above the ground level to prevent migration of freshly hatched first instar nymphs of mealy bugs and stone weevils to migrate on branches in the month of November–December.
7. Early harvesting of mature fruits to avoid fruit fly infestation, and collect fruit fly infested and dropped fruits and destroy them.
8. Fruit fly population can easily be monitored with pheromone traps, although trap catches are not sufficient enough to avoid the risk to the crop in different areas.
9. Removal of webs made by leaf webber by leaf removing device and burning them in August to September to control leaf webber.
10. Prunning of overcrowded and overlapping branches for control of leaf webber in September–October.
11. Conserve the natural enemies like coccinellids, chrysopids and spiders by avoiding sprays of broad spectrum insecticides during their peak activity period and minimum tillage.
12. Spray neem extract (4%) or azadirachtin (6 ppm) at fortnightly interval against leafhopper. Synchronize the spray activity at evening hours to avoid killing of pollinators.

To mitigate the dependency on insecticides, Peng and Christian (2005) demonstrated a successful IPM model using weaver ants, *Oecophylla smargdina* as a key element which was shown to be equal to, or better than chemical insecticides in controlling the all major insect pests of mango in Northern Territory of Australia.

21.5.2 Citrus

India occupies sixth position among citrus growing countries in the world and is the second largest group of fruit crops of India with a production of 6.0 million tons from 0.71 million ha (Chadha and Choudhary, 2007). Citrus is grown in a variety of soil and ecosystems, and influenced by wide array of insect and mite pests, which can cause serious quantitative and qualitative losses. More than 300 species of insects and mites have been recorded on different *Citrus* spp. from Asia and other countries. However, the key pests are leafminer, citrus psylla, mealybugs, and aphids.

Citrus leafminer, *Phyllocnistis citrella* (Stainton) has been observed a potential menace to citrus agro-ecosystem in majority of the Asian countries. The larvae feed on the epidermis of tender leaves making serpentine mines of silvery color. Severely infested leaves became distorted and crumpled and finally fall off and also encourages the incidence of canker during rainy season. Huang and Li (1989) reported that more than 20% of the leaves are damaged and have no influence on growth and yield, and the economic threshold was estimated as 0.74 larva / leaf. The extent of damage depends upon the new vegetative growth and number of flushes in a year. Psyllids are widely distributed in Asia and other citrus growing countries. The damage is caused by the nymphs and adults who suck the sap from buds and leaves. The affected leaves get curled and shoots become dry. The psyllid also acts as a vector of greening disease of citrus. Besides *Citrus* spp., it attacks *Murraya exotica* and *M. koenigii*. There are no systematic data available on extent of damage; however, citrus psylla has been reported causing loss to mandarin to the tune of Rs. 40 million (about US $ 1.04 million) alone in Vidharva region of Maharashtra in India. Several species of mealy bugs namely, *Planococcus citri, P. pacificus* and *Icerya purchasii* have been recorded infesting citrus throughout the world. Mealy bugs infest leaves, tender shoots, flower buds and fruits. In severe infestation, growth of plant is arrested and fruits drop is induced. Sooty mould develops on the infested trees. In an acid lime orchard near Bangalore, as high as 65% of the fruits were infested by *P. citri*. Although, aphids are worldwide in distribution, they do not cause serious direct damage except for transmitting tristeza virus in citrus trees. The damage symptoms caused by aphids are exhibited by curling of young leaves and premature fruit fall. Normally, aphids attack during flowering but occasionally severe outbreaks occur when rainy season is followed by dry weather.

IPM Strategies:

1. Summer deep ploughing to expose soil inhabiting/resting stages of insect, pathogen and nematode population.
2. Use resistant rootstocks and select disease free nursery plants.
3. Be alert at the active phase of the growth. Avoid pruning during active growth periods. Excessive use of nitrogenous fertilizers should be avoided.

4. Prune affected shoots during winter and allow canopy to open from centre so that sufficient sunlight is intercepted below the canopy. Destroy ant colonies. Clipping of infested leaves and their pruning is advised.
5. Removal of early and late growing flushes and pre-flush pruning.
6. Sticky bands on the trunk portion of the tree shall keep avoiding the climbing of the crawlers from the ground.
7. Raking the soil around trunk during summer months helps in the desiccation of eggs and help in exposing mealy bugs to natural enemies.
8. Conservation and augmentation of natural enemies against citrus aphid. Use recommended neem products.
9. *Planococcus citri* can be brought under effective control by releasing 10 *C. montrouzieri* per plant (Mani and Krishnamoorthy, 1990). Release *Leptomastix dactylopi* @ 5000–7000/adults/ha against citrus mealy bug.
10. Release *Chrysoperla* grubs @ 10–15/plant against citrus mites.
11. Commencement of new flushes should be sprayed with neem seed extract (2%) at 10–12 days interval to check the leafminer infestation.

21.5.3 Litchi

Litchi, a delicious fruit is generally considered to be free from serious insect pests and does not even require the regular control measures in some regions like Florida (Campbell and Knight, 1983). Growth and production of litchi tree is hampered by the attack of more than 40 species of insect and mite pests (Hameed et al., 1992 and Khangura et al., 1992). Some of these pests have the ability to ruin a well established orchard if proper control measures are not initiated at appropriate time. These include fruitfly, fruit borers, eriophyid mite, shoot borers, leaf rollers, scales and bark eating caterpillars. It is well documented that litchi tree is very sensitive to a number of insecticides especially oil based sprays, hence, an utmost care should be taken to avoid phytotoxic effect on litchi. He (2001) discussed the bionomics and the control of major pests of litchi, causes of the outbreak of some minor insects and suggested strategies for the integrated management of insects in two different types of litchi orchards at Guangdong in China. Approximately 100% of litchi trees are infected by the litchi mite, (*Eriophyes litchii*) and around 50% are damaged by a bark feeding borer (*Indarbela* spp.). The oriental fruitfly, *B. dorsalis*, has been observed as major pest in Bihar region in India on ripe fruits. Fruits are rendered unfit for local consumption as well as for export.

During the harvest season up to 30% of litchi fruits were damaged by litchi fruit borer (*Coponomorpha cramerella* Snellen) and other lepidopterous larva. The caterpillars bore into the developing fruits and feed on seeds. The bore hole gets filled with the excreta of the caterpillar and infested fruits start rotting. Litchi mite, *Aceria litchi* Kiefer is the major pest of litchi and widely distributed in all litchi growing areas of the world. In India, it has been reported from Bihar (Roy and De, 1950), Punjab (Nijjar, 1972), U.P, Orissa and Assam (Sharma, 1985). The pest attacks the young leaves, shoots, flower buds and fruits. Nymphs and adult mites puncture and lacerate the leaf tissues on the ventral side and suck sap. The characteristic symptoms of the pest presence are velvety swellings of chocolate brown color on the underside of leaves and curling of leaflets. Mite fed leaves curl and dry to form light roll whereas flower bud do not set fruits; if set they remain undersized and fall prematurely resulting in serious loss. Bark boring caterpillar, *Inderbela quadrinotata* Walker and *I. tetraonis* Moore are the polyphagous pests which are particularly common in old and neglected litchi orchards in India. Besides litchi, it also attacks citrus, mango, guava, ber, mulberry, pear as well as other fruits. The caterpillar is the damaging stage which after hatching gnaws the bark and bores into the trunk of the tree. Thus, interrupting the sap flow and subsequently arresting the tree growth. *Anoplophora macularia* have been reported as the serious pest of litchi orchard in Taiwan (Chang, 1970) and *Selagena* spp. from sub-tropical South Africa (Villeirs and Matthee, 1973). A heavy damage in litchi trees is inflicted by bats and certain species of birds like parrots and squirrels if protective measures are not taken in time.

IPM Strategies:

1. To manage litchi stalk borer, plough the fields after the harvest to kill the hibernating larvae in the fruits. Collect and destroy all the fallen infested fruits.
2. The mite affected leaves and twigs should be cut and burnt after harvesting the fruits (Mathur and Tondon 1974). Control measure must be preventive because once the mite is established it is almost impossible to eradicate it. It is therefore, recommended that layers be prepared from non-infected plants and dipped in a mixture of 50 ml dimethoate and 50 ml of moistening agent dissolved in 50 lit of water when they leave the nursery.
3. Before planting the operation should be repeated twice at 10–14 days interval (Sauco and Menini, 1989).
4. The easiest and best control measure for *Inderbela spp* is to insert kerosene soaked cotton wads into the hole followed by closing the exit hole with mud during September–October. The operation should be repeated in January-February, if necessary.
5. Conserve natural enemies like *Mesochorus* sp., *Chelonus* sp., *Bracon* sp. and *Apanteles* sp.

21.5.4 Olive

Olive, *Olea europaea* L., a symbol of prosperity and peace, is a sub-tropical, evergreen tree and one of the world's oldest cultivated crops originated in the Mediterranean region. It has great socio-economic importance and being discovered as a health-restoring, antiviral and antibacterial boon to mankind. The main bottle neck in the olive fruit production is the ravages caused by several insects, diseases, nematodes and weed pests throughout the world. Among the insect pest, olive fruit fly (*Bactrocera oleae*), olive psyllid (*Euphyllura olivina* Costa), olive moth (*Prays oleae*) and black scale (*Saissetia oleae* Bern) have been reported to be of major importance (Daku et al., 2000) and green stink bug (*Nezara virudula* L.) in India (Kaul et al., 2007a). While studying the pest complex in Himachal Pradesh, Thakur et al. (1989b) observed seventeen insects infesting cultivated olive and among sap suckers, the olive psylla to be a regular pest (Kaul et al., 2007b). Farahbakhch and Moini (1975) presented a list of all the known pests from olive growing areas in Iran, which include 95 species of insects and 6 species of mites.

Olive fruit fly is one of the key pests causing substantial damage to olive. It can be found in all Mediterranean olive-growing countries. To the east, it extends as far as India; to the west as far as the Canary Islands. The economic losses caused by this pest include pre-harvest fruit drop and reduction of olive fruit and oil quality due to increased acidity caused by fungi entering the fruit through the *B. oleae* maggots exit hole. The olive psylla also known as jumping plant lice, *E. olivina* are considered as one of the most important sflowering predator for olive trees causing 60–100 percent loss (Zouiten and Hadrami, 2001). This species is widely distributed in many parts of the world where olive is grown (Mathur, 1975). The first report of Olive psylla, *Euphyllura pakistanica* from India was made by Thakur et al. (1989b) on cultivated olive. *S. oleae* is widely distributed, extending from Central Asia to Africa. The olive tree is one of a large number of host plants on which *S. oleae* has been found. In general, it completes one generation per year in the Mediterranean although, in some areas and under favourable conditions, a second autumn generation may develop. The preferred habitat is the lower surfaces of olive trees. *S. oleae* damages the olive tree directly by sucking the sap, and indirectly by releasing honeydew onto the leaves. This honeydew is a substrate for the development of different fungi and is thus responsible for the spread of a sooty mould. By coating the leaves, this sooty mould impedes photosynthesis and respiration and finally induces more or less serious leaf drop.

IPM Strategies:

1. Tilling the area under the tree and in entire olive orchard after harvest helps in killing the pupae of olive fruit fly. Management includes bait sprays, trapping of adult flies, harvest timing, fruit sanitation after harvest, and conservation of biological control agents. Small plywood rectangles dipped in 0.1% aqueous solution of deltamethrin for 15 minutes and added to bait stations containing either sex pheromone or ammonium bicarbonate, a food attractant, gave cost-effective control in a large test orchard.
2. Pruning to provide open, airy trees discourages black scale infestation and is preferred to chemical treatment. In addition, biological control is effective, since a number of natural enemies, including both parasites and predators attack black scale. The most frequently encountered parasites are *Metaphycus flavus, Metaphycus helvolus and M. bartletti*.
3. Control of olive moths can be done using biological insecticides based on *Bacillus thuringiensis*.
4. Spray neem oil (1% *Azadirachtin*) at a rate of 0.5% against olive psyllid, *Euphyllura spp*.
5. Cultivate resistant varieties.

21.5.5 Guava

Out of 80 species of insect pests recorded on guava, only few of them are considered as pest of regular occurrence and causing serious damage to the guava trees. These are bark eating caterpillar (*Indarbela* spp.), fruit fly (*Bactrocera* spp.) mealy bug and scale insect (*Chloropulvinaria psidii*). The bark eating caterpillar and fruit flies have worldwide distribution, while scale insects and mealy bugs are more common in south India and tea mosquito bug, *Helopeltis antonii* Signoret in central India. The principal pests on guava in Florida are redbanded thrips, Caribbean fruit fly, guava moth, and guava whitefly. Scale insects may also intermittently infest guava plantings (Malo and Campbell, 1994; Pena and Johnson, 2001). For increasing the productivity in existing guava orchards it is required to adopt proper canopy and ground management practices, adequate nutrient application, good irrigation management, use of suitable rootstocks and effective and timely control of pest and diseases through eco-friendly approaches (Kumar et al., 2007).

Intensive surveys of guava growing regions of Indian subcontinent revealed that guava fruit borer, *Deudorix isocrates* (Fabricius) incidence is rapidly increasing (2.5–22.5%) with crop loss range from 5 to 35 percent. Common occurrence of another fruit borer, *Dichocrocis punctiferalis* (Guenee) in rainy season guava was also noticed throughout the guava growing belts in the country. Four other species of fruit borers, namely, *Cryptophleba illepida, Rapala varuna, Deudorix isocrates* and *D. epijarbas* have been reported damaging the guava fruits (Kaul and Kesar, 2003) and aonla fruits (Shankar et al., 2007). *C. illepida* causes extensive damage ranging from 40 to 60%. Guava fruit flies have been a major limiting factor in production of rainy season guava. Infestation of fruit fly ranged from 20 to 46 percent with crop loss of 16 to 40 percent, which is a matter of serious concern. Infestation of scale insects and mealy bugs, on leaves, shoots and fruit was also common in most of the orchards surveyed but these insects were in check by the presence of their natural enemies (Haseeb, 2007).

IPM Strategies:

1. Lucknow 49 (round big) is the most resistant cultivar to fruit damage by *Bactrocera correcta*.
2. Release of C*ryptolaemus montrouzieri* @ 20 adult beetles/tree is found effective against *C. psidii* in farmer's field (Mani and Krishnamoorthy, 1990).
3. The predators, *S. epius* and *C. montrouzieri* are commonly associated with the mealy bugs and *M. hirsutus*. Release of *C. montrouzieri* helps in managing these two mealy bug species on guava. The striped mealybug *Ferrisia virgata* is a very serious pest of guava in south India. *Cryptolaemus montrouzieri* has controlled the pest effectively within 30 days of its release (Mani et al., 1989).
4. Among the different natural enemies, the parasitoids, *Aenasius advena* (Compere), *Blepyrus insularis* (Cam.) and the predators, *S. coccivora, Mallada boninensis, Brumus suturalis* (Fabricius) and *Spalgis epius* (Westwood) play a significant role in suppressing the *F. virgata* population.

21.5.6 Pome Fruits

Apple and pear, commonly called pome fruits, are invaded by a multitude of insects, common to both these crops. Rapid expansion in area under commercial cultivars of pome fruits has also led to establishment of many indigenous insect pests as major and secondary pests. About 70 insect and mite pests have been reported attacking pome fruit crops throughout the world.

21.5.6.1 Apple and Pear

San Jose scale, *Quadraspidiotus pernicious* (Comstock) is one of the world's most severe pests of deciduous fruit trees. The pest is believed to be a native of Northern China but first noticed by the fruit growers at San Jose in Southern California in 1873. Within next few decades the insect spread to almost all the deciduous fruit growing areas of the world and is now recognized as cosmopolitan pest of great economic importance. San Jose scale has a very wide range of host plants and is disseminated through infested nursery stocks to various fruit growing countries of the world (Kozar et al., 1994). The aphids are brown or grayish-purple, medium-sized insects. Both nymphs and adults cause damage by sucking cell sap from the aerial and subterranean plant parts. Continuous sucking of the cell sap by nymphs and adults results in swelling and gall formation on aerial and underground parts. Appearance of galls on roots causes death of rootlets and their ultimate decay. The growth and vigour of the plants are adversely affected due to non transportation of food material from either side as the galls act as barrier. The main mode of dispersal of woolly apple aphid is through the infested nursery stock. Therefore, it is important to check the nursery plants periodically for aphid infestation. Codling moth, *Cydia pomonella* (Linnaeus) is localized to Ladakh region in Jammu and Kashmir (India) and also recorded as serious pests of apple from many other countries of the world. Young caterpillar of codling moth immediately after hatching burrows into young fruit through calyx end or from any side of the fruit. In the initial stage, caterpillar feeds on the pulp in a small cavity just beneath the entry hole which is covered with fragments of frass (ribbon like excreta). Thus, it is not seen from outside since there is no surface scar on the fruit (Wearing, 1975; Falcon and Huber, 1991). The caterpillar makes transverse tunnel into the core region and feeds on the immature seeds for about 4 weeks. Soon the larval tunnel becomes black due to secondary fungal and bacterial infection. As a result, the attacked fruits are rendered useless and become unfit for human consumption. The attack of fruit flies reduces the yield. Adult females lay eggs in small batches of 2–10 inside the ripening fruits by making punctures with their ovipositors. On hatching the maggots feed on the pulp and fruit becomes soft, ferments and drops. The attack is more serious on late maturing varieties. Full grown maggots come out of the infested fruits and jump to suitable places for pupation. These borers are among the worst enemies of peach, plum, apricot, almond and pear in temperate and sub-tropical regions of the world. *Sphenoptera lafertei* is a secondary invader as it has been recorded reproducing only in weakened stone fruit trees. The pest is widely distributed in northwest India and other species *S. dadkhani* is reported from Punjab. Adults feed on the foliage but do not cause serious damage. Grubs tunnel under the bark in the inner phloem and the shallow, broad and irregular burrows thus formed are packed tightly behind them with fine frass and excreta. As a consequence of continuous feeding, sap wood (phloem and cambium) becomes powdery and the bark over it dries and splits. The bark-eating caterpillar is a polyphagous pest and is widely distributed in India. Neglected and old trees suffer more damage to that of vigorously growing trees. The larvae feed on the bark and make galleries. As a consequence of injury, movement of the sap is checked. The vigour and fruiting capacity of the tree are adversely affected. The typical behavior of the caterpillar like nocturnal habit, shallow hiding hole, feeding under protection of web and single generation in a year make the pest less vulnerable to chemical control. Caterpillars of leopard moth are found in many temperate countries of the world. This pest was earlier reported to occur in the Himalayan region and is now well distributed. The caterpillars feed on woody portion of the stem and branches by making tunnels. As a result, the frass is excreted continuously from the affected plant parts. The foliage of the infested trees showed yellowing and browning of leaves which remained attached to the terminal shoots and did not fall even during dormant season. The site of entry is near the collar region of the tree trunk, 10–20 cm above the ground or on the terminal shoots. The attacked twigs become weak, wither and dry up (Navon et al., 1997). Tent caterpillar, *Malacosoma indica* Walker is an important pest of apple in north-western India and is more serious in Shimla hills. It is a polyphagous pest of several deciduous fruits but apple is most preferred host. The caterpillars feed gregariously on leaves leaving behind only midrib and other strong veins. Tents up to 0.2–0.5 m length are formed in which caterpillars live and damage the plants during night and rest during day time inside tents, cracks and crevices, under loose soil or clods and fallen debris around the stem. Sometimes soft bark of shoots is also damaged. Indian gypsy moth, *Lymantria obfuscata* (Walker), caterpillars are highly polyphagous throughout the world. The Indian gypsy moth occurs as an important pest of temperate fruits including pear in most fruit growing areas of the country (Masoodi, 1985; Srivastava and Masoodi, 1985). The caterpillar devours the entire leaf except midrib completely and thus denuding tree during May-June. Repeated defoliation in the successive years weakens the trees and renders them vulnerable to secondary pests (Miller et al., 1987).

IPM Strategies:

1. Pruning is important to remove heavily infested twigs or small branches during winter. It also allows the better penetration and coverage of bio-pesticides. The pruned wood must be burnt immediately.
2. Avoid the bud wood from trees infested with scale. It is a very hardy insect and can withstand great fluctuations in temperatures. None of the commercial varieties have been reported resistant against its attack, so far.
3. There are several predators and parasites, the potential natural enemies include ectoparasitoid *Aphytis* sp., endoparasitoid *Encarsia perniciosi* and coccinellids

predator, *Chilocorus bijugus, C. circumdatus* and *Coccinella septumpunctata* are very important (Bull et al., 1993).

4. About 40 percent increase in parasitization occurred in Kashmir valley when *Encarsia* and *Aphytis* were released and about 70 percent parasitization by *Aphytis* has been reported from Himachal Pradesh, respectively.
5. In Himachal Pradesh, *C. bijugus* release at 10–20 beetles/infested tree reduced infestation (Bhagat et al., 1988; Thakur et al., 1989a,b). The major limitation about use of these bio control agents is their non-availability at commercial scale.

Role of predators and parasitoids in Apple Pest Management

Quadraspidiotus perniciosus is one of the most serious pests of apple and many other deciduous fruit trees in Kashmir, Himachal Pradesh and Uttar Pradesh. A number of coccinellid beetles such as *Chilocorus infernalis* (*C. bijugus*), *C. rubidus, Pharoscymnus flexibilis* and *Sticholotis marginalis* have been recorded feeding on this pest, but these beetles are unable to give the desired natural control. These beetles have been introduced from Jammu and Kashmir to Thanedhar area of Himachal Pradesh. Both the predators have established and provided reasonable control of San Jose scale (Rao et al., 1971; Singh, 1989).

In 1958 and 1960, three strains of *Encarsia perniciosi viz.*, Californian, Russian and Chinese, were introduced. In addition, *Aphytis diaspidis* (origin: Japan) was introduced from California. All the strains were established; the Russian strain of the parasitoid gave 89 percent parasitism in Himachal Pradesh. *A. diaspidis* in combination with *E. perniciosi* gave 86.5 percent parasitism. In the beginning, low parasitism by Chinese strain was attributed to small number of parasitoids released. In Kashmir, the Russian and Chinese strains appeared to be superior to Californian and IIinois strains. American and Chinese strains of *E. perniciosi* were also released in the Kumaon hills of Uttar Pradesh; the population of the pest was reduced by about 95 percent. In Kashmir, releases of *E. perniciosi* and *A. proclia* resulted in an increase of parasitism from 8.9 to 64.3 percent. Studies on the biology of *E. perniciosi* revealed that the multiplication rate of the parasitoid was over 10 times. In apple, release of *Encarsia perniciosi* or *Aphytis proclia* @ 2000 / infested tree and *Chilocorus infernalis* @ 20 / infested tree gives effective control of San Jose scale (Rao et al., 1971; Singh, 1989).

In India, the first consignment of the exotic parasitoid *Aphelinus mali* to control woolly aphid was imported in 1930 from England. The parasitoid was not effective in Kumaon hills due to the activity of *Coccinella septempunctata*, which fed on parasitised and unparasitised aphids alike and provided nearly complete control. But the parasitoid was quite effective in Kullu valley of Himachal Pradesh. The parasitoid has since then spread to Kashmir valley. *A. mali* was also released around Shimla and it has established well. However, the current status of this parasitoid indicates that it gives good control in valleys, but is less effective on slopes. It has established in majority of the woolly aphid infested orchards (Rao et al., 1971; Singh, 1989).

Cydia pomonella is a serious pest of apple and other fruits in Ladakh district of Jammu & Kashmir. Two exotic egg parasitoids *Trichogramma embryophagum* and *T. cacoaciae pallidum* were evaluated. Based on the results, weekly releases of the egg parasitoids are recommended. A survey for two consecutive years brought out the need to initiate control measures by monitoring the pest by large scale use of pheromones, conservation of natural enemies, and synchronization of the first release of *T. embryophagum* with the first appearance of the moth, and subsequent releases at weekly intervals at 2000 per tree. Fortunately, the codling moth has not crossed the Zojila pass in Jammu and Kashmir, and it may be possible to check the pest in Ladakh region itself if proper measures are adopted (Rao et al., 1971; Singh, 1989).

Indian Gypsy moth, *Lymantria obfuscata* is a common pest of apple, poplar, willow, walnut, peach, plum, cherry, etc. in Kashmir. It has been found to cause severe damage to many tree and fruit crops in temperate regions of Himachal Pradesh and Uttar Pradesh. Egg parasitoid *Anastatus kashmirensis*; larval parasitoids *Glyptapanteles indiensis, G. flavicoxis, G. liparidis, Cotesia melanoscela, Hyposoter lymantriae, Rogas indiscretus, Exorista rossica, Palexorista conspicua*; pupal parasitoids *Brachymeria intermedia* and *B. lasus* are the dominant parasitoids of Indian gypsy moth. In addition to these pupal parasitoids, *Pimpla laothoe, Theronia atalantae* and *Calosoma himalayanum* have been recorded as population regulatory factors of the Indian gypsy moth (Rao et al., 1971). *Amblyseius finlandicus* was the most common predator on mite *Tetranychus urticae* attacking apple in Kashmir. The life cycle of the host synchronised with that of the predator (Rao et al., 1971).

21.5.7 Peach

Peach is the major stone fruit grown commercially in temperate to sub-tropical conditions. Approximately eighty insect pests have been recorded infesting the peach. But the most common insect pests which hampers the quality produce and yield are peach leaf curl aphid, peach mealy aphid, peach green aphid, san jose scale, fruit moth, peach fruit flies, flat headed stem borer, bark eating caterpillar, peach twig borer, grey weevils and cockchafer beetles.

Newly laid peach leaf curling aphid, *Brachycaudus helichrysi* (Kaltenbach) oviparous nymphs are green but the color of the adults depends on food i.e. nymphs feeding on leaves are green while those feeding on bark are brown. Arrival of the alate males synchronizes with the maturation of oviparous gynoparae and females are more numerous than males. *M. persicae* is a polyphagous pest infesting large number of crops. It is distributed throughout the world and causing more harm as a vector of viral diseases. In India, it also infests peach, plum, almond, apple, apricot, cherry and pear. The attack of fruit flies reduces the yield. Adult females lay eggs in small batches of 2–10 inside the ripening fruits by making punctures with their ovipositors. On hatching the maggots feed on the pulp and fruit becomes soft, ferments and drops. The attack is more serious on late maturing varieties. Full-grown maggots come out of the infested fruits and jump to suitable places for pupation.

IPM Strategies:

1. Regular pruning of current year's growth during December to reduce egg deposition activity by aphids. Some peach cultivars like Stark Early Giant, Early White Giant and Flavour Crest escape infestation and are moderately susceptible (10–30% leaf whorl infestation).
2. Fruit fly pupae in the soil can be destroyed by ploughing and digging the tree basins and keeping field sanitation.
3. Fruit fly populations in the subsequent generations can be reduced by collection and deep burying of infested fruits.
4. Monitoring of activity of fruit flies can be carried out successfully with the help of methyl eugenol baiting traps.
5. Avoiding post bloom spray to encourage biotic agents like coccinellids, syrphids, anthocorid bugs, etc and to mitigate the pest complexes in peach fruit crop ecosystem.

21.6 Adoption of BIPM Approaches

Small scale farmers' perception about pests, pesticides, and pest control as well as their decision making process in pest management have been shown to be influenced by a range of political, social, economic, cultural and institutional factors. Farmers' acceptance of IPM practices depends on many factors that are internal and external to the farmers themselves. Factors that may influence the likely rate of IPM adoption are related to farm characteristics and the outside influences composed of social, economic, political, and institutional factors. Socioeconomic, cultural and behavioral characteristics of farmers are also expected to play a significant role in farmer decisions relating to IPM adoption. The horticultural development is moving with a rapid pace throughout India and rest of the world. The location specific technologies should be developed and generated to enhance the adoptability of bio-intensive pest management technologies among local farmers as the agro ecological conditions may vary from one location to other.

21.6.1 Strategies for Adoption of BIPM

Introduction of inferior planting materials from other region has to be avoided. Indexing and certification program should be implemented properly to ensure availability of quality planting material. Production technologies in fruit crops and rejuvenation technologies for declined mandarin orange orchard, etc., are some useful technologies for dissemination among farmers so as to increase the productivity and quality of produce. Certain other fruit crops like litchi, guava and low chilling peaches have shown good potential and need research support for their commercial scale cultivation. Orange is a main horticultural crop of north eastern region of India and research to increase its productivity and quality needs to be prioritized. In this region cultivation of oranges can pave the way for successful venture in increasing its productivity and quality. For this support by an increasingly sophisticated network of research, education, and outreach programs from universities, government agencies, and non-profit organizations is required.

21.7 Future Thrust

21.7.1 Establishing Farmers Field School (FFS)

The farmer field school (FFS) is a group based learning process that has been used by a number of governments, NGOs and international agencies to promote integrated pest management (IPM). The first FFS were designed and managed by the UN Food and Agriculture Organization in Indonesia in 1989. Since then more than two million farmers across Asia have participated in this type of learning. FFS in Asia have involved over two million farmers in more than a dozen countries. It is essential to have a good program leader who can support the training of facilitators, get materials organized for the field, solve problems in participatory ways and nurture field staff facilitators. This person needs to keep a close watch on the FFSs for potential technical or human relations problems. They are also the person likely to be responsible for monitoring and evaluation. He or she is the key to successful program development and needs support and training to develop the necessary skills. The basic format of an IPM-FFS consists of three activities i.e., agro-ecosystem observation, analysis and presentation of results. The Agro-Ecosystem Analysis (AESA) is the FFS's core activity, and other activities are designed to support it. The agro-ecosystem analysis process sharpens farmer's skills in the areas of observation and decision-making, and helps develop their powers of critical know-how and do-how. The process begins with small group observation of the IPM and non-IPM plots.

Since mid 1980s, the emphasis on participatory approaches to IPM has intensified (Roling and van de Fliert, 1994; Nelson, 1994). In the participatory model, the IPM programs are viewed as an integral part of the participatory research and extension system. The FFS applied extensively initially in Asia and later in Africa and Latin America (Roling and van de Fliert, 1994) and the participatory IPM applied and refined in several developing countries by the IPM Collaborative Research Support Program (Norton et al., 1999), is the most prominent examples of participatory approaches to pest management decision making.

21.7.2 Seasonal Calendars (Time Analysis Tool)

Seasonal calendars are also used to analyze time related changes for each agro-ecosystem, but over the shorter term (within a year). These have been successfully used in apple in the USA and mango and citrus in India. Climate, cropping patterns, major agricultural operations, labor use, price movements, social activities, etc. are presented monthly so that comparisons can be made and key periods identified.

21.7.3 Problem Cause Diagrams (Decision Analysis Tool)

Problem cause diagrams or ‘problem-solution trees’ are used to analyze the causes of problems, identify the linkages between them, understand the way farmers cope with the problem, and identify appropriate solutions. Problem diagrams begin with a broad statement of the overall problem, which is then broken down into component problems, and eventually the root causes; these are then examined to identify farmer responses to the problem, and finally, alternative solutions are proposed.

21.7.4 Development of Bio-villages

Eco jobs and micro credit to boost village income led to the birth of the bio-village movement in Pondicherry, India. The term “bio-village” is derived from the Greek word bios, which means living, and our priority was just that: human centred development. Poverty persists in conditions where human resources are undervalued whereas land and material resources are overvalued. The bio-village model of rural and agricultural development is designed to rectify this imbalance by conserving and enhancing natural resources, eradicating poverty and empowering women. This program has been in progress in 19 villages in Pondicherry since 1994, covering a population of 24,000 people, though the plan is to extend the scheme to around 375,000 people throughout the region by 2007. One part of the program is eco-farming, meaning that chemicals and capital-the building blocks of modern farming are replaced with knowledge and biological inputs like vermiculture (exploitation of earthworms), bio-fertilizers and bio-pesticides. This in turn creates new eco jobs for rural people. The other part of the program is the creation of more avenues for rural non-farm employment based on marketing opportunities.

New opportunities for earning a living are devised through analyzing a family’s resources. As a result, landless laboring families take to household mushroom cultivation, ornamental fish-rearing, coir rope-making, rearing small ruminant animals under stall-fed conditions and other enterprises which are within their means. Those with a small plot of land can take to hybrid seed production, floriculture, dairying, poultry and other high value enterprises. Groups of asset less women engage in aquaculture in community ponds. All these exercises are based on micro-level planning, and enterprises supported by micro-credit. A range of activities helps enhance total income (which has risen on average by $23 per month per capita for villagers) and minimize risks. Education and training, social organization and producer-oriented marketing are all crucial to the program's success. Self-help groups operate a community banking system involving low transaction costs and high loan recovery. Most importantly, the bio-village movement is based on inclusion and not exclusion. The local women and men who become trainers are inducted into a Bio-village Corps of Rural Professionals. The bio-village model helps bridge all four divides-demographic, digital, economic and technological. It promotes harmony with nature and with each other. It is based on eco-technologies, which are environmentally benign, economically viable and socially equitable. It shows the path to an ever-green revolution in agriculture, where productivity advances can take place without leading to ecological or social harm.

The Centre continues its efforts to operationalize sustainable development through the biovillage paradigm, which aims to optimize the use of natural resources and enhance the opportunities of the rural poor. Multi-stakeholder analysis, participatory research and development, need based training and capacity building and promotion of grass root institutions are the major strategies adopted to develop bio-village models in different agro-climatic regions. Networking and partnerships were established with agencies like government departments, NGOs, banks, research institutions, international development agencies, community based organizations and Panchayati Raj Institutions (These are democratic decentralized institutions of rural India) in implementing the project activities.

21.7.5 Establishment of National Parks

The national park concept is a distinctive contribution of the people of the United States to the world to conserve the resources of the parks and to provide recreation to the people. More than 100 nations have followed this country's lead in establishing parks or equivalent reserves to protect areas of natural, scenic, or cultural importance. Most of these nations have studied the US system as a model for national park management. The enormous diversity within America's national park system is reflected in the broad mission and responsibilities of the National Park Service (NPS), the federal agency charged with primary responsibility for conserving the physical, biological, and cultural resources of the parks. The NPS is responsible not only for conserving geographic sites that range from extensive wilderness ecosystems to urban recreational areas and historic places, but also for protecting rare geologic features, managing diverse plant and animal populations, and preserving priceless scientific and cultural artifacts. The national parks are more than natural and cultural treasures—they are an important source of national self-esteem. As the conventional IPM varies from region to region the national parks should be established on region basis to teach and demonstrate the farming community about the insect pest, their nature of damage, feeding habits, biology, natural enemy's fauna, and their identification guide. They must also be aware about the adverse impact of pesticide, their toxicity, bio-magnification in the food system and ecosystem, safe waiting period of the used chemicals, their use of application during spraying or dusting to minimize the drift losses. The pesticide appliances and their better and efficient handling may also be demonstrated to regulate the pesticidal poisoning and any mishappening. The aim behind forming the national parks to make the farming community aware and equip them with latest know-how and do-how about the recent technology so that they can contribute their genuine share in the nation's economy with green and ever green prosperous and sound technology.

21.7.6 Inclusions of Big Corporate Houses in Pest Management

More proactive and collaborative approach by industry is required first of all in forging working partnerships. The main barrier to alliance building continues to be a paradigm clash on exactly what implementing IPM means at the farmer and institutional level. The crop protection industry (including retailers and distributors) must demonstrate the important role it already plays as an information link and resources to the farmer and farming communities, and that it can bring real value in the multi stakeholder movement to advance IPM in the region. More crop focused tools and information, alongside product information would provide important contributions to the role of IPM, and provide evidence of industry's genuine commitment to this objective.

- IPM provides demand stimulus for continuing research and development for IPM compatible compounds,
- Extend the life cycle of products, for example through better management and control of resistance development in pest organisms.
- The contribution of IPM to sustainable agricultural and environmental conservation.
- Active IPM promotion offers industry the opportunity to build relationships with other agricultural and environmental stakeholder groups, and demonstrates its recognition of its social responsibilities.

The old IPM paradigm, espoused by many advocates, holds that natural biological control is the cornerstone for insect IPM, and that all else is secondary in a self-regulating, balanced agro-ecosystem. However, today's need for intensive agricultural production and resulting high cropping indices have reduced the natural buffering capacity and, along with it, the efficacy of biological control within these systems. Other tools are now more than ever necessary to enhance the natural recovery and management of pest-predator balance, and weeds/disease levels in today's intensive agricultural ecosystems.

Big corporate companies have significantly advanced integration of IPM into their corporate plans and policy. Corporate houses attitudes towards IPM and bio-intensive pest management have become increasingly positive with regard to the benefits that IPM offers to the crop protection industry and to the long term sustainability of agri-horticulture. Many big corporate houses are coming in the agriculture sector with innovative ideas like contract farming, medicinal farming, and taking land on lease for farming, manufacture and preparation of bio-control agents, plant derived botanicals, mycopesticides, some actinomycetes molecules and IPM devices like phermones, delta or sticky traps, traps for fruit flies etc. Most of the big companies are actively working towards IPM compliance in their activities: new product portfolios and human resource capacity to strengthening the plant protection services in the country and abroad.

21.7.7 Amendments in Government Policies

The adoption of new technologies and practices in farming activities is of crucial importance to feed the rapidly increasing population and severe scarcity of productive agricultural lands. Raising agricultural productivity through new technology is also essential to the alleviation of poverty and to assure the country's economic growth. Equally important over the long term is helping farmers adopt more environmentally sound agricultural practices. As the sources for further expansion of agricultural land are exhausted, almost all increases in agricultural production will have to come from higher output per hectare. The trend of shifting from resource based to technology based farming systems also requires an explicit policy framework for providing new technologies and information to agricultural producers. Indeed, the institutionalization of IPM practices in developing as well developed countries may contribute towards this transition to technology based agriculture.

As farmers' economic situation improves and the agricultural input markets consolidate, farmers' ability to purchase off-farm inputs, including pesticides, will increase. Therefore, it is necessary that increasing pesticide use be tempered by an integrated approach of pest management that will optimize crop production and maximize net economic returns while minimizing pesticide use and damage to human health and the environment. In this context, introduction of IPM practices constitutes an essential tool for achieving sustainable agricultural development for any country or nation.

The integrated impact assessment in general terms refers to the economic analysis of the full range of the consequences (immediate, long term, intended and unexpected) of the introduction of a new technology, project, or research program.

21.8 Conclusion

There is a need to create awareness and make the farmers receptive to the new technology through farmer's participation, demonstrations and training. Demonstration and training facilities with respect to growing of horticultural crops and raising nursery have to be made available as per requirements. Therefore, there is a need for establishing a sound marketing system with forward and backward linkage so that vast potential of horticulture crops can be exploited and tapped through adoption of improved production and protection technology.

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ERRATUM

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