

Integrated Pest Management

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Defining integrated pest management (IPM) is not easy. Although numerous definitions can be found, the goal is usually the same, to coordinate pest biology, environmental information and available technology to prevent unacceptable levels of pest damage by the most economical means, while posing the least possible risk to people, property, and the environment. IPM is a science-based decision-making process that identifies and reduces risks from unwanted pests and the control strategies used in all arenas from agricultural, residential and public areas to wild lands. The IPM 'tool box' has almost limitless combinations of options and applying multiple tactics minimises the chance that a pest will adapt to any one tactic. However, new programmes will only succeed if they meet the economic goals of the growers, are socially accepted and are ecologically based. Herein the authors discuss the concept of IPM; available strategies; examples of successful implementation; and potential new tools.

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Introductory article

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The advancement of IPM will hinge on new technology, and a more fundamental understanding of organisms and ecosystems.

Introduction

Integrated pest management (IPM) is a sustainable approach to managing pests that promotes the use of a variety of tactics in a way that minimises economic, health and environmental risks. Often, but not always, health and environmental risks are minimised through a reduction in pesticides (e.g. herbicides, insecticides and fungicides). Pests encompassed by IPM include any unwanted plants, invertebrates, vertebrates or microorganisms in both agricultural and nonagricultural settings. **See also:** [γ-Aminobutyric Acid \(GABA\) Receptors](#)

The IPM 'tool box' of tactics includes pest-resistant or pest-tolerant plants, and cultural, physical, mechanical, genetic, biological and chemical controls. Applying multiple control tactics simultaneously minimises the chance that a pest will adapt to any one tactic. The goal of IPM is not necessarily to eliminate all pests, but to suppress their abundance and damage to acceptable levels. IPM requires an understanding of the biology of the pest organism and its ecosystem or environment. IPM is an integration of many disciplines and its definition has evolved over the years and is quite ambiguous today (Abrol and Shankar, 2012).

IPM was designed to reduce pesticide use

Although many of the tools and strategies used for pest management existed for centuries, the incentive for approaching the management of pests using a multitactic and integrated approach became apparent soon after the wide-scale use of chemical pesticides in the 1950s. Reliance and overuse of chemicals resulted in the development of resistance in many pest species, which prompted the use of increased rates and frequency of applications. This became known as the 'pesticide treadmill'. Repeated pesticide applications resulted in pest resurgence, negative impacts on nontarget organisms, escalating costs and harm to the environment and human health.

An example of the 'pesticide treadmill' occurred in cotton grown in the southern United States. With the availability of dichlorodiphenyltrichloroethane (DDT) and related insecticides, vast amounts were applied on a regular basis for control of the boll weevil. The insecticides provided excellent control of the weevil, so growers began to switch from short-season cotton, which inherently provided some control of the pest, to long-season cotton, which had higher yields, but required more insecticide applications. The multiple applications resulted in the development of insecticide resistance in boll weevil by the mid-1950s (Koul *et al.*, 2008). Cotton growers then switched to other classes of insecticides, the organophosphates and carbamates, which provided adequate control of boll weevil but eliminated natural enemies and did not necessarily control other key pests, such as bollworm. Growers, therefore, applied higher doses and mixes of different classes of insecticides. Over time, both pests became resistant to many insecticides, resulting in even higher rates and frequency of application (Koul *et al.*, 2008). This scenario was repeated in many agricultural crops in the 1950s and 1960s, and led to a drastic need for improved and more sustainable pest management approaches such as IPM.

In addition, the publication of *Silent Spring* by Rachel Carson in 1962 increased public awareness of many of the environmental and health risks posed by pesticides, adding additional incentives to reduce pesticide use. Public pressure also led to government legislation that regulated and restricted the use of pesticides. Many of the pesticides, especially the chlorinated hydrocarbons, such as DDT, that persist in the environment and bioaccumulate in animal tissue, have been removed from markets around the world. Additional pesticide classes and uses have also been eliminated. For example, in Indonesia, 57 insecticides were banned by Presidential decree in 1987. Many of these were broad-spectrum organophosphates. **See also:** [Carson, Rachel Louise](#)

Some of the earliest IPM efforts were simply an integration of biological control and insecticides (Pedigo and Rice, 2008). By better timing pesticide applications and reducing rates, natural enemies were preserved, allowing them to contribute to pest control. The IPM strategy has evolved and today encompasses many different control tactics and, to varying degrees, has been widely adopted.

There has also been a focus on the interactions of pests and their natural enemies in an agroecosystem context, which permits risk assessment, the establishment of damage thresholds and monitoring programmes. Historically there has been more IPM emphasis and implementation for arthropods in agriculture, but in recent years there has been a broadening of the scope of IPM programmes to encompass all pests in all settings. Where it has been fully implemented, IPM has been shown to be the logical approach for managing most pests (Pimentel, 2007).

Fundamentals of IPM

IPM is built on the foundation of natural pest control, actively monitoring/scouting for pests, and the application of thresholds and critical densities in regards to controls. The decision to use a pesticide or take other action against pest infestations requires an understanding of the amount of damage, infestation, stress that the crop, urban landscape or forest can tolerate without an unacceptable economic or aesthetic loss, and an assessment of the risk posed by a given pest density (Radcliffe *et al.*, 2009). The level of infestation or damage at which some action must be taken to prevent a loss is referred to as the 'action threshold' or 'economic threshold' if economics are factored into the decision making process. Action thresholds have been developed for many crops, commodities and urban venues. Ideally, these thresholds adjust for changes in market prices, stage of crop growth, cost of control, etc., but in reality, most are based on a fixed infestation or damage level (Pedigo and Rice, 2008).

To estimate the severity of pest infestations, the crop or commodity should be regularly sampled. Sampling in IPM programmes can be grouped into three broad categories: detection, estimation and decision sampling. In all three types of sampling, the process is similar and sampling may provide a direct assessment of pest densities by examining the crop and recording the number of pests or amount of damage observed (Radcliffe *et al.*, 2009). In addition, traps may be used to capture a subset of the pest populations providing a relative estimate of pest abundance. Data collected from sampling are used to estimate how close the infestation or damage level is to the threshold, and to make an informed decision on whether additional control measures should be implemented. **See also:** [Agricultural Systems: Ecology](#)

IPM Strategies

Pest-resistant varieties

One of the mainstays or foundations of IPM is the use of varieties or species that are tolerant or resistant to pests. Resistance may take the form of being less preferred by the pest, affect its growth and development, or be outright toxic to the pest. **See also:** [Plant Defences against Herbivore Attack](#)

Resistance to plant diseases and nematodes is more common than to arthropods. Some of the advantages of this IPM tactic include: compatibility with other IPM tactics, a cumulative impact on pests, relatively low cost, exceptional ease of adoption and minimal impact on the environment. Historically, the development of pest-resistant plants required artificial selection over many generations of breeding, which was relatively time consuming, but recent advances in genetic engineering have dramatically shortened this process. One of the most widely adopted genetically-engineered pest-resistant crops is Bt-transgenic corn, which contains endotoxins of the soil bacterium *Bacillus thuringiensis* (Bt). Different Bt protein toxins are active on different insect pest groups such as lepidopterans. The toxins primarily expressed in transgenic crop plants are effective against lepidopteran pests and must be ingested to cause mortality. This toxin has been genetically engineered into a number of other crops, including cotton, potato, eggplant and soybean. As with pesticides, the development of resistance is possible and has been documented. Resistance-management strategies, including limiting the number of hectares planted with Bt corn, or including refuges of nontransgenic plants within fields planted to transgenic crops have been implemented (Radcliffe *et al.*, 2009). **See also:** [\$\gamma\$ -Aminobutyric Acid \(GABA\) Receptors](#); [Biological Control](#); [Transgenic Plants](#)

Cultural control

A cultural control is most often an existing horticultural practice that is modified to make the environment less favourable for pests. Some examples include proper selection of planting sites to avoid a pest; adjustment in planting dates or time of harvest to avoid the pest; allowing turfgrass to grow taller so that it can better compete with lawn weeds; optimal use of fertilisers to encourage vigorous and healthy plants more able to withstand pest infestations and trap crops, which aggregate pests for more efficient control. Sanitation is often considered a cultural control and may involve such practices as removing crop residue after harvest or cleaning tools to prevent transmission of disease. Crop rotations and maintaining a fallow period are important cultural controls for many field and row crops. Cover crops can be a useful vegetation management tool for perennial crops.

Mechanical and physical control

Mechanical control may involve the use of barriers (e.g. row covers and screening) to protect plants or animals from pests: trenches or traps to capture pests, pruning of infested plant parts and hand removal of pests. Cultivation remains the most widely implemented method of nonchemical weed control, and mowing can be an important method of weed and insect control in orchards. Physical controls include the modification of environmental temperature and/or humidity, and modified atmospheres during storage of grains, fruits and vegetables

to minimise infestations of certain arthropod and disease organisms. Cold storage, for example, may not be lethal to insect pests of stored products, but the reduced temperature greatly slows their rate of growth and feeding damage.

Biological control

The use of natural enemies to suppress pests is referred to as biological control. There are several types of natural enemies, including predators, parasitoids, pathogens and antagonists. The first three most often apply to arthropod and weed pests; the latter is associated with disease organisms. With rare exception, all pests have natural enemies that are constantly suppressing their densities without any intervention by humans. This is referred to as natural control. Predatory arthropods are generally free-living species that eat large numbers of prey during their lifetime. Most often, both adult and immature stages are predatory. Parasitoids are complex organisms whose immature stages develop on or within a single host, ultimately killing the host. Different parasitoids attack the many different stages of insects (eggs, larval, pupal and adults). Pathogens are disease-causing organisms that include fungi, viruses and bacteria. Pathogens are often dependent on environmental conditions for reproduction and actual impact on pest populations. Antagonists are microbes that compete with or displace disease-causing organisms. **See also:** [Biological Control by Microorganisms](#)

Regulatory control

One aspect of regulatory control is the enforcement of specific IPM tactics to reduce pest infestations. These include mandatory planting or harvest dates and eradication programmes, which require that a crop or commodity be destroyed or treated with a pesticide if a specific pest organism is present. Another important aspect of regulatory control is to minimise the accidental introduction of pests into new regions. Many countries have regulations that place restrictions on transport and introductions of plant and animal species. Innumerable nonnative pests are encountered daily around the world from people moving pests from one location to another. Currently, over 40% of the arthropod pests in the United States are introduced, nonnative species. The most important weeds of rangeland and natural areas including species such as Russian thistle and purple loosestrife were also exotic pest introductions. Likewise, many of the aquatic weeds infesting the south-eastern United States are exotic species. Many of these species started as ornamentals around homes, but escaped into public waterways wreaking havoc to boat transport, fishing and recreation. Despite the existence of regulations and extensive detection efforts, exotic pest introductions are happening at an alarming rate. **See also:** [Invasion of Introduced Species](#)

Genetic control

The rearing and release of sterilised male insects is an example of genetic control and is often referred to as sterile insect technique (SIT). The objective is to inundate a wild population of native insects with sufficient sterile insects, such that reproduction is greatly reduced along with the risk of infestation or damage from the pest. This tactic is most often used where the geographic area needing control is very large, making most other tactics uneconomical. Examples of pests controlled by this approach include the screwworm (a pest of cattle), the pink bollworm and Mediterranean fruit flies. Breeding for pest resistance is sometimes considered a genetic control.

Chemical control

If all other IPM tactics are unable to keep a pest population below acceptable levels, the use of a chemical pesticide is justified. In most agricultural cropping systems, pesticides remain the principal means of controlling pests. Generally, they are relatively inexpensive, easy to apply, fast acting and effective. Because pesticides can be formulated as liquids, powders, aerosols, dusts, granules, baits and slow-release forms, they are very versatile.

Pesticides are classified by the type of pest they control. For example, weeds, insects and fungi are controlled by herbicides, insecticides and fungicides, respectively. Pesticides can be conventional, also known as broad-spectrum, chemicals that kill many organisms or may be narrow in spectrum of pests they will kill. The narrow-spectrum pesticides are often referred to as biorationals. Biorational pesticides are more selective and generally less harmful to nontarget organisms and the environment than conventional pesticides. Biorational insecticides include microbial-based insecticides (such as *Bt* products), behaviour-modifying chemicals (such as pheromones), insect growth regulators and insecticidal soaps.

The selection of the appropriate pesticide should be based on many factors: what is being treated (e.g. crop, commodity, urban structure or human), target pest(s), efficacy of the chemical and cost of material and application. In addition, consideration should be given to the potential environmental impact. One method to calculate the potential impact of pesticides on the environment that has been proposed is the environmental impact quotient (EIQ). The EIQ considers such factors as toxicity, half-life of the chemical in the soil or on plant surfaces, leaching potential, health risks to farm workers, consumer exposure and ecological effects. **See also:** [Ecotoxicology](#)

The IPM Continuum and Measuring Adoption

A widely accepted measure of IPM adoption is to consider a given system on a continuum, ranging from heavy use of pesticides and relatively little use of other tactics to the

use of more biologically based and cultural pest management tactics with little reliance on pesticide inputs. Where a particular system falls on the continuum can vary based on a number of factors including the availability of cost-effective IPM tools, the real and perceived risk posed by the pest (e.g. insect vector of human disease versus vector of plant disease), the value of the commodity to be protected (e.g. golf course green versus home lawn), and the cost of controls, to name a few. A variety of measures have been used to assess the level of IPM adoption. Quantifying reductions in risks (economic, environmental and health) posed by pest management programmes is important. Reductions in the amount of pesticide used (quantity per unit area, total volume, etc.) and economic savings are easy to quantify. Other measures, especially those related to reduced risks to the environment and human health, are more complicated and difficult to quantify (see [Figure 1](#)).

Examples of Successful IPM

IPM in schools

IPM is used in many schools and day care centres to reduce risks from both pests and pesticides. Pests of particular concern include those that compromise health or physical safety, for example, rodents, stinging insects, cockroaches, bats and pigeons. One of the most successful, large-scale school IPM programmes in the United States was implemented in New York City, which is home to over 1 million students ranging from prekindergarten to high school. The physical structure, including main school buildings, annexes, mini-buildings, portable classrooms and administration buildings exceeds 1700 in number. Classrooms may be located in modern, well-designed facilities, a historical landmark building or even commercial space. The latter situation is particularly challenging due to the potential for pest movement from the other businesses operating in proximity to the school section of the building.

In 1986, the elimination of hazardous pesticides within New York City's schools was given the highest priority. A variety of pest management tactics and materials were incorporated to prevent or mitigate pest migration and infestation including using sealants and door sweeps to exclude arthropods and rodents, destruction and removal of nests of stinging insects and improved sanitation practices throughout the schools. The proactive use of monitor boards throughout the schools became a key component in assessing pest populations, gauging control measures and following trends. Monitors eliminated the need for broadcast chemical applications by identifying problem areas for targeted bait applications and trap placements. These and other measures combined with scheduled inspection/service visits by certified pest management professionals allowed the complete elimination of all typical pesticide concentrates by the year 2000.

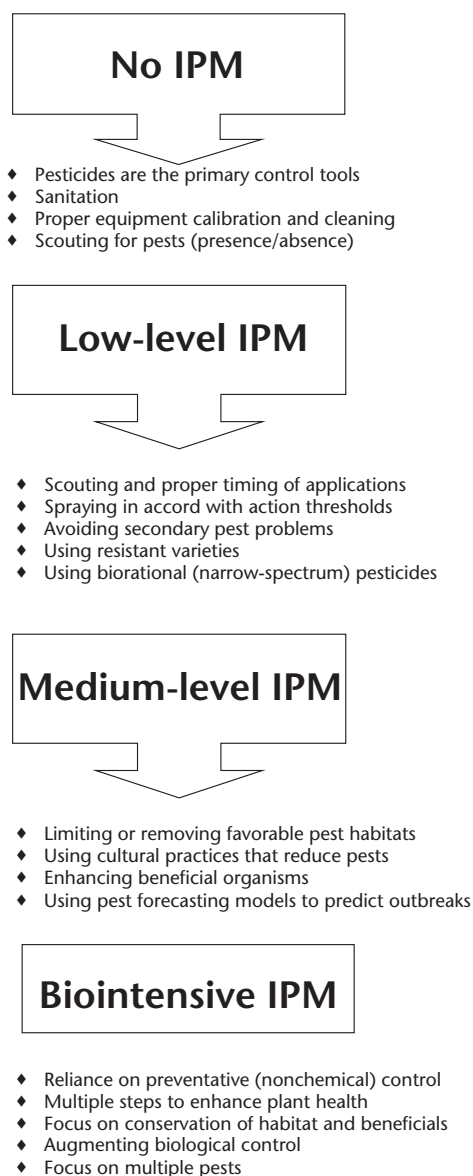


Figure 1 The IPM continuum, ranging from heavy reliance on pesticides with little use of other tactics (no IPM) to little pesticide use and more reliance on biologically based and cultural tactics (biointensive IPM).

Spotted wing *Drosophila* research

Government sponsors can coordinate the actions of researchers, educators and growers in the field to carry out successful IPM programmes. Spotted Wing *Drosophila*, *Drosophila suzukii*, or SWD, is a small ‘fruit fly’ that has upset crop production across North America as it has moved eastward since it was found in California in 2008. The 3 mm adult female SWD saws through soft-fleshed fruit as it approaches its peak of ripeness, laying eggs in raspberries, blueberries, blackberries, strawberries, grapes and late-season peaches, all valuable crops in the north-eastern United States.

In 2011–2012, the Northeastern IPM Centre, supported by the United States Department of Agriculture, awarded about US\$210 000 in funds for SWD research in the region. A Northeastern Regional IPM project grant in 2012 awarded just over US\$160 000 to Richard Cowles, a scientist at the Connecticut Agricultural Experiment Station, for research on sustainable management of SWD. The Centre also funded three Urgent IPM projects in the fall of 2011 totalling just under US\$30 000. Glen Koehler, an associate scientist at the University of Maine, received one of those grants. In August of 2011 he began receiving reports that growers were experiencing intense pest pressure from SWD. Going into 2012, Koehler knew that New England fruit growers faced an imminent threat and needed information on whether the problem would reoccur. If it did, growers would need to know where and when SWD had spread. He organised the group so they could share the same trapping and monitoring methods and thus combine the data from their observations for greater efficiency.

As part of that collaboration, Koehler worked with Cowles to organise a meeting in March 2012 of 40 extension and research staff from New England and New York to learn about SWD biology, monitoring and management. Cowles devised the bait and provided biological insight that Koehler used to design a simple, inexpensive, and effective New England-wide SWD survey protocol. The grant funds made it possible to build and distribute over 1000 traps and enough bait formula for season-long trapping at 244 different sites, with multiple traps per site. Survey leaders in each of the cooperating states provided labour and vehicles for weekly visits to collect trap contents, count SWD, and record observations. Other researchers provided access to a database and mapping system to archive and display the New England observations on colour-coded maps as soon as data were entered. Through this collaboration, researchers obtained a top-level view of the SWD threat. Researchers determined that they had prevented US\$6 million of crop losses in 2012, as estimated by crop specialists surveyed in each state.

IPM for cotton in the Southwest US

Since 1990, IPM practices in cotton have significantly reduced pesticide use as well as pest-management costs to growers in the US desert Southwest. In the early 1990s, growers were applying an average of 12–14 pesticide sprays per season, and in 1995 applied 4.15 pounds of insecticide active ingredient per acre of cotton grown. In 1996, new IPM practices became available for cotton growers, including the development of whitefly-specific insect growth regulators and pest-resistant cotton varieties, as well as the adoption of biological and natural controls. Also beginning at that time, growers adopted progressive resistance-management plans that included agreements to share and limit the use of critical pesticide chemistries across multiple cropping systems.

As a result of these IPM practices, the use of all insecticides dropped from an average of 4.15 pounds per acre to

just 1 pound per acre. The use of broad-spectrum insecticides dropped even more significantly from 1995's peak. Comparing the period of 2006–2011 with 1995, pyrethroid use was reduced by 97%, organophosphate use by 92%, carbamate use by 97% and the chlorinated hydrocarbon, endosulfan use by 82%, with an overall reduction of insecticide use in cotton by 85%. In addition, control costs also dropped markedly, from their peak of US\$300 per acre in 1995 to approximately US\$50 per acre in the period 2006–2011.

Decision aid tool for cotton stink bug management

With the success of boll weevil eradication and the dramatic reduction in organophosphate insecticides, stink bugs rose to the top of the pest priority chain for cotton growers. Total cotton losses in the southeastern United States in 2008 related to stink bug damage were estimated approximately US\$53 million. A new dynamic threshold improved economic returns, but 90% of stakeholders indicated that the greatest need was a tool for scouting and pest identification. To fill this gap, extension entomologists from universities in the southeast developed a plastic decision aid card to help growers determine when and if to treat for stink bugs. Previous research indicated that most economic damage occurred when bolls were between 0.9 in. and 1.1 in., so the card contained two punched-out holes to help growers and consultants decide which bolls to sample for damage. A 2011 survey of licenced independent crop consultants showed that approximately 80% used the cards and usefulness of the cards was rated at 8.1 on a 10-point scale. Cost estimates from 2011 show that using the card and dynamic threshold had the potential to save southeastern growers in excess of US\$30 million that year. Consultants in the mid-south United States, Arizona and Brazil are using the decision aid cards now as well.

Areawide codling moth management

In 1994, the United States Department of Agriculture-The Agricultural Research Service (USDA-ARS) established a process to support IPM adoption and use through implementation of areawide pest management programmes intended to suppress or maintain a low-level population of key target pests over a large, definable area rather than on a farm-to-farm basis by using environmentally sound, yet effective approaches. These programmes were intended to result from a stakeholder partnership and collaboration. Codling moth, *Cydia pomonella*, is a key pest of apple and pear production worldwide. It is the key pest in the western United States where most organophosphate insecticide sprays used on these crops are applied for its control. Azinphos-methyl was the recommended pesticide, and it was applied 4–6 times per season resulting in disruption of natural enemies of many secondary pests.

The areawide codling moth management programme was established in 1994 in contiguous sites in Washington,

Oregon and northern California. Mating disruption using pheromones was the primary technology used in the programme, together with biorational pesticide sprays and sanitation as needed. The initial area for the codling moth management programme was 1064 ha. By 2000, the area under codling moth mating disruption had reached 54 000 ha, and there was an 80% overall reduction of organophosphate pesticides within the area of the programme with most sprays targeting secondary pests and border areas to prevent invading mated codling moths from overwhelming the mating disruption strategy. Damage was always less where the areawide programme was established than in corresponding conventional control orchards.

A 2013 sustainable practice survey of pear growers in California found an overwhelming majority use IPM to manage their orchard pests. For example, over 93% of growers report scouting for key pests throughout the year to inform their pest management decisions, and 91% of growers use pheromone mating disruption as the primary management tool for codling moth.

The Future of IPM

Scientific advances in molecular biology genetic engineering and computer technology have the potential to make major contributions to IPM. These disciplines will contribute many novel tools and advancements to pest management in the years to come. However, there are still opportunities to improve management using existing tools. In fact, most successes with IPM have come from an improved understanding of pests rather than the development of novel control tactics (Kogan, 1998). **See also:** [Genetically Modified Food: Ethical Issues](#); [History of Molecular Biology](#)

One technique that appears to be promising is known as RNA interference (RNAi). Recent advances in molecular biology have shown that gene expression can be effectively silenced in a highly specific manner through the addition of double-stranded RNA. The specificity is sequence-based, and depends on the sequence on the strand of inserted RNA. This mechanism essentially allows for the turning off and on of specific protein coding genes in various organisms. It was first discovered in plants and has been used to engineer several species of plants resistant to numerous pests. This tool is now being investigated as a pesticide to interfere with protein coding genes of various insect pests (Abrol and Shankar, 2012). **See also:** [RNA Interference \(RNAi\) and MicroRNAs](#)

Some of the greatest barriers to IPM adoption include perceived risk and lack of trust, as well as lack of convincing information. One necessity of future IPM programme is a clear and concise method for delivering information. Unfortunately, to date these types of plans have been virtually nonexistent in IPM programmes (Gurr *et al.*, 2012). The urgent needs of future IPM programmes are to determine the needs of the stakeholders and methods to disseminate that information in a clear and concise

manner. With the advent of the internet and the smart-phone, access to resources is constant and limitless. Numerous websites currently exist that help establishing IPM programmes with information ranging from pest identification to appropriate control techniques. These new tools have tremendous potential to change the way information is exchanged among researchers, extension agents, crop consultants and growers.

There is no doubt that these disciplines will contribute many novel tools and advancements to pest management in the years to come. Crop consultants will play a major role in implementing IPM tactics on the farm level as pest management becomes increasingly information intensive, and control tactics become more pest specific. The advancement of IPM will hinge not only on new technology, but on a more fundamental understanding of organisms and ecosystems. The success of these programmes will rest on how they are evaluated on the three dimensions of sustainability: economics, environment and society. New programmes will require a much deeper understanding of the agroecosystem ecology and will only succeed if they meet the economic goals of the growers, are socially accepted by society, and are ecologically based. Therefore, IPM specialists must strive to understand these changes and implement practices and tools that work synergistically to achieve desired outcomes while simultaneously posing the least risks to people, property and the environment.

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Further Reading