ellites. These sensors measure the amount of microwave energy coming from the soil. Recent research has shown that the amount of this energy depends primarily on the amount of water in the soil. Current research by ARS and the National Aeronautics and Space Administration is systematically testing prototype instruments on airplanes and comparing their measurements with ground measurements.

Microwave remote sensing offers three unique advantages over other types of remote sensing. First, clouds and rain have no effect, so it can be used in any weather. Second, it does not require sunlight for illumination, which means that measurements can be made at any time of day or night. Finally, the effects of vegetation on the ability to sense moisture in the soil below are usually correctable.

To be of value, soil moisture information must be available on a frequent basis. It should also be available to users almost immediately (like the images we see from weather satellites) before changes in crop conditions, weather, or soil water content make the information worthless.

In another application, new research shows that microwaves hold great promise for determining the depth or water equivalent of the snowpack. ■

# Integrated Pest Management, a Sustainable Technology

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The farm value of cultivated crops and animals produced in the United States and used for food and fiber exceeds $160 billion annually. Pests—including insects, mites, pathogens (disease-causing organisms), weeds, nematodes, rodents, and others—significantly contribute to high farm production costs and reduced quality and yields. Farm production losses to pests are estimated to exceed 35 percent annually. Continued sustainable agricultural production will rely on effective, safe, environmentally benign, and efficient crop and animal protection methods.

## Goals of Integrated Pest Management

Integrated Pest Management (IPM) is an ecological approach to pest suppression. Briefly stated, the goals of IPM systems are to reduce losses in crop and animal quality and yield caused by pests and to increase net profits to the producer. Methods are selected that cause minimal environmental damage and pose little or no risk to human health. IPM involves selection, integration, and implementation of pest control actions on the basis of predictable economic, ecological, and sociological consequences. Success is most likely when the focus is on a large area. Although this paper focuses primarily on integrated management of crop pests, these same management principles are being applied to livestock pests.

Development and use of many efficient and economical pesticides during and since the 1940's have permitted unprecedented crop and animal protection and improved public health. Since these control agents have been available, however, many of the components of IPM (integrated pest management) systems—such as crop rotations, sanitation, time of planting, resistant varieties, and genetic and biological control methods—have been neglected.

However, the bright future of the pesticide era became clouded as the problems of secondary pests (in addition to the target pests), destruction of natural enemies, pesticide resistance, and environmental and health hazards were recognized. Experience has shown that adoption of a single control measure for suppression of a target pest or pest complex is destined to fail sooner or later.

Integration of multiple pest suppression techniques has the highest probability of sustaining long-term crop protection. Since the 1960's, there has been much interest in and effort to develop IPM.

Much progress has been made, and efforts to integrate IPM into crop management systems continue. These efforts include the introduction of community-involved, areawide approaches to suppression and management of pests. This is a commonsense approach that has evolved with our increasing awareness of the limitations of attacking local infestations without considering total pest populations. Areawide pest suppression involves the coordinated efforts of many parts of an agricultural community cooperating to use effective pest management strategies.

Essential prerequisites for establishing successful IPM systems are a thorough knowledge of the following:

- Crop and animal production methods
- Biology and ecology of each pest species
- Basic information on genetics, behavior, and physiology of pest species
- Relationships and interactions of the pests with the crop and other biological and physical components of the ecosystem
- Potential economic damage of each pest and pest complex

This information is necessary if community-involved, areawide programs are to effectively identify and integrate control technologies that are compatible with crop production methods as well as other parts of the ecosystem.

Knowledge of farmland production potential, agronomic inputs, and plant growth and development is essential in development of IPM systems. Cultivar selection and planting date, as well as cultural practices (irrigation, fertilization, and tillage) may have a major influence on pest severity. Decisions on the need for control action are based not only on the pest population levels but also on the present and predicted weather, the levels of existing biological control agents, and the stage of plant development and potential for yield losses. Similar information is vital in development of animal protection IPM systems.

## IPM Technologies and Procedures

An array of technologies and data analysis procedures have been developed for informing growers and other decisionmakers about those strategies and tactics most appropriate for use in implementing specific IPM systems. These include: economic thresholds, sampling technology, modeling, natural controls, geographic distribution, effects of pest migration and movement, host resistance, and pesticides.

Field evaluation is the most effective method to determine how biological predators find and consume their prey. Bruce Shambaugh releases ladybeetles into a small field cage enclosing wheat plants infested with Russian wheat aphids.
*Laurie Smith/USDA 91BW0620*

**Economic Thresholds.** The economic threshold of a pest population is the population level below which the cost of taking control action exceeds the losses caused by the pest. Pest population levels that can be tolerated within a crop system can vary because of crop harvesting schedules and inherent crop tolerance to pest attack.

Ladybeetles are collected from wheatfields that have high numbers of them, to be released into fields with low numbers. Bruce Shambaugh holds a release net with predators just swept from rows of wheat plants in Cheyenne, WY.
*Laurie Smith/USDA 91BW0618*

Economic thresholds may also vary from area to area, among cultivars, and even between farms that are in the same area but under different management systems. Further, levels must be adjusted when two or more pests are attacking the same crop. For insects and mites, thresholds will vary depending on the population levels of naturally occurring parasites and predators that may control the pests. Pest population levels requiring control action in animal production systems are less well defined than in crop production systems, but the need for this information is equally important. Application of the economic threshold in determining the need for control action has helped producers reduce the number of pesticide applications or other control measures and increased net profits to the individual grower.

**Sampling Technologies.** Appropriate and cost-effective sampling methods for each pest are necessary to determine pest levels for purposes of establishing economic thresholds. These methods range from simple to complex and include such techniques as the following:

- Counting the numbers of insects, mites, biological control agents, or pathogen lesions on a few leaves
- Counting nematodes in soil samples and counting weed species and densities in several

locations in crop fields
- Using sophisticated vacuum machines that collect insects from crop plants or spores from the air

Data reflecting the number and locations of samplings must be accurate enough to allow sound decisions on whether to take action. Field research for various pests and conditions determines how many samples are needed from how many locations.

**Modeling.** A basic principle of IPM is that it must have a systems approach to good decisionmaking. Farming systems are complex, involving many factors. Changes in one part affect others. It is not only the biological system that affects deci-sionmaking, but often also economic factors and social pressures. Neither budgetary nor human resources are sufficient to allow detailed field experiments that include all possible variables. So we turn to simulation models.

These models have helped us develop our understanding of the complexities of biological systems; however, they have not been useful in solving specific problems in the field. Knowledge-based systems (called expert systems by some) have the potential for improving decisionmaking at the farm level. Importantly, incorporation of models in IPM systems has required the user to define available knowledge regarding the problem and to provide information to explain deficiencies that occur between model simulation and field observations. Models also provide prediction capabilities that ensure that management decisions are increasingly accurate.

**Natural Controls**. IPM's basic framework is built on natural controls. These include natural enemies, weather, climate, and food resources. Natural enemies play an important role in regulating populations of all pest classes, in both natural and farm ecosystems. For arthropod pests such as insects and mites, parasites and predators are

Ladybeetles being released into a wheatfield low in predators. Bruce Stambaugh opens an ice cream carton containing beetles recently collected by sweep net from a nearby field.
*Laurie Smith/USDA 91BW0619*

major natural control agents. A primary focus of IPM is on conservation of these natural enemies to maintain insect and mite pests below economic thresholds. Where possible, selective pesticides are used that are least harmful to natural enemies. So the effort is focused on conserving natural enemies and introducing appropriate species from other regions. Microbial pesticides have been developed and are being used where they are effective.

Biological control for pathogens, nematodes, weeds, and other pests is also achieving increased success. Weather plays a very important role in the incidence and extent of infection by pathogens. The knowledge and understanding of interaction of temperature, humidity, and rain on disease incidence is critically important. The amount of fungicides required to control diseases can be greatly reduced based on this knowledge and on accurate weather predictions.

**Geographic Distribution.** Areawide management systems that target the total pest population involve, in most cases, large geographic areas that may extend across county, State, and national boundaries. Therefore, local, State, national, and sometimes international cooperation, in addition to an understanding of the technical complexities of target pest suppression, is essential to ensure a high degree of success.

**Effects of Pest Migration and Movement.** Many pests and natural enemy species move short distances as their populations grow. This may occur for many reasons, including crowding and search for food as a result of host depletion in the initial habitat. Some pests, such as insects and pathogens, migrate or are carried long distances by winds and atmospheric weather patterns. Other pests can move only short distances but may be carried long distances by ground animals, birds, or humans. They are often transported in or on plant products, a major cause of the introduction of pests into formerly noninfested regions.

Movement of pests over even short distances affects IPM strategies. For example, pathogens, insects, rodents, and other pests often move from one crop to another in adjacent fields or from adjacent natural habitats to agricultural crops. IPM strategies must be developed to deal with such situations.

Long-distance migration and movement of pests are of particular importance in areawide management systems. Where there are no effective natural barriers such as mountains or large bodies of water, artificial barriers such as the release of sterile insects or quarantine of certain plants and produce can be useful to prevent or reduce unwanted movement of pests. The pest management technique of releasing sterile insects for suppression of the screwworm and pink bollworm in the United States is an excellent example of the use of barrier zones to prevent infestation from migrating pests.

**Host Resistance.** Host resistance is another key component of pest management. Over time, many plants and animals evolve resistance mechanisms that enable them to prevent or survive attacks by pests. Geneticists, in many cases, have made outstanding progress in identifying and incorporating pest resistance characteristics in farm production systems.

However, many of our crops and animals do not have adequate defense mechanisms against introduced or native pests, given the conditions under which we grow them. Also, breeders have not always attempted or been able to incorporate resistance into desirable cultivars and farm animals. In recent years, much progress has been made in finding genes for disease resistance and transferring them to plants and animals. The rapid development of new methods for gene transfer promises that host resistance will play a much greater role in IPM in the future.

**Pesticides.** Discovery and use of synthetic pesticides greatly improved farmers' ability to cope with pests and enabled modifications in farming practices, espe-

Maintaining laboratory colonies of a pest is an essential step in rearing the numbers of its natural enemies needed for biological control programs. Here a technician at the APHIS Biological Control Laboratory in Mission, TX, infests new wheat seedlings with Russian wheat aphids to build up the colony. The lab-reared aphids will serve as prey for several species of predators and parasites under study at the lab.
*Laurie Smith/USDA 91BW0617*

cially with the use of herbicides. These benefits, however, have been accompanied by low-level contamination of ground water, other undesirable environmental effects, and potential health risks for humans, livestock, wildlife, and domestic animals. Further, many pesticides, including many of the safer and more selective ones, are no longer effective against several key pests. So it is important to reduce the use of pesticides to the absolute minimum necessary to maintain economical production and storage of food and fiber. Also, reduced use is effective in preventing or delaying development of pest resistance.

A key component of IPM is judicious use of pesticides only as needed and in consideration of the environment, health, and economics. The IPM approach is essential for reducing the undesirable side effects of pesticide use. The combination of suppression tactics used in IPM programs will reduce not only environmental effects, but also the incidence of pests' resistance to pesticides and lead to development of pest-resistant cultivars or "biopesticides." More sustainable protection systems should result from the use of pesticides in a more balanced manner.

### IPM Success Stories

Successfully implemented IPM programs have provided economic benefits to farmers and more environmentally acceptable crop and animal protection practices. The systems and programs are being continually refined and improved based on experience, continuing research, technology transfer, and Extension education efforts.

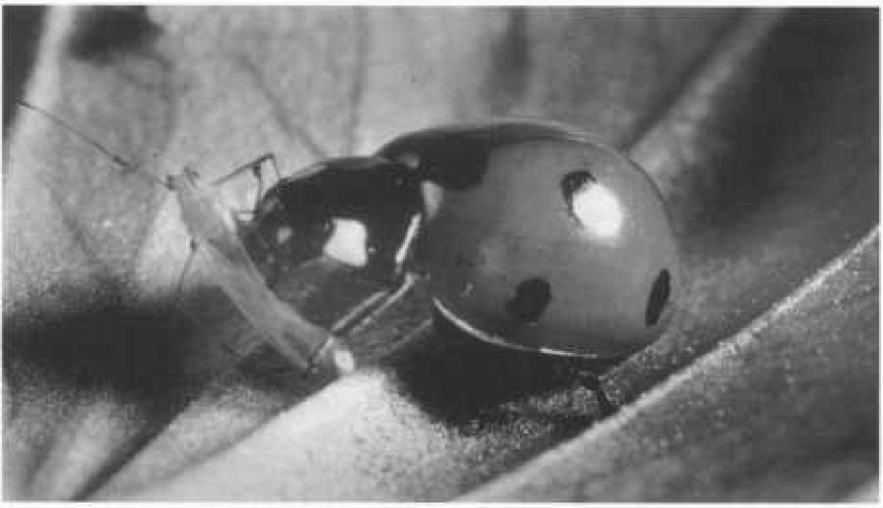
Some of the outstanding successes of IPM in suppressing major pest populations—such as the boll weevil eradication program—have relied on early detection, selective pesticide use, and cultural practices. In other programs—such as suppression of Mediterranean fruit fly, pink bollworm, and screwworm populations—sterile insect releases have been the main component of IPM systems supported by intensive population sampling, attractants, cultural practices, and other methods.

Host plant resistance has provided the foundation for effective IPM approaches to control the alfalfa aphids. Native parasite releases have been successfully used as the focal IPM component to suppress fly populations around poultry houses and livestock yards, and a complex of imported parasite species has been used to control alfalfa weevil. Many other equally successful applications of IPM have demonstrated the validity of the concept. IPM, in each case, has provided increased economic benefits to the farmer within the framework of environmentally acceptable pest management methods.

**Implementing IPM.** The implementation of IPM systems in agriculture requires more research, development, extension and transfer, and farmer time and effort than the simple use of pesticides. Some producers have been cautious in adopting IPM because it takes time to develop effective practices that producers can feasibly incorporate into existing crop management systems. Often, significant modifications in farming practices must be made to adopt IPM systems. These practices might include, for example, crop rotation, destruction of crop residues, and variations in time of planting.

The USDA sustainable agriculture effort is a substantial program to test and promote efficient agricultural production practices that may involve reduced economic and physical resources. IPM is an essential component of these efforts.

**Communities Using IPM.** IPM systems can be adopted by individual farmers, by small groups, or by farmers across broad agricultural systems. The nature of the farming systems and the pest problems often dictate whether single, small group, or regional adoption will be most effective. Where farms are scattered, crops are diverse, and pest migration from other farms is not a factor, adoption by the individual is ap-



Biological control employs natural enemies to control pest insects. Here a Coccinella septempunctata or "C7" ladybeetle attacks an aphid. Ladybeetles are general predators and eat a variety of aphid species.
*Laurie Smith/USDA 91BW0616*

propriate. In specialized areas with extensive plantings of the same crop or crops where pests move freely from one farm to another, IPM systems must be adopted by all farmers in the region to be successful.

An example is cotton in parts of Texas, where destruction of crop residues after harvest drastically reduces the survival of the boll weevil through the winter and eliminates the need for pesticide applications that often destroy natural enemies and create secondary insect pest attacks. The group and regional adoptions require much community involvement and support.

### Long-Term, Areawide Suppression

Areawide suppression or management of total pest populations incorporates the principles and tactics of IPM as an ecological approach to pest control. Coordinated agricultural community involvement in pest population management over large areas is becoming more prevalent in research, extension, and teaching efforts dealing with most of the key pests. The areawide approach focuses suppressive measures on the total pest population, as opposed to uncoordinated efforts by individual farms or small local areas to control limited segments of the population—an approach that will not work on pests that move or migrate extensively. Areawide programs include producers as active participants in the program, a practice that helps ensure success. The producer is not a bystander, nor are Extension personnel and private consultants. The entire community has an active part in the program. ■