The Technologies 3

Any assessment of biologically based pest control faces an immediate paradox. A wealth of technical information and research findings characterize the field, and there is near uniform agreement that use of biologically based technologies (BBTs) is desirable, if they can safely provide adequate pest control.[1] Nevertheless, actual adoption of these technologies is low. Explanations for this seeming contradiction usually center on numerous "obstacles" that hinder adoption of BBTs—some related to current limits to what the technologies can do, others to social, economic, and institutional impediments. This chapter begins by evaluating BBTs and discussing difficulties in setting performance standards for these technologies. It then describes current and potential uses of BBTs in the United States and identifies the factors affecting their future adoption.

EVALUATING THE TECHNOLOGIES

A complex mix of technical, social, and institutional factors contribute to the past successes and disappointments of BBTs (box 3-1). Certain highly effective BBTs have failed because of economic factors or improper use. Straightforward assessment of the technical capabilities of BBTs according to their track record of success is thus impossible. In general, BBT adoption has occurred most frequently where conventional pesticides are unavailable (e.g., because of pest resistance or small market size), unacceptable (e.g., in habitats that are environmentally sensitive or places where human contact is high), or economically infeasible (e.g., because the cost of pesticide use is high relative to the economic value of the resource, as in rangeland management).

Comparison with Conventional Pesticides

Direct appraisal of the technical capabilities of BBTs is also complicated by the question of what standards to apply. In practice, the level of pest control set by conventional pesticides is

[1] See end of chapter 2 for detailed description of the biologically based technologies discussed here and throughout the assessment.

CHAPTER 3 FINDINGS

- Although conventional pesticides dominate U.S. pest management practices, biologically based technologies (BBTs) have penetrated most major applications and joined the mainstream. For example, BBTs are the method of choice for certain widespread pests like the European gypsy moth (*Lymantria dispar*), and have been adopted by a number of major food-processing companies.
- Current use of BBTs is patchy, however. Adoption has occurred most frequently where conventional pesticides are unavailable, unacceptable, or economically infeasible. In such situations, the chief advantages of BBTs become significant assets—namely, that they reduce reliance on conventional pesticides, have generally low impacts on human health or the environment, and, in the case of classical biological control, provide lasting and low-cost suppression of individual pests.
- Most BBTs provide partial solutions to the pest problems faced by farmers and other users and usually must be integrated with other control techniques to provide an overall package of pest suppression. They tend to fare poorly when evaluated against the performance standards set in place by conventional pesticides.
- The field of BBTs is characterized by a wealth of technical information combined with far fewer on-the-ground applications. People involved in the research, development, and use of BBTs attribute the low adoption to numerous technical, social, economic, and institutional obstacles. These obstacles represent real and valid impediments, but they make a precise assessment of the true capabilities and future potential of BBTs difficult.
- Removal of the nontechnical obstacles through a variety of policy actions would surely improve the success record of BBTs. Nevertheless, significant technical issues still need to be resolved, and this problem can be addressed only through appropriate adjustment of the national research agenda.

often the benchmark used for judging other methods. Key features of such appraisals are:

- target range—how many pests are affected;
- kill level and rate—to what extent the pest population is suppressed and how rapidly;
- field persistence—how long a single application continues to provide control; and
- shelf life and stability of commercial products.

Conventional pesticides generally have a wide target range, high kill level, rapid kill rate, long field persistence, and extended shelf life. By any measure, most BBTs do not compare well according to these criteria. Many BBTs have a narrower target range; act more slowly; suppress, but do not locally eliminate pests; and, if sold commercially, have a shorter field persistence and briefer shelf life. Exceptions to these generalizations do exist, of course. Classical biological control can provide lasting pest suppression, and microbial pesticides applied as seed treatments may suppress plant pathogens over a growing season or longer (138).

Conventional pesticides are often described as “stand-alone” approaches to pest control; a single chemical provides significant suppression of many pests. In contrast, most BBTs affect only one or a few pests, and some affect only one life stage of a pest. Pheromone mating disrupters, for example, are “adult-based” strategies and do not affect juvenile pests already present. *Bacillus thuringiensis* (Bt), in contrast, works only on the feeding juveniles (e.g., caterpillar larvae).

The timing for effective use of many BBTs is also relatively narrow, because it must coincide with a particular vulnerable life stage of the pest or specific environmental conditions. Like certain conventional pesticides, the effectiveness of many BBTs is influenced by aspects of the weather, such as temperature and humidity. Also, some are impaired by conventional pesticides; natural enemies, for example, are killed by many chemicals. As a result, recent spraying at the

BOX 3-1: Outcomes of Biologically Based Pest Control

Some notable successes…

Classical biological control

Ash whitefly (*Siphoninus phillyreae*)—First noticed in California in 1988, the pest soon spread to 28 counties in that state as well as to Arizona, and New Mexico. It attacked ornamental trees that make up 17% of street trees in urban areas. Within two years of biological control introductions in 1990, the fly was under complete control, generating net savings in excess of $200 million.

Skeletonweed (*Lygodesmia juncea*)—The rust fungus *Puccinia chondrillina* was released in several western states in 1976. Skeletonweed is now under excellent control in California, Idaho, Oregon, and Washington because of the disease.

Augmentative biological control

Strawberries—An estimated 50 to 70% of California strawberry acreage uses the beneficial mite *Phytoseiulus persimilis* against the two-spotted spider mite *Tetranychus urticae*, an important pest. Use grew rapidly in 1987 when the widely used pesticide Plictran was removed from the market by federal regulation. Other alternatives were not available and growers turned to natural enemies.

And some disappointments

Classical biological control

European gypsy moth (*Lymantria dispar*)—Despite a century of research and introductions of over 50 different biological control agents, most recently in 1994, biological control has not yet been successful and problems with the pest continue to worsen.

Augmentative biological control

Convergent lady beetles (*Hippodamia convergens*)—Lady beetles collected from field populations in California have dominated the market for yard/garden use of natural enemies since they were first sold in the early 1900s. Results of research on the beetles have consistently been disappointing, however, because most fly away within 24 hours after they are released. Some companies are beginning to market lady beetles "preconditioned" to ensure a more sedentary behavior, but the claims of enhanced efficacy remain to be well documented.

(continued)

BOX 3-1: Outcomes of Biologically Based Pest Control (Cont'd.)

Some notable successes…

Microbial pesticides

Bt—Various products based on the bacterium *Bacillus thuringiensis* are now the most widely used microbial pesticides in the United States and worldwide. The primary uses are for control of European gypsy moth (*Lymantria dispar*), various caterpillar pests, and the Colorado potato beetle (*Leptinotarsa decemlineata*).

Black vine weevil (*Otiorhynchus sulcatus*)—In cranberry bogs, this pest has been successfully controlled by nematodes. Favoring success were the soil conditions, susceptibility of the pest, safety of the product, lack of other alternatives, and high value of the crop. In addition, Ocean Spray, a farming cooperative that is the primary user, worked closely with the manufacturer to develop suitable application methods.

And some disappointments

"Milky spore" for control of Japanese beetle (*Popillia japonica*)—First introduced as a classical biological control in the 1930s, commercial formulations of *Bacillus popilliae* became available for control of the pest in turf during the 1980s. A number of lawn care companies experimented with these products, but poor quality control in production meant inconsistent product performance. As a result, lawn care company representatives do not believe that milky spore is effective and will not use it for control of Japanese beetle grubs. For some members of the industry, this experience has generated a high level of distrust for microbial pesticides in general.

Collego—This microbial pesticide is based on a pathogen of northern joint vetch (*Aeschynomene virginia*). First sold in 1982 by Upjohn, Inc., Collego offered excellent control over northern jointvetch in rice fields. The product was taken over by Ecogen, but production costs rose after the change. Eventually, the market size proved too small to justify continued production, and Collego was withdrawn from the market in 1994.

Elcar—This viral insecticide was developed by Sandoz, Inc. for use against the bollworm (*Helicoverpa zea*) where resistance to conventional pesticides was occurring. The virus was very effective and its initial prospects were good. But entry of pyrethroids onto the market at about half the price of the virus turned it into a financial disaster, and Elcar was removed from the market. Interest in this approach is reemerging because the bollworm is developing resistance to pyrethroids as well.

(continued)

BOX 3-1: Outcomes of Biologically Based Pest Control (Cont'd.)

Some notable successes…	And some disappointments
Pheromone-based products	
Pink bollworm (*Pectinophora gossypiella*)—Mating disruption approaches on 27,000 acres of the Parker Valley in Arizona starting in 1989 resulted in a decrease of damage to cotton bolls from 25% (with standard regime of conventional pesticides) to 0% (with the pheromone approach).	European elm bark beetle—Attempts to mass-trap the beetle, the vector of Dutch elm disease, have been unsuccessful because they do not attract enough insects or attract them only after the damage has occurred. Codling moth (*Cydia pomonella*)—Several products are available but the level of fruit protection achieved varies with the product, the initial level of infestation, and the distance of the orchard from sources of mated codling moth females. Inconsistent formulation and poor choice of application sites appear to be sources of the variable outcomes in farm-by-farm application. Researchers believe greater success is likely using an areawide management approach.
Sterile insect approach	
Screwworm (*Cochliomyia hominivorax)*—Large-scale releases of sterile males, starting in the 1950s, effectively eliminated the pest from the United States and northern Central America.	Mediterranean fruit fly (*Ceratitis capitata*)—The success or failure of this approach in the Los Angeles basin is unknown and a source of controversy among scientists. As of November 1994, this pest was still present despite releases of 14 billion sterile flies in 1993.

SOURCES: Office of Technology Assessment, U.S. Congress, 1995; W. Cranshaw, Department of Entomology, Colorado State University, Fort Collins, CO, "Biologically Based Technologies for Pest Control: Urban and Suburban Environments," unpublished contractor report prepared for the Office of Technology Assessment, U.S. Congress, Washington, DC, 1994; K. Jetter and K. Klonsky, Department of Economics, University of California, Davis, CA, "Economic Assessment of the Ash Whitefly (*Siphoninus phillyreae*) Biological Control Program," unpublished contractor report prepared for the California Department of Food and Agriculture, Sacramento, CA, June 30, 1994; "Milky Spore Disease May Not Be Effective Biological Control for Grubs," *Turf Grass Trends* 13, May 1994; J. Randall and M. Pitcairn, Exotic Species Program, The Nature Conservancy, Galt, CA and the Biological Control Program, California Department of Food and Agriculture, Sacramento, CA, "Biologically Based Technologies for Pest Control in Natural Areas and Other Wildlands," unpublished contractor report prepared for the Office of Technology Assessment, U.S. Congress, Washington, DC, November 1994; R. Van Driesche et al., Department of Entomology, University of Massachusetts, Amherst, MA, "Report on Biological Control of Invertebrate Pests of Forestry and Agriculture," unpublished contractor report prepared for the Office of Technology Assessment, U.S. Congress, Washington, D.C., December 1994.

control site or drift of pesticides from adjacent areas can affect performance of certain BBTs.

For these reasons, BBTs do not provide a high enough level or broad enough range of pest suppression to satisfy the full needs of farmers and other users whose expectations have been set by conventional pesticides. BBTs thus need to be used in a more integrated fashion with other control techniques to provide an overall package of pest suppression. This requirement means that the performance of BBTs may often depend on the quality of the specific integrated pest management (IPM) system in use—whether it deals with the full range of likely pest problems and can respond to changing pest control needs.

An Important Benefit of BBTs

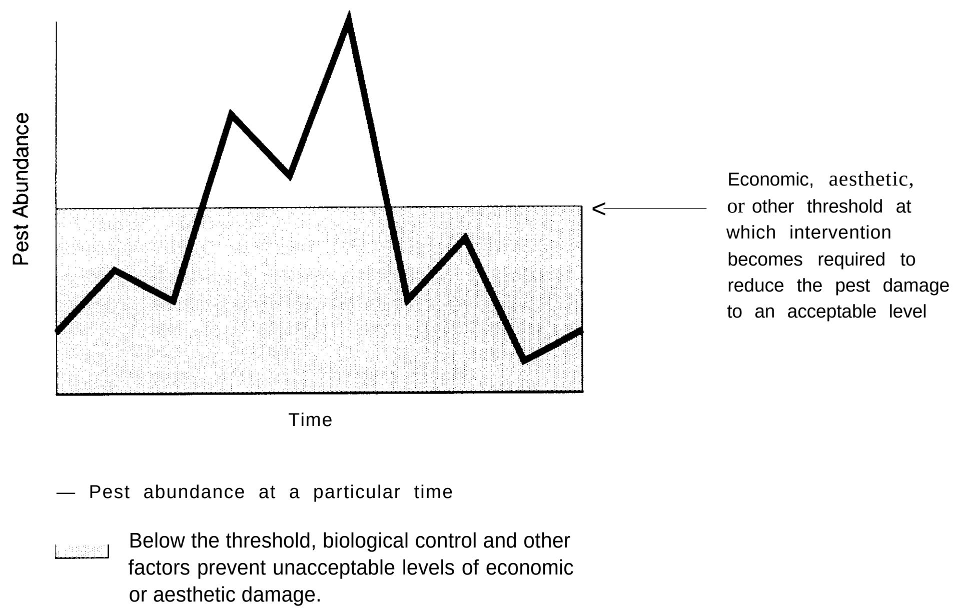
Some of the very characteristics that make BBTs compare poorly with conventional pesticides become advantages in pest management systems that seek to minimize pesticide inputs. Such systems usually involve monitoring (scouting) of pests so that pesticides are applied only when outbreaks occur.

To most people, this concept is simple: Killing pests stops their unwanted effects. To experts, however, this simplicity masks underlying complexity. The harmful effects of a pest are directly related to its abundance. If a potential pest is never abundant enough, its harmful effects may remain at an acceptable level or perhaps undetected. Many pest control practitioners today intervene only to control a pest when it reaches a threshold abundance where unacceptable effects are likely to occur (figure 3-1; see table 2-2 in chapter 2). Potential pests sometimes remain below this level because of the action of naturally occurring biological control agents or other factors, such as weather.

The BBTs covered in this assessment include practices to enhance naturally occurring control when a pest is below its threshold (i.e., conservation of natural enemies) and intervention methods to push pest abundance back below the threshold (i.e., microbial pesticides). The distinction between the two is somewhat fuzzy because certain BBTs, such as augmentative biological control, can be used both to prevent and control pest outbreaks (i.e., when pest densities are either below or above the threshold abundance in figure 3-l).

Conventional pesticides also have been used in both ways. A major difference between BBTs and conventional pesticides concerns the ways in which they affect naturally Occurring control. Many conventional pesticides kill natural enemies as well as pest organisms. Certain pests that otherwise might be kept below threshold levels by natural enemies subsequently surge to outbreak levels (see box 2-2). In contrast, the specificity of BBTs means they are far less likely to harm natural enemies. These technologies thus are more compatible with pest management sys-

FIGURE 3-1: Intervention is Not Always Neccessary to Prevent Unwanted Pest Damage



SOURCE: Adapted by OTA from J.K. Waage, Director, International Institute of Biological Control, Ascot Berks, UK, letter to the Office of Technology Assessment, US. Congress, Washington DC, July 14, 1995.

tems that seek to maximize naturally occurring pest control and to minimize pesticide inputs.

Gaps in the Information

The patchy implementation of BBTs to date means that no precise evaluation of their capabilities is possible. Existing data focus more frequently on BBTs successes than on lessons learned from failures—and in many cases, the necessary long-term followup for evaluating impacts or effectiveness in IPM programs is lacking.

An additional problem arises because so much of the information on BBTs comes from research results. Scientists do not always use the term *control* to mean a level of pest suppression that is applicable to actual field applications. Moreover, because field conditions can greatly alter the impacts of BBTs, research findings can not be directly translated into predictions about potential effectiveness under conditions of practical use (175). This problem is especially significant for areas like plant pathogen control, where very few BBTs are yet in place (308).

What We Do Know about the Effectiveness of BBTs

Biological Control

When successful, classical biological control programs in which the natural enemy of a pest is identified, imported, and released, can provide lasting, highly selective, and effective control. Some programs have caused 100- to 1,000-fold drops in pest density (411). Not all biological control programs are successful, however. In 1990 it was estimated that the 722 biological control agents previously introduced in the United States had resulted in some level of suppression for 63 arthropod pests (123).[2] Some level of control has resulted for 21 U.S. weeds as a result of classical biological control introductions against 51 target species (420).

Results of classical biological control programs are usually reported as "complete," "substantial," or "partial" control (69,123,153). Complete control usually refers to a level of pest suppression at which no additional controls are necessary against the pest. It is the least common outcome of classical biological control, representing about 18 percent of all successful U.S. programs against arthropod pests (153).

Biological control successes generally occur slowly. A significant proportion of the U.S. successes in classical biological control against arthropod pests thus far (at least 85 percent) were accomplished prior to 1964 (69,123,153). Experience indicates that only about a half-dozen major successes can be expected in the United States per decade (415). Although, some researchers attribute the recent slow rate of success to inadequate institutional support from the U.S. Department of Agriculture (USDA) since the 1970s (58), while others suggest that the "easier targets" have already been addressed using this method (9). Recent successes are more common for weeds; only 45 percent of today's successes occurred prior to 1977 (153,420).

Successful biological control programs typically report benefit-cost ratios from reduced pest impacts and decreased use of pesticides of 10:1 to 30:1, with some as high as 200:1 (162,411). These ratios do not incorporate the costs of other failed biological control programs (286,318). One reason for the high per-program returns is that a successful classical biological control program can provide lasting benefits that accrue indefinitely into the future with little, if any, further investment. Many of the greatest successes in classical biological control have occurred in permanent or semipermanent environments such as orchards, forests, or rangelands, where perma-

[2] No readily available data show what proportion this figure represents of all U.S. arthropod pests against which classical biological control has been attempted. On a worldwide basis, for all pests targeted by classical biological control programs, approximately 16 percent are now completely controlled and another 40 percent are partially controlled by this method (411). Note that several natural enemies may be introduced before control occurs, and a project against a single pest can take anywhere from a few years to several decades.

nent establishment of natural enemies is most likely to occur (60).

Benefit-cost ratios have been calculated for relatively few classical biological control programs because documenting program impacts is difficult and costly (58). Little routine monitoring follows most biological control releases, and effects can take five, 10, or more years to become apparent (191,41 1,420). Moreover, the effectiveness of a biological control agent may vary across the pest's distribution because of differences in temperature, moisture, elevation, and other factors that affect survival and population size of the natural enemy and its target pest. The result can be a mosaic ranging from excellent to no control, depending on the specific site (420).

Even fewer attempts have been made to evaluate the overall effectiveness of repeated augmentative releases of natural enemies (41 1,263). The few scientific studies have been conducted on too small a scale to make accurate inferences about results under conditions of actual use (41 1), and scientists are divided about the feasibility and effectiveness of the approach (263,173), The utility of natural enemies in enclosed greenhouses is generally undisputed. Researchers vary, however, in their views as to the potential effectiveness of augmenting natural enemies in field crops; some believe that discernible levels of pest suppression result more from the positive impacts of reduced insecticide use on natural enemies already present in fields, than from the deliberately released natural enemies. At present, high cost and quality control also are issues (e.g., are the natural enemies sold alive and active?) (263,173). Another question concerns the scale at which augmentative releases will be most successful—on small farms, on large farms, or areawide. Nevertheless, companies marketing natural enemies and farmers who use these products believe they are effective and dispute scientists' more mixed view of this technique (269,59).

Augmentative use of fishes for control of aquatic weeds and mosquitoes is a special case. These fishes can be quite effective, although they act more slowly than pesticides and do not eliminate pests completely. Because their use is confined to water bodies of sufficient size, clarity, and warmth to sustain the animals, their usefulness is sometimes limited (191,315) For example, mosquito fish *(Gambusia* spp.) are impractical for certain significant mosquito habitats such as tree holes, tires, and temporarily flooded wetlands-all major sites of mosquito reproduction (191,315). Introductions of fishes for biological control also raise several significant ecological risk issues (see chapter 4).

Although the program to control of the boll weevil (Anthonomus grandis grandis) *relies on conventional pesticides, the pest's successful suppression in some states has resulted in greatly reduced insecticide usage; natural enemies are now more common in cotton fields and keep a number of other former insect pests under control.*

Agricultural Research Service, USDA

Conservation of natural enemies has highly variable effects, depending on the specific crop and location. Quantitative estimates of impacts are impossible because the approach is rarely used as a major and deliberate component of pest management (41 1). Instead, increased effects of natural enemies are more often a consequence of management practices implemented for other goals (such as reduced pesticide use) (9,411). Maximizing the conservation of natural enemies more widely would require the development of extensive site-specific information (41 1). Overall, the approach works only for pests that have potential natural enemies (native or introduced) in the area (411).

The most widely cited evidence for the potential effects of conservation of natural enemies comes from rice production in Asia. There, modification of insecticide spray schedules to enhance the impacts of natural enemies has dramatically reduced outbreaks of the rice brown planthopper (*Nilaparvata lugens*), a destructive rice pest (411). In the United States, the most common way farmers seek to conserve natural enemies is by selecting conventional pesticides that have relatively low impacts on natural enemies (61). Biological control experts hold differing views as to whether any chemical pesticides cause sufficiently low damage to natural enemies for this approach to be successful. Some believe that only microbial, pheromone, or cultural alternatives will enable enhanced reliance on conservation of natural enemies (411).

Microbial Pesticides

The performance of various microbial pesticides differs greatly, as does the degree to which that performance is affected by environmental conditions. Pesticides based on Bt are potent if applied to the early larval stages of susceptible insect pests. Application during other stages causes their effects to drop severely. Effectiveness also varies with the pest's feeding rate; as a result, many Bt products are formulated to include feeding stimulants. Because Bt products can be manufactured using large-scale fermentation techniques, they are less expensive to produce than many other microbial pesticides.

The various Bt-based pesticides are very specific. This precision minimizes nontarget impacts but also has disadvantages. For example, three caterpillars—*Heliothis virescens* (tobacco budworm), *Heliocoverpa zea* (bollworm), and *Spodoptera exigua* (beet armyworm)—are frequent cotton pests. Current Bt products are highly effective against the first, less so against the second, and relatively ineffective against the third (411). In general, Bt products have been most useful against forest caterpillars, Colorado potato beetle (*Leptinotarsa decemlineata*) larvae, and a number of caterpillar pests of vegetables and other crops. Recent evidence suggests that certain pests may develop resistance to Bt, which could limit its future utility (see chapter 4).

Nematodes that have been developed for pest control products kill pests rapidly (within 48 hours).[3] They also show broader spectrum effects than Bt. Control of insect pests is comparable, and sometimes even superior to insecticides, with data showing 100- to 1,000-fold drops in pest densities for such diverse organisms as caterpillars, aphids, armored scales, sawflies, and whiteflies (411). Nematode products are applied using standard spray equipment, traps, or baits; they are generally tolerant of most pesticides and fertilizers (113). Environmental sensitivity—nematodes need adequate moisture and temperatures from about 53 to 86 degrees Fahrenheit—is a limitation of nematode products. They have been used successfully in moist soils but not in plant foliage. The shelf life of nematode products ranges from three to 12 months under refrigeration, but some of the newer formulations can last up to five months at room temperature. Although nematodes can be mass-produced, the high cost remains a problem.

Only two virus-based products are now in use, the European gypsy moth nuclear polyhedrosis virus (NPV) and the beet armyworm NPV virus.[4] Viruses, in general, are expensive to produce because techniques do not yet exist to mass-produce them without living hosts; according to industry representatives, new production tech-

[3] These include the steinernematid and heterorhabditid nematodes. Other nematodes that have not been developed for pest control provide a slower rate of kill. OTA categorizes nematode-based products as a type of microbial pesticide because the nematodes involved are microbes (microorganisms) (276) and sold in commercial formulations (see chapter 2). Some scientists and commercial producers categorize nematodes as natural enemies in part because EPA does not regulate these products as a type of microbial pesticide (see chapter 4). The issue is largely semantic.

[4] Another six have been registered for control of forest and crop pests, including two within the past year for celery looper (*Anagrapha falcifera*) and codling moth (*Cydia pomonella*).

nologies will soon be available that allow less costly production. Viruses also persist in the field only briefly because sunlight causes them to lose activity. A few viruses are broader spectrum, affecting several insects in the same taxonomic family or order, although effects of a given virus on different species can vary (411).

Microbial pesticides based on fungi have high virulence and are amenable to mass production. Their biggest drawback is requiring a moist habitat for activation. Fungus-based herbicides developed thus far against weeds have been highly host-specific, relatively fast-acting, and lethal (420). Fungi developed for use against insect pests have broader host ranges (although narrower than Bt products) and are most effective at high pest densities.

Only one microbial pesticide for plant pathogen control has been in use for any length of time. Galltrol suppresses the pathogen that causes crown gall disease (*Agrobacterium tumefaciens*) (138).[5] However, this one product's effectiveness provides only limited insight into the general usefulness of microbial pesticides against plant pathogens. Crown gall disease is a special case; because the disease results from infection of plant wounds, the microbial pesticide has to be active for only a few hours while the plant wound closes. The plant then ceases to be susceptible to infection (308).

Pheromones and Other Approaches

In successful programs against pink bollworm (*Pectinophora gossypiella*) and oriental fruit moth (*Grapholita molesta*), pheromone mating disrupters have given results equal to or better than those of insecticides (41). The use of pheromones to disrupt mating works only on pests using these chemicals to find mates over long distances, such as most moths—which are a large proportion of the most important insect pests. Pheromones are truly species specific, with each working on only a single pest. They do not injure natural enemies and can be combined with insecticides. In some cases, it may be necessary to combine pheromones and pesticides to reduce the pest population sufficiently so that it can be managed with mating disruption (411). Some pheromone products have performed erratically in the field; the problem has been attributed to poor formulation and to labels that supply inadequate information for proper use (41,175). High costs of pheromone use is another problem.

Experience with the screwworm (*Cochliomyia hominivorax*) program has shown that the sterile insect approach can be quite successful. During the 1970s, however, that program suffered some periods of poor performance as a result of some unsound assumptions about the behavior of the flies; the experience underscores the importance of basic knowledge of the pests' life cycle and behavior when using this approach (411). Efforts to suppress additional pests using sterile releases have had only limited success. Other genetic manipulations of pests are being studied and have not yet demonstrated their potential.

CURRENT USE OF BBTS IN THE U.S.

Table 3-1 summarizes available data on current usage of BBTs in the United States.[6] Usage of BBTs is uneven. The vast majority now in place are for control of insect pests in arable agriculture (cultivated lands), forestry, and aquatic environments. However, use is growing for insect control in urban and suburban settings as new nematode and pheromone bait products become available for turf and household pests. BBTs have virtually no role at present in the control of weeds in arable agriculture, even though this is where approximately 57 percent of conventional pesticide use occurs in the United States. Weed control has been best addressed in rangelands, pastures, and waterways, specifically by classical

[5] About a half-dozen new microbial pesticide products for use against plant pathogens became available in 1994 and 1995.

[6] The focus here is on the United States because the success of a technology abroad may not necessarily translate directly into potential for U.S. adoption. There are marked international differences in farming practices and in important social and economic factors. For example, virus-based pesticides have achieved wider use in countries where lower labor costs keep the cost of production low.

biological control. Few BBTs are yet in use against plant pathogens.

Applications

The goals of pest management vary with the application site. Application sites also differ in who practices pest control and in the range of available, acceptable, or feasible pest control technologies. The necessary or desired level of pest suppression is higher under some circumstances than others; for example, blemish-free fruit production requires very low rates of insect damage, whereas greater pest abundance may be tolerated in forests or rangelands. BBTs may be easier to adopt in the latter circumstance because the technologies usually suppress, but do not locally eliminate, pests. Other pest control technologies that compete with BBTs are more common in some applications, such as major crops. These factors, combined with the uneven availability of BBTs, have generated today's hit-or-miss pattern of BBT use.

Arable Agriculture

Current use of BBTs in arable agriculture (cultivated lands) is confined almost completely to insect pests. A number of major food processors and growers have begun to rely on BBTs in "biointensive" IPM systems (figure 3-2). From 1990 to 1993, for example, the Campbell Soup Company worked closely with Mexican tomato growers to eliminate all uses of chemical insecticides. The resulting system combined monitoring, Bt, pheromones, and *Trichogramma* wasp releases to provide comparable control of insect pests at a lower cost (30).

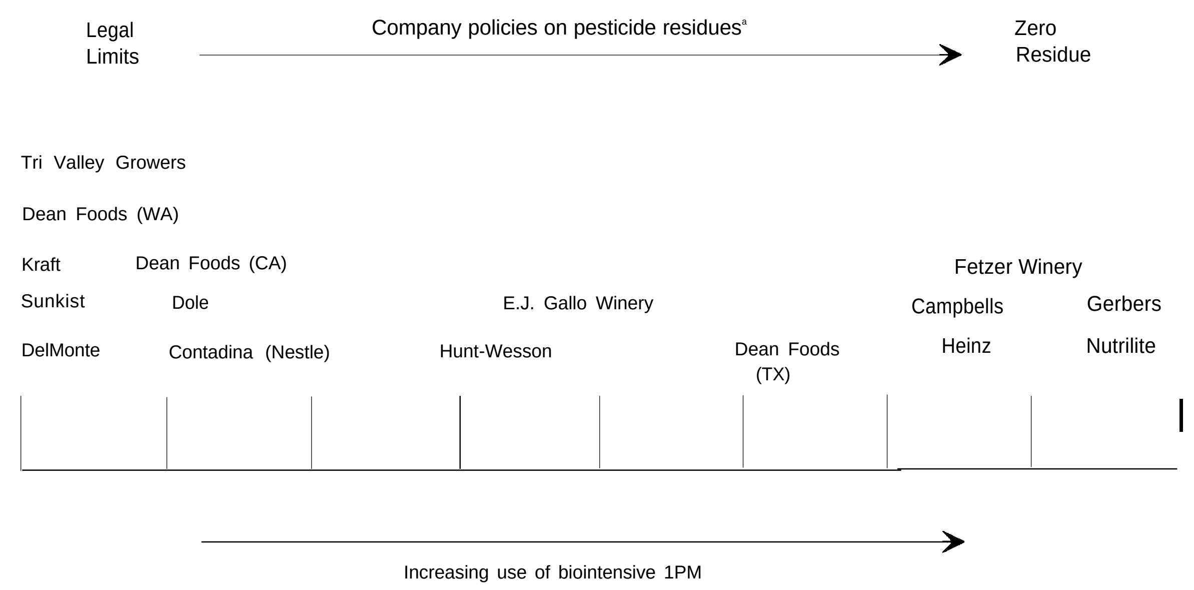
Millions of acres of U.S. crops are currently protected from one or more pests by the introduction of classical biological control agents which have provided some level of suppression for 63 arthropod pests (123,411). Most of these biological control agents were introduced some time ago, but others are fairly recent; for example, introduction of parasites against the alfalfa weevil (*Hypera postica*) from 1980 through 1992 contributed significantly to a reduction in that pest's abundance and impacts (174).

Augmentative releases of natural enemies by farmers occur primarily in vegetable, fruit, and nut crops (table 3-1) (377). Many of these uses are relatively recent. However, augmentation is a long-standing practice in some areas. In the 1930s a number of California citrus growers formed the Filmore Citrus Protective District, a cooperative that now produces natural enemies for use against citrus pests such as mealybugs and scales on more than 9,000 acres (173).

Augmentative use of natural enemies in greenhouse agriculture is growing (411). The approach is widespread in Europe, where cultivation of vegetable crops in greenhouses is more common. Greenhouse agriculture in the United States occurs on only several hundred acres. The greenhouse industry for ornamental plants is much larger (valued at $2.5 billion in 1993), but the potential for use of natural enemies here is lower because less pest damage is tolerated on the products and new chemicals may provide significant competition (box 3-2) (411).

Few data quantify how frequently farmers deliberately modify farming practices to conserve natural enemies on U.S. croplands. Intercropping, modification of cropping practices, and selection of crop varieties to enhance natural enemies all look promising to researchers but have not been widely adopted (411). Some California vineyards and almond growers report that certain vegetation practices enhance natural enemies of arthropod pests and plant pathogens (257,258). Other management practices that incidentally conserve natural enemies are more broadly used. One example is the routine monitoring of natural enemies and pests in commercial orchards; farmers delay use of insecticides if the ratio of predators to pests is high enough to prevent pest damage (411). Vegetable, potato, and cotton growers commonly consider the effects of pesticides on natural enemies when deciding which chemicals to use and when to apply them (table 3-1) (377). Similar practices are widespread among Pennsylvania apple growers (282).

Figure 3-2: Adoption of Biointensive IPM by Major Food Companies



SOURCE: Off Ice of Technology Assessment workshop on The Role of the Private Sector in Biologically Based Technologies for Pest Control, Washington, DC, September 20-21, 1994.

NOTE: The term *biointensive IPM* refers to an 1PM system designed to increase plant health, This goal is generally obtained through the use of BBTs for pest control in addition to other crop management practices. This figure was presented during the OTA Workshop on the Role of the Private Sector. It is included here for illustration purposes only, OTA makes no claim as to the accuracy of the data.

[a] Assignment along this continuum is based upon the company's stated policy regarding the pesticide residue in the final shelf product and the company's level of use of BBTs in 1PM programs.

TABLE 3-1: Available Data on the Use of BBTs in the U.S.

Applications	Insect/ invertebrate pests	Weeds	Plant pathogens
Agriculture arable crops	**Biological control** ■ 63 arthropod pests are under some level of suppression by classical biological control. ■ 28 states operate their own biological control programs. ■ Biological control is used in 10% of greenhouses, 8% of nurseries and 8% of sod production.[a] ■ Augmentative releases take place on an estimated 19% of the cultivated fruit and nut acreage.[b] ■ Farmers purchase natural enemies for use on 3% of the cultivated vegetable acreage.[b] ■ More than 86 U.S. companies produce or market natural enemies with annual sales of approximately $9 to $10 million. ■ Beneficial mites are used on an estimated 50 to 70% of California strawberry acreage. ■ Farmers change or select pesticides to protect natural enemies on 37% of cultivated vegetable acreage.[b] ■ Growers decrease insecticides to protect natural enemies on 22% of cultivated acres of fall potatoes.[b] ■ Growers consider natural enemies when making pesticide decisions for 57% of cultivated cotton acreage.[b]	**Biological control** ■ No weeds are currently under classical biological control. ■ No augmentative biological control agents are available.	
	Microbial pesticides[c] ■ Bt-based microbial pesticides are used on vegetable crops, potatoes, cotton and corn. ■ 46% of nematode sales in 1993 were for use on arable crops.[d]	**Microbial pesticides** ■ No microbial pesticides are now on the market.[e]	**Microbial pesticides** ■ Two microbial pesticides have annual sales exceeding $100,000 for crown gall disease (*Agrobacterium tumefaciens)*. ■ Three microbial seed treatments were first sold in 1994 for seed planted on 3 to 5 million acres of cotton, peanuts, and beans. ■ Three new microbial products for control of postharvest diseases became available in 1994 and 1995.

(continued)

TABLE 3-1: Available Data on the Use of BBTs in the U.S. (Cont'd.)

Applications	Insect/ invertebrate pests	Weeds	Plant pathogens
	Pheromones ■ In 1994 there were 20 registered, commercially available pheromone formulations for the control of over 20 moth pests. ■ Pheromone products are used on 37% of the cultivated fruit and nut acreage.[f] ■ Pheromone products are used on 7% of the cultivated vegetable acreage.[f] ■ Pheromones were used against oriental fruit moths on approximately 10,000 acres of peach and nectarine orchards in 1990. ■ In 1993, pheromones were used to disrupt mating of codling moths (*Cydia pomonella*) on more than 24,000 acres of apple and pear orchards (slightly less than 5% of the total U.S. apple and pear acreage). ■ In 1995, pheromones are expected to be used on over 81,000 acres in Arizona (about 25% of the state's cotton acreage). **Other methods** ■ Sterile insect approach has successfully eliminated the screwworm (*Cochliomyia hominivorax*) from the United States; the method is now in use against the Mediterranean fruit fly (*Ceratitis capitata*) in California.		**Other methods** ■ Cross protection is being used in Florida on a pilot basis for control of citrus decline.
Rangeland/ uncultivated pastures/ forests	**Biological control** ■ 500,000 parasitic wasps were sold for gypsy moth control in 1994.	**Biological control** ■ 18 species of weeds are under some level of suppression due to classical biological control. ■ Programs to conserve and distribute natural enemies operate in Oregon and Montana. ■ 28 natural enemies are now sold by at least seven retail companies for augmentative uses.	

(continued)

TABLE 3-1: Available Data on the Use of BBTs in the U.S. (Cont'd.)

Applications	Insect/ invertebrate pests	Weeds	Plant pathogens
	Microbial pesticides[c] ■ One protozoan microbial pesticide (*Nosema locustae*), produced by two U.S. companies, is in use for grasshopper control. ■ For control of the European gypsy moth, in 1994, Bt was used on more than 374,000 acres in 11 states, and Gypchek (a virus-based pesticide) was used on nearly 6,000 acres in 4 states.		
Urban/ suburban environments	**Biological control** ■ Ash whitefly (*Siphoninus phillyreae*) is under complete control by classical biological control. ■ Natural enemies such as lady beetles, green lacewings, and trichogramma wasps are sold to gardeners. ■ Horse owners are a major market for fly parasites. **Microbial pesticides**[c] ■ Bio-Path roach bait with microbial pesticide has been marketed since 1993 for control of cockroaches. ■ Homeowners represented 35% of U.S. nematode sales in 1993.[d] ■ Bt is sold for consumer use against garden pests and mosquitoes. ■ Four formulations of the fungus *Beauvaria bassiana* became available in 1995 for control of ornamental and turf pests. **Pheromones** ■ Pheromone sticky traps are sold in garden centers for use against moth pests and Japanese beetles (*Popillia japonica*).		**Microbial pesticides** ■ One microbial pesticide is marketed to protect nursery plants, such as rose bushes and other ornamental plants, from crown gall disease. ■ Two microbial pesticides became available in 1995 for use as a greenhouse soil amendment and golf course inoculant.
Aquatic environments	**Biological control** ■ Competitor snails are widely used in Puerto Rico for control of snails that carry human disease. ■ At least three fishes are used for mosquito control. ■ At least seven aquaculture facilities commercially sell mosquito fish. ■ Two fishes are used to control nuisance fish.	**Biological Control** ■ Three species are under some level of suppression due to classical biological control. ■ Grass carp have been released into lakes/rivers/streams of 35 states. ■ Limited use is made of other fishes for weed control.	

(continued)

TABLE 3-1: Available Data on the Use of BBTs in the U.S. (Cont'd.)

Applications	Insect/ invertebrate pests	Weeds	Plant pathogens
	Microbial pesticides[c] ■ Bt-based microbial pesticides are in use for mosquito and blackfly control.		

[a] Based on a limited survey by the USDA NAPIAP program; the meaning of biological control was unspecified.

[b] Based on extensive survey by the USDA Economic Research Service. The survey used the term *beneficial*, but did not specify the meaning. Growers may have included bees in their responses. This is a significant problem for interpreting data on fruits and nuts, but less so on vegetables and cotton.

[c] Annual U.S. sales of microbial pesticides are between $60 million to $100 million annually, mostly for use in agriculture and forestry. Some 249 microbial pesticides are now registered with EPA. This number does not, however, indicate how many are currently produced commercially or their level of use.

[d] Nematodes were sold for control of 33 insect pests on 40,000 acres in 1993. This was expected to increase to 88,000 acres for 1994. The market can be broken down to 35% for homeowners, 46% for minor use crops, and 2% miscellaneous.

[e] Based on extensive survey by the USDA Economic Research Service. Pheromone use could include monitoring and control methods.

[f] Two products formerly were on the market in the United States, Collego for control of northern joint vetch (*Aeschynomene virginia*) and DeVine for control of citrus strangler vine (*Morrenia odorata*). Although effective against their intended targets, neither could sustain large enough markets to justify continued production. DeVine has just recently been put back on the market by Abbott Laboratories as a result of cooperative efforts with EPA.

SOURCES: Compiled by the Office of Technology Assessment, U.S. Congress, 1995, from: R. Cardé and A. Minks, "Control of Moth Pests By Mating Disruption: Successes and Constraints," *Annual Review of Entomology* 40:559-585, 1995; D.J. Greathead and A.H. Greathead, "Biological Control of Insect Pests By Insect Parasitoids and Predators: The Biocat Database," *Biocontrol News and Information* 13(4):61N-68N, 1992; C.D. Hunter, *Suppliers of Beneficial Organisms in North America* (Sacramento, CA: California Environmental Protection Agency, 1994); A. Kuris, Department of Biological Sciences and Marine Science Institute, University of California, Santa Barbara, CA, "A Review of Biologically Based Technologies for Pest Control in Aquatic Habitats," unpublished contractor report prepared for the Office of Technology Assessment, U.S. Congress, Washington DC, October, 1994; Oregon State University, Integrated Plant Protection Center, *Areawide Management of the Codling Moth: Implementation of a Comprehensive IPM Program For Pome Fruit Crops in the Western United States* (Corvalis, OR: July 1994); M. Padgett, Economic Research Service, U.S. Department of Agriculture, Washington, DC, personal communication, June 26, 1995; U.S. Department of Agriculture, Economic Research Service, *Adoption of Integrated Pest Management in U.S. Agriculture,* prepared by A. Vandeman, et al., Bulletin No. 707 (Washington, DC: 1994); U.S. Department of Agriculture, Forest Service, *Gypsy Moth News,* (35): September 1994; U.S. Department of Agriculture, National Agricultural Pesticide Impact Assessment Program, *The Biologic and Economic Assessment of Chlorpyrifos and Diazinon in Ornamentals and Sod Production*, 1994; R. Van Driesche et al., Department of Entomology, University of Massachusetts, Amherst, MA, "Report on Biological Control of Invertebrate Pests of Forestry and Agriculture," unpublished contractor report prepared by the Office of Technology Assessment, U.S. Congress, Washington, DC, December, 1994; A.K. Watson, Department of Plant Science, McGill University, Quebec, Canada, "Biologically Based Technologies for Pest Control: Agricultural Weeds," unpublished contractor report prepared for the Office of Technology Assessment, U.S. Congress, Washington, DC, November 1994.

NOTE: This table summarizes all data available to OTA; the summary is not comprehensive.

BOX 3-2: How Changes in Available Pesticides Affect Adoption of BBTs

Chloronicotinyls (synthetic nicotines) are one of the newest classes of insecticides. The first of these, imidacloprid, was marketed by the Miles Corporation in 1994. The chemical has several useful qualities. It diffuses throughout a plant after being applied to the roots and can persist in woody tissues for weeks or years. Many plant-feeding insects are susceptible. Perhaps most important, imidacloprid is thought to be relatively nontoxic to humans. Finally, it moves slowly through soils—enhancing its insecticidal impact and diminishing the risk of groundwater contamination.

The effect of imidacloprid and related chemicals is likely to be a reduction in use of BBTs. This effect has already been seen in the poinsettia industry, where several greenhouses being set up for biological control of whiteflies in 1994 opted instead to use potting mix treatments of imidacloprid. If experience is any guide, at least one important greenhouse pest—the silverleaf whitefly *(Bemisia argentifolii)* --is likely to develop resistance to imidacloprid within a few seasons, This situation will again stimulate interest in BBTs.

SOURCES: W. Cranshaw, Department of Entomology, Colorado State University, Fort Collins, CO, "Biologically Based Technologies for Pest Control: Urban and Suburban Environments, " unpublished contractor report prepared for the Office of Technology Assessment, U.S. Congress, Washington DC, 1994; R. Van Driesche et al., Department of Entomology, University of Massachusetts, Amherst, MA, letter to the Office of Technology Assessment, US. Congress, Washington D. C., July 1995.

Microbial pesticides based on Bt are by far the most commonly used in agriculture. They are frequently the method of choice when a pest develops resistance to chemical control methods (41 1). The major uses are for pests of vegetable crops, with recent increases in use on potatoes, cotton, and corn following the discovery of new Bt strains and development of new delivery methods (411). Increases on cotton relate, in part, to the tobacco budworm's development of resistance to pyrethroids (41 1). Some 1PM programs integrating Bt show economic returns equivalent to those of conventional pest control programs because pesticide costs decline in the Bt programs (41 1).

Until recently, Bt-based products were the only microbial pesticides available for use against arthropod pests. The fungus *Beauvaria bassiana* has now been formulated for use against a variety of pests, including grasshoppers, Mormon crickets *(Anabrus simplex),* locusts, whiteflies, aphids, thrips, mealybugs, leafhoppers, psyllids, and mites. Two products by Troy Biosciences based on this fungus, Naturalis-O and Naturalis-T, have recently come on the market. Two other products, Mycotrol-GM and Mycotrol-WP, have just been registered by the EPA and are expected to be available soon.

Microbial pesticides based on the bacterium Bacillus thuringiensis, or Bt, are the most common ones in use today.

Agricultural Research Service, USDA

Virus-based products have not been available in the United States for control of agricultural pests (with the temporary exception of Elcar; see box 3-l). One virus product, Sped-X from Biosys, just came on the market for use against the beet armyworm. NPV viruses that affect the celery looper and codling moth were registered with EPA this year. Virus-based pesticides are now used against vegetable, fruit, and cotton pests in

China, Asia, India, Egypt, Australia, Kenya, and Central and South America; in Brazil alone over one million acres of soybeans are treated with virus-based pesticides each year (411).

The principal uses of pheromones today are as mating disruptants in cotton, fruit, and vegetables. Aerial applications of pheromones to disrupt mating of the pink bollworm in the Parker Valley of Arizona led to a decline in cotton damage from 23.4 percent in 1989 with a conventional pesticide program to zero percent in 1993 (411). Areawide use of the pheromone approach has grown to an estimated 81,000 acres in 1995, or about a quarter of the state's total acreage of the crop (411). Other highly successful commercial applications have been for the oriental fruit moth in peaches and the tomato pinworm (*Keiferia lycopersicella*). From 1991 to 1993, applications of Isomate, a pheromone to disrupt the mating of the codling moth, grew from 4,633 to 24,710 acres of apple and pear orchards in the western United States (259). Adoption of these programs occurred because pest resistance made conventional pesticides marginally or completely ineffective (411).

The most successful use of the sterile insect technique has been in the program to eradicate the screwworm, which eats the flesh of livestock and deer. Releases of sterile male screwworms in the United States began in 1951 and the pest was eliminated from the country by 1982 (see box 5-2 in chapter 5). Continuing programs have eradicated the pest from the north of Central America as well. An ongoing program in place in California against the Mediterranean fruit fly (*Ceratitus capitata*) has not eliminated the pest: The fly persisted in the Los Angeles basin in 1994 despite releases of 14 billion sterile flies in 1993 (411). Whether this result represents a failure of the sterile insect technique or repeated introduction of the pest is unclear.

Various BBTs (natural enemies, microbial pesticides, behavior-modifying chemicals) are under investigation for control of pests in grain storage facilities (344). Cleanit AG of Switzerland is developing a product based on a pheromone that repels mice to reduce rodent damage (115). None are yet in use.

Virtually no BBTs are in use today for control of weeds in arable agriculture.[7] Classical biological control has been attempted for four weeds without success to date. Potential microbial pesticides have been explored for 23 crop weeds, and effective agents found for 13. Two were eventually marketed: Collego was registered in 1982 for control of northern joint vetch (*Aeschynomene virginica*) and DeVine was registered in 1981 for control of citrus strangler vine (*Morrenia odorata*) in Florida citrus groves. These products were later withdrawn from commercial sale because they did not generate large enough markets (see box 3-1 earlier in this chapter). The problem with DeVine was that it proved too effective, persisting in the field and giving good weed control for more than three to four years at some sites (420,49). Small markets also resulted because each microbial product controlled only a single weed, whereas farmers usually have to deal with many weeds at once. This year, the producer of DeVine, Abbott Laboratories, cooperated with EPA to bring the product back on the market (49).

Conventional pesticides have never been able to control some serious plant diseases caused by viruses and bacteria (138). Microbial products and systems for control of plant diseases are just now becoming commercially available (138). These microbes may suppress disease-causing microbes by producing antibiotics or other injurious compounds, by competing with them for nutrients or other essential resources, or by inducing resistance to the disease in the host plant. The extent to which the new microbial approaches will be adopted and the level of control they will provide are uncertain. The best-documented agricultural use of a BBT against a plant pathogen is for crown gall disease—a tumor-producing disease caused by bacteria

[7] A number have, however, been successful against weeds on uncultivated lands, as the next section describes.

(*Agrobacterium* spp.) and affecting crops such as grapes. No pesticides work against this disease (138). Strains of a related species (*A. radiobacter*) suppress the disease, but each strain works only against certain disease strains. Two microbial pesticides for crown gall are sold in the United States, Galltrol by the AgBioChem Company and Norbac 84C by the NorTel Lab, with annual sales exceeding $100,000 (138).

In 1994 at least three new microbial products that enhance plant growth, in part by suppressing root-dwelling bacteria, came on the market: Kodiak, Epic, and Quantum 4000 from the Gustafson Company (138). These seed treatments, which colonize growing roots once seeds germinate, are used in combination with chemical fungicides. Sales in 1994 were for seeds sufficient for planting three million to five million acres of cotton, peanuts, and beans; this figure is expected to expand to 20 to 30 million acres by the year 2000 (138). The first commercial products for control of postharvest plant disease (which blemishes and causes rot on harvested crops) are just now coming on the market also. Bio-Save 10 and 11 (products based on the bacterium *Pseudomonas syringae* from EcoScience Corporation) and Aspire (product based on the yeast *Candida oleophila* from Ecogen) became available in 1995 for control of major postharvest diseases of apple, pear, and citrus (161).

Disease-suppressive soils and composts reduce crop diseases, it is thought, through the action of bacteria, fungi, or other microbes that dwell in these materials. Suppressive soils occur naturally in some areas or can be created by specific farming practices. Almost all are maintained by individual farmers, and no commercial products are available (138). Suppressive composts are widely used in horticulture but are not advertised for their disease-suppressive characteristics.

Pastures, Rangelands, and Forests

Pest problems in these habitats pose special problems. The lands generally are of lower economic value, making it difficult to justify the costs of expensive pest control programs based on conventional pesticides. Many forests and rangelands also encompass environmentally sensitive habitats, such as those adjacent to waterways, where use of pesticides may be restricted or prohibited. The most commonly used BBTs in these areas are various forms of biological control because of the low costs and general lack of impacts on nontarget organisms.

Rangelands and pastures are two of the few areas where BBTs currently are used for weed control. Classical biological control agents have been introduced against 40 U.S. weeds. Currently the approach has provided some level of suppression for 18 weeds and excellent control over some or most of the range of seven of these species (420). The successes include musk thistle (*Carduus nutans*), controlled by the weevil *Rhinocyllus conicus*, and skeletonweed (*Chondrilla juncea*), by *Puccina chondrillina* (420).

A number of programs propagate and distribute weed natural enemies to enhance their effects. The Oregon Department of Agriculture's weed program has introduced 42 natural enemies against 20 target plant pests since it began in the 1970s. Program staff now collect and transfer biological control agents across weed-infested areas to maximize the agents' impacts. In Montana, county extension agents cooperate with high schools and local 4-H clubs to run a similar program involving high school students (266). At least seven commercial suppliers now harvest weed biological control agents collected from the field for sale to ranchers, land managers, and others (155).

Rangeland managers sometimes modify livestock grazing practices to help reduce weed populations. The extent and the effectiveness of this practice are unclear. In areas managed to conserve native biodiversity, the use of livestock to help reduce weeds is sometimes undesirable because the cattle do not confine their impacts to target weeds (332). Under some circumstances, however, cattle grazing can enhance plant biodiversity. Other BBTs for weed control are not yet in use. Plant diseases have been evaluated as potential microbial pesticides for five weeds of

In Montana students and teachers are part of a hands-on program to distribute natural enemies of noxious weeds that degrade rangelands,

W. Pearson, Stillwater Weed Control

pastures, rangelands, and forests, but none has been developed into a commercial product (420).

Biological control has had less success against insect pests of forests and rangelands. Few programs have been undertaken, and these have had mixed results. The most notable success is the larch casebearer *(Coleophora laricella);* introduction of five insect parasites from 1931 through 1983 has provided significant suppression of the pest throughout its North American range of hundreds of millions of acres (284).[8] In contrast, the repeated expensive efforts to control European gypsy moth since 1906 by classical biological control have failed to produce significant suppression of the pest (table 3-1) (284).

Microbial pesticides have proved more successful than classical biological control against the European gypsy moth. Bt now forms the core of the nation's multistate gypsy moth suppression program conducted by the U.S. Forest Service, the Animal and Plant Health Inspection Service (APHIS), and state agencies (382,384). This is the single largest use of Bt in the United States, with annual applications occurring on at least 374,000 acres (382). Isolated infestations of European gypsy moth have been eliminated by Bt applications, but the microbial pesticide has yielded more mixed results in reducing defoliation in high-density areas (284). The European gypsy moth NPV virus (Gypchek), produced by a commercial firm under contract to the Forest Service, also is now applied to about 6,000 acres annually (382). The virus is costly and in limited supply; in 1994 the state of North Carolina appropriated almost all of the U.S. supply to combat the newly arrived Asian gypsy moth.[9]

Several additional techniques complete the current BBT arsenal against European gypsy moth. Two natural enemies are sold by a private company (the National Gypsy Moth Management Group) to federal, state, and municipal agencies for augmentative use at isolated infestations and along the leading edges of moth outbreaks (284). In 1994, an estimated 500,000 wasps (costing from $0.25 to $0.52 each) were sold, to be applied at a rate of 50 per acre. Impacts of these natural enemies are uncertain. Finally, a gypsy moth pheromone has been used to identify and monitor the spread of gypsy moth infestations.

Pheromone-based approaches have limited success in controlling U.S. forest pests (284). The only known successful use of mating disruptants has been to control the western pine shoot borer, *Eucosoma sonamana*, in pine plantations, where pest levels were suppressed 75 percent (60). In the late 1970s and early 1980s, the mass trapping approach was used in Scandinavia against the spruce bark beetle on over 4.5 million acres of forest (310). The pest's abundance declined, but it is unclear whether the pheromone

8 However, according to some scientists, the success of the larch casebearer program is impossible to prove. Too little monitoring 'as conducted to establish a clear cause and effect relationship between the biological control releases and the suppression of the pest (203A). Proving this type of causality in ecological systems is, however, notoriously difficult,

9 The Asian gypsy moth disperses more readily than the European gypsy moth and harms different trees. Detection of the Asian strain in the United States not on] y caused worry about its immediate impact but also raised concern that the two strains would interbreed and give rise to an especially damaging type of gypsy moth.

method caused the drop (39). Nevertheless, it would be the method of choice if another pest outbreak occurred because conventional pesticides are prohibited there (310).

Other pheromone techniques are under development or used occasionally, in particular, against the southern and mountain bark beetles. Pheromones that enhance beetle aggregation have been applied to tree stands prior to cutting, causing the beetles to aggregate and then die when the trees are cut and removed (284). A pheromone that protects trees from attack by repelling beetles has recently been patented and has been tested in the National Forests in Louisiana, and a second is under development (284).

Grasshoppers are the only significant insect pest of rangelands to be targeted thus far by BBTs. Of the more than 300 native grasshopper species of western rangelands, 10 to 15 periodically have population outbreaks and become major pests (284). A microbial pesticide for grasshoppers, based on the protozoan *Nosema locustae,* is produced commercially by two U.S. companies: Bozeman Bio-Tech (Montana) and M&R Durango (Colorado). The current number of acres treated with this product is very small compared with the number treated with chemical pesticides (411). A product based on the fungus *Beauvaria bassiana* was registered by Mycotech Corporation in 1995, as mentioned earlier in this chapter. Two other BBT alternatives under research are a fungus (*Entomophaga praxibuli*) and a parasitic wasp (*Scelio parvicornis*). The latter was recently denied a permit for release by the USDA Animal and Plant Health Inspection Service because of concerns about potential nontarget impacts (299).

Natural Areas, Parks, and Wildlands[10]

Until recently, few BBTs were targeted specifically at pests of natural areas and wildlands. Increasing awareness of how invasive nonindigenous (exotic) species are threatening native biodiversity (338), however, has led natural area managers begin to explore BBT options for pest control—classical biological control, in particular (box 3-3).

Classical biological control has particular advantages in natural areas and wildlands (284). An established biological control agent can provide indefinite control of a pest, tracking its spread and bringing it under control at new sites. Biological control may thus be the only economically feasible option for certain widespread pests like yellow starthistle (*Centaurea solstitialis*)—a weed that displaces native vegetation and degrades wildlife habitat on western rangelands—for which the costs of conventional pesticides would be exorbitant. Classical biological control agents, if properly screened are unlikely to have undesirable environmental impacts (see chapter 4, however, for a discussion of potential impacts and screening methods).

Natural area managers have not wholeheartedly embraced biological control (284). The primary concern is whether impacts of the control agent are confined to the pest or also affect other organisms. Far more so than in agriculture, concerns of natural area managers extend to a wide variety of organisms, and many see potential nontarget impacts as a serious liability. For similar reasons, natural area managers view use of biological control for native pest species with a good deal of alarm. Certain species may be pests in some locales but integral components of native ecosystems in others. Poison ivy (*Toxicodendron radicans*), for example, is an important source of wildlife forage. Moreover, native pests are far more likely to have nonpest relatives in this country that would be especially vulnerable to their biological control agents (332).

Despite these concerns, natural area managers have begun to proceed cautiously with classical biological control programs. Most have been

[10] Natural areas and wildlands are distinguished from rangelands, forests, and pastures. The latter are managed primarily for their resource values, such as cattle grazing and timber. Natural areas and wildlands, in contrast, are managed to support native plants and animals; they include many federal and state parks, refuges, and wilderness areas.

BOX 3-3: How Conservationists are Turning to Biological Control to Help Save Biodiversity

The imported red fire ant (*Solenopsis invicta*) first entered the United States from South America in the 1930s. It has since spread to 250 million acres from Texas to Virginia. Conventional pesticides have proved ineffective at controlling the pest, despite expenditures of more than $200 million. Some experts believe that the mass sprayings in the 1950s and 1960s may even have hastened its spread by weakening native ant species that could compete with the fire ant.

The red fire ant is well known for its aggressive stings to humans that can cause allergic reactions and even death in sensitive individuals. It has similar effects on domesticated animals. Texas veterinarians rank fire ants as a serious threat to animal health and report that annual costs to treat stung animals amount to $750,000 in that state alone.

Now conservation biologists across the country are warning that the red fire ant may have dire impacts on biodiversity as well. In places, some scientists believe that it has reduced native insect species by as much as 40 percent. Seed-harvesting ants have disappeared in many areas of Texas, along with certain lady beetles, spiders, scorpions, and other arthropods. Studies of Texas pigmy mice show alterations in the mice's behavior and ecology where the red fire ants are present. Survival of white-tailed deer fawns is reduced by half where the ants occur: Facial stings sometimes blind or kill fawns. Declines in one endangered grassland bird (the loggerhead shrike) correlate directly with the presence of fire ants. And the evidence suggests that several other migratory grassland birds may be similarly affected.

According to E.O. Wilson, a well-known biodiversity and ant expert from Harvard University, control of the fire ants may be necessary to avert a small-scale catastrophe for insect biodiversity in the South. Such concerns have prompted scientists in Texas and Utah to search for biological control agents to use against red fire ants. Several flies (*Pseudacteon* spp.) that parasitize the ants are currently under study. Instead of providing direct control of the fire ant, researchers expect the parasites to reduce the fire ant's ability to compete with native ants. Several other biological strategies are being considered, such as treating the ant colonies with the species' own pheromones to halt reproduction. Scientists in Florida also are investigating ways of baiting fire ants into carrying the pathogenic fungus *Beauveria bassiana* back to their nests.

The imported red fire ant is but one of several pests now being targeted for control because of their impacts on biodiversity. Purple loosestrife (*Lythrum salicaria*) and melaleuca (also known as the paperbark tree, *Melaleuca quinquenervia*) are other prominent examples. Both are wetland weeds that displace native plants and degrade wildlife habitats.

SOURCES: J. Grisham, "Attack of the Fire Ant: Scientists Hope New Methods of Biocontrol Can Stop the Advance of this Imported Pest," *BioScience* 44(9):587-590, October 1994; C.C. Mann, "Fire Ants Parlay Their Queens Into a Threat to Biodiversity," *Science* 263:1560-1561, March 18, 1994; J. Randall and M. Pitcairn, Exotic Species Program, The Nature Conservancy, Galt, CA and the Biological Control Program, California Department of Food and Agriculture, Sacramento, CA, "Biologically Based Technologies For Pest Control in Natural Areas and Other Wildlands," unpublished contractor report prepared for the Office of Technology Assessment, U.S. Congress, Washington, DC, November 1994.

conducted by federal, state, and local agencies. A handful of related projects have taken place in private reserves; one was recently approved by the Nature Conservancy (284). Most of these programs have piggybacked on better-supported programs aimed at pests of agriculture, rangelands, commercial forests, urban lands, and navigational waterways, because many of these pests also affect natural areas and wildlands. Examples include the gypsy moth, numerous rangeland weeds, salt cedar (*Tamarix* spp.), and hydrilla (a weed that blocks waterways).

Classical biological control programs in Hawaii have targeted at least one weed invading nature reserve forests, banana polka (*Passiflora mollissima*), using introduced plant diseases

(420). Only a few pests of natural areas in North America that have few or no impacts elsewhere, such as purple loosestrife (*Lythrum salicaria*) and melaleuca (*Melaleuca quinquenervia*), are currently the subjects of ongoing classical biological control programs by federal and state agencies (109,284). Natural area managers generally hold little hope that many new BBTs will be developed specifically for these areas (284).

Urban and Suburban Environments

Pest control takes place in intimate association with human populations in urban and suburban environments. Consequently, potential exposure to pesticidal products is high. Markets have developed for BBT products, in part because of their appeal to consumers who wish to avoid direct contact with conventional pesticides. BBT approaches lacking a commercial product have been exploited only rarely in urban and suburban environments because research by academic and government scientists has generally been lacking. For example, classical biological control has been used against few pests of turfgrass and shade trees (60).

Various bait-type products are sold for control of structural pests (including cockroaches and termites) that infest houses and other buildings. Control of these pests is a multibillion dollar industry in the United States. A new microbial product that came on the market in 1993 is called Bio-Path. It consists of a bait station that harbors fungus spores (*Metarrhizum anisolpliae*) designed to infect entering roaches, which then spread the pathogen to other individuals (60).

Use of natural enemies and microbial pesticides around food preparation and storage areas is another recent development. At least one natural enemy is now sold commercially for use in food storage facilities—the parasitic wasp *Bracon hebetor,* for control of Indianmeal moth (*Plodia interpunctella*) in peanuts. Some controversy has surrounded attempts to expand uses into food preparation areas. The small company Praxis met resistance from state and federal regulators when it began selling pest control programs based on parasitic wasps and nematode pesticides for use in cafeterias and restaurants (70) (see box 4-8 in chapter 4).

Natural enemies have found application in interiorscapes (interior plantings) of shopping malls, hotels, office buildings, zoos, and museums (320). One attraction is that they reduce liability considerations related to public exposure to pesticides. An example is the "Tropical Discovery" display of the Denver Zoological Garden, where establishment of natural enemies has cut the costs of pest control in half and reduced potential impacts of pesticides on animals in the exhibit. Use of natural enemies as an overall strategy in interiorscapes can be hampered if none are available for certain pests like brown soft scale (*Coccus hesperidum*),[11] necessitating use of insecticides that may damage natural enemies where such pests are present (60).

Homeowners seeking to deal with turfgrass pests make up about 35 percent of the U.S. market for nematode-based pesticides (411). The grass seed industry now sells several varieties containing endophytes that enhance pest resistance. Sales of turfgrasses with endophytes are expected to grow because of increasing consumer demand for "environmentally friendly turfgrass" (306). Consequently, the development of techniques to transfer endophytes to new grass species is an especially active area of research in the turfgrass industry.

Nevertheless, interest in BBTs by the lawn and landscape industry has been patchy. One 1990 survey of 17 commercial arborist firms found that 11 used Bt, nine used pheromone traps, and three made augmentative releases of natural enemies (248). An important problem has been inconsistent product performance (see description of milky spore in box 3-1, earlier in this chapter). Another is that microbial pesticides compete directly with other "natural" pesticides. For example, Bt-based pesticides active against

[11] A natural enemy for control of brown soft scale is expected to become commercially available in late 1995 (410A).

leaf beetles came on the market for shade tree care in the mid-1980s. Short field persistence, the need for careful timing of application, and high prices resulted in market failure for these products, especially when botanically derived neem pesticides, which appeared in the early 1990s, proved to be more effective alternatives (60).

Another reason for the relatively low interest in BBTs among landscape companies is the industry's increased emphasis on ensuring that plants are healthy by meeting the plant's environmental requirements. Recommended practices include promoting populations of beneficial microorganisms (i.e., conserving them) to prevent plant diseases (110). BBT products are seen as an adjunct to this approach (295).

Although few classical biological control programs have been targeted toward insect pests of urban and suburban environments, an important recent exception is the ash whitefly (*Siphoninus phillyreae*). Control of this pest by an imported wasp parasite (*Encarsia inaron*) has proved so effective that the whitefly is no longer a major pest in California; the biological control agent has now been released to suppress other infestations of ash whitefly in Arizona and Nevada (60).

Three microbial products are available for control of plant pathogens. Urban and suburban applications of Galltrol are limited to protecting nursery materials, specifically roses and other ornamental plants, for sale to consumers (60). Bio-Trek and T-22G are formulations of *Trichoderma harzianum* that became available in 1995 for use as a greenhouse potting soil amendment and a golf course inoculant. No BBTs currently address urban and suburban weed problems, but products for broadleaf weed (i.e., dandelion) control are under development (60,233).

Aquatic Environments

Most applications of BBTs to aquatic pests thus far have been for control of weeds that block navigational waterways and of the larvae of mosquitoes that pose a risk to human health. The method of choice has often been introduction of fish predators.

The grass carp (*Ctenopharyngodon idella*), a fish that consumes most aquatic plants, has been stocked in more than 35 states for control of aquatic weeds (191). The fish clear plants from waterways so effectively that habitats of other fishes, invertebrates, and waterfowl may be destroyed. At least 21 states now require released grass carp to be sterile to limit their impacts, although another 10 states still allow uses of normal reproductive fish.[12] Certain other fishes, such as blue and red tilapia (*Tilapia aurea* and *T. zillii*), also have been introduced to a lesser extent for aquatic weed control (191).

Classical biological control programs have yielded some control for three important aquatic weeds—alligatorweed (*Alternanthera philoxeroides*), water hyacinth (*Eichhornia crassipes*), and water lettuce (*Pistia stratiotes*) (191). Fungi that could be developed into microbial pesticides have been identified for two aquatic weeds, water hyacinth and Eurasian water milfoil (*Myriophyllum spicatum*), but neither has been developed commercially (420).

Mosquitoes spend the earliest part of their lives as swimming larvae and are the most significant insect pests in aquatic habitats. The mosquito fish (*Gambusia affinis*) is the one most commonly used to control the pest. It is now free-living throughout much of the United States as a result of its widespread release for this purpose (191). Several other fishes (e.g., the flathead minnow, *Pimephales promelas*, and the blue-gill sunfish, *Lepomis macrochirus*) have been put to similar use.

Certain microbial pesticides are in use or under development for mosquito control. A strain of Bt (specifically, *Bacillus thuringiensis israelensis* or Bti) is now widely applied for control of mosquitoes and blackflies. Its use is lim-

[12] Sterility is accomplished by making the fish triploid, that is, having three sets of chromosomes rather than the normal complement of two.

ited to upland and freshwater habitats; it is not effective in major sites for mosquito breeding in salt marshes (134). Another microbial pesticide derived from *Bacillus sphaericus* also is commercially available for mosquito control.

Scientists have identified several fungi that kill mosquitoes (*Coelomyces* spp. and *Lagenidium* spp.). A number of other invertebrates (flatworms, nematodes, and copepod shrimp) have been shown experimentally to consume mosquitoes. None has yet been put to practical use in mosquito control programs (191).

BBTs have also been applied to control invertebrate and fish pests. Releases of a snail competitor (*Marisa cornuarietis*) into Puerto Rican waterways during the 1960s greatly reduced populations of the snail *Biomphalaria glabrata*, a carrier of the parasitic worm that causes schistosomiasis. Prior to the biological control program, this human disease infected approximately one million people in Puerto Rico. Northern pike (*Esox lucius*) and walleye (*Stizostedion vitreum*) have been used to control nuisance fishes, such as the ruffe (*Gymnocephalus cernuus*) (191).

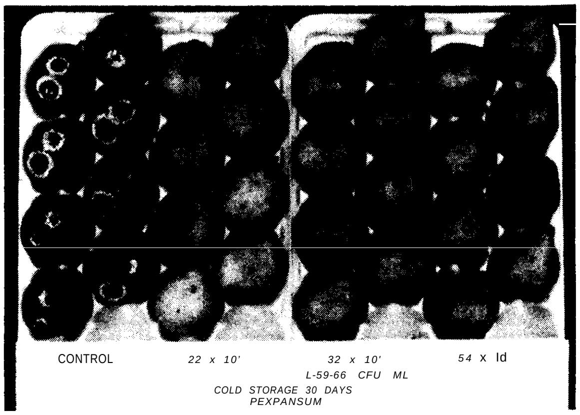
The U.S. invasion of the zebra mussel (*Dreissena* spp.) in the 1980s brought new national attention to the economic and environmental hazards of nonindigenous aquatic pests (338). Scientists have begun to examine various fishes and microorganisms for biological control of this costly pest. Some scientists believe that BBTs have considerable potential for application to aquatic environments generally; for example, classical biological control might control the European green crab (*Carcinus maenas*), a shellfish predator that was recently detected near San Francisco and may imperil the Washington State oyster industry (191). The Australian government has just started a new research center—funded at $1 million annually and with a planned staff of five—to identify biological control agents for nonindigenous marine pests that threaten fisheries or marine ecosystems (192). An important issue, should U.S. interest in aquatic uses of BBTs grow, relates to the virtual lack of federal regulation and the erratic attention by states to deliberate introductions of aquatic species as biological control agents (338) (see box 4-2 in chapter 4).

What's Coming Next

New Microbes and Microbial Pesticides

A wide variety of microbial pesticides are currently under development. When these reach the market they will greatly expand the repertoire of commercial product types. The extent to which these products and approaches will be adopted is uncertain. In some cases, development of new microbial pesticides will involve identification of new strains of microbes currently available. Bt products with activity against a greater range of pests are likely to be developed. Ecogen has already marketed a product (Foil) that acts against both caterpillar and beetle pests by combining the genes of two bacterial strains through conjugation—a naturally occurring process through which bacteria exchange genes.

Other pesticides rapidly coming on line will be based on types of microbes not yet in wide use. Several commercial companies are developing microbial pesticides based on fungi for insect control, including EcoScience Corporation (Bioblast for termite control); Mycotech Corporation (Mycotrol-GH for grasshopper, mormon cricket and locust control, and Mycotrol-WP for whiteflies, aphids, thrips, mealybugs, and psyllids); and Troy BioSciences (Naturalis-O for use on ornamentals against whiteflies, aphids and mites and Naturalis-T for turf use, controlling mole crickets and cinch bugs). Commercial development is well advanced for microbial products (based on bacteria *Pseudomonas fluorescens* and *Erwinia herbicola*) to control fire blight, a very destructive disease of apples and pears caused by the bacterium *Erwinia amylovora*, with sales expected to begin in 1995 (138,161). SoilGard, a product based on the fungus *Gliocladium virens*, for damping-off diseases of seeds and seedlings in greenhouse production of vegetables and ornamental bedding plants, is now in the final phases of development by W.R. Grace Co. (138).



Development of microbial pesticides for controlling the diseases that cause harvested produce to spoil is an active area of research. The unblemished fruit have been treated with a microorganism that prevents the pears from rotting.

Agricultural Research Service, USDA

A number of other microbe-based approaches and products are being researched but are not yet near product development or field use. Scientists predict that more insect viruses (many already identified) will become an attractive option as resistance to conventional pesticides emerges in common pests. Microbial approaches to European gypsy moth control based on protozoans[13] and fungi are under investigation as ways to help combat this tenacious pest (41 1,284). Considerable research interest continues to center on control of common plant diseases such as take-all and root rot diseases of wheat (1 38).

Novel delivery systems for microbial control agents are also under development. One involves putting microbial pesticides that work against plant pathogens into beehives so that bees transport the microbes to the plant (138). Another is based on modifying the algae food of mosquito larvae to contain a mosquito poison (85).

Genetic Manipulations of BBTs and Pests

BBTs are based on living organisms and their products. Consequently, it is not surprising that efforts to improve BBTs focus to a significant degree on genetic modifications through breeding, selection, genetic engineering,[14] and other techniques.

Most microbial pesticides now on the market were developed through the selection of efficacious microbe strains. Many companies involved in the development of microbial pesticides are now attempting to alter such features as kill rate, field persistence, environmental range, and the number of target pests through genetic engineering. Mycogen has recently put four products on the market all based on Cellcap, its genetically engineered Bt encapsulated within a *Pseudomonas fluorescens* bacterium (42). Ecogen brought a genetically engineered Bt on the market in 1995 called Raven (167). Sandoz Corporation recently conducted field tests of genetically engineered Bt in California and elsewhere in the country. Efforts to genetically engineer microbial pesticides are widespread, and they involve most potential product types, including those affecting insects (Bt, NPV viruses, and nematodes), weeds, and plant pathogens (138,191,41 1,420).

The scientific community is divided over the desirability of this approach. Some researchers believe that improvement through genetic modification will be essential for certain types of microbial pesticides to become widely adopted. Others express concern that, as microbial pesticides become more equivalent to conventional pesticides, scientists will engineer out the very characteristics of target specificity and short field persistence that make Bt and other current microbial pesticides relatively benign (41 1).

Similar questions divide scientists over ongoing attempts to genetically modify natural enemies. In this research, breeding, selection, or genetic engineering is being used to enhance the compatibility of natural enemies with conventional pesticides (152). A less precise version of this approach is already practiced in the natural enemy industry; a number of companies collect

13 Protozoans are certain single-celled organisms whose internal structure is more like that of cells from higher organisms than bacteria.

14 Genetic engineering refers to recently developed techniques through which genes are isolated in a laboratory, manipulated, and then inserted stably into another organism. Offspring of the recipient contain the new genes.

their breeding stocks from areas where pesticide use is high and the natural enemies are more likely to have developed some resistance to chemicals. Some entomologists worry, however, that pesticide-resistant natural enemies will discourage the development of biological control methods for other pests (411).

Genetic modification of the pest instead of its control agent has long been practiced in the sterile insect approach. Attempts to extend this method to other types of organisms, such as the sea lamprey (*Petromyzon marinus*)—a parasitic fish that impairs the Great Lakes sport fishery—have been studied but have not yet proved effective (191).

Another approach to genetically modifying pests, by producing pest strains lacking noxious qualities, was first suggested 25 years ago. It is currently under study for a number of medically important pests. Efforts are under way to create genetically engineered mosquitoes that cannot carry and transmit to humans the parasite that causes malaria (4). Similar approaches have tried to make snail vectors of human diseases unable to carry human parasites; as yet, those approaches have been unsuccessful because the genetically altered strains are less viable (191).

Genetic modification of the pest is also being applied to plant diseases. Researchers are trying to develop less damaging ("hypovirulent") strains of the microbes that cause chestnut blight (*Endothia parasitica*, a fungus) and Dutch elm disease (*Ceratocystis ulmi*, another fungus)—diseases responsible for the near elimination of native chestnut (*Castanea sativa*) and elm trees (*Ulmus* spp.) from the American landscape (60,284). The method has already proved successful in Italy where, following inoculation of chestnut trees, a hypovirulent strain spread to become the most common form of the chestnut blight fungus, and chestnut trees are again being harvested commercially.

Although outside the scope of this assessment (see box 2-5 in chapter 2), among the most widely discussed technologies coming on line is genetic engineering of plants for enhanced resistance to pests and pathogens. A number of crop plants, including tomatoes, potatoes, and cotton have been altered to express Bt toxins. Corn seed that has been genetically engineered to produce the Bt toxin has just been approved for commercial sale. Widespread use of such crop cultivars might increase the speed with which pests become resistant to Bt (see chapter 4). The introduction of virus coat protein genes into plants to enhance their resistance to certain viral diseases is being explored, with a new virus-resistant squash expected to become commercially available soon. Questions remain regarding the possibility that introduced virus genes might recombine with other viruses attacking the plant and form new, and possibly more damaging, viral strains.

Other New Tools

Practical applications of techniques discussed in this section lie at least a decade in the future. Allochemicals, for example, are chemicals that plants under attack by a predator emit and that attract the predator's natural enemies. These chemicals might be used to attract and concentrate natural enemies or to trap or deflect pests. Secretion of allochemicals is one of several important plant attributes that may have been weakened in the development of agricultural cultivars because the role of the chemicals in biological control was not well understood (411).

Scientists also are beginning to understand how plants' own sophisticated defense mechanisms might be exploited to suppress plant diseases. These defense mechanisms can be enhanced by exposing the plant or its seeds to certain microbes or chemicals. "Induced resistance" has been demonstrated in at least 25 crops; commercial products based on this approach are under development (233,138). Development of methods to transfer endophytes into plants (including agricultural crops) in which they do not naturally occur is another method under study to increase disease and pest resistance. Plants can also be "cross-protected" by infecting them with a milder strain of a disease agent; this process has been demonstrated in various crop plants. It is now being used on a pilot basis in Florida for control of diseases caused by the citrus tisteza virus which affects 25 million to 30 million sour orange trees in the United States. The same method is being used commercially in South Africa, Brazil, and Australia. Large scale use of cross protection, however, lies well into the future because significant technical problems remain; for example, the same mild strain that gives protection to one crop may produce disease symptoms in another (138).

OBSTACLES TO EXPANDED USE OF BBTS

Explanations of why BBTs are not in wider use usually center on a number of commonly acknowledged obstacles. Certain technical obstacles reflect hard limits to what the technologies can do or how they are produced and delivered in the field. They can be addressed only by adequate adjustment of the research agenda and by provision of mechanisms to ensure that research results become available for field applications (table 3-2). The greater emphasis, however, even among technical experts, is usually on the social, economic, and institutional factors that affect the development and adoption of BBTs, and these require policy solutions.

Integration of BBTs into Pest Control Systems

BBTs almost always need to be integrated into an overall system for pest management—usually an integrated pest management system—that incorporates a variety of tools and techniques to prevent pest problems or to control outbreaks when they occur. While IPM adoption in the United States is growing, it is by no means the dominant approach to pest control. This lack of well-developed IPM systems significantly limits the use of BBTs.

Even the IPM systems in existence today do not always do a good job of incorporating BBTs. Developing integrated programs that include BBTs requires a sustained commitment of resources and expertise (e.g., ref. 133). BBTs must also compete directly with other methods that often provide a superior level of control (see box 3-2, earlier in this chapter). The research on microbial pesticides to bring performance more in line with conventional pesticides is not surprising in this light (149).

Moreover, BBTs require a level and type of knowledge not yet acquired by many pest control practitioners or even by people who advise users, such as members of the Cooperative Extension Service or private pest control consultants. Appropriate information on BBTs may thus be lacking, even where there are users who would be willing to experiment with these approaches (see chapter 5). The proliferation of Internet sites containing information on pest management may eventually provide easier access to information resources for those having the right equipment and software. (See appendix 3-A immediately following this chapter for current list of relevant sites.) At present, however, tracking down correct information is not straightforward or easy; information on the Internet varies in quality and lacks a centralized organization or means of access.

Another problem is that, to a large extent, the field of biological control developed separately from that of IPM (319). This separation poses real difficulties for the full incorporation of biological control into IPM systems. Coordination with other control methods is not always an explicit goal of U.S. research on biological control. Some experts in biological control believe it should never be integrated in IPM programs with conventional pesticides. A symptom of this disciplinary separation is the recent failure to include representation of APHIS's National Biological Control Institute in USDA's current initiative on IPM.

Compatibility with conventional pesticides might be an important determinant of how effectively BBTs can be combined into certain types of IPM programs. Pheromones and many microbial pesticides can be used alongside conventional pesticides (175). Certain microbial pesticides are actually more effective when used in conjunction with chemicals. Biological control poses a different challenge, though. Natural ene-

TABLE 3-2: Priority Research Needs Identified by OTA's Contractors

Research Need	Potential Resulting Benefit
Develop basic information on the biology and ecology of pest systems, including the taxonomy and systematics of pests and control agents	Enable development of more predictive approach to the identification of possible control agents for specific pests Enable development of more sophisticated approaches to biologically based pest management
Improve methods to test for nontarget effects of BBTs	Minimize environmental hazards
Develop application techniques for existing and new BBTs	Enable better use of BBTs under field conditions
Identify new and more efficacious microbes	Improve performance of microbial pesticides
Integrate BBTs into IPM systems	Increase use of BBTs in situations where they will be effective
Improve formulation, production, packaging, and delivery techniques for microbial pesticides (including *in vitro*[a] production methods for viral pesticides)	Reduce costs and improve performance of microbial pesticides
Improve production, packaging, and delivery techniques for natural enemies (including *in vitro*[a] production methods)	Reduce costs and improve performance of natural enemies
Improve formulations for delivery of pheromones	Improve performance of pheromones
Monitor classical biological control agents after release	Improve ability to predict which agents will work Improve documentation of actual efficacy of biological control
Identify BBTs to address pests of natural areas, aquatic habitats, and urban/suburban environments	Address current pest control needs Transfer existing technologies to new applications

[a] *In vitro* refers to production outside a living organism. Current production techniques for most viral pesticides and natural enemies are *in vivo*, that is, the agent is produced on or inside a living organism.

SOURCES: Compiled by Office of Technology Assessment, U.S. Congress, 1995, from G. E. Harman and C.K. Hayes, Departments of Horticultural Sciences and Plant Pathology, Cornell University, Ithaca, NY, "Biologically Based Technologies For Pest Control: Pathogens That Are Pests of Agriculture," unpublished contractor report prepared for the Office of Technology Assessment, U.S. Congress, Washington, DC, October 1994; A. Kuris, Department of Biological Sciences and Marine Science Institute, University of California, Santa Barbara, CA, "A Review of Biologically Based Technologies For Pest Control in Aquatic Habitats," unpublished contractor report prepared for the Office of Technology Assessment, U.S. Congress, Washington, DC, October, 1994; J. Randall and M. Pitcairn, Exotic Species Program, The Nature Conservancy, Galt, CA and the Biological Control Program, California Department of Food and Agriculture, Sacramento, CA, "Biologically Based Technologies for Pest Control in Natural Areas and Other Wildlands," unpublished contractor report prepared for the Office of Technology Assessment, U.S. Congress, Washington, DC, November 1994; R. Van Driesche et al., Department of Entomology, Univeristy of Massachusetts, Amherst, MA, "Report on Biological Control of Invertebrate Pests of Forestry and Agriculture," unpublished contractor report prepared for the Office of Technology Assessment, U.S. Congress, Washington, D.C., December 1994; A.K. Watson, Department of Plant Science, McGill University, Quebec, Canada, "Biologically Based Technologies for Pest Control: Agricultural Weeds," unpublished contractor report prepared for the Office of Technology Assessment, U.S. Congress, Washington, DC, November 1994.

NOTE: This list was derived by comparing and compiling suggested research priorities from background reports prepared by OTA's contractors on the application of BBTs to various categories of pests. A few additions were made by other experts.

mies sold for augmentative uses are highly sensitive to pesticides; suppliers often recommend waiting several weeks following pesticide application before releasing natural enemies.

If pesticides could be selected to minimize their impacts on natural enemies, it might be easier to incorporate the various forms of biological control into IPM systems. One problem is that such information is not widely available. Brian Croft, a professor at Oregon State University, has been accumulating a related database for several years, but support for the project has been erratic and no government agency has attempted to make the information easily accessible to farmers (61,62). Similar data are required for registration of pesticides in Germany (106) (see chapter 4). The impending loss of minor use pesticides may cause some chemicals that are more compatible with natural enemies to become unavailable.

Moreover, it is unclear whether certain BBTs—biological control, sterile insect approaches, and mating disruption—will offer their maximum effects as part of farm-based IPM programs. Some scientists from the USDA Agricultural Research Service believe that certain BBTs work best as part of areawide pest management programs (box 3-4).

BOX 3-4: The Areawide Pest Management Concept

Areawide pest management is an approach that has been widely promoted by E.F. Knipling—former director of the Agricultural Research Service's Insect Pest Management Program and well-known originator of the sterile insect approach that has been so successful in screwworm (*Cochliomyia hominivorax*) eradication.

The concept underlying this approach is that biological methods, specifically, biological control and sterile insect releases, will be most effective if used on a larger geographical scale than just the single farm. Such large-scale programs reduce residual pest populations off the farm and address the tendency of pests and their control agents to move from site to site.

According to Knipling:

> The foundation of most current integrated pest management programs (IPM) is reliance on natural control factors to the maximum extent before resorting to the application of insecticides. While, on a short-term basis, this can go a long way towards reducing the amount of insecticides used, it does not in any way lessen the dependence of individual growers on insecticides as the major component in the integrated system.... We know from experience that natural controls—as vital as they are—do not provide the protection needed for a wide range of persistent insect pests....

Knipling asserts that classical and augmentative biological control will rarely provide the level of control desired by farmers unless the density of the biological control agent is boosted through mass propagation and repeated releases. He believes that several important pests are good candidates for the method, including boll weevil (*Anthonomus grandis*), European corn borer (*Ostrinia nubilalis*), and tropical fruit flies. Knipling's approach remains largely untried to date because of the high costs of even pilot trials of projects at such a large scale.

Evidence from pink bollworm (*Pectinophora gossypiella*) management in Arizona, however, has shown that areawide uses of pheromones can be quite effective. USDA is currently considering areawide programs based on pheromones for codling moth (*Cydia pomenella*) and corn rootworm (*Diabrotica* spp.) as part of its ongoing IPM Initiative.

SOURCES: E.F. Knipling, former Director of Insect Pest Management Program, Agricultural Research Service, U.S. Department of Agriculture, MD, personal communication, June 5, 1995; U.S. Department of Agriculture, Agricultural Research Service, *Principles of Insect Parasitism Analyzed From New Perspectives*, E.F. Knipling, AHN 693 (Washington, DC: U.S. Government Printing Office, 1992).

Understanding the Ecology of Pest Systems

Repeatedly, scientists have called for increased study of the biology and ecology of pest systems. Such information underlies the development of all biologically based pest management, but our current level of knowledge is not high. Increased understanding of pests—how they spread and what causes their populations to rise and fall—would allow better targeting of BBTs to the pests' vulnerabilities. More knowledge of the ecological relationships between pests and their control agents might enable scientists to better predict what controls are likely to work and for what specific pests. As practiced today, the identification of new microbial pesticides and biological control agents is usually based on trial and error, making progress slow.

For example, researchers cannot with great confidence identify in advance *the* specific biological control agent, or even in many cases the *type* of control agent, that will actually suppress a given pest. Instead, scientists usually identify a number of potential agents, release them, and then see which ones, if any, provide some level of pest suppression. Monitoring and evaluation of the impacts of previous biological control programs would help in the development of predictive models to sharpen the focus in classical biological control programs and would improve assessments of the potential ecological risks of biological control releases (see chapter 4). But a chronic lack of such followup studies in the United States means that little such information is now being generated through current programs. The programs of other countries, such as Australia and South Africa, do a far better job in this area (76).

Better understanding of the ecology of pest systems will not, on its own, ensure greater success. Existing theory is not always well incorporated into the development of biological control programs. Moreover, theory only goes so far. The idiosyncrasies of each pest problem will still require case-by-case development of solutions.

Technical Needs and Economic Issues Related to Larger Scale Use

Larger-scale use of BBTs would entail large-scale production, distribution, and application of natural enemies, sterile insects, and microbial pesticides. The necessary technologies are not well developed in many cases. Mass production and application of natural enemies, for example, would be expensive and difficult using current techniques (173). Government agencies and commercial companies currently rear most natural enemies on living material (*in vivo* production). The techniques are labor intensive and expensive. A few of the natural enemies now sold commercially, such as convergent lady beetles (*Hippodamia convergens*) and certain natural enemies of rangeland weeds, are collected from free-living populations. Such collection poses other problems related to effects on the wild populations and the ethics of allowing private companies to remove from public lands natural enemies that have been placed there at public expense (see chapter 4) (185).

As living organisms, natural enemies have a short shelf life and require great care in handling (e.g., a temperature-controlled environment). Basic information about the timing, numbers, and methods of application for natural enemies is scarce. All of these limitations contribute to the current problems with many natural enemies—they are difficult to use, costly, and perform erratically in the field. The development of artificial media for rearing natural enemies (*in vitro* production) would streamline and probably greatly decrease the cost of production. Better packaging and handling methods, as well as better information on application rates and techniques, could improve the consistency and performance of natural enemies. The same technologies could be applied to the production of some types of sterile insects for mass release and could reduce the cost of such programs.

Problems with production and packaging techniques also characterize microbial pesticides. Crossover of fermentation techniques from the pharmaceutical industry has contributed greatly to the development of production capabilities for certain microbial pesticides, including Bt and some fungus-based products. Viruses, however, are still produced in live hosts. This labor-intensive approach has made them so expensive that only one is widely used in the United States (European gypsy moth NPV virus), whereas a number of other NPV viruses are extensively applied in other parts of the world where labor is cheaper (411). Industry representatives generally agree on the need for the development of cost-effective methods of production and storage/packaging techniques to enhance product shelf life and to improve quality control and performance (149,113).

A major problem is that very little expertise or funding exists in the public sector for developing production methods for natural enemy and microbial pesticide production (138). Similarly, the development of formulations for microbial pesticides and pheromones is typically not well funded. Nor are most scientists, universities, or government research agencies usually willing to participate in research on such practical matters (138). Such research reaps few rewards in the scientific community. The restrictions on open communication imposed by the proprietary nature of the work may further hinder progress (327A).

Past efforts in universities and federal research laboratories have usually stopped, for example, once a microbial strain is identified, with the expectation that it will be picked up by the private sector. But this halt is premature. In the comprehensive cost accounting that companies must do before investing in a product, a number of variables are important—direct R&D costs, costs of production, waste volume generated and costs of disposal, market size, product profitability, and others. Seemingly counter-intuitive decisions by companies *not* to invest in a technology become logical when the total cost equation is examined (149).

Poorly developed production, packaging, and application technologies tend to drive up costs of BBTs, and drive down field performance. The overall result is to reduce the competitiveness of BBTs with other available methods of pest control. Most end up relegated to niche markets where overall expected sales are small. Some BBTs would generate only small markets under the best of circumstances because they address one or only a few pests. Anticipated small markets can doom BBTs where the start-up development costs are high, because the market size may not justify investment by the private sector. According to weed scientists, there are numerous "orphaned" microbial pesticides that would be effective against weeds, but the small market does not warrant the development costs (420).

IMPROVING THE ODDS OF FUTURE SUCCESS

The obstacles just described reflect difficulties in developing BBTs and in moving existing BBTs into practical use. They occur at several key points in the research, development, and implementation of BBTs (figure 3-3). OTA's list is not new. Similar issues have been raised many times over the past 18 years (box 3-5), typically during workshops and meetings of scientific experts, the major goal of which has been to set substantive aspects of the research agenda. Still, numerous issues pertaining more to institutional functioning than to the science of BBTs remain unaddressed. The chapters that follow focus on these institutional problems as well as more technical considerations. Each identifies major issues and provides options that might help resolve these problems in the future.

BOX 3-5: The Message from Experts Remains the Same, but Progress in Bringing BBTs into Use Has Been Slow

In 1978 a special study team coordinated by USDA's Office of Environmental Quality Activities issued the report *Biological Agents for Pest Control: Status and Prospects.* Most of the report's major conclusions are as true today as they were 17 years ago. According to the report:

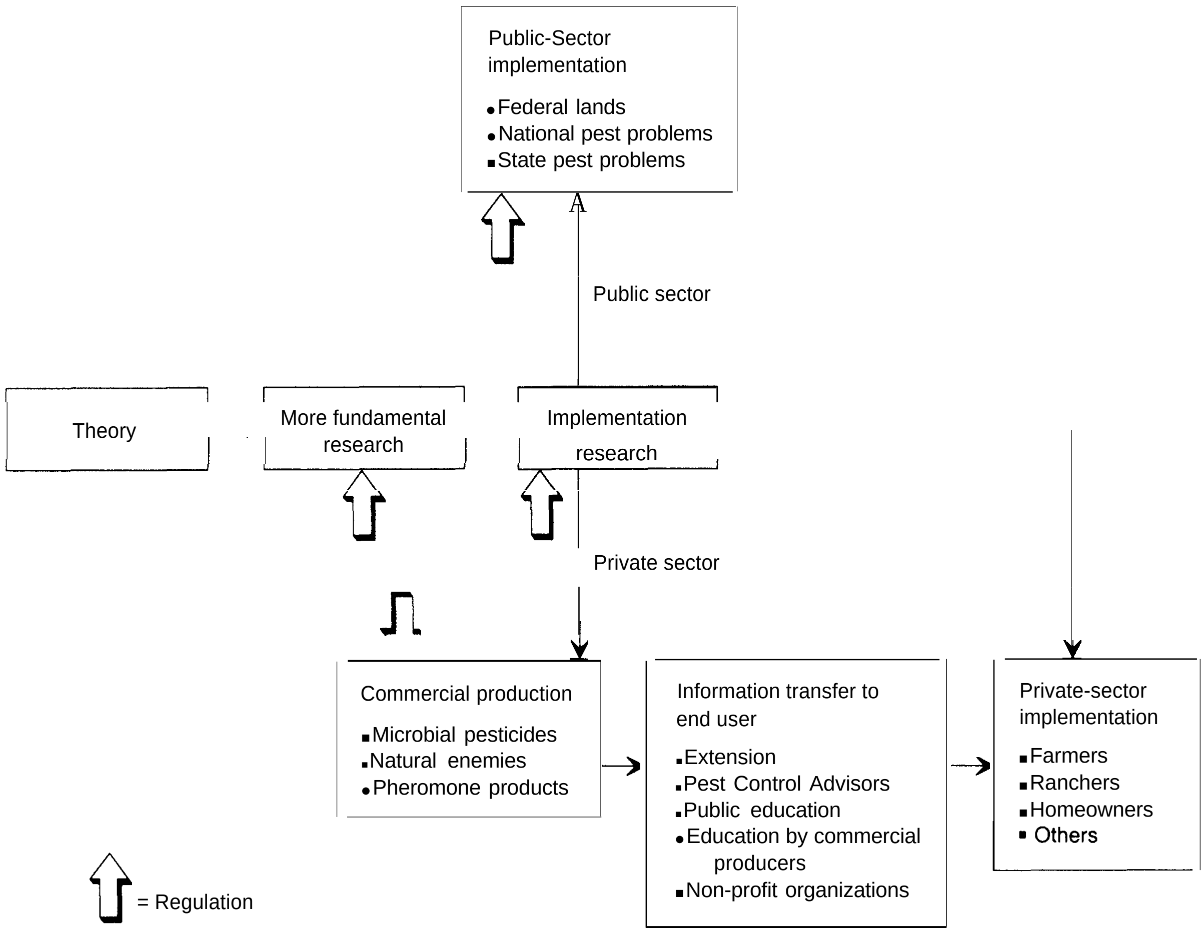
> Pest control is an acceptable and necessary part of modern agriculture and forestry, and is required for the protection of public health and welfare. However, some of the methods used during the past three decades have produced some undesirable side effects. Future needs for pest control can be expected to increase, and, as they do, prevailing conditions and attitudes are likely to dictate an increased emphasis on pest management systems which include the use of alternative methods such as biological control agents.... The practical feasibility of using biological agents... has been amply demonstrated, and the basic principles relevant to the operational aspects of the use of these agents are reasonably well understood.

The study's major findings parallel those of OTA in this report and included the following:

- More research is needed to improve *a priori* predictions of success; to develop production, storage, and application techniques; and to assess the impacts of use;
- Large-scale implementation does not follow easily from demonstrated effectiveness on a small scale;
- Information on pesticide alternatives is not easily available;
- Users need better technical assistance;
- Private enterprise needs incentives to enter this area;
- The regulatory structure needs to be reviewed and clarified; and
- Mechanisms are necessary to coordinate federal and state agencies, the private and the public sectors,

SOURCE: U.S. Department of Agriculture, Biological *Agents for Pest Control: Status and Prospects,* (Washington, DC: U.S. Government Printing Office, February 1978).

FIGURE 3-3: Key Stages of BBT Research, Development, and Implementation



SOURCE: Office of Technology Assessment, 1995.

APPENDIX 3-A: INTERNET SITES FOR INFORMATION ON BIOLOGICALLY BASED PEST CONTROL

Federal agency sites	Address	Description
APHIS Home Page	http://www.aphis.usda.gov	Provides information on the different program areas and proposed rules of the agency.
Consolidated Farm Service Agency	http://bbskc.kcc.usda.gov/cfsa.htm	Contains a large collection of agricultural research data and provides access to various agricultural publications, some pertaining to BBTs.
CSREES Partners in Research, Education, and Extension	http://www.reeusda.gov/partners/partners.htm	Provides a list of the cooperative extension offices and land grant universities and access to their Internet sites. Currently developing a search engine for all CSREES programs.
Federally Funded Research in the United States	http://medoc.gdb.org/best/fed.fund.html	Features information on the research performed by USDA and a variety of other federally funded programs. Provides search engines.
National Biological Control Institute	http://www.aphis.usda.gov/nbci/nbci.html	Supplies information on biological control, implementation, and facilitation grant programs, and the NBCI staff, as well as access to the Biological Control News.
Pest Management Bulletin	http://chppm-www.apgea.army.mil/ento/index.htm#bulletins	Offers information on pest management, some based on BBTs (a publication of the U.S. Army Center for Health Promotion and Preventive Medicine Entomology Program).
Cooperative extension sites		
Cooperative Extension Information Servers	http://www.esusda.gov/partners/ces-locs.htm	Lists the information servers of the cooperative extension system by state (not all cooperative extension sites offer information on agriculture).
Cornell University College of Agriculture and Life Sciences, New York State Agricultural Extension Station	http://aruba.nysaes.cornell.edu:8000/geneva.htm	Provides a search engine for all of the current programs and research of this extension station. Allows easy access to their information on biological control.
Illinois Cooperative Extension Service, Horticulture Solution Series	http://www.ag.uiuc.edu/~robsond/solutions/hort.html	Offers solutions to a various horticultural problems, including pest control, to both homeowners and horticulturists, including some involving BBTs.
Oregon Extension Entomology Report	http://www.oes.orst.edu/entomol.htm	Lists current pests of Oregon and different control measures, including biological controls.
Integrated pest management sites		
Cooperative Extension System IPM National Pest Management Materials Database	http://info.aes.purdue.edu/ipmdb.html	Lists general pest management information sources. Provides a search engine to report summaries and contacts for obtaining reports. Includes information on BBTs.

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Federal agency sites	Address	Description
CRC for Tropical Pest Management Biological Control Program	http://www.ctpm.org/	Offers IPM and BBT alternatives for pest control in agriculture. Includes literature citations.
National IPM Information System @ Colorado State University- Pest Alert Bulletins	http://www.colostate.edu/Depts/IPM/news/news.html	Offers information on identification of insect pests and pest control measures, including some biological solutions. Serves both homeowners and farmers.
North Carolina State University component of the National IPM Network	http://ipm_www.ncsu.edu	Provides access to various IPM newsletters (national and international) focusing on present research projects.
Entomological sites		
Colorado State University Department of Entomology	http://www.colostate.edu/Depts/Entomology/ent.html	Features pictures of insect pests and their natural enemies. Provides access to entomology newsletters.
EntNet	listmgn@entsoc.org	Provides instructions for subscribing to the Internet list server created by the Entomological Society of America.
Florida Entomologist	gopher://sally.fcla.ufl.edu:70/11/FlaEnt	Provides information, mainly research articles, on insect control. Some mention of BBTs.
Gypsy Moth Home Page at Virginia Polytechnic Institute and State University, Department of Entomology	http://www.gypsymoth.ento.vt.edu/Welcome.html	Provides information on gypsy moths, including control methods such as Bt.
Mississippi State University Department of Entomology	http://www.msstate.edu/Entomology/ENTPLP.html	Provides access to numerous newsletters and databases that contain information on classical and augmentative biological control methods.
Resistant Pest Management Newsletter	http://www.msstate.edu/Entomology/EntHome.html	Focuses on pesticide-resistant insect pests in Mississippi and alternative control methods, including some BBTs.
Rincon Insectaries	http://www.rain.org/~sals/rincon.html	Offers information on Rincon's natural enemy products.
Sites for farmers by farmers		
Farmer to Farmer	http://www.organic.com/Non.profits/F2F	Allows California farmers to communicate via this newsletter and to share success stories of biological control used against common pests.
Noah's Ark Don't Panic, It's All Organic Homepage of an Organic Farmer	http://www.rain.org/~sals/my.html	Escorts user to various WWW and gopher sites helpful to organic farmers, including sites for identifying pests and control methods. Provides information on the Organic Food Law and the California Certification Standards of Organic Farming.

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Federal agency sites	Address	Description
Sustainable and alternative farming sites		
Alternative Farming Systems Information Center	http://www.inform.umd.edu:8080/EdRes/Topic/AgrEnv/AltFarm	Provides links to sustainable agriculture sites and documents as one of the 10 information centers at the National Agriculture Library of USDA. Supplies bibliographies, many on BBTs.
Information on Sustainable Agriculture	gopher://zeus.esusda.gov:70/11/initiatives/sustain	Supplies information on current research on sustainable agriculture and various news bulletins.
Plants and Sustainable Agriculture	http://www.envirolink.org/pubs/Plants.html	Provides access to sustainable agriculture newsletters and information sources, some containing information on BBTs.
University of California Sustainable Agriculture and Research Education Program	http://www.sarep.ucdavis.edu/	Reports technical reviews, technical information, and summaries of journal articles and workshop presentations on subjects related to sustainable agriculture.
General agriculture research sites		
Purdue University Office of Agriculture Research	http://info.aes.purdue.edu/AgResearch/agreswww.html	Provides a search engine of the agriculture research conducted at Purdue University, some in the area of BBTs.
Biotechnology sites		
Biotech-Related WWW Sites and Documents	http://inform.umd.edu:86/EdRes/Topic/AgrEnv/Biotech/.www.html	Provides access to publications and WWW and gopher sites related to biotechnology.
Biotechnology Information Center	http://www.inform.umd.edu:8080/EdRes/Topic/AgrEnv/Biotech	As one of the 10 information centers at the National Agricultural Library of USDA, provides access information services and publications covering agricultural biotechnology, including a bibliography and resources guide, miscellaneous publications, biotechnology education resources, biotechnology newsletters (national and international), biotechnology patents and biotechnology software.
Institute for Biotechnology Information	http://www.bio.com/ibi/ibi1.html	Serves as a database of U.S. biotechnology companies. Includes information on key personnel, R&D, products, budgets, financing history, addresses, and phone and fax numbers. Contains an action database for the significant activities and strategic alliances of biotechnology companies worldwide.

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Federal agency sites	Address	Description
Public Perception of Biotechnology Home Page. Department of Crop and Soil Environmental Sciences and the Center for the Study of Science in Society. Virginia Polytechnic Institute and State University	http://fbox.vt.edu:10021/cals/cses/chagedor/index.html	Offers information on a study of the public perceptions of agricultural and environmental biotechnology, including microbial pesticides.
Advocacy and industry group sites		
ANBP	http://www.rain.org/~sals/anbp.html	Reports on regulation of natural enemies and offers information on other issues affecting the natural enemy industry through the News Quarterly of the National Bio-Control Industry.
Biotechnology Industry Organization	http://www.bio.com/bc/bio/biohome.html	Provides a list of members of the Biotechnology Industry Organization, a trade association representing biotechnology companies of all sizes (including agricultural biotechnology companies). Includes membership information and access to newsletters.
Pesticide Action Network North America	gopher://gopher.igc.apc.org:70/11/orgs/panna	Offers information on an organization advocating replacement of conventional pesticides. Includes some citations on BBTs.

SOURCE: Office of Technology Assessment, U.S. Congress, 1995.

NOTE: Many of the sources containing information on biologically based pest control are still under construction. The site contents and addresses were current as of August 1, 1995. This information is subject to change.