CHAPTER 4

A History of Pest Control

EARLY PEST CONTROL—FROM PREHISTORIC TIMES TO THE RENAISSANCE

The organisms that disturbed prehistoric man's nomadic hunting–gathering life-style must have been few. As humans of this period grew no crops and had no permanent homes and few possessions, we can imagine that their pest problems would have been limited to those organisms, such as lice, fleas, flies, and mosquitoes, that caused people physical discomfort. Prehistoric control of these pests—picking, slapping, and squashing—could hardly be called a science.

It was only after the development of agriculture (approximately 10,000 years ago), the establishment of permanent settlements, and the introduction of a life-style that required the storage of greater or lesser quantities of food and other items that a concerted effort to control a large variety of organisms became necessary. Early pest control practices were often based on mysticism or superstition, such as an offering to a god or the performance of a ritual dance (Figure 4-1). But gradually, over the millennia and through the process of trial and error, a few useful methods became known—some are still successfully employed today.

Well before 2500 B.C., the Sumerians were using sulfur compounds to control insects and mites. By 1200 B.C., thousands of miles to the east in China, plant-derived insecticides (like present-day botanicals) had been developed for seed treatment and fumigation uses. The Chinese also used chalk and wood ash for prevention and control of both indoor and stored-product pests. Mercury and arsenic compounds were employed to control body lice and other pests. Interestingly, the beneficial role of natural

M. L. Flint et al., *Introduction to Integrated Pest Management*

FIGURE 4-1. Enamel plate from ancient Ashur (now part of Iraq), representing an Assyrian noble in a locust prayer before the god Ashur, 650 B.C. (after Harpaz, 1973).

enemies and the value of adjusting crop planting times to avoid pest outbreaks had been recognized by the Chinese several centuries before Christ.

Similar techniques were in common usage among China's Greek and Roman contemporaries. In 950 B.C. Homer noted the value of burning for locust control. Herodotus (450 B.C.) mentions the use of mosquito nets and the practice of building high sleeping towers to avoid mosquitoes. A long-established use of fumigants by the Greeks was described by Aristotle in 350 B.C., and in 200 B.C., the Roman Cato reported the use of oil sprays, oil and bitumen sticky bands, oil and ash, and sulfur bitumen ointments for pest control. A pest-proof granary (similar to that in Figure 4-2) was designed by the Roman architect Marcus Pollio in 13 B.C.; it shows a clear understanding of the benefits of habitat modification in preventing pest problems. Additional protection from both mice and weevils could be obtained by treating the granary floor with a mixture of clay, chaff, and the fluid from oil presses.

However, not all pest control practices in the Roman Empire were as well founded biologically. Frustrated by seemingly insurmountable problems such as plagues of locusts or plant diseases, the people of early civilizations would recurrently turn to religion and superstition for help with their pest problems. For instance, a Roman agricultural text of 50 A.D. (*De re Rustica*) suggests the following for protection from caterpillars: "a woman ungirded and with flying hair must run barefoot around the garden, or a crayfish must be nailed up in different places in the garden." Also, the Romans traditionally performed certain rites in April to appease the goddess Robigo, who was identified with cereal rust diseases—the worst pest of the period (*Maxima segetum pestis*).

In China, the evolution of pest control technology continued during the first thousand years after Christ. It was favored by what was already

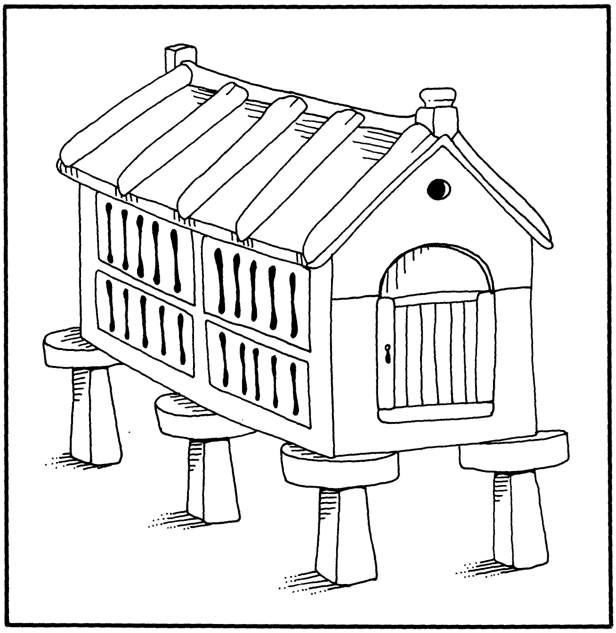

FIGURE 4-2. Galician "horreo" or granary. The design is unchanged from the time of the Celtic Invasion of Spain (ca. 500 B.C.). Made of granite slabs and wood, the horreo is fire- and vermin-proof. It rests on columns topped by circular stone rat guards. Rats are unable to climb upside-down around the stone guards and cannot get to the grain stored above. This practical protection from granary rat pests may have been the forerunner of the classical capital!

FIGURE 4-3. The earliest recorded use of natural enemies to control pest insects was the use of predatory ants in citrus orchards to control caterpillar and beetle pests in China. Nests were established in the orchards by Chinese growers, and bamboo bridges were placed between branches to facilitate the ants' movements from tree to tree.

a tradition of intense interest in and knowledge of insects (the cultivation of silkworms is reported to have been established in 4700 B.C.) and by a philosophical view of the world that early recognized food webs, feedback mechanisms, and other natural population controls. This understanding is well illustrated by the following passage from a Chinese text written in the third century A.D.:

> A factor which increases the abundance of a certain bird will indirectly benefit a population of aphids because of the thinning effect which it will have on the coccinellid (lady bug) beetles which eat the aphids but are themselves eaten by the bird. (Cited from Konishi and Ito, 1973.)

With such a basic appreciation for the functioning of ecosystems it is not surprising that the Chinese were responsible for the earliest application of biological control. It is recorded that by 300 A.D. the Chinese were establishing colonies of predatory ants in their citrus orchards to control caterpillars and large boring beetles. The ants' activities were facilitated not only by the strategic placement of nests in the orchards but also by the construction of bamboo runways that provided the ants with an easy transit route from one pest-infested tree to another (Figure 4-3).

Other pest control methods being employed in early China show a similarly remarkable sophistication in technique. Ko Hung, the great alchemist of the fourth century, recommended a root application of white arsenic when transplanting rice to protect against insect pests. Sulfur and copper were being used for lice control and pig oil was applied to protect sheep from parasites.

While China was continuing to advance its pest control approaches, European methods in the centuries after the fall of the Roman Empire relied increasingly on religious faith, superstition, and legalistic pronouncements, and less on biological knowledge. A few examples (from Dethier, 1976) illustrate:

571–630 A.D.	As protection against locusts, followers of Islam displayed prayers of Mohammed on poles in fields.
666 A.D.	St. Magnus, Abbot of Flussen, repulsed locusts and other pests with the staff of St. Columbia.
1476 A.D.	In Berne, Switzerland, cutworms were taken to court, pronounced guilty, excommunicated by the archbishop, and banished.

THE RENAISSANCE AND THE AGRICULTURAL REVOLUTION

In Europe, the Renaissance brought a rebirth of the search for scientific knowledge and an increased understanding of the organisms that became pests. The introduction of the compound microscope in the seventeenth century resulted in a burst of new information about man's various tiny competitors. Using the microscope, van Leeuwenhoek discovered bacteria in 1675. Other scientific advances in the seventeenth century included Redi's proof that insects do not arise spontaneously from decaying material but develop from eggs laid there, Valisneri's demonstration of the nature of insect parasitism, the discovery of human blood circulation by Harvey, and the recognition of the existence and function of numerous other organs in both humans and insects. In the first half of the eighteenth century, Linnaeus laid the foundation of true systematics with his development of the system of binomial nomenclature. Needless to say, a good system of nomenclature and identification was essential to the development of sound pest control.

During this period, approaches to pest control began to reflect greater biological understanding, although in many cases they were still limited in effectiveness (Figure 4-4). Reamur (1683–1756) discussed the significance of host–parasite relationships in pest outbreaks and suggested the use of entomophagous insects, specifically lacewings, to keep a greenhouse free of aphids. Later, Linnaeus suggested the use of ground beetles, ladybugs, lacewings, and parasites for the biological control of pests. He also advised the use of a predatory stink bug for control of bedbugs and the use of snails to reduce growth of moss on apple trees. Provision of nesting boxes for insectivorous birds in orchards and forests began to be a common practice in Germany in the early 1800s.

The late seventeenth and early eighteenth centuries also saw the rediscovery and/or introduction into Europe of various botanical insecticides: pyrethrum, derris, quassia, and tobacco leaf infusion—all effective insecticides. The dangers of the use of other toxic poisons became known in the 1700s as well. In 1754, Aucante in France observed arsenic poisoning among agricultural field workers, and in 1786 France prohibited the use of arsenic and mercury steeps for seed treatment.

The period 1750–1880 in Europe was a time of agricultural revolution. Farming, for the first time, began to become more of a commercial than subsistance enterprise: average yield changed from four seeds produced per one seed planted to ten seeds per one planted. This increase in yield was due largely to changes in land distribution and agricultural practices. These changes included a reorganization of land holdings that eliminated the landlord–serf relationship, the expansion of planting acreages, and the introduction of new farming techniques such as sophisticated manuring practices and good rotation systems involving nitrogen-fixing fodder crops. During the mid-1700s farmers began to grow crops in rows, thus permitting weed removal with the horse-pulled hoe.

The greatest single cause of large-scale crop disaster then, as it is now, was not pests but weather. Weather-induced damage may be "direct" (e.g., drought, flood, early freeze, tornado) or "indirect" (e.g., wheat diseases such as rusts and black scab, which are favored by high humidity) by providing an environment conducive to the development of epidemics of plant diseases and other pests.

As the period of "agricultural revolution" was peaking in the mid- to late nineteenth century, European countries and their colonies experienced some of the worst agricultural disasters ever recorded: the potato blight in the late 1840s in Ireland, England, and Belgium; the outbreak of powdery mildew in the 1850s in the grape-growing areas of Europe;

FIGURE 4-4. An eighteenth-century flea trap to be worn around the neck. Fleas entered the outer perforations (bottom left) and were caught on a sticky tube inside (top left). No record of the effectiveness of this trap remains. However, we do know that fleas were a constant harassment to people of all classes during this period in Europe.

the epidemic of the fungus leaf spot disease of coffee, which caused Ceylon to switch from coffee production to tea cultivation; and the invasion of Europe by an American insect, the grape phylloxera, which nearly put an end to the wine industry in France (1848–1878). Undoubtedly, the unprecedented severity of these outbreaks was due, at least in part, to the new, larger-scaled, commercially oriented farming practices and to newly arrived pests or strains of pests brought in by increased international travel.

Predictably, during this period there was a sudden surge of interest in perfecting pest control techniques. The first books and papers devoted entirely to pest control began to appear in the early nineteenth century. The first textbook on plant pathology was published in 1858 (by Kuhn) and listed climatic and soil conditions, insects, parasitic higher plants and microorganisms as causes of plant diseases. However, at this time (unlike in insect pest situations) there were few useful controls for plant diseases. Thaddeus William Harris's *Treatise on Some of the Insects Injurious to Vegetation*, published in 1841, was the first textbook in America on the control of insects, and it continued to serve as the prime source book for such information up until the 1870s. Examples of some of his pest control recommendations are listed in Table 4-1.

Although Harris's remedies are often labor-intensive and time-consuming relative to today's management programs, they were at least partially effective and reflected a broad knowledge of pest biologies and pest–host interactions. Suggested remedies ranged from hand-picking and shaking (Figure 4-5), encouraging natural enemies, employing various cultural practices (e.g., adjusting planting time to disadvantage the pest, enhancing plant growth and vigor with manure fertilization, sanitary practices such as burning after harvest, selection of pest resistant varieties), constructing physical barriers to pests (e.g., tree-banding with sticky substances), to the use of toxic and noxious substances (including whitewash and glue, tobacco, walnut, hops and other plant infusions, sulfur, soapsuds, whale oil, resin and fish oil, and lime and turpentine).

Two pests nearly devastated the European wine industry in the latter half of the nineteenth century—an epidemic of powdery mildew and the introduction of an insect from America, the grape phylloxera. The solution of these problems marked a turning point in pest control. These were probably the first major pest outbreaks in which human-directed efforts played the primary role in the control and containment of the pest. They also spurred the evolution of methods and pest control that were to dominate the scene for another fifty years.

The attack on the grape phylloxera problem was multifaceted. A phylloxera-eating mite was imported from America and established in 1873 but failed to become an effective control for the pest. Attempts at chemical control proved uneconomical and ineffective. A new approach, the use of an insect pathogen, was suggested by Louis Pasteur in 1874 but was never actually attempted. Pasteur's main research project at the time was the control of pebrine, a disease of the silkworm that was plaguing the silk industry in France in the last quarter of the nineteenth century. Pasteur wondered why such virulent diseases couldn't be put to some good use.

The breakthroughs that actually eliminated the phylloxera as a serious pest in Europe, however, were the successful utilization of host plant resistance and the evolution of the technique of grafting. A variety of American grape that was resistant to the phylloxera was discovered around 1870. This discovery was followed by the development of the

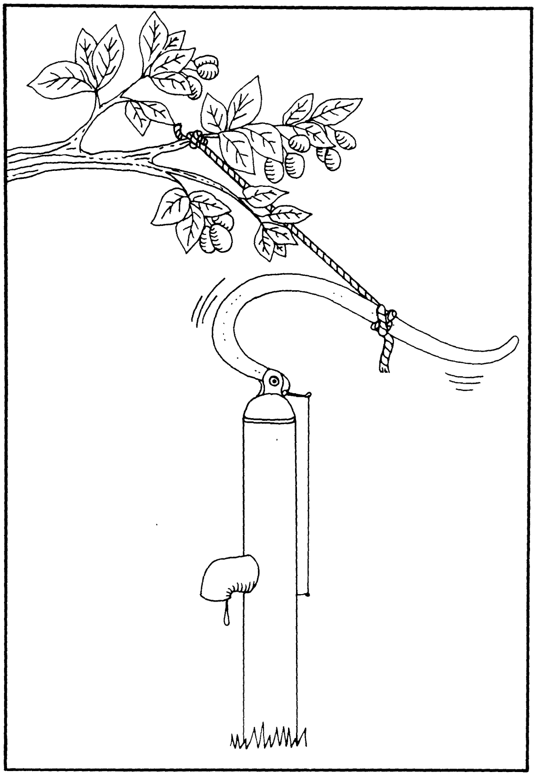

FIGURE 4-5. An ingenious method of control for curculios (a type of weevil with boring larvae) injuring plum and apricot trees, devised by Colonel T. Forest of Germantown, Pennsylvania, in the early 1800s. "Having a fine plum tree near his pump [he] tied a rope from the tree to his pump handle, so that the tree was greatly agitated every time there was occasion to pump water. The consequence was that the fruit on his tree was preserved in the greatest perfection" (from Dethier, 1976).

grafting technique that allowed the rootstocks from these resistant grape varieties to be joined on the popular European varieties. The resulting grafted plants did not suffer serious damage from the phylloxera.

The solution to the powdery mildew fungus problem came about by accident. A farmer, in an attempt to stop the pilfering of his grapes by passersby, applied a poisonous-looking mixture of copper and lime to his roadside plants. On later examination, he discovered that these roadside plants had escaped infection by the fungus. This "accident" resulted in the development of two fungicides that were to dominate plant pathogen control for many years to come. These were Bordeaux mixture (hydrated lime plus copper sulfate), still the most widely used fungicide in the world,

TABLE 4-1
Suggested Insect Controls from T. W. Harris's *Treatise on Some of the Insects Injurious to Vegetation* (1841)

Coleopterous borers on trees	Protect the woodpecker
Pine weevil	Cut off shoots in August and burn them; stick cut branches in the ground in the egg-laying season to trap eggs
Plum curculio	Jarring; gathering fallen fruit, spraying fruit with whitewash glue
Pear-tree scolytus	Pruning
Apple-borers	Clean culture; put camphor in plugged holes
Flea beetles	Sprinkling with tobacco and red pepper; watering with Glauber's salt and water; tobacco water; infusions of elder leaves, walnut leaves, hops, ground plaster of Paris, charcoal dust, powdered soot, sulfur, and Scoth snuff; torches; covering with millinet on frames
Cockroaches	Poison baits
Mole crickets	Poison baits and pigs
Squash bugs	Early hand picking and forcing the growth of plants by manuring
Vine leafhopper	Fumigation with tobacco under a movable tent, syringing with whale-oil soap and water
Aphids	Solutions of soap or a mixture of soapsuds and tobacco water used warm; also hot water; one-half ounce of carbonate of ammonia to one quart of water; lime; fumigating with sulfur or tobacco
Scale insects	Two parts of soft soap in eight parts of water mixed with lime to make a whitewash; two pounds of potash to seven quarts of water; one quart salt to two gallons of water
Peach-tree borer	Remove the earth around the base of the tree, crush the cocoons and borer, cover the wounded parts with moist clay, surround the trunk with a strip of sheathing paper extending two inches below the level of the soil, and place a fresh mortar around the root to confine the paper (do this in the spring or in June)
Hairy caterpillars (woolly bear caterpillar and allies)	Pay children to collect them by the quart
Salt marsh caterpillar	Mow the marshes early in July and, if possible, for several years in succession; burn over marshes in March
Cutworms	Soaking of the grain before planting in copperas water; rolling the seed in lime or ashes; mixing salt with the manure; fall plowing of sward lands intended for

TABLE 4-1 (*Continued*)

Cutworms (*continued*)	wheat or corn the following year; manuring soil with sea mud; protecting cabbage plants by wrapping a walnut or hickory leaf (or paper) around the stem
Cankerworms	Tree banding with clay mortar, strips of old canvas or strong tarred paper, a collar of boards smeared with tar, collars of tin plate, a belt of cotton wool, or troughs of tin or lead filled with cheap fish oil; melted Indian rubber; dusting leaves when wet with dew with air-slaked lime; one pound of whale-oil soap to seven gallons of water used as a sprinkle with a garden engine; jarring the trees; use of pigs to destroy pupae under the ground
Codling moth	Gather windfalls; wind cloth around the tree or hang in the crotches to attract larvae ready to spin; scrape off the loose and rugged bark; drive away the moths at egg-laying time by smoke of weeds burned under the tree
Clothes moths	Expose garments, furs, or feathers to the air and to the heat of the sun for several hours, then brush, beat, and shake before packing away. Brush over walls and shelves of closets with spirits of turpentine. Put powdered black pepper under the edges of carpets. Place sheets of paper sprinkled with spirits of turpentine, camphor, or coarse powder, leaves of tobacco, or shavings of Russian leather among clothes when put away in summer. Put small articles into brown paper bags securely closed, also put in a few tobacco leaves or bits of camphor. Use chests of camphor wood, red cedar, or Spanish cedar. Cloth linings of carriages: wash or sponge on both sides with a solution of corrosive sublimate of mercury in alcohol strong enough not to leave a white stain on a black feather. Fumigate with tobacco smoke or sulfur. Expose to steam for fifteen minutes. Place the infested garment in an oven heated to 150°F.
Angoumois grain moth	Heat for twelve hours at 168°F; early threshing and winnowing of wheat
Jointworms	Burn stubble, also straw and refuse; manuring and thorough cultivation, promoting rapid and vigorous growth of the plant
Hessian fly	Selection of varieties; burning the stubble
Horseflies	Protect animals by washing their backs with a strong decoction of walnut leaves

and Paris Green (copper acetoarsenite). Both were later found to have important insecticidal attributes as well, and Paris Green became one of the most commonly employed insecticides in the late nineteenth century.

Materials used for chemical control of pests did not change much in the fifty years after 1880. The active ingredients in most of these materials were compounds of arsenic, antimony, selenium, sulfur, thallium, zinc, copper, or plant-derived alkaloids. Hydrogen cyanide gas was also in use for fumigation purposes and various oils were used in the control of pests. Over the next decades these products were refined and made more useful by development of better application devices and techniques, by better timing of applications, and by the addition of inert but useful agents to facilitate surface adhesion and even distribution of materials.

Chemical control of weeds found its first application in 1896 when iron sulfate was found to kill broad-leaved weeds but not cereal crops. Over the next ten years many other simple inorganic compounds—e.g., sodium nitrate, ammonium sulfate, and sulfuric acid—were put into very limited use as herbicides. However, at that time labor was so inexpensive that few farmers were interested in chemical methods of weed control. Most depended on a combination of clean cultivation, tillage, crop rotation with weed-competitive crops, and hand weeding to keep their weeds pests under control.

It was also in the late nineteenth century that the importation and establishment of natural enemies for biological control was shown to be one of the most effective means of combatting insect (and later, weed) pests. The first major success of this technique was in the control of the cottony cushion scale in California. The cottony cushion scale was accidentally introduced into California in the late 1860s; by the 1880s it had spread throughout the citrus growing areas in California and was threatening to wipe out that industry. The native home of the pest was determined to be Australia. With this assumption, the United States government sent an entomologist, Albert Koebele, to Australia to send back natural enemies of the scale to be established in California. Of the natural enemies he found in Australia, Koebele sent back two: a parasitic fly, *Cryptochaetum iceryae*, and the vedalia beetle, *Rodolia cardinalis*. The vedalia beetle (Figure 4-6) turned out to be an exceptionally fast and effective control. One hundred and forty of these predators were carefully shipped back to California and turned loose on a screened-in cottony cushion scale-infested orange tree. Within a year and a half, the descendants of these 140 beetles had checked the cottony cushion scale over the citrus-growing areas of the state. Control by the vedalia beetle has been so successful that since its establishment in 1890, the cottony cushion scale has never (with one exception—see page 76) risen to pest status

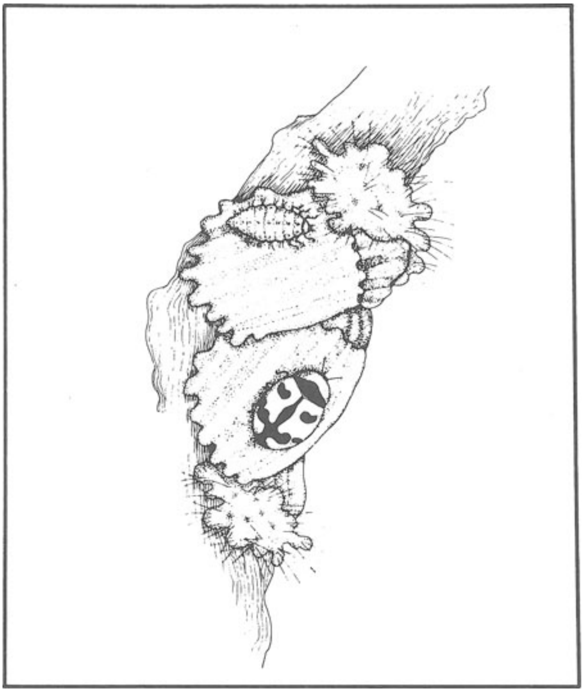

FIGURE 4-6. The vedalia beetle and larva feeding on the cottony cushion scale.

again. The introduced parasitic fly also became an important control factor in coastal areas of Southern California.

The 1890s saw an incredible succession of breakthroughs in medical entomology. It was during this period that arthropods were proven to be carriers (or "vectors") of disease organisms. The first proof was Smith and Kilborne's work in 1893 with Texas cattle fever, a protozoan disease of cattle, showing it to be tick-borne. The rest fell like dominoes: Bruce, in 1896, showed the African sleeping sickness pathogen to be carried by tsetse flies; rat fleas were shown to harbor the plague or "black death" bacterium and mosquitoes were identified as vectors of the malarial protozoa in 1897; the role of flies in the mechanical transmission of typhoid fever was proven in 1898; and in 1900 mosquitoes were positively identified as carriers of the yellow fever virus.

Accordingly, it became apparent for the first time that many serious diseases could be contained through the control of their arthropod vectors. The control of these disease-transmitting animals grew into a whole new area of pest management. The building of the Panama Canal (completed in 1915) represented the first large-scale success in controlling a medically important insect vector. The failure of the French in their attempt to build the canal in the last quarter of the nineteenth century can be at least partially credited to their inability to control malaria and yellow fever—due primarily to their ignorance of the role of mosquitoes as vectors. Mosquito control in the early 1900s focused on destruction of breeding sites by draining, filling, impounding, and periodic flushing and occasionally involved the use of a larvicide such as kerosene.

By the turn of the nineteenth century, five major approaches to pest control were well established and in common use: (1) biological control, (2) mechanical and physical control, (3) cultural control, (4) chemical control, and (5) use of resistant varieties. Pest control practice today still relies almost entirely on the utilization of methods in these five categories. Advances in the last 75 years have resulted largely from modifications of materials and practices in these areas, the introduction of new materials and techniques, and the successful employment of practices in two or more of these areas simultaneously and consciously for improved and longer-lasting pest prevention and control. A sixth approach, legal control, through the use of inspections and quarantines to prevent the entry and spread of pest-infested materials, was firmly established in the United States in 1912 by the Plant Quarantine Act of that year.

THE EARLY TWENTIETH CENTURY

By the early 1900s the number of people actively employed as economic entomologists, plant pathology experts, and other pest control specialists was substantial. Textbooks from that period show that these sciences were well developed. A close look at an entomology text of the period, E. Dwight Sanderson's *Insect Pests of Farm, Garden and Orchard*, published in 1915, reveals considerable progress in insect control thinking from Harris's haphazard approach of 1841. Sanderson shows us an approach that is systematic, well formulated, biologically based, and clearly thought out in a stepwise fashion in case after case; it is an approach to pest control that could be instructional and appropriate for students even today. Texts of this period stressed the importance of correct identification of pests and the need for a solid understanding of pest biology, especially in the timing of application of control measures.

Sanderson's 1915 text considered proper farm methods as a key to good pest control. These methods included crop rotation, arrangement of planting times to avoid pest outbreaks, and the destruction of weeds or "volunteer" crop plants, which might maintain pest populations during period of crop absence. Sanderson also pointed out the importance of

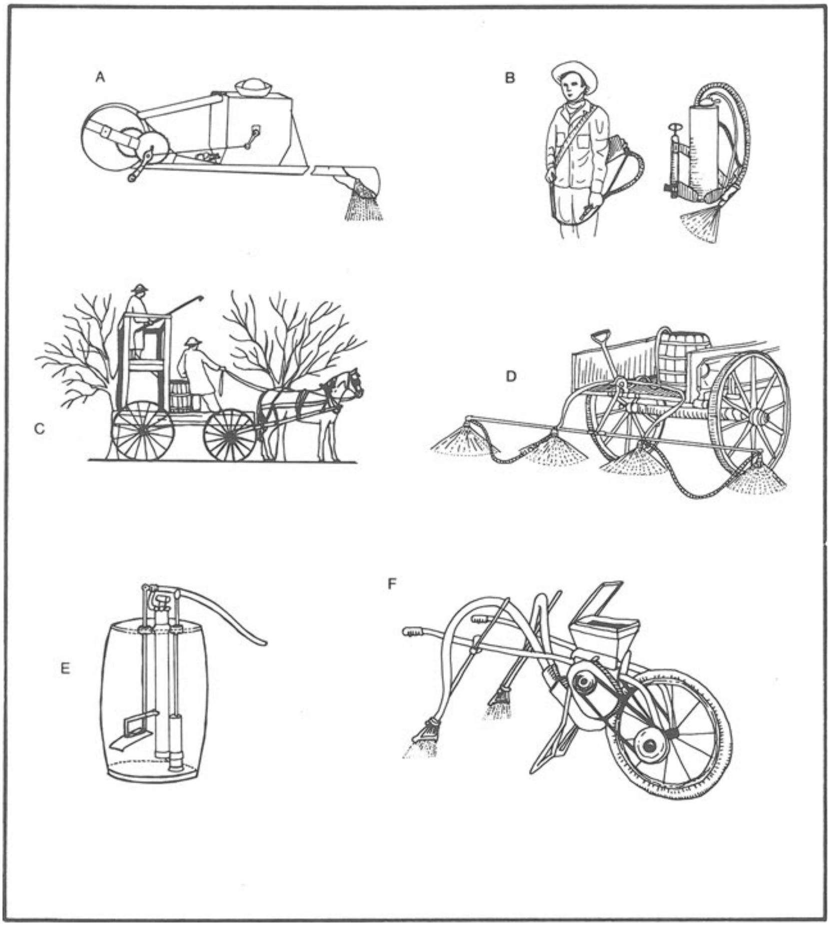

FIGURE 4-7. Early pesticide application equipment, ca. 1915. (A) A powder-gun for applying insecticides in dust form. (B) Compressed-air sprayer, individually held. (C) Spraying orchard trees from a rough tower bolted to a one-horse wagon. (D) Row-spraying attachment for use with barrel pump, adjustable for various widths of rows. (E) Barrel pump. (F) Wheelbarrow applicator for dusts.

proper fertilization and soil preparation in pest control, noting that a healthy crop can better withstand pest injury. He advocated the practice of "clean farming" by destroying fall stubble and refuse in which such pests as the corn stalk borer, the cotton boll weevil, and the chinch bug might overwinter. He also suggested the use of "trap crops" to attract pests away from the economically important crops—e.g., the use of corn to lure the egg-laying female *Heliothis zea* moth away from the cotton plants. Corn is the favorite host of *H. zea* (variously known as the corn earworm, cotton bollworm, and tomato fruitworm) but it is usually not available late in the season, so the moths are forced to seek out cotton. Sanderson recommended planting just a few rows of corn in a cotton field (to be destroyed after egg-laying had taken place) to greatly reduce a bollworm problem.

Sanderson divided the insecticides of the period into four classes according to their mode of action: (1) stomach poisons (killing via ingestion), (2) contact insecticides (clogging up respiratory system or corroding cuticle), (3) repellents, and (4) gases for fumigation purposes. Lead arsenate, a stomach poison highly toxic to man and other animals as well as insects, was the most commonly used insecticide until the introduction of fluorine compounds in the 1920s. During the early twentieth century, the usefulness of pesticides was greatly increased by the development of better application equipment. Figure 4-7 shows some of these early designs. The airplane was first used for pesticide spraying in 1921 in Ohio against the catalpa sphinx moth.

Physical and mechanical control devices were important aids in insect control in the early twentieth century (Figures 4-8 and 4-9). These included the screening of houses, mosquito nets, and the use of sticky bands around tree trunks to keep climbing insects from getting up to the leaves. The invasion of fields by hordes of land-migrating insects such as chinch bugs and army worms was prevented by constructing barriers of oils, dusty-sided furrows, low fences of sheet metal, and other ingenious means. Mechanical devices such as hopper dozers were employed to catch a variety of insects. Flypaper, fly traps, moth traps, light traps, and various kinds of bait traps were in common use during this time. Physical manipulation such as the flooding of fields or heating or cooling of stored products were effective pest controls. It was well recognized at this time that a physical control—the draining of swamps, marshes, and other accumulations of standing water—was the most effective method of destroying mosquitoes and horse flies.

Advances in plant pathogen control during the first four decades of the twentieth century occurred in several areas but were dominated by the establishment of plant breeding for resistance as an active area of research. Early plant breeding successes included the development of resistance to rusts in cereals and to *Fusarium* wilts of cotton, watermelon, and cowpea. Crop rotation and crop refuse destruction were recognized as effective in controlling many plant pathogens. Bordeaux mixture continued to be the leading fungicide, although several organic compounds such as the organomercuries, salycylanilide, and the dithiocarbomates had been introduced before 1940.

Progress in weed control proceeded on several fronts. The feasibility

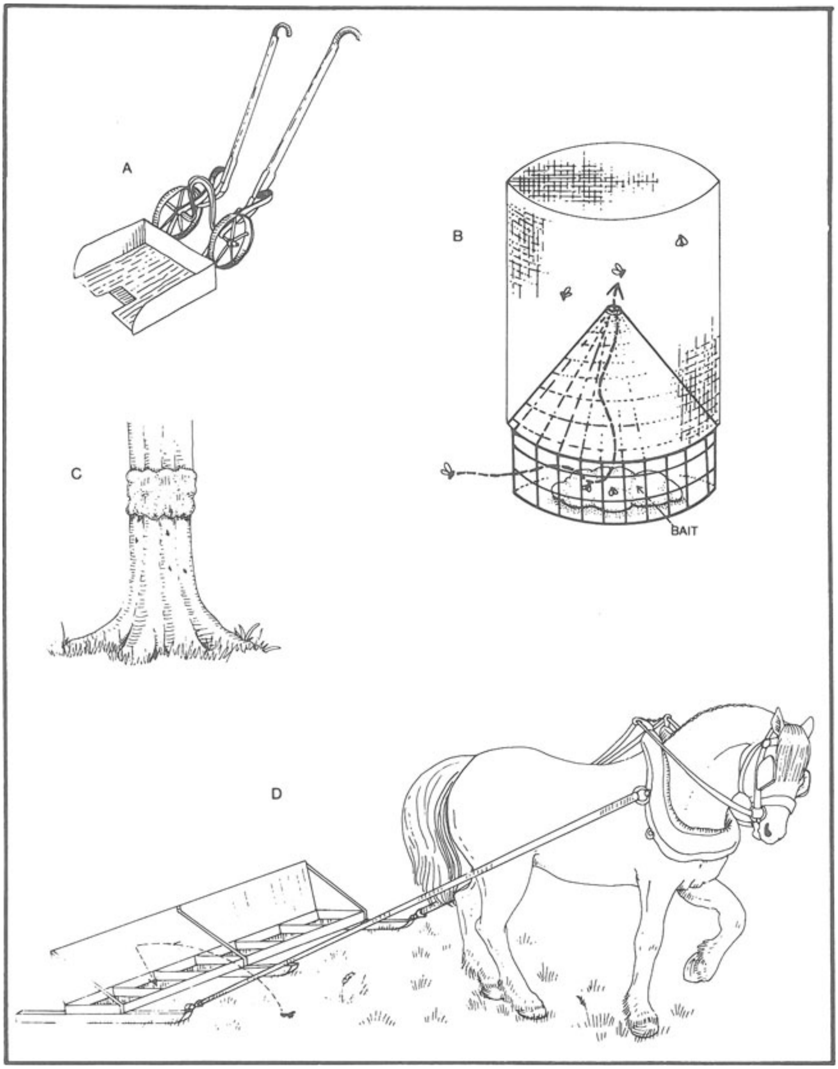

FIGURE 4-8. Physical and mechanical control devices of the early twentieth century. (A) A hopperette, designed for catching leafhoppers. Immediately after weedy areas, grass, or forage crops are cut, a hopperette can be pushed through the infested area; thousands of leafhoppers will fly into the machine and adhere to the sticky substance on its sides and bottom. (B) A fly trap. Flies are attracted to bait in the bottom of the trap, then fly up into the cone and cannot get out. With an attractive bait and a correctly sized trap, buckets of flies can be caught in a short period of time. (C) Sticky band or "tangle foot" around the trunk of a tree. Insects migrating up into the leafy portions of the tree get stuck in the band. (D) A hopperdozer. This is similar to the hopperette described in (A), but it is larger and designed particularly for catching grasshoppers. Oil or kerosene is placed in the trough of the hopperdozer to kill the pests once caught.

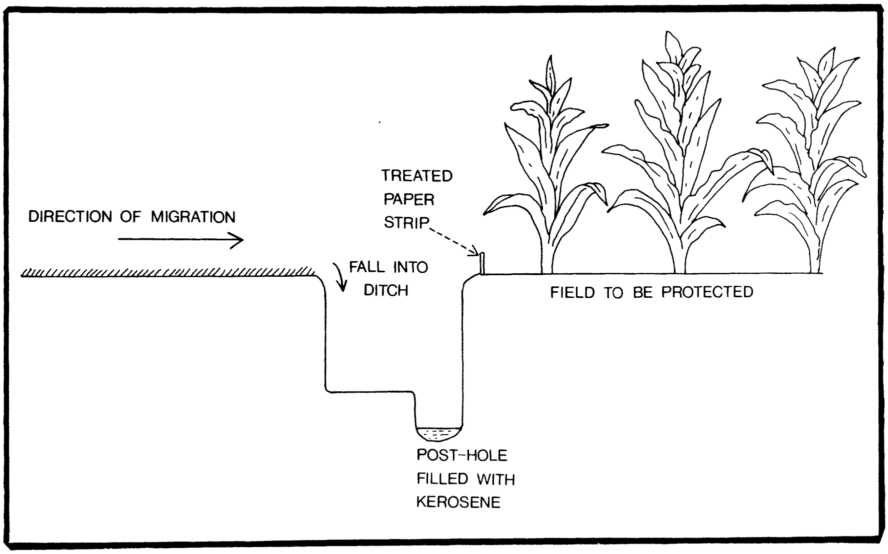

FIGURE 4-9. Paper strip barrier and post hole trap for protection of crops from migrating insects (e.g., chinch bug nymphs, migrating larvae of army worms). Migrating insects fall into ditch and are killed in kerosene. Tarred paper, saturated with creosote, repellent to chinch, is an additional deterrent preventing these insects from being blown across the barrier.

of controlling weeds by biological means was dramatically illustrated in Australia in 1926 with the successful introduction of the *Cactoblastis* moth and other cactus-feeding insects for the control of prickly pear cactus. Within ten years, over 60 million acres had been cleared of this nasty pest. The establishment of standards for weed-free seed and the development of better farm equipment and cultivation methods were important components of weed control during the first decades of the twentieth century.

AFTER WORLD WAR II—THE REVOLUTIONIZING OF PEST CONTROL BY DDT AND OTHER SYNTHETIC ORGANIC PESTICIDES

The science of pest control progressed steadily during the first 40 years of the twentieth century; but it was the pressures presented by World War II that caused the greatest revolution in twentieth century pest control—the development of the synthetic organic pesticides.

World War I had been fought primarily in Europe, and the pest problems that plagued the fighting troops there were the usual uncomfortable but rarely serious problems—lice, fleas, bedbugs—brought on by the inevitable crowded and often unsanitary wartime conditions. However, much of World War II took place in the tropics, and the insect-vectored diseases in these areas—malaria, typhus, sleeping sickness, dengue, relapsing fever—had the potential of becoming truly devastating to the entire war effort. Both sides realized this immediately. Research on more effective insecticides became a top priority.

In the United States hundreds of chemicals from manufacturers around the world were put through a screening process for insecticidal activity. One of these routinely tested materials, dichloro-diphenyl-trichloroethane (DDT), manufactured by the Geigy Chemical Company of Switzerland and developed by a Swiss chemist, Paul Mueller, was just what the researchers had been looking for—a substance toxic (even in minute quantities) to virtually every test insect! The wartime benefits conferred by DDT and similar insecticides, through their diminution of various diseases, should not be underestimated.

While the Western Allies were developing the chlorinated hydrocarbons, the Germans had come up with another equally toxic group of insecticidal compounds—the organophosphates (including HETP, parathion, and schradan). A third group of synthetic organic insecticides, the carbamates, was also discovered in the 1940s by Swiss workers; but these materials did not come into popular use until the late 1950s, with the development and marketing of carbaryl in the United States. The first use of these new insecticides was, of course, for control of insects that carried human disease. But after the war they found a ready market in peacetime agricultural enterprise. Their success was immediate. They were cheap, effective in small quantities, easy to apply, and widely toxic. They seemed to be truly "miracle" insecticides.

The pesticide industry boomed. In the early 1900s, pesticides were usually mixed up in the back shed by the farmer himself, according to directions in the latest farm journal. As pesticides came into more widespread use and became regulated, small industries specializing in pesticides sprang up. But with the coming of the synthetic organic pesticides and large numbers of petroleum-derived products, some of the world's largest corporations became involved in the development, manufacture, and marketing of pesticide products. The introduction of selective herbicides (such as 2,4-D) in the 1940s was soon followed by the development of low-volume sprayers and other field application equipment and technology. Thus, the application of pesticides, a practice confined largely to orchard and high cash crops, became a common procedure in just about every agricultural crop and, subsequently, in urban and recreational areas as well.

The effect of the new pesticides on the attitude of those who controlled pest organisms was revolutionary. Where farmers had formerly talked of "controlling" pests, expecting to have to tolerate certain levels of the noxious species, they now talked of "eradicating" pests. People envisioned the extermination of entire species of pest insects, plant pathogenic organisms, and weeds, and expected 100% kill from their pest control actions. The new chemicals were such successful poisons that there seemed to be no need to continue carrying out many of the old pest control practices, which previously had been a preventative habit—rotation, crop sanitation, encouragement of natural enemies, special cultivation practices, drainage of standing water for mosquito control, and similar operations. In some instances these practices were simply disregarded and discontinued.

Many students and researchers in the pest control disciplines became increasingly concerned with studying the killing efficiencies of chemicals. Research in this area was emphasized, often at the expense of research directed at gaining a better understanding of the biologies of the pests and their natural enemies. Thus the control of pests, which had always been considered a fundamentally ecological problem, began to assume the trappings of an offshoot of chemistry and engineering, sometimes involving little or no ecological understanding. This trend is perhaps best reflected in the subject matter of papers published in America's major applied entomological journal of the period, the *Journal of Economic Entomology*. Figure 4-10 shows that the number of papers in the *Journal* describing research in general biology (including records of pest incidence and damage, bionomics, ecology, and physiology) went down significantly during the period 1927–1952, while reports of research involving laboratory and field testing of insecticides began to clearly dominate the *Journal* after 1935.

The use of insecticides and other pesticides over this period became as normal and automatic to the grower as cultivating his field or sowing his seed. In the case of insect pests, he rarely bothered to see if the bugs were actually there in significant numbers—but simply sprayed according to a time schedule—e.g., weekly after seedling emergence until a week before harvest. It was an uncomplicated, easy-to-follow procedure, and growers regarded it as inexpensive and foolproof insurance against pest damage. And they were often urged on by pesticide company representatives, who had become the farmer's chief source of information about a wide range of pest problems. Unfortunately, problems with the heavy dependence on chemical control began to arise, and these problems were of an ecological–biological nature. They were ignored by most at first, and many were ignored for a long time; but eventually these problems

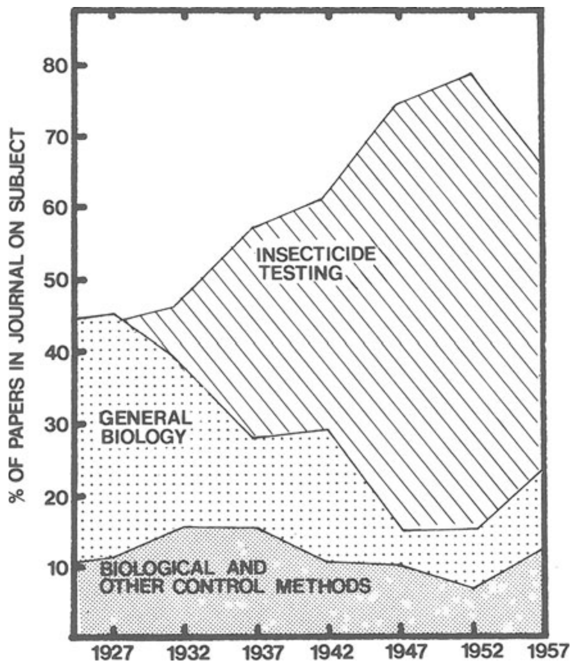

FIGURE 4-10. Trends in applied entomological research as reflected in the *Journal of Economic Entomology*, 1927–1957. Note how insect control research increasingly focused on insecticide testing and became less concerned with the biologies of the pests that were being controlled (data from Jones, 1973).

produced situations of such severity that they could no longer go unnoticed.

The earliest hint of impending disaster was the *development of resistance* to the killing power of the insecticides by some major pests. The first reported case of tolerance to DDT was in the house fly in Sweden in 1946. Within 20 years, some 224 species of insects and acarines had been recorded as resistant to one or more groups of insecticides: 127 agricultural and 97 pests of medical or veterinary importance. As of 1975, 75% of the most serious agricultural insect pests in California had developed resistance to at least one major insecticide, and in fact, a number had developed resistance to two or more materials (Table 4-2).

Insecticide resistance was not a new phenomenon, and it should not have been completely unexpected. Even before the arrival of the "miracle" insecticides in the 1940s, seven cases of resistance to the old-fashioned insecticides had been recognized: the resistance of the San Jose

TABLE 4-2
Pesticide Resistance in the Arthropod Pests Causing Over One Million Dollars Damage to California Agriculture in 1970[a]

Pest species	Types of pesticide for which resistance was demonstrated[b]	Resistance reported or suspected in California
Citrus red mite, *Panonychus citri*	DDT, OP, sulfur	×
European red mite, *Panonychus ulmi*	DDT, OP, sulfur	×
Pacific spider mite, *Tetranychus pacificus*	DDT, OP	×
Two spotted mite, *Tetranychus urticae*	DDT, OP, sulfur	×
Citrus thrips, *Scirtothrips citri*	DDT, cyclodienes, tartar emetic	×
Consperse stinkbug, *Euschistus conspersus*		
Lygus bug, *Lygus hesperus*	DDT, cyclodienes, OP	×
Pear psylla, *Psylla pyricola*	DDT, cyclodienes, OP	×
Cabbage aphid, *Brevicoryne brassicae*		
Citrus aphid, *Aphis citricola*		
Green peach aphid, *Myzus persicae*	DDT cyclodienes, OP, carbamates	×
California red scale, *Aonidiella aurantii*	OP, HCN	×
San Jose scale, *Quadraspidiotus perniciosus*	Lime sulfur	
Cotton bollworm, corn earworm, tomato fruitworm, *Heliothis zea*	DDT, cyclodienes, OP, carbamates	×
Beet armyworm, *Spodoptera exigua*	DDT, cyclodienes, OP, carbamates	
Cabbage looper, *Trichoplusia ni*	DDT, cyclodienes, OP, carbamates	×
Artichoke plum moth, *Platyptilla carduidactyla*	OP	×
Potato tubeworm, *Phthorimaea operculella*	DDT, cyclodienes, OP	
Pink bollworm, *Pectinophora gossypiella*	DDT, OP, carbamates	×
Peach twig borer, *Anarsia lineatella*	DDT, lead arsenate	×
Omnivorous leafroller, *Platynota stultana*		
Codling moth, *Laspeyresia pomonella*	DDT, OP, lead arsenate	×
Oriental fruit moth, *Grapholitha molesta*	DDT	
Cotton leaf perforator, *Bucculatrix thurberiella*	DDT, cyclodienes, OP, carbamates	×
Alfalfa weevil, *Hypera* sp.	Cyclodienes	×

[a] From Luck *et al.* (1977).
[b] DDT, DDT and relatives; OP, organophosphates; HCN, hydrogen cyanide.

scale in 1914 to lime–sulfur sprays; the resistance to California red scale in 1916, the black scale in 1916, and the citricola scale in 1938 to HCN fumigation; the resistance of codling moth larvae in 1928 to arsenical sprays; the resistance of screwworm larvae in 1942 to phenothiazine; and the resistance of the citrus thrips to tartar emetic–sucrose sprays in 1942. In contrast to the post-World War II situation, the use of these earlier materials was limited and the development of resistance was bothersome but not disastrous to the crops involved. Cultural methods or other insecticides were easily found to take the place of the ineffective materials. It is notable that in this 28-year period no insect developed resistance to more than one insecticide chemical. This phenomenon may be due partly to the nature of these materials and their modes of toxicity and partly to the fact that large populations of insects in the 1920s and 1930s were never exposed to the constant and repeated application of insecticides that became commonplace in the 1950s with the synthetic organic materials. The development of resistance to pesticide chemicals has not been limited to insect pests. While only a few cases have been reported, plant pathogens, weeds, and rodents have all developed strains resistant to chemicals applied for their control.

Development of resistance in a population of an organism is a common and logical evolutionary reaction to stress. Without a remarkable ability to evolve rapidly and adapt to sudden and often drastic changes in climate and habitat, insects would never have been able to dominate the animal kingdom as they have for many eons. The development of resistance is also known in the area of medicine, where certain strains of human disease organisms are no longer killed by medication (for instance, bacterial resistance to penicillin). When a large population of an organism is exposed to a certain kind of stress such as a toxic chemical, sometimes one or a few individuals may survive while the rest of the population is killed. This may be due to some physical factor (e.g., they were protected from exposure to the toxic chemical owing to sloppy application technique or for some other reason); however, survival may also be the result of one or more traits carried in the individuals' genetic makeup (their chromosomes) which somehow make them less susceptible to the toxin. Examples of such characteristics include the ability to manufacture detoxifying enzymes, behavioral mechanisms that prevent fatal exposure, a less permeable epidermis, or similar characters or combinations of characters. Since only individuals possessing these protective characters (or individuals that happen to escape because of some physical protection) will survive, it is easy to see that the next generation will contain a higher percentage of pesticide-resistant organisms. If every generation is exposed to the toxic chemical, soon only largely resistant individuals will constitute the population (Figure 4-11). Often a trait pro-

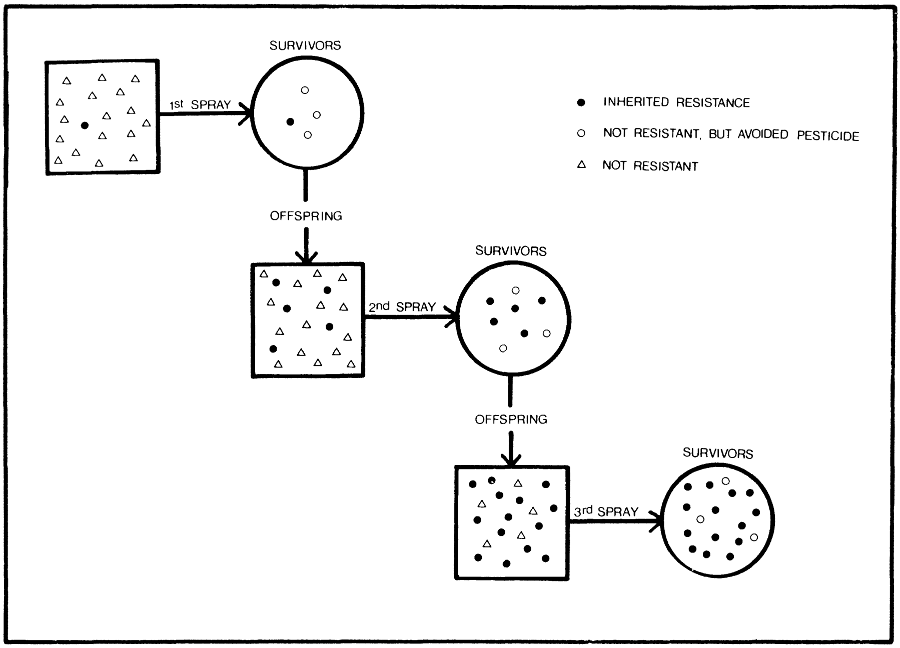

FIGURE 4-11. Schematic diagram of the increase in pesticide resistance in a repeatedly sprayed pest population over three generations.

viding resistance to one pesticide, such as a less permeable epidermis or an ability to detoxify a certain kind of poison, will allow the pest to tolerate another pesticide material as well, thus compounding the resistance problem.

Another problem growers began to notice was *target pest resurgence* (See Figure 4-12). After spraying with one of the modern insecticides to control a pest, growers noticed that its populations would sometimes drop drastically and then suddenly surge to higher levels than before. Pest resurgence occurred because the insecticides, as broad-spectrum poisons, killed natural enemies of the pest as well as the pest itself. Any natural enemies surviving the insecticide application would often starve to death since pest populations would be temporarily too low to provide adequate food; they would be forced to emigrate to other fields in search of food, or sometimes they would go into a reproductive lapse because of food shortage. The pest insects, on the other hand, would be able to do better than ever; their food source (the crop) would be readily available, often virtually inexhaustible, and now there would be no natural enemies to restrict or limit their population growth. Figure 4-13 shows such a case

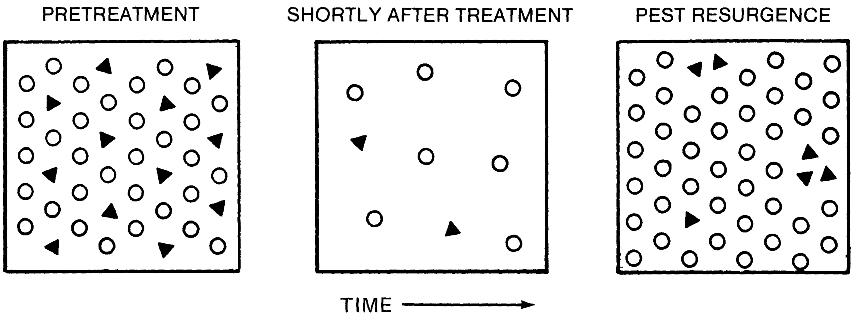

FIGURE 4-12. Target pest resurgence. Diagrammatic sketch of the influence of chemical treatment on natural enemy pest abundance and dispersion, and resulting pest resurgence. The squares represent a field or orchard immediately before, immediately after, and some time after treatment with an insecticide for control of a pest species (○). The immediate effect of the treatment is a strong reduction of the pest but an even greater destruction of its natural enemies (represented by ▲s). The resulting unfavorable ratio and dispersion of pest individuals to natural enemies permits a rapid resurgence of the former to damaging abundance (from Smith and van den Bosch, 1967).

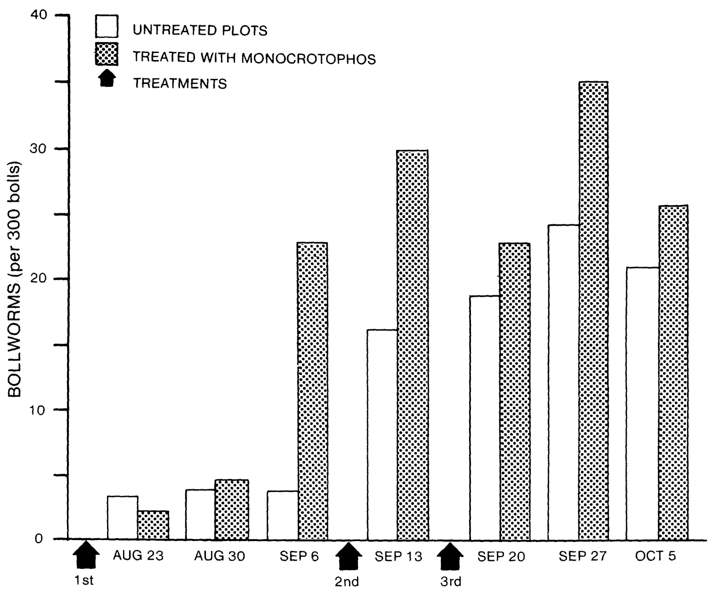

FIGURE 4-13. Target pest resurgence following applications of an insecticide for "pest control." In this experiment, plots treated with monocrotophos, an insecticide federally registered for bollworm control, suffered heavier bollworm infestations than untreated plots. Simultaneous samplings of predators revealed that the insecticide destroyed bollworm predators, which permitted resurgence of the pest. The data are from an experiment conducted at Dos Palos, California, in 1965 (from van den Bosch and Messenger, 1973).

of pest resurgence involving the bollworm in California cotton. Field sampling showed that the rapid increase in the population of the pest later in the season was indeed due to the destruction of predatory and parasitic insects.

The third type of problem engendered by dependence on the "miracle" insecticides is that of *induced secondary pest outbreak*. This occurs when a plant-feeding species, previously not a pest, suddenly erupts to damaging levels. This eruption is usually the result of the pesticides' destruction of natural enemies, which until then had kept the new pest under effective biological control (Figure 4-14).

A model case of secondary pest outbreak presented itself when DDT sprayed in California citrus orchards for control of other citrus pests caused a devastating outbreak of the cottony cushion scale. The cottony cushion scale, as discussed earlier in the chapter, had been kept under complete biological control since 1890 when the predaceous vedalia beetle and a parasitic fly were imported from Australia and established in California citrus orchards. These natural enemies exerted such an effective control that the cottony cushion scale had been almost forgotten. Their presence became painfully apparent, however, when the vedalia beetle proved particularly susceptible to DDT and the scale, released from nearly sixty years of biological control, again caused havoc in the citrus orchards where DDT had been used. It was not until DDT applications were adjusted and new populations of the vedalia beetle reestablished themselves in the sprayed orchards that the cottony cushion scale again ceased to be a pest.

The common reaction to these three repercussions from the use of the modern pesticides—(1) pest resurgence, (2) secondary pest outbreak, and (3) pest resistance—was an increase in pesticide use. When an insect developed resistance to a low dose of an insecticide, heavy doses would be applied until the pest could finally be killed, or another insecticide or a combination of several insecticides would be used. When a pesticide application resulted in target pest resurgence, the pesticide would be applied more and more frequently. And when a secondary pest outbreak occurred, the new "pest" would be treated like the original pest and extra applications (often involving additional materials) added to the spray schedule. The result of this increased use of pesticides was more pesticide resistance, more pest resurgence, and more secondary pest outbreak! This syndrome has been aptly termed "*the pesticide treadmill*"—once on it the farmer could not seem to get off. An excellent example of farmers being caught on the pesticide treadmill is discussed in the following chapter in the story of central American cotton.

A fourth problem resulting from the use of the "miracle" insecticides has been *environmental contamination*. The potential environmental haz-

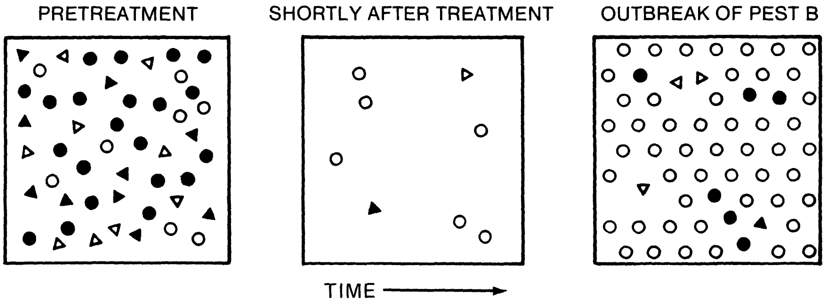

FIGURE 4-14. Secondary pest outbreak. Diagrammatic sketch of the influence of a chemical treatment on natural enemy, pest abundance, and dispersion with resulting secondary pest outbreak. The squares represent a field or orchard immediately before, immediately after, and some time after treatment with an insecticide for control of pest A (●). The chemical treatment effectively reduces pest A as well as its natural enemy (▲), but has little or no effect on pest B (○). Subsequently, because of its release from predation by predator B (△), pest B flares to damaging abundance (from Smith and van den Bosch, 1967).

ards posed by the use of such broadly lethal zooicides had been pointed out right after the introduction of DDT by a tiny minority, but these dissenters received little public attention until the publication of *Silent Spring* by Rachel Carson in 1962. People soon discovered that these poisons, especially the chlorinated hydrocarbons like DDT, were everywhere in the environment—in Antarctic penguins, boreal frogs, fish in the depths of oceans, the lowliest decomposer organisms, and the milk of human mothers. Pesticides were being widely applied and then drifted via wind and water to places remote from the areas of application. Agricultural workers, pest control operators, and other people exposed to various insecticides, especially organophosphates, became the victims of both acute and chronic poisoning.

The United States banned most uses of DDT in 1972, and subsequently has severely restricted or banned the use of aldrin–dieldrin, endrin, heptachlor, DBCP, and chlordane. But the problems of environmental contamination have not disappeared with the banning of a few chemicals. In many cases, agriculturalists, foresters, pest control operators, and other pesticide users have simply substituted new products, and with these new products, new problems have resulted. The 1976 story of the poisoning of industrial workers and the crippling of a major fishing industry by the insecticide Kepone points out succinctly how close to home environmental contamination must get before people will take the issue seriously. In Chapter 5, several case histories of environmental contamination by pesticides are discussed in more detail. Clearly, the only way to curtail such contamination is to make much more discriminating use of these environmental poisons. Well-designed and carefully executed integrated pest management programs, relying extensively on cultural and biological controls, can contribute greatly to minimizing pesticide abuses.

THE DEVELOPMENT OF INTEGRATED PEST MANAGEMENT

The development of integrated pest management has been the most recent chapter in the history of pest control. In integrated pest management, various combinations of methods are utilized in a compatible manner to obtain the best control with the least disruption of the environment. Although many of the cultural, physical and biological control methods worked out in the first third of the twentieth century are utilized, IPM is not, as some might think, a return to pre-World War II pest control. While many good techniques for individual pest problems were worked out during that period, these techniques were independently developed and were rarely coordinated into pest management programs that evaluated the effects of two or more pest management operations on each other. Although early methods often were the result of an admirably sound biological knowledge of pest life cycles and were directed at the pest's "weak points," few of the methods recognized the importance of assessing population numbers of both pest and natural enemy populations to predict future population trends and determine if pest control action was actually needed. This is the key to integrated pest management.

Although the concept of integrated pest management has only been popularly accepted for the last ten to fifteen years, the roots are much older. In the late 1940s, Ray F. Smith and others suggested the need for supervised control specialists who would carry out routine field monitoring of pest populations and their natural enemies and who would prescribe to the grower what, if any, control action was needed. This suggestion has been significantly implemented only in the last decade and a half.

Agricultural entomologists were at the forefront of the development of integrated pest management. Perhaps because the problems of pest resistance, pest resurgence, and secondary pest outbreak have been most severe among insect pests, it was a group of entomologists who first elaborated the concept of economic levels and thresholds and the concept of integrated control itself. Over the last thirty years, entomologists have also perfected several new control tools compatible with the integrated pest management concept and minimally disruptive to ecosystems. These tools include the use of insect pathogens for pest control, the use of in-

TABLE 4-3
Major Events in the History of Pest Control

Date	Event
400,000,000 B.C.	First land plants
350,000,000 B.C.	First insects
250,000 B.C.	Appearance of *Homo sapiens*
12,000 B.C.	First records of insects in human society
8,000 B.C.	Beginnings of agriculture
4,700 B.C.	Silkworm culture in China
2,500 B.C.	First records of insecticides
1,500 B.C.	First descriptions of insect pests
950 B.C.	First descriptions of cultural controls (burning)
300 A.D.	First record of use of biological controls (predatory ants used in citrus orchards in China)
1650–1780	Burgeoning of insect descriptions (after Linnaeus) and biological discoveries in Renaissance
1732	Farmers first begin to grow crops in rows to facilitate weed removal
1750–1880	Agricultural revolution in Europe
Early 1800s	Appearance of first books and papers devoted entirely to pest control
1840s	Potato blight in Ireland (no controls available to curb disaster)
1870–1890	Grape phylloxera and powdery mildew controlled in French wine country (introduction of Bordeaux mixture and Paris Green; use of resistant rootstalks and grafting)
1880	First commercial pesticide spraying machine
1888	First major biological importation success (vedalia beetle for control of cottony cushion scale)
1890s	Introduction of lead arsenate for insect control
1896	Recognition of arthropods as vectors of human disease
1896	First selective herbicide (iron sulfate)
1901	First successful biological control of a weed (lantana in Hawaii)
1899–1909	Development of strains of cotton, cowpeas, and watermelon resistant to *Fusarium* wilt (first breeding program)
1912	U.S. Plant Quarantine Act
1915	Control of disease-vectoring mosquitoes allowed completion of Panama Canal

(*Continued*)

TABLE 4-3 (*Continued*)

Date	Event
1921	First aircraft spray (in Ohio for catalpa sphinx)
1929	First area-wide eradication of an insect pest (Mediterranean fruit fly in Florida)
1930s	Introduction of synthetic organic compounds for plant pathogen control
1939	Recognition of insecticidal properties of DDT
1940	Use of milky disease to control Japanese beetle (first successful use of insect pathogen for control)
1940s	Organophosphates developed in Germany, carbamates in Switzerland
1942	First successful breeding program for insect pest resistance in crop plants (release of wheat strain resistant to Hessian fly)
1944	First hormone-based herbicide (2,4-D)
1946	First report of insect resistance to DDT (housefly in Sweden)
1950s, 1960s, and 1970s	Widespread development of resistance to DDT and other pesticides
1950s	First applications of systems analysis to crop pest control
1959	Introduction of concepts of economic thresholds, economic levels, and integrated control
1960	First insect sex pheromone isolated, identified, and synthesized (gypsy moth)
1962	Rachel Carson's *Silent Spring*
1972	Banning of DDT in United States

secticides that selectively kill pests with minimum negative effects on beneficial organisms, the use of insect pheromones (especially sex attractants, which have been particularly useful in sampling populations), and the use of genetic manipulation (e.g., host resistance to pests and release of sterile males). Methods of monitoring populations have vastly improved, as has the entomologist's ability to understand the factors that contribute to pest outbreaks through the development of computerized models that can simultaneously consider far more variables in the managed ecosystem than can the unaided human brain.

Plant pathologists, weed scientists, rodent control specialists, wildlife managers, and many other ecosystem management and pest control specialists have begun jointly to develop complete integrated pest management systems for the ecosystems that they manage. Examples of these developments are described in the chapters that follow. Major events in the history of pest control are summarized in Table 4-3.