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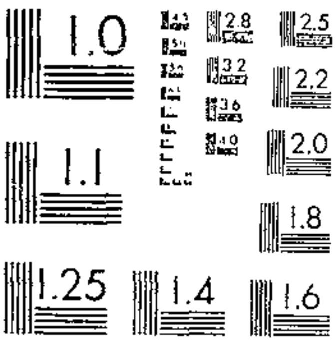

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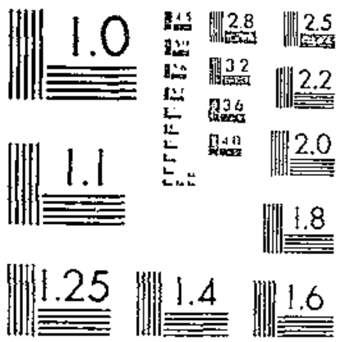

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INTEGRATING CONTROL OF THE JAPANESE BEETLE— A Historical Review

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INTEGRATING CONTROL OF THE JAPANESE BEETLE— A Historical Review

By Walter E. Fleming, *collaborator*

The Japanese beetle (*Popillia japonica* Newman), a plant pest of foreign origin, was first found in the United States in 1916 in a nursery in southern New Jersey. Previously the beetle lived only in the main islands of the Japanese archipelago. Apparently it had come to this country before restrictions on the importation of plants and plant products had been established by the U.S. Plant Act of 1912.

The beetle is not a serious agricultural pest in Japan, where no favorable large areas exist for its reproduction and development, and its natural enemies are adequate to keep its population low. Also, the supply of food is not as abundant as that found in the Eastern United States. (Clausen et al. *1927*)[1]

The beetle entered the United States without its natural Japanese enemies. In New Jersey it found a generally favorable climate, large areas of permanent turf for developing the immature stages, almost 300 species of plants to satisfy its voracious appetite, and at that time no important native enemies. The annual beetle populations increased in numbers and destructiveness and spread into new areas. The increase in numbers was caused not only by the lack of enough native enemies but by the new and favorable environment. By 1974 the beetle had occupied much of the United States east of the 85th meridian.

Adult beetles damaged small fruits, tree fruits, truck and garden crops, ornamental herbaceous garden plants, ornamental shrubs and vines, shade and ornamental trees, and many noneconomic wild plants. The grubs destroyed large areas of turf in lawns, golf courses, and pastures, and damaged the roots of other plants. The life history and habits of the beetle have been summarized by Fleming (*1972b*).

Because little information was available on the beetle or its control, the former U.S. Bureau of Entomology established the Japanese Beetle Laboratory in 1917 at Riverton, N.J., to study the life history and habits of the insect in its new environment and later to develop biological, chemical, and other methods for its control. In 1920 the Bureau began a search in

[1]The author's name and the year (in italics) are the key to the reference in Literature Cited, p.55.

the Orient for predaceous and parasitic insects attacking the beetle or attacking related Scarabaeidae and the shipment of the most effective of these species to the United States for colonization in the beetle-infested area. The Laboratory undertook studies of the pathogens attacking the beetle. One of the most impressive achievements of the Laboratory was the development of the knowledge of pathogens attacking the beetle and mass-producing and colonizing some of these organisms in the field.

During the past half century, artificial spread of the Japanese beetle by agricultural products has been controlled by quarantines. Biological, chemical, and other methods have been developed to retard the natural buildup and spread of beetle populations and to protect plants from damage by the adult beetle and its grub.

Shortly after the beetle was found in New Jersey, efforts were made to eradicate the pest, or at least to inhibit its natural spread by utilizing available techniques and materials.

Reports on control of the beetle appeared in Federal and State publications and in scientific journals, but additional unpublished information is filed at the Japanese Beetle Research Laboratory, now at the Ohio Agricultural Research Center, Wooster. These records, both published and unpublished, have been reviewed and codified so that information will be available for possible use in future programs of integrated control of the beetle.

INTERACTION OF THE BEETLE WITH ITS HABITAT

Temperature and Rainfall

The beetle adapts to an environment where (1) the mean soil temperature during the summer is between 17.5° and 27.5° C, (2) the soil temperature during the winter is above — 9.4°, and (3) the precipitation is adequate and uniformly distributed throughout the year, averaging not less than 250 mm (10 in) during the summer. Sufficient summer rainfall is needed to prevent desiccation of the eggs and newly hatched grubs. Sufficient precipitation also is needed during severe winters to provide a snow cover to keep the temperature of the soil within the limits of the cold tolerance of the over-wintering grubs. (Ludwig *1928;* Fox *1939*)

Soil temperatures favorable for the development of the immature stages of the beetle occur over much of the eastern part of the United States. The normal summer rainfall totals about 300 mm in the Atlantic

States and about 250 mm in the Central States. However, summer droughts of irregular though frequent intervals are characteristic of these areas. (Hawley *1949*)

Extremely dry weather during the summer destroys many of the eggs (Hawley *1949*; Fleming *1955, 1960*). Like those of other scarabaeid beetles, the eggs must absorb water before and during embryonic development (Ludwig *1932*). If there is not sufficient moisture in the soil, the eggs perish. However, during dry summers the female beetle has a marked predilection to deposit her eggs in low-lying poorly drained land and in irrigated fields and turf where the soil is more moist than elsewhere in the vicinity (Fox *1939*). This habit of the beetle favors its survival in a drought-stricken area. The grubs are more resistant to desiccation than the eggs. Each of the three larval instars can withstand a loss of body moisture equivalent to half its initial body weight; further loss is fatal. The fatal limit in the loss of weight by desiccation was 44 percent by early prepupae, 34 percent by late prepupae, and 31 percent by pupae. The desiccation of prepupae or pupae did not modify the water content of the adult beetles (Ludwig *1936*).

The second- and third-instar grubs, the overwintering stages, are well adapted to withstanding long periods of inactivity at temperatures below the developmental threshold of 10° C, except when the alimentary tract is cleared for molting, during molting, and immediately after molting. The minimum temperatures withstood by grubs is dependent on the intensity of cold, the duration of exposure, and their maturity and condition. A temperature of — 9.4° in the soil is about the highest likely to cause a mortality of the grubs approaching 100 percent under natural conditions in the field. (Fox *1935, 1939*)

Sudden or extreme changes in the temperature of the air produce slight changes in the temperature of the soil. A blanket of snow during the winter keeps the temperature of the subjacent soil within a few degrees of 0° C, even during prolonged periods of intense cold that otherwise would be fatal to the grubs (Fox *1939*). A freezing rain instead of snow forms ice in the soil which crushes many grubs and causes a high mortality (Hawley and Dobbins *1941*). The absence of snow on the ground during severe winters permits the soil temperature to decline to the fatal limit (Schread *1944, 1945*).

A deficiency of rainfall in the summer or a soil temperature fatal to the hibernating grubs in the winter causes a reduction in the beetle population the following summer, but adequate summer rainfall and favorable winter temperatures cause an increase in the number of beetles the next summer. The effect of these factors is especially apparent when two or more favorable or unfavorable years occur in succession.

Ground Cover

In parts of Japan the beetle was the most abundant where grasslands occur (Clausen et al. *1927*). In southern New Jersey most of the eggs were laid in pastures and other grassy areas (Davis *1920a*). Although most eggs were deposited in pastures, lawns, and golf courses, the beetle also laid eggs in fields of rye, clover, corn, beans, tomatoes, and nursery stock (Smith and Hadley *1926*).

Langford et al. (*1940, 1941b*) made extensive surveys in Maryland and Hawley (*1944*) in southern New Jersey to determine the soil grub population in lands growing crops common to these areas. The soil populations reflected the preferences of the female beetle in selecting sites for oviposition in rural areas. From these data Fleming (*1972b*) made estimates of the distribution of the grub population in the soil according to the ground cover:

Percentage of the soil population	*Oviposition site*
19.5	Pastures
11.7	Asparagus fields
11.2	Fields of timothy and clover
10.6	Alfalfa fields
10.3	Corn fields
6.6	Fallow land
6.5	Potato fields
5.9	Pepper fields
5.8	Soybean fields
4.2	Orchards
1.2	Fields of wheat or rye
.3	Nonagricultural land
.3	Woodlots

The development of the crop also modifies the number of eggs deposited. More eggs are deposited in a cornfield in silk than in fields where silking is past or delayed. Beetles feeding on soybeans with a dense growth lay few eggs in the field. More eggs are laid in asparagus fields with abundance of tall brush than in fields with low brush. Beetles feeding on clover and alfalfa deposit few eggs in fields when the growth is thick, but after harvest many eggs may be deposited in the fields. The presence of such favored weeds as smartweed (*Polygonum* spp.) throughout a field tends to increase the number of eggs deposited in the field.

During the summers of deficient rainfall when pastures become hard and dry, the beetles oviposit in cultivated fields. Under these conditions more eggs may be deposited in cultivated fields than in pastures.

pH of Soil

The alimentary tract of the grub is distinctly alkaline. The pH is 8.0 to 8.4 in the foregut, 9.4 to 9.5 in the ventriculus, and 7.5 to 7.6 in the hindgut. The acidity of the soil had little effect on the pH of the alimentary tract. The alkalinity of the tract of grubs feeding in soil with a pH of 3.47 was the same as for those feeding in soil with a pH of 6.45, showing that there was a strong buffering action in the digestive secretions. (Swingle *1931a, 1931b*)

Although grubs have a broad tolerance to soil pH, statewide surveys in Ohio during 1954-58 showed that the density of grub populations decreased progressively with the increment in the pH. The average annual grub populations ranged from 2.2 to 6.0 per square foot in soils with the pH less than 5.0 and from 0 to 0.6 in neutral and alkaline soils. The high grub populations continued yearly in the strongly acid soils as long as favorable weather prevailed during the egg and young grub stages. (Polivka *1960b*)

EFFORTS TO ERADICATE THE BEETLE

Efforts have been made since beetles were first found to eradicate isolated colonies, or at least to inhibit their natural dispersion, utilizing materials and techniques then available. Chlorinated hydrocarbon insecticides were used with some success. However, since then the Environmental Protection Agency (EPA) has forbidden the use of such insecticides except in certain emergencies, and their use for control of the Japanese beetle has been discontinued.

New Jersey 1918-20

At the close of the summer of 1917, a survey showed that the original beetle colony covered an area of 2.5 square miles in southern New Jersey. There was no precedent that would serve as a guideline in the eradication of this colony. Federal and State agencies had difficulty in destroying the beetle in an environment favorable for its propagation and spread because of the following:

(1) The beetle is a strong flier, moving readily from plant to plant.

(2) The beetle feeds on a large number of economic plants and weeds.

(3) The beetle is difficult to poison with arsenicals and is repelled by insecticides and fungicides.

(4) The beetle spends about five-sixths of its life as a grub underground where it is difficult to locate, except when abundant, and hard to reach with insecticides.

State and Federal agencies planned to establish a barrier band 1/2 to 1 mile wide enclosing the infested area to prevent further spread of the beetle. Within this band the noneconomic food plants of the beetle would be cut and burned or coated with a repellent. The wild plants in the network of headlands and fence rows and along roadsides would be eliminated or coated with a repellent. Within the infested area the beetle population would be reduced by collecting the adult beetles by hand and by applying an aqueous solution of sodium cyanide to infested turf to kill the grubs.

The work to exterminate the beetle was delayed, however, until the summer of 1918 because of inadequate labor, equipment, and material. Wild food plants in the barrier zone, headlands, and along roadsides were dusted with a mixture of lead arsenate and lime, but the dust did not adhere well to the foliage so that it was difficult to keep the plants coated with the repellent. Boys, who were paid 80 cents a quart, collected 450 quarts of beetles within the infested area, but hand collecting made no noticeable change in the density of the beetle population. The beetle had no difficulty in passing through the barrier zone, and by the end of the summer the infested area had increased to 6.7 square miles.

In the fall of 1918, about 17 acres of heavily infested pastures were treated with sodium cyanide to kill the grubs. The cost of this treatment limited its application to small heavily infested areas. The grub mortality ranged from 38 to 100 percent. The noneconomic plants in the headlands and along roadsides were cut and burned during the fall and winter.

During 1919 the general program of eradication continued with modifications. Lime and sulfur dust and lime-sulfur solution, both less repellent than lead arsenate-lime dust but nonpoisonous to animals, were used in the barrier zone, on headlands, and along roadsides. The economic food plants within the area were sprayed with lead arsenate. In spite of the efforts to limit the dispersion of the beetle and reduce the population, the spread of the insect that summer was the greatest for any season up to that time. At the end of the summer, the infested area had increased to 48 square miles.

In the fall of 1919, about 50 acres of heavily infested pastures was treated with sodium cyanide. Much work was done during the winter in destroying the noneconomic food plants in the barrier zone, then 28 miles long.

A final effort was made in 1920 to eradicate the beetle. Plants in the barrier zone were dusted with lime and sulfur; noneconomic plants along roadsides were killed with various weed killers; heavily infested orchards were sprayed with lead arsenate; and beetles were collected by hand. At the end of the summer the infested area had about doubled in size to include 92 square miles in New Jersey and 11 square miles in Pennsylvania.

The program to eradicate the beetle in southern New Jersey was discontinued at the close of the summer of 1920 because it had not prevented the rapid increase in beetle populations from year to year and the great expansion of the infested area. (Agee *1919, 1920;* Goodwin *1919;* Howard *1918, 1919, 1920, 1921;* Davis *1920a, 1920b, 1920c;* Smith and Hadley *1926*)

The program to exterminate the beetle in southern New Jersey was undertaken in response to public demand before adequate information was available on the habits of the insect or practical methods had been developed for its control. A coating of a repellent on the plants in the barrier zone made them less attractive to the beetle, but it did not prevent the beetle from flying across the barrier zone. Collecting beetles by hand and treating a relatively small acreage with sodium cyanide to kill grubs, also did little to reduce the dense beetle populations. Failure to obtain even satisfactory control of the beetle stimulated research on the life history and habits of the insect and on the development of better control methods.

Maryland 1927-48

When isolated colonies of beetles began to appear in Maryland in 1927, traps were used throughout the State to detect and capture the adults, and the soil was treated with emulsified carbon disulfide to destroy the immature stages. The elimination of the isolated colonies was not always accomplished, but the program retarded the development of dense populations for about 10 years. (Cory and Sanders *1929*; Cory and Langford *1944*)

Beginning in 1937, dense populations of beetles invaded Maryland from Pennsylvania and Delaware and moved progressively southward. A statewide cooperative program was initiated in 1938 to retard the spread of the beetle and to protect crops and ornamental plants. The control activities included (1) the colonization of the insect parasites *Tiphia popilliavora* Rohwer, *T. vernalis* Rohwer, and *Hyperecteina aldrichi* Mesnil, the parasitic nematode *Neoaplectana glaseri* Steiner, and the milky disease bacteria *Bacillus popilliae* Dutky and *B. lentimorbus* Dutky to increase the effectiveness of the native biotic control complex; (2) the operation of about 127,000 traps to capture beetles; (3) the application of sprays and dusts containing lime, lead arsenate, rotenone, or DDT to protect crops and ornamental plants; (4) the application of low-gallonage concentrated sprays of insecticides by airplane and special ground equipment; (5) the application of lead arsenate, DDT, or chlordane to lawns and golf courses to protect the turf from grub injury; and (6) the modification of agronomic practices to avoid beetle damage. The program was largely successful because it reduced the density of beetle populations, retarded the spread of the insect, and protected the plants. (Cory and Langford *1944, 1945;* Langford *1940;* Langford et al. *1939, 1941b*)

Many insecticides mentioned in this publication have been removed from the market by the Environmental Protection Agency. They are mentioned here only as a historical review.

St. Louis, Mo., 1934-44

In the 1930's lead arsenate was applied extensively as a topdressing to turf where isolated colonies had developed to retard the buildup and dispersion of the beetle from these colonies. One extensive application of lead arsenate to turf was at St. Louis, Mo., about 800 miles from the generally infested beetle area. In this program against the beetle from 1934 to 1944, 347 tons of the arsenical were applied to about 700 acres of turf. Thousands of traps were operated throughout the city and also in the environs to locate infested areas and to evaluate the effectiveness of the treatment. By 1937 the thriving beetle colony was so reduced that only one beetle was captured in the traps. It was probably a hitchhiker as it was caught in a freight yard. During the following 7 years, only 130 beetles were captured in the St. Louis area. There is no doubt that the program retarded the spread of the insect into the agricultural areas for many years. (Stockwell *1935*; Dawson *1936, 1937, 1938*; Denning and Goff *1944*)

Blowing Rock, N.C., 1945-48

DDT was applied in 1945 to control an isolated colony of beetles at Blowing Rock, N.C., a summer resort and a bird sanctuary in the northwestern part of the State. It was applied as a dust at the rate of 25 pounds per acre to 257 acres of infested turf, and during the first 2 years it was sprayed or dusted on deciduous trees, shrubs, and vines subject to attack. A few acres of infested turf were not treated to follow the trend of the natural beetle population. Traps were placed throughout the treated and untreated areas.

From the trap captures in the untreated area, estimates showed that if DDT had not been applied to the 257 acres the number of beetles captured would have increased from 138,945 in 1944 to 9,865,095 in 1948. Actually the number of beetles captured declined progressively to 15,908 in 1948. The beetle population in the treated area remained low for several years, but in the surrounding countryside the beetles increased and spread rapidly.

The soil treatment practically eliminated the ground beetles, but it seemed to have little permanent effect on the native scarabaeid grubs, or on the staphylinids, wireworms, weevils, or ants. Sowbugs were killed but earthworms, garden slugs, millipedes, and centipedes did not seem to be affected. DDT seemed at that time to have no permanent effect on species of birds, small mammals, and fish. (Fleming and Hawley *1950*)

Sheldon, Ill., 1954-58

In 1953 a large isolated colony of beetles was found along the Illinois-Indiana border near Sheldon, Ill. The infested farms produced heavy crops of corn and soybeans and lesser amounts of alfalfa, red clover, and small grains. The area also produced limited amounts of milk, eggs, poultry, beef, pork, and sheep.

During 1954-58, granular dieldrin at the rate of 2 or 3 pounds per acre was broadcast by airplane to 17,844 acres of farmland in Illinois and to 3,460 acres in Indiana. An aerial spray at the rate of 3 pounds of dieldrin per acre was applied to a few acres.

The treatment applied early in the spring killed only about 50 percent of the third-instar grubs in the soil before pupation. Adult beetles were usually present in the treated area during the summer following the application of dieldrin. The insecticide had no effect on oviposition. However, grubs hatching in the treated soil were killed. Soil treated in the spring of 1954 and repeatedly plowed and cultivated was free of grubs in the fall of 1958. The beetle population in the heavily infested treated area was reduced to a low level, but in the lightly infested area that was not treated, the beetles increased progressively in numbers and spread into additional acres. In 1958 the beetles were found on approximately 50,000 acres around Sheldon. Although the treatment did not eliminate the beetle, it reduced dense populations of the insect to a low level and retarded the rate of spread.

Many species of economically important insect pests that came into occasional or frequent contact with the treated soil were controlled for 1 to 5 years, but a few species increased after the treatment. Some predators were adversely affected or eliminated by the dieldrin, whereas other predators and parasites appeared unharmed. The treatment did not eliminate earthworms.

Livestock confined to pastures or farmlots treated by airplane with granular dieldrin showed no ill effects, but milk from cows was contaminated. However, poisoning and death occurred in livestock, particularly sheep, exposed to drift from aerial sprays of dieldrin.

The magnitude of dieldrin residues found on forage treated with granular dieldrin depended upon the condition of the forage at the time of treatment. If the plants were wet with dew, the residue was much higher than when the plants were dry. The treatments were made early in the spring to minimize the contamination of the forage. (Luckman and Decker *1960*)

Sacramento, Calif., 1961-64

The beetle was first found in Sacramento in 1961. Traps were placed throughout the city and within a radius of 25 miles. Captures showed that the infestation covered 300 city blocks in Sacramento and 20 city blocks in West Sacramento, an area of about 1,000 acres. The only beetles captured outside the city were at two remote locations. One beetle, found at Mather Air Force Base, was considered a hitchhiker and not related to the city infestation. Three dead beetles found in traps at Citrus Heights proved to be a hoax, as later evidence showed that these beetles had been planted there.

A campaign started immediately to eradicate the pest. Carbaryl, 1 pound to 100 gallons of water, was sprayed on the foliage to kill the adult beetles and chlordane, 10 pounds per acre, was applied as a topdressing to the soil within the infested area to kill the grubs. The application of carbaryl was repeated at 10-day intervals during the flight of the beetle to maintain a toxic residue on the plants. During the summer of 1962, only five beetles were captured within the area treated the previous year and 26 in the untreated part of West Sacramento. Additional spray and soil treatments were applied to eliminate these infestations. The total acreage treated in the Sacramento area during 1961 and 1962 was approximately 3,500 acres; no beetles were found in intensive surveys in 1963 and 1964.

Several factors contributed to the eradication of the beetle in Sacramento. There is no rainfall during the summer when the beetle is in flight and the city is surrounded by thousands of acres of dry-farmed land where the beetle could not survive. Therefore, the city was not subjected to continuous reinfestation from outside sources. The luxuriant foliage and turf in the residential areas, maintained by frequent heavy watering, provide an excellent environment for the development of the beetle and tend to preclude widespread flights of the insect in search of food and oviposition sites. (Gammon *1961*)

Tennessee 1965-66

In 1964 an isolated colony of beetles was discovered in a 400-acre valley in eastern Tennessee. The valley was almost surrounded by densely forested hills that extended 300 to 500 feet above its floor. These hills prevented migration of the beetle into and out of the valley. The valley was largely farmland in pasture and fields of corn, soybeans, and clover. The lawns around the nine houses in the valley were bluegrass. The home gardens contained string beans, squash, sweet corn, carrots, lettuce, okra, grapevines, and apple trees. The shade trees around the homes included maple, willow, and hemlock. Adult beetles were most numerous around an apple-grape complex at the center of the valley and in fields of soybeans and patches of okra.

The valley was sprayed eight times by helicopter at 7-day intervals between June 8 and August 3, 1965, with an ultra-low volume of undiluted technical malathion at the rate of 8 ounces per acre. In 1966 and 1967 malathion was applied twice during the 2 weeks after adult beetles began to emerge from the ground.

Each application of malathion killed 70 to 100 percent of the beetles on the plants. The traps captured only 70 percent as many beetles in 1966 as in 1965. The spraying interrupted the normal buildup of a light population of beetles.

Malathion killed many unidentified parasitic insects. It eliminated the Mexican bean beetle (*Epilachna varivestis* Mulsant) and greatly reduced populations of grasshoppers (*Melanoplus* spp.). Malathion controlled some mosquitoes (Culicidae) but had little control of the house fly (*Musca domestica* Linnaeus). Spraying had no effect on the Calliphoridae, Carabidae, Cercopidae, Chrysomelidae, Coccinellidae, Gryliidae, Meloidae, Mycetophagidae, Tabanidae, or Vespidae. (Hamilton et al. *1967*)

Illinois 1966-68

Nearly 8,000 acres in St. Clair and Madison Counties, Ill., surrounding a beetle-infested soybean field of 10 acres, were sprayed in 1966, using four low-volume aerial applications of carbaryl at the rate of 0.8 pound per gallon per acre to reduce or destroy the beetle colonies. Most of the infested area was immediately north of the city limits of East St. Louis and included farms and land around homes, highways, and railroads. The area also extended as a narrow band of land along the Mississippi River immediately south of the larger area into the city and included stockyards, railroad yards and the grounds of a chemical plant and homes.

Effectiveness of the carbaryl sprays against the beetle was determined by collecting sprayed foliage of peach, plum, grape, and soybean in the field and caging beetles with the leaves. When the sprayed foliage was picked 1 to 7 days after the application of the spray, 97 to 100 percent of the beetles exposed to the residue on the leaves died within 2 days. When the foliage was picked 8 to 14 days after spraying, 58 to 98 percent of the beetles died within 3 days, and when it was collected 21 to 28 days after spraying, 93 to 99 percent of the beetles died within 7 days. This slow action of carbaryl might permit female beetles to oviposit before death.

Because the beetle population was light and irregularly distributed, the effect of the spraying on the population was determined by traps set in the same locations each season. In 1966 a 1.3-fold increase in the beetle population occurred over that in 1965. The sprays during the summer of 1966 killed a high percentage of the beetles. This kill may be the reason for the 97 percent fewer beetles being captured during the summer of 1967 than in 1966. In 1968 the population increased over that of 1967 but was 85 percent less than that of 1966. The degree of reduction that could be attributed to the 1966 spraying could not be definitely determined because a deficiency of 3.82 inches in the rainfall during that summer also reduced the 1966-67 population developing in the soil. The low-volume aerial sprays of carbaryl, however, were probably the primary reason for the low populations in 1967 and 1968. (Hamilton et al. *1971a*)

QUARANTINES

Federal quarantines 40 and 48, which became effective in 1920, regulated the interstate movement of all kinds of farm products and plants from the beetle-infested areas. Infested States imposed quarantines to regulate the intrastate movement of these products and plants. The general policy was to permit unrestricted movement within the regulated area of all agricultural products and plants and to restrict shipments beyond this area to uninfested products and plants. However, other items of commerce not regulated by the quarantines did, at times, carry the beetle to distant points.

When these quarantines were established, no precedent existed for treating the many agricultural products to remove or kill the beetle to obtain certification for shipment outside the regulated area. Satisfactory treatments were slow to develop because it was often easier to damage the agricultural product than to remove or kill the insect. Eventually, many satisfactory treatments were developed and authorized. (Fleming *1972a*)

The quarantine on farm products was in operation from the emergence of the adult beetle until none could be found in the area, approximately 3 months of the year. The authorized treatments for fruits and vegetables included the mechanical separation of the beetle from the products, and the fumigation of the products with various chemicals to kill the insect.

Safeguarding the movement of nursery and greenhouse plants and soil was the most important part of the quarantine because the immature stages of the beetle are in the soil throughout the year. Infestation of greenhouses and cold frames was prevented by screens and by following sanitary procedures. The authorized treatments included removal of all soil from the plant roots by washing with water, immersion of the soil of balled and potted plants in hot water or dilute insecticide dip, injection of a fumigant into the soil of balled and potted plants, fumigation of balled nursery stock in a chamber, application of a dilute insecticide emulsion or solution of a fumigant to the surface of the soil in the field before digging the plants, and mixing organic or inorganic residual insecticides with the soil before or after planting nursery stock.

In contrast to the fumigants that persist for only a short time in soil, a residual insecticide may be effective for several years in killing successive grub generations that hatch in the soil. With this treatment, large wholesale nurseries were able to treat plots of nursery stock en masse, instead of individual plants, and to dig and prepare the plants for shipment in the usual manner.

The quarantines were effective in preventing the artificial spread of the beetle by agricultural products, but they did not regulate the movement of other articles of commerce. The hazard always existed for adult beetles to hitchhike in private cars, trucks, railroad cars, ships, and airplanes, and escape when their conveyances reached a destination. Trucks and railroad cars carrying agricultural products were fumigated or treated with an insecticide dust during the flight of the adult beetle, but the treatment was not used in trucks and railroad cars carrying other products. Insecticides were applied to airplanes leaving infested airports when adult beetles were present. Although the opportunity for the artificial spread of the beetle in this manner at times seemed great, the establishment of isolated colonies at remote places did not seem to be in proportion to this hazard.

BIOLOGICAL CONTROL

Biological control of the beetle is the result of the actions of its natural enemies that eat, parasitize, or infect the pest. It is the existence of a condition where its enemies reduce beetle populations below the numerical level of economic damage. Fleming (*1958c, 1963b, 1968*) has summarized the biology, propagation, and colonization of the various predators, parasites, and pathogens attacking the grubs and adult beetles.

Native Predators, Parasites, and Pathogens

Insectiverous wild birds and domestic fowl feed readily on adult beetles, and moles, shrews, and skunks destroy large numbers of grubs. These predators, along with the few predaceous and parasitic insects indigenous to the Eastern United States, periodically have reduced beetle populations within limited areas, but their efforts have been too restricted and too sporadic to have much effect on the population within a region.

Entomogenous pathogens in the soil were the most effective of the native biological control complex in reducing grub populations. Diseased grubs were found in the field in New Jersey as early as 1921 (Smith and Hadley *1926*), and by 1933 in Delaware and Pennsylvania (Hadley and Hawley *1934*). Fox (*1937*) made periodic soil surveys for 7 years within 12 miles of where the beetle was first discovered and determined the destructive effect of the pathogens. Beginning late in June and extending through July and August, the grubs of the new generation increased steadily in numbers until the maximum population was reached early in September. Then there was a progressive decrease in the population until mid-November when the soil temperature reached 10° C, and the activities of the grubs and the pathogens ceased for the winter. At that time the grub mortality was 21 percent. Late in March the grubs and the pathogens became active again. Early in June, before emergence of adult beetles from the soil, the grub mortality increased to 43 percent.

When the rainfall was favorable for the development of the eggs and newly hatched grubs in New Jersey during 1920-35, a grub mortality of 43 percent was not sufficient to prevent a 1.5- to 3.5-fold increase in beetles the following summer (Fleming *1972b*). The growth rate of an isolated beetle colony in eastern Tennessee was 1.8- to 2.2-fold per year (Ladd et al. *1972*). Under favorable conditions there was an average 2-fold increase in beetle populations per year.

Although the female beetle has the capacity to lay 40 to 60 eggs during her life (Smith and Hadley *1926*; Hadley and Hawley *1934*; Fleming

1963b, *1972b*), all eggs are rarely deposited in the field. An estimate showed that only 4 eggs per female would be sufficient to maintain the adult population at the same level the following summer, even with a 43 percent decrease.

Foreign Predators and Parasites

The former U.S. Bureau of Entomology imported 7 species of Tachinidae, 14 of Tiphiidae, 2 of Scoliidae, and 1 each of Carabidae, Ithonidae, and Pyrogotidae from the Orient for colonization in the beetle-infested area in the United States. Five of the species became established, but only two of them, *Tiphia popilliavora* Rohwer and *T. vernalis* Rohwer, persisted in this country. Both species of *Tiphia* parasitize only grubs of the genus *Popillia*. Because the Japanese beetle is the only member of that genus in this country, the survival of *Tiphia* is dependent to a large extent upon adequate populations of *Popillia* grubs.

When the *Tiphia* wasps were colonized in areas of adequate grub population, the parasites soon became established, increased rapidly in numbers and effectiveness, and spread to uncolonized areas. After *Tiphia* became abundant in densely populated beetle areas, about 60 percent of the grubs were parasitized. In addition to the action of the native pathogens, parasitism to this extent caused a progressive decrease in beetle populations, even when the rainfall was favorable for development of the immature stages. However, as grub populations decreased, the effectiveness of the *Tiphia* was reduced because it became increasingly more difficult for the wasps to find the grubs in the soil. The parasitism was about 30 percent with a grub population of 2 per square foot and less than 20 percent with 1 grub per square foot. *Tiphia* wasps helped the native biotic control complex reduce dense grub populations but were of little value against light grub populations. (Balock *1934*; Brunson *1934*, *1937*, *1938*; Gardner *1938*; Hadley *1938*; Hawley *1944*; King *1931*, *1937*, *1939*; King and Halloway *1930*; King and Parker *1950*; King, Parker, and Willard *1951*)

Nematode *Neoaplectana glaseri* Steiner

The nematode *Neoaplectana glaseri* was found attacking *Popillia* grubs at Haddonfield, N.J., in 1929 (Glaser and Fox *1930*). It was a new species (Steiner *1929*). It did not attack plants (Glaser *1931*, *1932*). Glaser et al. (*1940*) discussed the biology and the importance of this nematode parasite of insects. *N. chresima* Steiner is another nematode of this genus parasitizing the grubs (Glaser et al. *1942*).

N. glaseri was colonized throughout New Jersey (Girth et al. *1940*) and in parts of Maryland (Cory and Langford *1944*). The optimum conditions for the establishment of the nematode are a soil temperature above 15.5° C, a wet soil, turf or other permanent ground cover, and a dense grub population (Glaser and Farrell *1935*). A film of moisture is necessary for the movement and respiration of the nematode. Ensheathed nematodes cannot withstand dessication (Girth et al. *1940*; Dutky *1959*). In a suitable environment *N. glaseri* parasitized up to 81 percent of the grubs (Glaser and Farrell *1935;* Girth et al. *1940*), but it was not generally effective throughout the area infested by the beetle.

Bacteria *Bacillus popilliae* Dutky and *B. lentimorbus* Dutky

Dutky (*1963*) and Fleming (*1958c, 1968*) have summarized the "milky diseases" of white grubs caused by *Bacillus popilliae* and *B. lentimorbus.* These bacterial strains that infect *Popillia* grubs are a part of the complex that infect different species of Scarabaeidae.

In 1933 grubs infected by *B. popilliae* were found in New Jersey (Hawley and White *1935*; Hawley *1952*). In 1935 the disease was prevalent at most places where the beetle had lived for several years, but it was not found in more recently infested areas (Hadley *1938*). Over 90 percent of the diseased grubs in the field was infected by *B. popilliae* or *B. lentimorbus* (White and Dutky *1940*).

The spores of these bacteria are resistant to adverse field conditions and may remain viable for several years and ready to infect successive generations of grubs (White *1940*). All larval instars of the beetle are susceptible to infection by *B. popilliae* (Beard *1945*) at soil temperatures between 16° and 36° C (Dutky *1940*), but infection by *B. lentimorbus* is largely restricted to first- and second-instar grubs (Dutky *1963*) at temperatures between 16° and 30° (Dutky *1940*). A decomposing cadaver liberates 2 billion (Langford et al. *1942*; Beard *1945*) to 5 billion (Dutky *1940*) spores in the soil.

The rapidity of the buildup of spores in the soil is influenced by the density of the grub population and the length of time that the soil temperature stays above 21° C. A definite increase in the number of spores occurred within 1 year in Virginia (White and Dutky *1940*), but 3 to 4 years were required in New York (Adams and Wheeler *1946*) and Connecticut (Garman et al. *1942*) with much shorter growing seasons.

In the absence of an artificial medium for producing the spores in abundance, Dutky (*1942a*) produced the spores in the blood of grubs and incorporated them in a dust for distribution in the field. The process was patented (Dutky *1941, 1942b*). During 1939 to 1951, a total of 178,000 pounds of spore dust containing 100 million spores per gram was applied to 101,000 acres at 132,000 sites in 14 States and the District of Columbia to accelerate the natural buildup and spread of the pathogen (Fleming *1968*). Spore dust was usually applied to two 1/2-acre plots of infested turf in each square mile of open country at 3.5-mile intervals and to one 1/2-acre in each 10 acres of a golf course, park, or cemetery (White and McCabe *1943*). In making an application, 2 grams of spore dust (200 million spores) were deposited at intervals of 10 feet over the turf (White and Dutky *1942*).

In a 10-year study at a site where *B. popilliae* had become well established, the pathogen caused a reduction of 86 to 94 percent in the successive annual grub populations by mid-June (White and McCabe *1950*). This demonstrated the high effectiveness and persistence of the bacterium in the field.

The public was enthusiastic over the use of *B. popilliae* to control grubs in lawns on private properties, but misinformation was widely spread. To provide valid information about the pathogen, Hadley (*1948*) and Fleming (*1961*) discussed the nature of the bacterium, the application of spore dust, and how much control of the grubs could be expected.

To obtain information on the status of *B. popilliae* in the field, soil assays were made in 1960-63 of 48 golf courses and pastures in 6 States that had been inoculated with spores about 20 years previously and of 12 uninoculated pastures within 1 or 2 miles of an inoculated site. The pathogen was found at all of the sites. The density of the spores ranged from 1 million to 1.6 billion per kilogram of soil at the colonized sites and from 1 to 800 million at the sites where it had developed naturally. (Fleming *1968*)

Ladd and McCabe (*1967*) continued the study and made assays of the soil at 35 selected sites in 11 New Jersey counties. The mean density of spores per kilogram of soil was 129 million in turf colonized 25 years ago with an initial grub population of 26.7 per square foot, 122 million in turf colonized at that time with an initial grub population of 5.8 per square foot, 332 million in uncolonized pastures, and 5 million in uncolonized cultivated fields. Because beetle populations have been relatively low in New Jersey since the mid-1940's, the demonstration of large numbers of infective spores in New Jersey soils is an indication of the efficiency, persistence, and natural spread of the pathogen.

Hutton and Burbutis (*1974*) reported that *B. popilliae* was still present and effective in most of the sites in Delaware where the soil had been inoculated about 30 years ago. In Connecticut, beetle populations declined during the late 1940's, and for 25 years the beetle had not been an important pest. Beard (*1964*) reported that infection of the grubs by *B. popilliae* was so extensive that the beetle would not become a problem except in areas where the bacterium and the other natural biological control agents were absent. Occasionally the development of localized colonies suggested a resurgence of the beetle, but dense populations did not develop until recently. In 1973 and 1974, in spite of the buildup of spores in the soil over the years, dense grub populations throughout Connecticut caused severe damage to turf. The incidence of infection was usually not more than 5 percent in areas where the bacterium had killed up to 94 percent of the grubs. (Dunbar and Beard *1975a*)

No adequate explanation was available for the resurgence of the beetle in Connecticut. Connecticut grubs were no less susceptible to infection than those from New York and Ohio, but in all cases the extent of infection by injection or ingestion of spores was less than obtained previously by Beard (*1944*). In a comparative ingestion test, 1940 spore dust infected 41.9 percent of the grubs and 1974 commercial spore dust only 17.2 percent. When the blood of infected grubs was injected into healthy grubs, the progeny of the old spores produced almost five times as many spores per grub as did the progeny of the 1974 spores, and the percentage of the grubs infected was 80 and 16.7, respectively, indicating a lower productivity and weakening of the 1974 bacterium. (Dunbar and Beard *1975a, 1975b*)

Biological Control Complex

The predators, parasites, and pathogens indigenous to the Eastern United States were not sufficiently effective to prevent a progressive increase in beetle populations. The dense beetle populations of the 1920's and 1930's favored the establishment and spread of the imported parasitic *Tiphia* wasps and *Bacillus popilliae*. The wasps and the bacterium were compatible. The colonization of the wasps and the bacterium so increased the effectiveness of the native control complex that beetle populations declined. Economic damage to plants has declined greatly in the Middle Atlantic States, and severe damage often is limited to isolated areas in that region. Researchers knew that the wasps were not effective when beetle populations reached a low level, but they did not know until recently that with low beetle populations the pathogen could also decrease in effectiveness.

PLANTING TO AVOID ADULT BEETLE INJURY

Immune Species

Although the beetle feeds on almost 300 species of plants, it feeds sparingly or not at all on many cultivated plants. Fleming (*1972b*) has summarized the extent of feeding on various plants according to families, genera, and species. When beetles were abundant, damage to plants was avoided by using species that were immune or seldom attacked by the insect. A list of plants that may be used for this purpose follows:

Small fruits: American cranberry, black huckleberry, European gooseberry, northern dewberry, northern gooseberry.

Orchard fruits: Pear, persimmon.

Truck and garden crops: Artichoke, brussel sprouts, cabbage, cantaloup, cauliflower, celery, onion, cucumber, eggplant, endive, carrot, pea, radish, kale, leak, lettuce, muskmelon, parsley, parsnip, peanut, potato, pumpkin, red pepper, rutabaga, salsify, spinach, summer squash, sweetpotato, tomato, turnip, watermelon.

Field crops: Barley, buckwheat, hops, millet, oats, rye, timothy, tobacco, vetch, wheat.

Ornamental herbs: Adam's needle yucca, ageratum, American columbine, American germander, American pennyroyal, American waterlily, American wormseed, anise, babysbreath, bearded iris, begonia, blue false-indigo, browneyedsusan, butterfly violet, caladium, carnation, catnip, Chile avens, Chinese lantern-plant, Christmas-rose, chufa, cockscomb, bamboo, cosmos, mignonette, portulaca, coneflower, coralbells, cornflower, gysophila, dogtooth violet, dusty-miller, Easter lily, European columbine, evergreen candytuft, false-dragonhead, flowering tobacco, forget-me-not, foxglove, fringed iris, gaillardia, balsam, nasturtium, petunia, verbena, goldenglow, ground-myrtle, hardy larkspur, hyssop, Iceland poppy, Japanese iris, Japanese spurge, lance coreopsis, lily-of-the-valley, mountain-bluet, motherwort, mullein, New England aster, oriental poppy, aswego-tea, oxeye daisy, Pacific bleedingheart, pampasgrass, pansy, perennial pea, phlox, purple loosestrife, pyrethrum, lily, sedum, skydrop aster, small white aster, snapdragon, southern maidenhair fern, spearmint, speedwell, spiderwort, strawflower, sweetpea, sweet scabious, sweet violet, sweet-william, tawny daylily, tiger lily, Virginia dayflower, wandering-Jew, wave aster, white-top, white turtlehead, wild bergamot.

Ornamental shrubs and vines: American bittersweet, American bladdernut, American elder, American holly, beautyberry, border forsythia, box, Canada yew, Carolina allspice. Catawba rhododendron, Chinese azalea, Chinese holly, Chinese redbud, climbing euonymus, climbing hydrangea, lilac, privet, coralberry, English holly, English ivy, European cranberry bush, firethorn, gardenia, groundsel-bush, Japanese holly, Japanese honeysuckle, lantana, mockorange, mountain-laurel, matrimonyvine, panicle hydrangea, Persian lilac, pinxterbloom azalea, rosebay rhododendron, smooth hydrangea, snowberry, swamp azalea, sweet autumn clematis, torch azalea, tubeclematis, weeping forsythia, winged euonymus, winterberry, winter honeysuckle, witchhazel.

Trees: Ailanthus, Atlantic white-cedar, American arborvitae, American hazelnut, American sweetgum, balsam fir, black locust, black oak, Bolleana poplar, boxelder, butternut, Canada yew, Chinese juniper, common juniper, common smoketree, cryptomeria, Douglas fir, English yew, flowering dogwood, hemlock, Hinoki-cypress, Japanese pagodatree, Japanese yew, laurel magnolia, Lawson white-cedar, maidenhair tree, mimosa, northern red oak, Norway spruce, Oriental arborvitae, pignut hickory, post oak, red ash, red maple, red mulberry, saucer magnolia, Sawara-cypress, scarlet oak, Scotch pine, shagbark hickory, silver maple, southern magnolia, southern red oak, tuliptree, Virginia pine, western yew, white ash, white oak, white poplar.

Hadley (*1940*), Cory and Langford (*1955*), and Fleming (*1955, 1960*) recommended that in planning new ornamental plantings or modifying established plantings in areas where the beetle is a problem, that consideration be given to herbs, shrubs, vines, and trees not preferred by the beetle.

Resistant Varieties

Often individual plants of a species preferred by the beetle receive only slight injury while adjacent plants of the same species are completely defoliated. Varietal differences have occurred with American basswood (*Tilia americana* L.), apple (*Malus sylvestris* Mill.), grape (*Vitis* spp.), Norway maple (*Acer platanoides* L.), peach (*Prunus persica* (L.) Batsch), rose (*Rosa* spp.), and other species seriously injured by the adult beetle.

Grapes

The grape varieties commonly cultivated in the northeastern United States are subject to defoliation by the beetle. Langford and Cory (*1948*) studied the relative susceptibility of different varieties to attack by the beetle in a large heavily infested vineyard growing many varieties of grapes. The injury ranged from defoliation to slight nibbling.

Varieties defoliated were America, Baco, Bell, Brilliant, Cabernot, Sauvignon, Concord, Cynthiana, Manito, New York (Geneva) 10839, N.Y. 11407, N.Y. 11456, N.Y. 13920, N.Y. 20159, Niagara, Norton, Pinot de Chardonnay, Rommel, Seibel 128, Seibel 1000, Seibel 1xx, Seibel 2xx, Seibel 2056, Seibel 5279, Seibel 5409, Seibel 6339, Seibel 9110, Bertile-Seyve 2862, Couderc 13, Couderc 4401, Seyve-Villard 12309, WineKing, and Worden. These varieties were preferred by the beetle and were fed on continuously throughout the summer with complete destruction of the foliage. Beetles collected first on these varieties and left them last. They ate the entire leaf except the main ribs. Most of these varieties have thin, glossy, succulent foliage, but some of them have leathery foliage. Most varieties have considerable European grape (*Vitis vinifera* L.) in them. The American species included in these crosses include *V. aestivalis* Michx., *V. labrusca* L., *V. lincecumii* Buckl., *V. riparia* Michx., and *V. rupestris* Scheele.

The varieties Catawba, Cloeta, Delicatessen, and Lomanto were only slightly less preferred by the beetle than those in the previous group. Cloeta and Delicatessen have leaves that are smooth and leathery above and glabrous on the underside— they were eaten entirely by the beetle except for the principal veins. The leaves of the varieties Catawba and Lomanto are somewhat tomentose or woolly on the undersurface, and when the beetles finished feeding, the leaves resembled fragile lace.

The varieties Diamond, Iona, and Westfield were much less attractive to beetles than those in the previous groups. The injury was moderate. The foliage is coarse and leathery above, and tomentose on the underside. Much of the leaf is not eaten. After beetle feeding, the leaves looked like coarse lace.

The variety Champanel was not relished by the beetle. Under conditions of heavy infestation the vines of this variety even next to preferred varieties seldom had more than an occasional beetle on them. The foliage and tender shoots are covered with a coarse tomentum, and the peculiar woolly foliage is a characteristic of one of its parents *V. champini.*

Apples

The foliage of apple varieties varies in susceptibility to beetle attack. Langford and Cory (*1948*) studied the susceptibility to injury of 55 varieties of 1- and 2-year-old apple trees growing in nursery rows. Sometimes the most preferred varieties would be completely defoliated while the least preferred showed practically no injury.

The varieties most preferred and severely injured were Yellow Transparent, C. P. Close, Starr, Red Duchess, Yellow Newton, Anoka, Crimson Beauty, Delicious, Golden Delicious, Gallia Beauty, Lodi Smokehouse, Twenty Ounce, Winter Banana, and Wrixparent.

The varieties somewhat less attractive but injured severely were Early Blaxtayman, Kendall, Lawfam, Macoun, Melba, Opalescent, Paragon, Redcanada, Turley, Williams, Red Astrachan, Winesap, Jonathan, Richared Delicious, and Stayman Winesap.

The varieties frequently attacked with moderate injury were Baldwin, Colora York, Early McIntosh, Grimes Golden, Lobo, Northern Spy, Rome Beauty, Redrome, Red Gravenstein, Redspy, Tolman Sweet, Ralls, Red Johnathan, Red McIntosh, Lowry, Medina, Red Warrier, Rhode Island Greening, and Secor.

The unattractive varieties which were injured only lightly and occasionally were Cortland, Milton, Orleans, McIntosh, Blaxtayman, York Imperial, and Wealthy.

Peaches

Peach foliage is less attractive to the beetle than apple or grape, but when beetles are abundant considerable damage may be done. The beetle rarely attacks leaves borne on new wood—it prefers to feed on the underside of mature leaves, making many small holes. The extent of feeding on peach leaves is related to feeding on the fruit. The beetle is strongly attracted to the odor of ripening peaches and at times gathers in such large numbers that the fruit is covered completely. The feeding on ripening fruit continues until nothing edible remains. Tree foliage with ripening fruit is eaten more extensively than that of trees without fruit or with immature fruit. The beetle does not feed on immature peaches unless they are diseased. Fruit ripening late in the season is seldom injured because at that time few beetles are in the orchards.

The varieties of peaches most severely injured by the beetle were Arp, Belle, Carman, Cumberland, Early Rose, Early Wheeler, Golden Jubilee, Greensboro, Raritan Rose, Redhaven, Rochester, Sunhigh, and Triogem.

Varieties moderately injured with 10 to 15 percent of the fruit eaten by the beetle were Goldeneast, Goldenglobe, Halehaven, J. H. Hale, Redrose, and Summercrest.

Varieties seldom attacked by the beetle and then only lightly were Elberta, Kimbo, and Hiley. (Smith and Hadley *1926*; Fleming and Metzger *1936a*; Hawley and Metzger *1940*; Fleming *1963a*)

Corn

The adult beetle injures corn (*Zea mays*) by feeding on the foliage, cutting the developing silk, and opening the tips of the husks to permit the collection of moisture that favors the growth of molds. Heavy infestations of sap beetles, particularly *Carpophilus lugubris* Murry, were associated with beetle injury (Lee, Langford, and Cory *1953*). Feeding on the foliage probably did not seriously affect yield. Adequate pollination of corn in the field requires 7 to 8 hours (Coon *1945, 1951*; Rutschky *1959*). When the silk is sheared off by the beetle during the flow of pollen, adequate fertilization of the ears is not accomplished.

During 1938-41 Langford et al. (*1944*) tested the resistance of 46 varieties of corn to injury by the beetle. Early, mid-season, and late varieties were planted so that all were in silk when beetles were abundant. The amount of damage varied with the varieties. At harvest 21.3 percent of the ears of the most resistant variety had been damaged, and 82.5 percent of the ears of the most susceptible variety. The loss of grain by beetle damage ranged from 5.5 to 40.6 percent.

Although the beetle preferred some varieties, varietal resistance was not established. When several varieties were planted in the same field, beetles tended to congregate on the most preferred varieties, but in the absence of preferred varieties more extensive damage occurred on varieties that previously had appeared to be somewhat resistant to beetle attack.

Soybeans

Feeding by the beetle on soybean (*Glycine max*) results in a partial or total plant defoliation. The beetles feed on both sides of the leaves and gnaw the tissue until only the larger veins remain. Most of the feeding occurs on the upper surface of leaves exposed to sunlight. The injured leaves turn brown and drop to the ground. Some feeding also takes place on the blossoms.

Coon (*1946*) and Hawley, King, and Dobbins[2] (unpublished) tested the resistance of almost 200 varieties of soybeans to injury by the beetle— all varieties were susceptible to attack. The varieties Chief, Illini, Viking, and Wilson 5 were considered to be moderately resistant and Earlyana, Hobara, Patoka, Richland, and Seneca the most susceptible to attack.

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[2]Unpublished records of J. M. Hawley, J. L. King, and T. N. Dobbins, former USDA entomologists.

The extent of injury was modified by the density and distribution of the beetles and by the attractiveness of the different varieties to the beetle. Feeding increased as the beetle population increased until peak population was reached. Then, as the population decreased rapidly, the beetles fed less. Distribution of the beetles in a field was heterogeneous. Beetles tended to gather in large numbers on certain plants while other plants of the same variety were less densely populated.

Early varieties that matured while beetles were abundant, or shortly thereafter, were the most attractive to the beetle. The feeding on the foliage was the most extensive. The plants failed to recover after the beetles disappeared and yields of beans and forage were low. On the other hand, the late varieties were less attractive to the beetle. After the beetle reached its peak and disappeared, the late varieties developed additional branches and leaves to such an extent that beetle injury was not apparent on the mature plants. Studies by Gould (*1960, 1963*) showed that removal of up to 25 percent of the foliage while the plants were growing vigorously had little effect on the yields, but leaf damage when the plants were beginning to mature reduced the yield.

Early and Late Planting

Corn

Much of the damage to ears of corn by the beetle was avoided by regulating the planting time so that silking occurred before or after beetles were abundant. During 1951-53 in northern Virginia no injury occurred in cornfields that were in silk before July 20 or after August 1 (Woodside *1954*). During 1938-41 in northern Maryland only light injury occurred in cornfields in silk after August 10 (Langford et al. *1944*). During 1943-45 most of the silk in cornfields in Nassau County, N.Y., was pollinated before beetles became abundant so that shearing the silk by the beetle had little effect on the development of the ears (Carruth et al. *1946*).

Woodside (*1954*) recommended early rather than late planting to permit corn to mature and be harvested early enough for seeding of small grain. Langford et al. (*1944*) and Cory and Langford (*1944, 1955*) recommended later planting, but Langford (*1940*) previously had questioned the value of late planting because sometimes frost injury occurred before the corn matured.

Herbaceous Ornamentals

Cannas, dahlias, and zinnias are usually seriously injured by the beetle; however, much of the bloom damage can be avoided by so delaying the planting that blooming occurs after the peak of beetle abundance.

REDUCING ADULT BEETLE POPULATIONS

Any method that reduces the number of beetles on the premises is of some value in insect control. Unless used with other control measures, the reduction in the population may not be sufficient for adequate plant protection.

Hand Collecting

Davis (*1920a, 1920b*) paid boys 80 cents a quart for beetles collected from such low-growing plants as smartweed (*Polygonum pensylvanicum* L.), sassafras (*Sassafras albidum* (Nutt.) Ness), and grape (*Vitis* spp.), favorite food plants of beetles. During 1919 about 450 quarts, or 1.5 million feeding beetles, were collected with a net and killed by saturating them with gasoline. Destruction of these beetles had little effect on the rapidly increasing beetle population.

One of the easiest ways to remove beetles from plants is to shake the plants before 7 a.m., e.s.t., when the temperature is low and the beetles are sluggish. Beetles do not fly under these conditions. Instead, they fold their legs compactly to their bodies, drop to the ground, and feign death. Fleming and Metzger (*1936b*), Hadley (*1940*), and Fleming (*1955*) used this method to catch beetles. Sheets of canvas were placed beneath the plants to catch the beetles as they fell. The beetles were then killed by dumping the contents of the sheets into pails that contained water and a little kerosene.

When only a few plants on the premises were subjected to injury, partial temporary protection was obtained by collecting beetles daily throughout the season. Because the beetle is a gregarious insect, an accumulation of them on a plant attracts other beetles flying in the vicinity. Van Leeuwen (*1932a*) found that when a plant was kept practically free of beetles by removing them as they alighted only about half as many were attracted to the plant as to a plant of the same species in the vicinity where beetles were allowed to accumulate. Systematic hand collecting, therefore, reduced beetle feeding and prevented defoliation of plants.

Cultural Control

Green fruits of apples, peaches, and grapes that ripened after the peak of the beetle season are not usually injured by beetles, but when the fruits are damaged by disease or other insects, they become attractive to beetles. After consuming the damaged fruits, beetles attack healthy green fruits.

Adequate control of the codling moth (*Laspeyresia pomonella* (Linnaeus)) and black rot (*Botryosphaeria ribis* Gross and Dug.) on apples, peach yellows (*Chlorogenus persicae* Holmes) and brown rot (*Monilinia fructicola* (Wint.)) on peaches, and grape berry moth (*Paralobesia viteana* (Clemens)) and black rot (*Guignardia bidwellii* (Ell.) Viala and Ravaz) on grapes retarded the buildup of beetle populations on the plants. (Smith and Hadley *1926*; Fleming, Metzger, and Osburn *1934a*; Fleming and Metzger *1936a*; Fleming and Maines *1947b*).

Beetles are also fond of certain weeds, including sarsaparilla (*Aralia hispida* Vent.), hedge smartweed (*Polygonum scandens* L.), eveningprimrose (*Oenothera biennis* L.), ragweed (*Ambrosia artemisiifolia* L.), sassafras (*Sassafras albidum* (Nutt.) Nees), marshpepper smartweed (*Polygonum hydropiper* L.), eastern bracken (*Pteridium aquilinum* (L.) Kuhn), foxgrape (*Vitis labrusca* L.), giant ragweed (*Ambrosia trifida* L.), dwarf mallow (*Malva rotundifolia* L.), Pennsylvania smartweed (*Polygonum pensylvanicum* L.), pickerelweed (*Pontederia cordata* L.), poison ivy (*Rhus radicans* (L.) Ktze.), and summer grape (*Vitis aestivalis* Michx.). These wild plants in or around a field or orchard are often a continuous source of infestation for the crops. With these weeds present, crops not normally attached by the beetle may be injured; however, the beetle population on a crop was reduced by eliminating these favored wild plants.

Mechanical Traps

Millions of beetles have been captured annually in mechanical traps. This method is an easy and inexpensive way to reduce beetle populations and curtail egg laying. Traps do not catch all the beetles, however. The best control is obtained when traps are used in large numbers over the entire community.

Chemical Lures

The beetle is attracted to a wide variety of unrelated odoriferous substances because beetles are cosmopolites when it comes to food choice. Fleming (*1969*) has summarized the scattered information on chemical lures during 1919-64.

Geraniol plus Eugenol.—In 1923 technical geraniol, a complex mixture of geraniol with other alcohols, esters, aldehydes, and other compounds, was found attractive to the beetle (Smith *1924a, 1924b*). Its use as an insect lure was patented (Smith et al. *1926*). The specifications developed by Metzger and Maines (*1935*) were not adequate to obtain only highly attractive technical geraniols (Jones and Haller *1940*). Beroza and Sarmiento (*1966*) suggested a technical geraniol of the desired composition might be procured through gas chromatography analysis. When the components of a technical geraniol were isolated and purified by Jones and Haller (*1941*), eugenol was the most attractive constituent (Fleming *1969*). Geraniol was not the primary attractant, as thought by Richmond (*1927*), who tested only various grades of technical geraniol.

Lots of technical geraniol varying in attractiveness from 65 to 90 percent and chemically pure (C.P.) geraniol with an attractiveness of 20 percent became equally attractive when mixed 9:1 or 10:1 with U.S.P. eugenol (Fleming *1969*). The 10:1 mixture was recommended as a lure by Metzger (*1928, 1932, 1934b, 1936*), Van Leeuwen and Metzger (*1930*), and Fleming et al. (*1940b*). Use of the geraniol-eugenol lure was discontinued in 1944 when technical geraniol was in short supply, expensive, and of poor quality.

The attractiveness of the 10:1 lure was enhanced by increasing the rate of evaporation. The attractiveness was increased 20 percent by doubling the evaporation and 40 percent by quadrupling it (Metzger *1933b*). However, increasing the amount of lure required to bait the traps proved unsuitable.

Changing the ratio of geraniol-eugenol from 10:1 to 1:1 increased the attractiveness 50 percent, but the modified formulation was considered too costly (Fleming and Burgess *1940*). However, when the 1:1 lure was diluted 30 percent with a 1:1 mixture of white mineral oil and deobase, the mixture proved a good lure. The diluted 1:1 mixture was 40 percent more attractive than the 10:1 lure (Muma et al. *1944*, *1945*). For this reason the diluted lure was used extensively in Maryland.

Attractiveness of geraniol-eugenol mixtures was enhanced by adding caproic acid (Langford and Cory *1946*), phenylethyl acetate (Langford and Gilbert *1949*), phenylethyl alcohol (Metzger *1935*), phenylethyl butyrate (Langford and Cory *1946*), or phenyl iso-valerate (Langford and Cory *1946*). The 10:2:1 geraniol, eugenol, phenylethyl alcohol mixture was used by the Department during 1936-39.

Anethole plus Eugenol.—The 9:1 mixture of synthetic anethole, derived from pine oil and meeting the specifications of the National Formulary, and U.S.P. eugenol was equivalent in attractiveness to 10:1 geraniol-eugenol (Fleming and Chisholm *1944*). Satisfactory lures were prepared with technical anethole almost meeting the requirements of the National Formulary, but mixtures made with anethole obtained by the fractional distillation of star anise oil and the lower grade of synthetic technical anethole were usually 76 to 90 percent as attractive.

The 9:1 mixture of technical anethole almost meeting the requirements of the National Formulary and U.S.P. eugenol was recommended by

Fleming and Chisholm (*1944*), Fleming et al. (*1946*), U.S. Department of Agriculture (*1949*), and Fleming (*1955*, *1958b*, *1960*, *1963a*). The general use of the anethole-eugenol lure was discontinued in 1965 when traps with that lure captured large numbers of bumblebees (*Bombus* spp.) (Hamilton et al. 1970). Ladd et al. (*1974b*) found that geraniol, geraniol-eugenol, anethole, and anethole-eugenol were equally attractive to bumblebees, whereas anethole and lures containing anethole were attractive to honey bees (*Apis mellifera* L.).

Phenylethyl Butyrate plus Eugenol.—A 9:1 mixture of phenylethyl butyrate (PEB) and eugenol was not significantly different in attraction from 9:1 geraniol-eugenol (Langford and Cory *1946*; Schwartz and Hamilton *1969*; Schwartz et al. *1966*, *1970*). The 9:1 PEB-eugenol lure replaced anethole-eugenol in 1966.

The addition of caproic acid to some PEB-eugenol mixtures greatly enhanced their attractiveness. The 8:1:1 mixture was 2.8 times as attractive as 9:1 geraniol-eugenol, and the 18:1:1 mixture 3 times (Langford and Cory *1946*). The 8:1:1 mixture was recommended by Langford and Cory as a replacement for geraniol-eugenol but was not used extensively.

Methyl Cyclohexanepropionate plus Eugenol.—McGovern et al. (*1970b*) found that a 9:1 mixture of methyl cyclohexanepropionate (MCP) and eugenol was 2.5 to 3.0 times as attractive as PEB-eugenol. Ladd (*1971*) found the 9:1 MCP-eugenol 2.6 times as attractive as 9:1 PEB-eugenol. The 9:1 MCP-eugenol was 7 to 9 times more volatile than 9:1 PEB-eugenol (McGovern and Beroza *1970*). The more frequent baiting of traps and the larger quantities of bait required made MCP-eugenol impractical as a substitute for PEB-eugenol.

Phenylethyl Propionate plus Eugenol.—Of the 23 chemicals that included the structural features of PEB or MCP tested in combination with eugenol, the most attractive was phenylethyl propionate (PEP). The 9:1 mixture was 2 times, and the 7:3 and the 1:9 mixtures 4.3 times as attractive as 9:1 PEB-eugenol. Because PEP is more volatile than eugenol, the composition of the 7:3 PEP-eugenol mixture would move during evaporation toward the 1:9 mixture. (McGovern et al. *1970a*) Ladd et al. (*1973c*) found that 7:3 PEP-eugenol was 2.5 times as attractive as 7:3 PEB-eugenol and 4 to 5 times as attractive as 9:1 PEB-eugenol. The 7:3 PEP-eugenol did not change in attractiveness during a 10-week exposure in the field (Ladd et al. *1974a*).

Of the phenylethyl esters of the carboxylic acids mixed 7:3 with eugenol, only the mixtures containing phenylethyl acetate or PEP were equally attractive. Mixtures containing the other esters were much less attractive. (Ladd et al. *1973c*)

The aryl-substituted phenylethyl and phenoxyethyl acetates and the alkyl-substituted phenylethyl and benzyl acetates mixed 7:3 with eugenol were less than 60 percent as attractive as 7:3 PEP-eugenol. However, an additive, heptyl-2-methyl butyrate, increased the attraction about 30 percent. (McGovern et al. *1973b*)

The 7:3 PEP mixture was patented by McGovern et al. (*1973a*) as a potent attractant for the beetle. This lure has been used by the Department since 1970.

Fermented Baits

Fermented malt sirup and fermented apple juice were more attractive to beetles than unfermented products (Van Leeuwen et al. *1928*). A fermenting sugar, however, was only one-fourth as attractive as 9:1 geraniol-eugenol (Schwartz et al. *1966*).

Sex Pheromone

Emerging virgin female beetles attracted large numbers of males flying in the vicinity (Smith and Hadley *1926*). One and 9 unmated females per trap attracted 380 and 2,975 males within 1 hour, respectively, showing that the virgin female had a powerful sex pheromone. During the summer three traps each containing 9 virgin females caught 19,248 males and 345 females. Traps baited with mated females or males attracted no more beetles than unbaited traps. Within 1 hour a trap baited with 9:1 PEB-eugenol caught 497 males and 879 females. (Ladd *1970c*) Virgin female beetles were attractive as long as they remained alive and unmated, though there seemed to be some decline in attraction with age (Goonewardene et al. *1970*). The survival of virgin female beetles was prolonged by Goonewardene et al. (*1973*) by feeding them with the synthetic diet and water described by Goonewardene and McKay (*1969*).

Yellow traps baited with virgin female beetles captured more male beetles than those painted red, black, green, or blue (Ladd et al. *1973b*). Traps placed 11 inches above the ground and baited with virgin female beetles caught more male beetles than those traps on the ground or 22 and 44 inches above the ground (Klein et al. *1972b*).

Traps baited each with 3 virgin female beetles for 9 weeks caught 22,702 males and 1,481 females; traps baited with 7:3 PEP-eugenol, the best chemical lure, captured only 1,131 males but 2,610 females. The ratio of males to females captured with the female lure decreased from 132.6:1 during the first week to 1.9:1 during the last week. With the chemical lure, the ratio ranged throughout the season between 1.2:1 and 0.3:1. (Klein et al. *1972a*)

During a 3-day exposure, traps baited with virgin females captured 3,463 males and 193 females and those with 7:3 PEP-eugenol captured

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660 males and 551 females. When both lures were in the same traps, however, the captures were 2,758 and 1,027, respectively. No significant difference was noted in the number of males or the total number of beetles captured by traps with both lures and those baited with virgin females, but traps with both lures caught more female beetles than those with either lure alone. (Klein et al. *1973a*)

The sex pheromone of the female beetle is produced in the abdomen. Extracts of abdomens with various solvents, however, were not attractive to male beetles. (Ladd *1970c*)

Construction of Traps

The trap first used in capturing beetles consisted of an unpainted galvanized iron bucket with a funnel fitted tightly into the top of the bucket and a holder for the bait in the bucket (Metzger *1928*; Richmond and Metzger *1929*). Fleming (*1969*) summarized the development of traps. The small survey trap patented by Armstrong and Metzger (*1935*) and the standard trap patented by Metzger (*1935a*) for use in densely populated areas have not changed fundamentally in construction. Both consist of a funnel, a four-winged baffle extending above and into the funnel, a bait receptacle mounted at the center of the baffle, and a receptacle for holding captured beetles.

Several modifications of the standard trap have been suggested, but the modifications were not adapted because the structural changes increased the cost of fabrication and were not welcomed by manufacturers. For example, the effectiveness of the trap was increased by cutting four apertures with flaps in the side of the funnel (Metzger *1934a*, *1934b*, *1935b*), by shielding the outside of the funnel and the beetle receptacle (Klein et al. *1973b*), and by replacing the perforated metal bait container with truncated-cone collars covered with a conical cap (Klein et al. *1973c*).

Color of Traps

Traps painted medium chrome green to blend with foliage caught more beetles than unpainted traps (Richmond and Metzger *1929*; Van Leeuwen and Metzger *1930*). Green traps captured more beetles than traps painted brown, yellow, red, blue, orange, white, indigo, black, or purple (Van Leeuwen and Metzger *1930*). The commercial traps, many shades of green, varied from light to dark and from a yellowish green to a bluish green. Metzger (*1932*) found that traps painted light green caught more beetles than those painted medium chrome green, olive green, dark green, chlorophyl green, or pea green and recommended that the traps be painted light green.

The effectiveness of the light-green trap was doubled when the baffle and inside the funnel were painted white (Van Leeuwen and Vander Meulen *1931*). The green and white traps, recommended by Metzger (*1932, 1936*), were used for many years to capture beetles. Fleming et al. (*1940a*) found that a green and white trap was as effective as an all-white trap, indicating that it was not necessary to use dual-colored traps.

Fleming et al. (*1940a*) compared the relative effectiveness of the green and white traps and those painted various colors as follows: Aluminum 50, pink 53, light blue 65, red 78, dark bluish green 82, dark blue 88, light medium green 89, white 97, bluish green 98, green and white 100, reddish orange 106, medium green 108, yellowish green 108, light chrome yellow 114, orange 129, and chrome yellow 150. Whittington and Brinkley (*1941*) confirmed that traps painted a chrome yellow were the most effective in capturing beetles.

Glossy chrome yellow traps also were recommended by Fleming et al. (*1940b*) and Fleming (*1955, 1958b, 1960, 1963a*). The yellow traps were in general use from 1940 through 1967. In 1965 large numbers of bumblebees (*Bombus* spp.) were captured by beetle traps (Hamilton et al. *1970*). Fifty percent of the bumblebees were captured by white traps, 44 percent by yellow traps, and 6 percent by green traps (Hamilton et al. *1971c*). Although green traps were less effective than yellow traps in capturing beetles, they were also less disruptive of populations of bumblebees.

Bait Dispenser

Bran Bait.—Evaporation of the geraniol-eugenol lure was regulated at first by mixing the attractant with a mixture of bran, molasses, glycerin, and water (Richmond *1927*). Metzger (*1928*) and Richmond and Metzger (*1929*) used 150 grams of the bait containing 2.5 percent geraniol and 0.25 percent eugenol for a standard trap. Van Leeuwen and Metzger (*1930*) almost doubled the number of beetles captured by increasing the amount of geraniol in the bran mixture to 10 percent and the eugenol to 1 percent.

The bran bait attractiveness decreased progressively as the geraniol and eugenol evaporated. During the trapping season, the bait was replaced at 2- to 3-week intervals. The bran bait was recommended by Van Leeuwen and Metzger (*1930*), Metzger (*1931, 1936*), and Fleming et al. (*1940b*).

Pumice and Ceramic Blocks.—Pumice and ceramic blocks saturated with geraniol-eugenol proved more convenient for dispensing the attractant than the bran mixture; several thousand of these impregnated blocks were used by the Department during 1936-38. However, about 80 percent of the bait evaporated during the first 2 weeks in the field, and attractiveness decreased progressively during a 6-week exposure. During the sixth week, the attractiveness became 25 percent less than that of the first week. (Fleming *1969*)

Bottle-and-Wick.—The development of the bottle-and-wick dispenser by Metzger (*1933b*) was an important improvement because sufficient liquid attractant could be put into the bottle to last the season, the liquid could be readily seen, and the rate of evaporation could be modified by changing the area of the exposed wick. The attractiveness of pure chemicals remained constant as long as the wick was saturated.

Components of the binary mixtures of geraniol-eugenol, anethole-eugenol, and PEB-eugenol had similar volatilities; serious changes in composition did not occur during evaporation. As methyl cyclohexane propionate is more volatile than eugenol, a preferential loss of the more volatile component of the mixture resulted, increasing the amount of eugenol in the reservoir and decreasing attraction to the beetle. McGovern and Beroza (*1970*) devised a wick which maintained the original composition of this mixture in the reservoir.

Effectiveness of Traps

Fleming et al. (*1940b*) estimated that a trap, under favorable conditions, captured about 75 percent of the beetles that approached it. Many beetles within the zone of attraction did not leave the plants on which they were feeding, nor, after flying toward the trap, settle on nearby foliage. Langford et al. (*1940*, *1941*) estimated that traps placed approximately 1 per acre over 6,749 acres in Cecil County, Md., caught 30 percent of the beetle population. In eastern Tennessee, 2,000 traps on 188 acres caught 39 percent of a marked beetle population in 1969, and 740 traps on 55 acres caught 30 percent of them in 1970 (Ladd cited by Fleming *1972b*). Thus, one or more traps per acre in rural areas captured approximately one-third of the beetles in the trapped areas.

Use of Traps

Beyond Known Infested Area.—The Department, in cooperation with State agencies, has operated 50,000 to 100,000 traps for many years beyond the known infested areas to determine the presence or absence of the beetle. Traps have often captured beetles when a diligent search of favored food plants in an area failed to reveal their presence. When the beetle first appeared in Maryland as isolated infestations, the capture of the first invaders in an area by traps often prevented the establishment of the insect for several years. (Cory and Langford *1955*)

Lightly Infested Areas.—Traps operated on a large scale in lightly infested areas have retarded the normal increase in beetle populations.

Hamilton et al. (*1971b*) placed 2,750 traps on 3,200 acres on Nantucket Island, Mass., and from the numbers of beetles captured, estimated that 3 years of mass trapping had reduced the beetle population at least 50 percent. Normally, there would have been about a twofold per year increase in the population.

The question exists whether traps greatly increase beetle populations in their vicinity. The most beetles are found on preferred plants, regardless of the presence or absence of traps. Preferred plants have a greater attraction to beetles than baited traps. More beetles are captured in traps near preferred plants than in those farther away. In suburban areas, traps usually attract beetles only from the immediate vicinity, but in open rural areas, traps may attract beetles 200 to 300 yards away. The large number of beetles on some properties and the relative small number on others depended primarily on the kind and abundance of food plants.

Densely Infested Areas.--Part of the program to retard the spread of dense beetle populations in Maryland involved the use of 127,000 traps in cities, towns, villages, and on farms. The traps captured 406 million beetles in 1938 (Langford et al. *1939*), over 1 billion in 1939 (Langford et al. *1940*; Cory and Langford *1944*), and over 2.7 billion in 1940 (Langford et al. *1941b*). When the beetle population was at its peak in 1948, over 3.7 billion beetles were captured (Cory and Langford *1955*). By 1954 only 19.7 million beetles were captured (Cory and Langford *1955*).

Protection of Plants.--In densely infested areas where defoliation of plants is common, enormous numbers of beetles were captured by traps without any apparent decrease in the extent and degree of plant damage (Fleming and Metzger *1936b*, *1938*; Fleming et al. *1940b*). However, traps were of value in protecting asparagus. When traps were placed on the windward side (Metzger)[1] or scattered throughout the fields (Langford et al. *1940*, *1941a*, *1941b*) that had been damaged severely by the beetle in previous years, the beetles were attracted from the asparagus to the traps, and the damage to the plants was negligible.

Toxic Trap Plants

Beetles feed lightly on geranium (*Pelargonium domesticum* Bailey) and moderately on the bottlebrush buckeye (*Aesculus parviflora* Walt). If feeding continues long enough, the beetles become paralyzed, fall from the plants, and die. The foliage is less toxic than the flowers. Studies showed, however, that these plants were not sufficiently attractive to

[1] Unpublished records of F. W. Metzger, former USDA entomologist.

induce beetles to leave other food plants in the vicinity. (Davis *1920a*; Ballou *1929*; Hawley and Metzger *1940*)

The castorbean (*Ricinus communis* L.) was advertised by a large seed grower as a trap crop for killing beetles. Metzger (*1933a*) found that the beetles fed lightly on some varieties and scarcely touched others, but there was no indication that these plants were toxic. Most of the feeding occurred late in the summer after the seed pods had developed and more preferred plants had been consumed. At that time dead beetles were found on the ground beneath the canopy of all food plants. (Metzger *1933a*)

Release of Sexually Sterile Male Beetles

The screwworm fly (*Cochliomyia hominivorax* (Coquerel)), a pest of cattle, was eradicated on the 180-square-mile island of Curacao, Netherlands Antilles, by the release of sexually sterile male flies (Knipling *1955*). The Curacao program was followed by a similar program that eradicated the screwworm fly in the Southeastern States.

Chemosterilants

At least 90 percent sterility of pairs of beetles was induced by tepa, apholate, metepa, and other aziridine compounds (Ladd *1966*, *1970b*); triphenyltin compounds (Ladd *1968a*); s-triazine-N^2, N^2-dimethylmelamine hydrochloride (Ladd *1970b*), and 3,5-bis (dimethylamino) 1,2,4-dithiazolium hydrochloride (Ladd *1970b*).

Topical applications of tepa, apholate, and metepa decreased the average longevity of male and female beetles 28 to 30 percent. The percentage of infertile eggs deposited by females increased with the increment in the dosage applied to male beetles. More than 90 percent infertility was produced by 12.5 ug tepa, 25 ug apholate, and 50 ug metepa (Ladd *1966*). The antifertility effects of tepa on male beetles were cumulative and permanent (Ladd *1968b*).

Topical applications of tepa were satisfactory for determining the limits of biological activity, but the method was not practical for large-scale treatment. Male beetles were sterilized by dipping for 10 seconds in a 0.0625 percent tepa solution. This dip sterilized 53 percent of the sperms in females previously mated with normal males. When males dipped in tepa solution were paired with virgin females, the infertility of the eggs ranged from 94 to 99 percent. (Ladd et al. *1968*)

The mating competitiveness of male beetles was not reduced by sterilization with tepa. The percentage infertility of ova laid by female beetles caged with different ratios of sterile to normal males, with the expected infertility in parentheses, showed ratio 0:1, 24 percent; 1:1, 61 percent (59 percent); 4:1, 75 percent (80 percent): 8:1, 86 percent (86 percent); and 16:1, 94 percent (90 percent). The close agreement between the calculated and experimentally determined values showed that tepa-treated males were fully competitive with normal males. (Ladd *1970a*)

The beetle is a promiscuous insect—male and female beetles have several sexual partners during their lives. The female beetle usually mates before each oviposition period. Normal males paired with normal females resulted in the production of only viable ova. Replacing the normal males with chemosterilized males caused a rapid decline in the production of viable ova until only infertile ova were produced. Replacing the chemosterilized males with normal males caused a rapid increase in the production of viable eggs. Thus, the fertility of eggs deposited by the female beetle was dependent upon whether her last mating partner was normal or sterile. (Ladd *1966*)

Sterilization by Gamma Radiation

When field-collected beetles were exposed to 0.87 to 64.5 krads of gamma radiation from cobalt 60, a progressive reduction resulted in the longevity of both sexes and an increase in the sterility of the ova. Male beetles exposed to 3.35 krads of radiation were reduced 11 percent in longevity and when mated with normal females engendered 95 percent sterile ova. Female beetles exposed to this dosage and not mated after radiation laid 97 percent infertile eggs, but when paired with normal males deposited eggs that were 85 percent infertile. No fertile eggs were produced when either sex was exposed to a dosage of 15 krads, but the longevity was decreased from 45 to 67 percent. (Ladd et al. *1973a*)

Releasing Sterile Male Beetles in an Isolated Population

A small isolated colony of beetles was discovered in 1964 in an eastern Tennessee valley. This small valley, 10 miles from the closest known infestation, is surrounded by wooded hills that rise steeply 300 to 500 feet above the valley floor.

As suggested by Knipling (*1964*) and following Hamilton et al. (*1967*), technical malathion (8 oz acre) was applied by air each week during the first 2 weeks in June in 1966 and 1967 to the 400 acres of the valley floor and surrounding slopes. This treatment reduced the beetle population to assure that subsequent releases of sterile male beetles would be more effective.

Beetles collected at other localities were sorted according to sex, following the method of Ladd and Bakley (*1968*). The male beetles were sterilized with tepa and marked with an identifying pigment. The sterile males were released once a week from late June to mid-August in 1966 and from early June to mid-August in 1967, 52,400 being liberated in 1966 and 183,000 in 1967. The ratios of sterile to normal males in the population increased progressively but the ratio did not reach 16:1, the ratio where 90 percent sterility of the ova occurred, until early in August in 1966 and late in July in 1967. Dependence on field-collected beetles made releasing adequate numbers of sterile males early in the summer impossible. (Ladd et al. *1972*)

High infertility of the ova did not occur early enough in either summer to modify the rate of growth of the isolated colony of beetles. The 18,000 beetles in the colony in 1966 were estimated to increase to 35,000 in 1967, 78,000 in 1968, and 140,000 in 1969. Release of sterile males in 1967 and 1968 did not reduce the approximate twofold increase in the population emerging the following summers. However, the indications are that beginning with the first emergence of the beetle, the release of adequate numbers of sterile male beetles would stabilize or reduce beetle populations in isolated colonies. (Ladd et al. *1972*)

Treatment With Juvenile Hormones

M. G. Klein and T. L. Ladd, Jr., in recent preliminary experiments,[4] found that the topical application of synthetic insect growth regulators to pupae resulted in the emerging adult beetles so bizarrely deformed that neither flight nor copulation was possible. Emergence was characterized by the presence of adult-pupal interstages and a general inability of the beetles to shed their pupal exuvia. The possibility of reducing beetle populations by disrupting the life cycle of the insect is an interesting development.

Fogging With DDT

A coarse aerosol fog produced from DDT dissolved in No. 2 fuel oil was effective in killing beetles by contact when the air was calm and the other meteorological factors enabled the fog to engulf the area, hang close to the ground, and dissipate slowly. These conditions occurred most frequently in the late evening or early morning. With the applicator moving at the rate of 4 miles per hour and dispensing 35 gallons of the solution, which contained 20 percent DDT, the fog killed 95 to 100 percent of the

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[4]Personal communication. Both are USDA entomologists.

beetles within a 100-foot-wide swath. The residual insecticidal value of the fog was negligible. Fogging two to four times during the summer kept the beetle population low. (Langford and Vincent *1948*)

DDT Mist

Mist blowers dispensing a 25-percent DDT emulsifiable concentrate diluted with twice its volume of water were used extensively in Federal-State programs to reduce beetle populations along roadsides and at airports. The mist blown into shrubs and trees killed most of the beetles on the foliage at the time of application, but the residual deposit on the foliage did not repel or kill other beetles coming to the plants. (Fleming *1955, 1960*)

Contact Insecticides

Beetles were killed by wetting them thoroughly with a coarse dilute aqueous spray containing sodium or potassium soybean oil soap (Leach and Brinley *1922*; Kelley and Moore *1923*). Sodium oleate was less injurious to foliage than the soybean oil soaps (Van Leeuwen *1926a*), and sodium soaps were more effective than potassium soaps (Vander Meulen and Van Leeuwen *1929*; Fleming and Baker *1934*). A spray containing 12 pounds of soybean oil soap (Kelley and Moore *1923*), or sodium oleate (Van Leeuwen *1926a*) in 100 gallons of water, the maximum quantity of soap that could be used safely on foliage, killed only 40 to 60 percent of the beetles. When chemical injury to foliage was not a factor, 95 to 100 percent of the beetles were killed with a spray containing 1 pound of soap in 3 or 4 gallons of water (Fleming, Metzger, and Osburn *1934b*; Hadley *1940*).

A more satisfactory contact spray was composed of 19 ounces of oleoresin of pyrethrum flowers, 11 pounds of sodium oleate, and 100 gallons of water. When applied as a coarse drenching spray, this formulation killed 85 to 100 percent of the beetles on trees and shrubs without damaging the foliage, but it did not prevent the plants from becoming reinfested. It was used extensively to reduce beetle populations, particularly in suburban areas. (Van Leeuwen *1926a, 1926b*; Van Leeuwen et al. *1928;* Fleming *1933;* Fleming and Metzger *1936b, 1938;* Hadley *1940*)

Cost of the spray was reduced without decreasing its effectiveness by using only one-half of the recommended amounts of oleoresin and sodium oleate and adding 6 fluid ounces of sodium silicate solution (Van Leeuwen and Vander Meulen *1927*), or by substituting a silicated coconut oil soap for the silicated sodium oleate (Van Leeuwen and Vander Meulen *1928*).

Dilute sprays containing DDT, technical methoxychlor, malathion, rotenone, or carbaryl—applied for plant protection from beetle attack—effectively killed beetles hit during the spray applications.

REDUCING GRUB POPULATIONS

Crop Rotation

Intensive agriculture, in which a few kinds of plants may occupy the land in nearly pure stands, provides abundant food and a favorable environment for the adult beetle and the grub. Growing a crop preferred by the beetle year after year on the same land increases the damage by the insect. Crop rotation has helped to reduce the injury.

Grubs do not thrive in plantings of alsike clover (*Trifolium hybridum* L.), red clover (*T. pratense* L.), white clover (*T. repens*), alfalfa (*Medicago sativa* L.), soybean (*Glycine max* (L.) Merr.), buckwheat (*Fagopyrum esculentum* Moench), oats (*Avena sativa* L.), barley (*Hordeum vulgare* L.), common rye (*Secale cereale* L.), or orchardgrass (*Dactylis glomerata* L.) (Fleming *1958a*). Rotation to avoid two successive crops of corn (*Zea mays* L.) on the same land keeps grub populations low (Hawley *1944*). A rotation used successfully included corn-soybean-small grain-clover.

Tillage

Cultivating the soil to 3 inches in the summer destroyed 25 to 30 percent of the eggs by bringing them to the surface where they were killed by exposure to the sun and wind. (Smith *1924b*)

Plowing to 6 inches followed by disking and harrowing to 3 inches killed 40 to 50 percent of the grubs in fallow fields and 25 to 30 percent in sodland. The lower mortality in pastures occurred because the disking did not always break up the clods of sod sufficiently, and the spike-tooth functioned largely to level the land. (Smith *1924b*; Cory and Langford *1955*)

"Rototillers" and "Rotocultivators," implements that pulverize the soil and prepare the land for planting in one operation, were more effective in killing grubs than the common farm implements. Baker[5] found that one pulverization on fallow or sodland killed about 70 percent of the grubs, two pulverizations about 82 percent, and three pulverizations about 94

[5]Unpublished records of F. E. Baker, former USDA entomologist.

percent. Cory and Langford (*1955*) reported that these implements destroyed up to 90 percent of the grubs.

The recommendations for using common tillage implements most effectively to kill grubs were not in agreement: Hadley (*1923*) recommended late fall or late spring, Smith (*1924b*) late fall or early spring, and Cory and Langford (*1955*) early fall or late spring. Subsequent tests confirmed that the best results were obtained in the early fall and the late spring when the grubs were near the soil surface.

Flooding

Flooding is a practical method in Massachusetts and New Jersey for controlling many species of insects that attack cranberries (*Vaccinium macrocarpon* Ait.). Beckwith et al. (*1927*) reported that the beetle grubs did not survive the winter in flooded bogs, but flooding a bog for 14 days in May had no effect on them. Fleming and Baker[6] found that when a bog was flooded in December the mortality of the submerged grubs was 9 percent in 15 days, 22 percent in 30 days, 52 percent in 90 days, and 77 percent in 150 days. In areas from central New England to North Carolina where streams overran their banks and submerged infested land for several weeks, there was no indication of a high grub mortality (Hawley *1944*).

Liming the Soil

Wessel and Polivka (*1952*) adjusted the acidity in an acid soil from pH 3.9 to 6.9 with sulfur and lime. During 1949 and 1950 almost one-third of the eggs were deposited in extremely acid soil and only about one-tenth of them in almost neutral soil.

From 1950 to 1957 surveys were made annually of the turf in a cemetery and two golf courses where a portion of the normally acid soil had been made practically neutral by applications of lime. The grub populations in the limed areas were always much smaller than those in the unlimed areas. A definite correlation was found between the acidity of the soil and the density of the grub population. (Polivka *1960a*)

Fumigation of Turf

Well-kept turf is usually capable of supporting 10 grubs per square foot without the aerial portion showing visible injury, but if the growth of

[6] Unpublished records of F. E. Baker, former USDA entomologist.

the grass is retarded by unfavorable growing conditions, a grub population of this density is sufficient to cause extensive damage. During the study, grub populations of 100 per square foot were not uncommon. When grubs were numerous, maintaining a good sward was impossible, even under favorable conditions.

Grubs were destroyed without serious injury to the turf by fumigation. The fumigant killed the grubs in the soil at the time of treatment, but it soon dissipated and had no effect on grubs hatching subsequently in the soil. The treatment was usually applied in the early fall when the eggs had hatched and the grubs were active and near the surface.

Carbon Disulfide

Emulsified carbon disulfide, applied systematically at low pressure at the rate of 400 pounds in 10,890 gallons of water per acre (when the grubs were near the surface and the soil was moist), killed 95 to 100 percent of the grubs. The treatment, which also destroyed the eggs, was less effective when the ground was dry and the grubs were deeper in the soil. Vigorously growing turf grasses withstood the treatment, except when the temperature was above 29° C, but turf severely damaged by grubs had little resistance to the chemical and was usually killed. The carbon disulfide partially sterilized the soil and subsequently stimulated the growth of the grasses. (Leach *1921*, *1925a*, *1925b*; Leach and Johnson *1923*; Leach and Thomson *1923a*, *1923b*; Leach and Lipp *1927a*; Fleming *1929*; Fleming and Baker *1935*)

Emulsified carbon disulfide also affected grubs of the oriental beetle (*Anomala orientalis* Waterhouse) (Zappe and Garman *1925*; Johnson *1927*) and the green June beetle (*Cotinis nitida* (Linnaeus)) (Lipp *1927*). Because of the chemical's inflammability and explosiveness, its use was discontinued.

Ethylene Dichloride

Emulsified ethylene dichloride applied at the rate of 240 pounds in 4,840 gallons of water per acre killed 90 percent of the grubs in turf within 3 weeks. All grubs were killed by doubling the amounts of the fumigant and the water. Ethylene dichloride caused some yellowing of the grass but no permanent injury. (Mason et al. *1943*)

Ethylene Dibromide

All grubs were killed in turf within 24 hours by applying 10 pounds of emulsified ethylene dibromide in 9,680 gallons of water per acre, or 20 pounds of the chemical in 4,840 gallons. The turf was not injured by the treatment. (Mason and Chisholm *1945*)

Parathion

Five pounds of parathion in 4,840 gallons of water per acre killed all of the eggs and grubs in turf without injury to the grass.[7]

Fumigation of Fallow Soil

Japanese beetle grubs are not usually a serious problem in vegetable gardens, but when a lawn is plowed and converted into a garden, the grubs may cause damage to the plants. The grub population may be reduced by fumigating the plowed land. The treated soil is usually left undisturbed for 10 to 14 days and then cultivated before planting.

Carbon Disulfide

Studies showed that 600 pounds of emulsified carbon disulfide in 16,335 gallons of water per acre killed 90 to 95 percent of the grubs to a 6-inch depth within 1 week. (Fleming, Metzger, and Osburn *1934b*; Fleming and Metzger *1936b*, *1938*)

Ethylene Dichloride

All grubs were killed to 9 inches within 3 weeks by applying 450 pounds of emulsified ethylene dichloride in 9,680 gallons of water per acre. The treatmeat was only partially effective in soils high in organic matter. (Mason et al. *1943*)

Ethylene Dibromide

Twenty pounds of emulsified ethylene dibromide in 4,840 gallons of water per acre killed all grubs to 9 inches within 1 week. Doubling the amount of the fumigant and the water was necessary to kill all grubs in soils high in organic matter. (Chisholm and Mason *1948*)

PROTECTING PLANTS FROM ADULT BEETLES

Screening

Plants were protected by enclosing them with cloth or wire netting when the adult beetle was in the vicinity; flowers and ripening fruits were protected with netting. Netting also protects choice plants in the home

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[7] Unpublished research of A. C. Mason, former USDA entomologist

yard. By screening ventilators and doors, beetles were excluded from commercial greenhouses. (Fleming, Metzger, and Osburn *1934b*; Fleming and Metzger *1936b*, *1938*)

Repellents and Residual Insecticides

Conspicuous deposits of toxic and nontoxic materials on plants repelled beetles—usually the more conspicuous the deposit the more repelling to the beetle. Fewer beetles approached plants with deposits than without deposits. Of the beetles hovering about plants, not more than 50 percent of them lighted on plants with deposits, but up to 80 percent flew to rest on untreated plants. Within 3 hours after alighting, 90 percent of the beetles left the treated plants, but only one-third left the untreated plants. These treatments showed that beetle populations tended to be light on plants with conspicuous deposits and heavy on untreated plants. (Van Leeuwen et al. *1928*; Van Leeuwen *1932a*)

Timely and thorough applications of the protective coating are important. As a general rule dusting or spraying should begin before the beetles become established on a plant. As the beetle is gregarious, a few beetles on a plant tend to attract others flying in the vicinity. First, the beetles attack the upper part of a plant, regardless of its height, and then work downward and inward. All parts of the plant must be covered by the protective coating. Any unprotected leaf, flower, or fruit is subject to attack. (Van Leeuwen *1932b*; Fleming, Metzger, and Osburn *1934a*; Fleming and Metzger *1936a*, *1938*; Hadley *1940*; Fleming *1955*)

Hydrated Lime

Hydrated lime is a good nontoxic repellent. Only 29 percent as many beetles attacked peach trees sprayed with lime as the unsprayed trees (Van Leeuwen et al. *1928*; Van Leeuwen *1932a*). A deposit of lime, however, does not adhere well to foliage and is removed easily by wind and rain. The addition of a small quantity of aluminum sulfate to a suspension of lime in water makes it adhesive (Lipp and Osburn *1935*).

Commercial fields of sweet corn were protected from beetle injury during pollination by dusting tips of the developing ears two or three times with 300-mesh hydrated lime (Hadley *1940*).

Two or three applications of a spray containing 20 pounds of hydrated lime and 3 pounds of aluminum sulfate in 100 gallons of water protected the foliage of shade trees and ornamental shrubs, the fruit and foliage of early and late apples, and after harvest, the foliage of blueberries, blackberries, and raspberries. The spray also protected the foliage of truck crops attacked by the beetle (Hadley *1940*). Although the lime spray protected the fruit and foliage of peach trees, it could not be used on the early varieties because of the difficulty in removing the residue from the fruit at harvest (Metzger and Lipp *1936*).

Frequent dusting with finely divided hydrated lime, or spraying with 1 pound of lime suspended in 3 gallons of water, protected plants in the home yard from beetle injury. (Fleming, Metzger, and Osburn *1934b*; Fleming and Metzger *1936b*, *1938*)

Lead Arsenate

Lead arsenate is a good repellent but a poor poison for the beetle. Of the beetles flying to trees sprayed with lead arsenate, 77 percent were repelled, but only 30 percent of those lighting on the trees were killed (Van Leeuwen et al. *1928*; Van Leeuwen *1932a*). A dosage of 0.0156 mg of lead arsenate was fatal to the beetle in 42 hours and 0.0035 mg in 72 hours (Van Leeuwen *1927*). The low mortality of the beetles on sprayed trees was the result of many beetles not feeding or not feeding enough to obtain a lethal dosage.

A spray containing 6 pounds of lead arsenate in 100 gallons of water to which 4 pounds of wheat flour was added as a sticker was used until the 1940's for the protection of the foliage of shade trees and deciduous shrubs, fruit and foliage of early and late apples and grapes, and the foliage of cherries after picking. Usually one or two applications of the spray were sufficient for protection during the summer. The use of the lead arsenate-flour spray on early apples was discontinued in 1934 because of the excess arsenical residue on the fruit at harvest. (Davis *1920a*; Hadley *1922*, *1923*, *1924*, *1940*; Kelley and Moore *1923*; Van Leeuwen *1925*; Smith and Hadley *1926*; Fleming, Metzger, and Osburn *1934a*; U.S. Department of Agriculture *1949*)

Lead arsenate was not used on peach trees because peach foliage is susceptible to arsenical injury. Unsuccessful attempts were made to overcome this injury without reducing the repellent value by decreasing the amount of lead arsenate in the spray (Hadley *1924*), adding hydrated lime (Van Leeuwen *1925*; Smith and Hadley *1926*; Vander Meulen and Van Leeuwen *1927*), or adding New Jersey dry mix (sulfur, lime, and calcium caseinate) (Smith *1925*; Van Leeuwen *1929*, *1932b*).

The lead arsenate-flour mixture was colored green to increase its insecticidal action (Vander Meulen and Van Leeuwen *1928*). The green lead arsenate was less repellent, but it was no more palatable to the beetles than the regular lead arsenate (Van Leeuwen et al. *1928*; Van Leeuwen *1932a*). Coating lead arsenate with lead oleate (Moore *1922*; Van Leeuwen and Vander Meulen *1926*) did not reduce the repel'ency but did increase the palatability. Many dead beetles accumulated under plants sprayed with coated lead arsenate (Van Leeuwen and Vander Meulen *1925*; Van Leeuwen et al. *1928*). Coated lead arsenate was not used on fruit trees and grapes because of the difficulty in removing the residue.

The most effective arsenical spray for killing large numbers of beetles contained 8 gallons of refined sugar sirup and the lead arsenate-flour mixture (Van Leeuwen et al. *1928*). Beetles gorged themselves on trees sprayed with sweetened lead arsenate, and as a result thousands of dead and dying beetles accumulated beneath the defoliated trees. Until 1928, the lead arsenate and sugar combination was the most effective spray that had been devised for killing beetles (Smith *1930*), but the sugar destroyed the repellent value of the arsenical and was injurious to foliage.

Rotenone-Bearing Materials

Certain rotenone-bearing materials, including derris (*Derris elliptica* (Roxb.) Benth.), cube (*Lonchocarpus utilis* A. C. Sm.), and timbo (*L. urucu* Killip and A. C. Sm.), plants belonging to the family Fabaceae, owe their toxicity to insects, to rotenone, and to the rotenoides (Roark *1941*). Deguelin and toxicarol are the most important of the rotenoides. Derris, cu' ', and timbo are not poisonous to humans and warm-blooded animals.

Many beetles were killed when drenched with a solution of 3 pounds of derris, cube, or timbo in 100 gallons of water. Most of the beetles were repelled by the inconspicuous deposits. When 8 pounds of molasses were added to the sprays, the beetles went readily to the foliage, but they fed to only a limited extent and few died. (Fleming and Baker *1936*)

Rain removed the rotenone-bearing materials in the field and sunlight decomposed them (Jones et al. *1933*). Rosin residue emulsified with ammonium caseinate made a good sticker for these materials (Goodhue and Fleming *1936*), but nothing was found to prevent their decomposition. Osburn (*1934*) maintained a repellent deposit on peach and apple trees by spraying each week and after heavy rains.

No satisfactory method existed for protecting nectarines, peaches, and plums ripening in July and August. Researchers found that these fruits could be protected by spraying them with 3 pounds of a rotenone-bearing material in 100 gallons of water as soon as beetles appeared in the orchard and 7 to 10 days thereafter as needed (Fleming and Metzger *1936a*; Hadley *1940*). This spray also gave some protection to ripening raspberries, blackberries, and blueberries and when applied at double strength to ripening grapes (Hadley *1940*). The spray was also useful in protecting ornamental plants in the home yard (Fleming and Metzger *1936b*, *1938*). For many years, derris, cube, and timbo were used to protect plants from injury by the beetle. (U.S. Department of Agriculture *1949*; Fleming *1955*, *1958b*, *1960*, *1963a*)

DDT

DDT is effective in killing beetles and protecting plants from attack. It was not a strong repellent, probably because the deposits on plants were not conspicuous, but beetles lighting on treated plants soon became paralyzed, dropped from the plants, and died. One application of a dilute DDT spray (1 pound in 100 gallons of water) usually protected orchard crops, shade trees, and ornamental shrubs throughout the summer, but occasionally a second application 2 or 3 weeks later was needed to protect new growth. Two applications of the dilute spray were needed to protect grapes. Large acreages of sweet corn were protected during pollination by applying 1.5 pounds of DDT per acre by airplane with a 5 percent dust or a concentrated spray (1.5 pounds in 3 gallons of water). Periodic dusting protected ornamental shrubs and vines in the home yard. (Fleming *1947a*, *1955*, *1958b*, *1960*, *1963a*; Hadley *1947*; U.S. Department of Agriculture *1949*)

The EPA forbids using DDT as an insecticide except in certain emergencies, and it is no longer used to control the Japanese beetle.

Methoxychlor

Methoxychlor kills beetles slower than DDT and it is not as effective in protecting plants from attack. However, it is less poisonous to man and animals and less hazardous to the environment.

Large fields of sweet corn were protected during the 5- to 7-day silking period by applying 1.5 pounds of methoxychlor per acre by airplane (30 pounds of a 5-percent dust or 3 gallons of a spray containing 1.5 pounds of wettable or emulsifiable methoxychlor) when about one-fourth of the field was in silk. If large numbers of beetles migrated into the treated corn from adjacent fields, a second application of methoxychlor 2 or 3 days later might be necessary.

A dilute spray (1 pound wettable or emulsifiable methoxychlor in 100 gallons of water), applied when beetles began to attack the plants, protected shade trees, ornamental shrubs and vines, orchard crops, and small fruits and vegetables for 10 to 14 days. When beetles attacked the plants again, the spraying was repeated and continued as needed at 10- to 14-day intervals.

The 5-percent dust or the dilute spray was used effectively to protect ornamental plants, vegetables, and fruit in home yards.

When methoxychlor is applied to edible plants, the required waiting period between the last application and harvest should be observed to avoid excess residue on harvested crops. Methoxychlor treatment should be discontinued 3 days before picking lima beans or snap beans; 7 days before harvesting apples, asparagus, cherries, plums, or sweet corn; 14 days before picking blackberries, blueberries, grapes, raspberries, or strawberries; and 21 days before harvesting nectarines and peaches. (Fleming and Maines *1950*; Fleming *1955*, *1958b*, *1960*, *1963a*; U.S. Department of Agriculture *1969*, *1973*)

Carbaryl

Carbaryl kills beetles slower than DDT, but it is less toxic to man and warm-blooded animals. A spray containing 1 pound of carbaryl in 100 gallons of water is also toxic to honey bees (*Aphis mellifera* Linnaeus), but killing bees was avoided by applying the spray during the hours when the bees were not visiting flowers. The 1-pound spray protected shade trees, ornamental plants, orchard fruits, berries, and vegetables from damage by the beetle for about 7 days. When beetles began to attack the sprayed plants, additional applications of the spray were made at 7-day intervals as needed.

Carbaryl should be discontinued 1 day before harvesting apples, asparagus, beans (lima and snap), okra, blueberries, cherries, or plums; 3 days before picking nectarines or peaches; and 7 days before picking blackberries, or raspberries, or harvesting corn to be used as fodder or forage. No waiting period exists for grapes and sweet corn because of the long periods between the last application and harvest. (Fleming *1963a*; U.S. Department of Agriculture *1969*, *1973*)

Malathion

Malathion is one of the safest insecticides. A spray containing 0.5 pound of malathion (2 pounds of a 25-percent wettable powder, or 1 pint of a 50 percent emulsifiable concentrate) in 100 gallons of water killed 95 to 100 percent of the beetles on the plants during the application. Malathion is also toxic to honey bees. The spray was applied as soon as beetles began to collect on the plants and at 5- to 7-day intervals as needed to control the beetles. Malathion also controls aphids and mites, except in some areas where resistant strains have developed.

Residues of malathion can usually be removed from most edible parts of plants by washing with cold water. Nevertheless, a waiting period should be observed between the last application and harvest. Malathion can be applied up to 1 day before harvest to asparagus, beans (lima and snap), blackberries, blueberries, and raspberries; up to 3 days before picking apples, cherries, grapes, plums, and strawberries; up to 5 days before picking sweet corn; and up to 7 days before picking nectarines and peaches. (Fleming *1960*, *1963a*; U.S. Department of Agriculture *1969*, *1973*)

Parathion

A spray of 0.5 pound of parathion in 100 gallons of water was effective in killing beetles and in protecting plants from beetle injury for about 5 days. Additional applications were made as needed to protect the plants.

Parathion is highly poisonous to man if inhaled or absorbed through the skin. It should be used only by trained operators who are familiar with the hazards involved with the chemical. Parathion should never be used in home gardens. (Fleming *1955*, *1958b*, *1960*, *1963a*)

Newer Insecticides

Lawrence et al. (*1973*) made preliminary exploratory tests in their search for a more effective material than carbaryl to control the beetle. In these tests the residue from 1 pound of carbaryl in 100 gallons of water killed 99 to 100 percent of the beetles during the following 10 days when rainfall was 0.12 inch; then the residue declined in effectiveness. A rainfall of 3.5 inches removed the carbaryl from the plants. The residue from acephate, best of the 25 chemicals tested at the rate of 1 pound per 100 gallons, killed 87 to 100 percent of the beetles during the following 17 days when there were two showers of 0.12 and 0.32 inch. Acephate resisted removal by rain.

Extracts of Plants Immune to Beetle Attack

Metzger and Grant (*1932*) applied alcoholic extracts of 390 plant species not attacked by the beetle to the foliage of apple (*Malus sylvestris* Mill.) and peach (*Prunus persica* (L.) Batsch) to protect the foliage from injury. Most of the extracts did not mask the attraction of the foliage. A few extracts seemed somewhat repellent, but the tests were not extensive enough to be conclusive.

Cherry leaves (*Prunus* spp.) coated with juice pressed from the leaves of the maidenhair tree (*Ginkgo biloba* L.), which beetles attack occasionally, were eaten as readily as uncoated leaves. *Ginkgo* leaves coated with the juice pressed from cherry leaves were eaten almost as readily as cherry leaves. *Ginkgo* leaves coated with glycerine containing a little eugenol or valeric acid, known attractants, were eaten extensively (Major and Tietz *1962*). This indicates that some plants might be immune to beetle attack because of the lack of an attractive substance.

Smudges

Smudge candles, composed of wood flour, potassium nitrate, and a repellent, smouldered for 5 to 8 hours and gave off thick clouds of smoke which were charged with the repellent vapor. The fumes from pine-tar oil, Dipple's oil, and a mixture of chloronaphthalenes repelled the beetle. When subjected to these fumes for 5 or 10 seconds, the beetles stopped feeding and flew off to light again on a part of the same tree that was not enveloped by the smoke (all parts of the tree were not enveloped by smoke at the same time). Air currents prevented smudges from adequately controlling the beetle. (Metzger and Grant *1930*)

PROTECTING LAWNS, GOLF COURSES, AND PARKS FROM GRUBS

No record was found of a residual insecticide in the United States to control white grubs until Leach (*1926*) demonstrated that certain arsenates in the soil killed *Popillia* grubs. The grubs were killed when they ingested a lethal dosage of the arsenical while burrowing through soil or feeding on the roots of plants. The action of a residual insecticide in soil is complex, being affected by the nature, concentration, and the distribution of the poison; by the chemical and physical characteristics of the soil; and by the development, activity, and the susceptibility of the grubs. (Fleming *1942*)

Newly hatched grubs are more susceptible to poisoning by a residual insecticide than fully developed third-instar grubs because less poison is required, the grubs are near the surface of the soil, and the warm soil during the summer leads to rapid insecticidal action. The velocity of poisoning at 21° C was three-fourths that at 27°; at 16°, one-half; and at 10°, one-fourth. The grubs are inactive at temperatures below 10° (Fleming and Maines *1944a*, *1944b*; Fleming *1948*)

The rate of poisoning is the most rapid in the light sands and sandy loams and the slowest in clay loams, silt loams, and mucks. The finely divided particles of the clay and silt loams and the mucks have a greater capacity for converting the insecticide into an inactive form than the coarser particles of the sands and sandy loams. (Fleming et al. *1936*; Fleming and Maines *1947a*, *1951*; Fleming *1948*)

After applying a residual insecticide, the turf should be watered to remove the deposit from the blades of grass and to avoid possible injury to children, domestic pets, and wildlife.

Lead Arsenate

A new lawn was made "grub proof" for about 10 years by mixing 1,500 pounds of lead arsenate per acre with the upper 3 inches of soil before seeding. The arsenical sometimes retarded early growth of the grasses. (Leach and Lipp *1926*, *1927a*, *1927b*; Fleming *1930*; Fleming and Osburn *1932*)

Established turf was protected for 3 or 4 years by topdressing with 5 pounds of lead arsenate per 1,000 square feet, or 217 pounds per acre (Leach *1928*, *1929*), and for 5 or 6 years with 10 pounds per 1,000 square feet, or 435 pounds per acre (Fleming and Osburn *1932*; Fleming *1936*; Fleming and Metzger *1936b*, *1938*; Hadley *1940*). Topdressing lawns and golf courses with 435 pounds of lead arsenate per acre was not injurious to the common grasses. The higher rate was usually used when grubs were numerous.

Lead arsenate was not applied to the soil of flower and vegetable gardens because it retarded or killed some plant species (Fleming *1937*). Arsenic assimilated by the vegetables proved hazardous to human health (Fleming et al. *1943*; McLean et al. *1944*), and it was not used on pastures because of its potential damage to livestock.

Fleming (*1958a*) showed that lead arsenate residues impair soil fertility. The water-soluble arsenic (arsenic acid) produced in the soil is injurious to plants. In preliminary experiments the water-soluble arsenic was reduced to a low level by applying ferrous sulfate, limonite, or greensand marl to the soil to convert the water-soluble arsenic to insoluble compounds (Melt *1941*). Bear (*1957*) recommended the application of 1 to 2 tons of iron sulfate per acre to overcome the phytotoxicity of arsenical residues. Deep plowing to dilute the arsenical content of the upper layer of soil was the only method used for many years to reduce the phytotoxicity.

Chlorinated Hydrocarbon Insecticides

The chlorinated hydrocarbon insecticides are much more toxic to the grubs than lead arsenate. To kill first-instar grubs in 15 days, 500 pounds of lead arsenate per acre at 27°C was required, but only 5 pounds of DDT, 2.5 pounds of toxaphene, 0.4 pounds of chlordane, 0.3 pound of dieldrin, and 0.07 pound of aldrin or heptachlor. The dosages of the chlorinated hydrocarbon insecticides were increased to kill third-instar grubs in the spring or fall and to provide residues sufficient to eliminate several annual broods of grubs hatching in the treated turf.

Chlorinated hydrocarbon insecticides did not inhibit female beetles from laying eggs or prevent the eggs from hatching, but grubs that contacted chemical particles in the soil (or by ingestion) developed tremors, lost their coordinated movement, and died.

In the spring, established turf was usually topdressed with 25 pounds of DDT or toxaphene per acre, 10 pounds of chlordane, or 3 pounds of dieldrin, aldrin, or heptachlor. These treatments killed 85 to 100 percent of the third-instar grubs before pupation and eliminated several annual broods of first-instar grubs soon after hatching. The persistence of these treatments with chlorinated hydrocarbon insecticides in established turf is summarized in table 1.

Residues of DDT and toxaphene approached the minimum needed to kill first-instar grubs in 10 years, while those of chlordane approached the minimum in 9 years, dieldrin in 7 years, aldrin in 5 years, and heptachlor in 4 years. (Fleming and Maines *1944a, 1944b, 1947a, 1951, 1952, 1953*; Fleming *1947b, 1948, 1950a, 1950b, 1955, 1958b, 1960 1963a, 1972a*; Fleming, Maines, and Coles *1951*; U.S. Department of Agriculture *1949, 1973*)

TABLE 1. *Persistence of chlorinated hydrocarbon insecticides in established turf*[1]

Period after application	Active residue per acre at indicated period with					
	DDT 25 pounds	Toxaphene 25 pounds	Chlordane 10 pounds	Dieldrin 3 pounds	Aldrin 3 pounds	Heptachlor 3 pounds
Years	*Percent*	*Percent*	*Percent*	*Percent*	*Percent*	*Percent*
1	98	80	28	67	30	17
2	92	62	15	47	17	10
3	80	48	10	34	10	7
4	62	40	9	24	7	4
5	44	34	7	17	4	
6	38	28	6	14		
7	30	24	5	10		
8	28	20	4.5	7		
9	26	16	4	4		
10	20	12				

[1] EPA has banned the use of all insecticides in this table. Table given for research data only.

The application rates of chlorinated hydrocarbon insecticides were in excess of the requirements to protect turf for short periods. Protection was obtained for 1 year with 2 pounds of chlordane, and 0.5 pound of dieldrin, aldrin, or heptachlor, and for 3 or 4 years with 5 pounds of chlordane or 1 pound of dieldrin.

No data indicated that white grubs would develop resistance to chlorinated hydrocarbon insecticides until 1969 when Tashiro et al. (*1971*) found a grub strain of the European chafer (*Amphimallon majalis* (Razoumowsky)) at East Rochester, N.Y., that was resistant to chlordane, dieldrin, and heptachlor. Kuhr et al. (*1972*) in a study of the resistance of chafer grubs to dieldrin found no gross differences between resistant and susceptible strains, except the lipid of resistant grubs contained over twice as much palmitic and oleic acids as that of susceptible grubs. In 1972 Tashiro and Neuhauser (*1973*) found a chlordane-resistant strain of Japanese beetle grubs at Liverpool, N.Y., and Niemczyk and Lawrence (*1973*) at Wooster, Ohio. A statewide survey of New York at 83 sites in 1973 and 120 in 1974 showed that chlordane-resistant *Popillia* grubs occurred at only four of them—Woodmere in Nassau County and Baldwinsville, Liverpool, and Syracuse in Onondaga County (Tashiro et al. *1975*). In 1974 in Connecticut, chlordane-resistant *Popillia* grubs were found at New Haven, but populations of grubs were susceptible at Hartford, Madison, Southington, Wallingford, and Watertown (Dunbar and Beard *1975b*).

Other Insecticides

Carbaryl and diazinon, applied as topdressings to turf, reduced grub populations, but they have a short residual life in the soil. Annual applications of these chemicals are necessary for grub control.

Carbaryl

Carbaryl was applied as a topdressing to turf at 18 pounds per acre in mid-July to coincide with the peak of grub oviposition. Late in September the mortality of the grubs ranged from 76 to 91 percent.[8] Tests showed that carbaryl was not an adequate substitute for the chlorinated hydrocarbon insecticides.

Diazinon

When diazinon was applied as a turf topdressing in mid-July at the peak of the oviposition period, the 4-pound-per-acre treatment eliminated

[8] Unpublished records of D. W. Hamilton, former USDA entomologist.

89 percent of the grubs and the 6.7-pound treatment, 97 percent. Applying 8 pounds of diazinon per acre late in September killed 99 percent of the grubs, but when applied in mid-November the treatment killed 83 percent, and when applied late in May it killed less than 25 percent of the grubs. Treatments applied in the fall or spring had no effect on the grubs hatching in the soil during the following summer.[8] Immediately after the application of diazinon, the turf must be watered thoroughly to wash the material into the soil.

The U.S. Department of Agriculture (*1973*) used an annual application, between late July and early October, of 5 pounds of active diazinon per acre as a granular formulation or an emulsifiable concentrate. The emulsifiable concentrate should be applied as a coarse spray in 1,000 gallons of water per acre.

SUMMARY

Much of the environment in the Eastern United States is favorable for the development and spread of the Japanese beetle, but often summer droughts and low winter temperatures in the soil reduce beetle populations. The published and unpublished records on the control of the beetle have been reviewed and codified so that the information will be available for possible use in future programs of integrated control of the insect.

Efforts to Eradicate the Beetle

Since 1918 efforts have been made to eradicate isolated beetle colonies, or at least to retard the natural buildup and spread of the insect. Most of the programs retarded but did not eradicate the beetle.

Quarantines

Federal and State quarantines were effective in preventing the artificial dispersion of the beetle by plants and other agricultural products.

Biological Control

The parasites, predators, and pathogens indigenous to the Eastern United States were not numerous enough to prevent an increase in beetle populations. Colonization of the *Tiphia* parasites, a parasitic nematode (*Neoaplectana glaseri*), and particularly the milky disease bacteria (*Bacillus popilliae* and *B. lentimorbus*) so enhanced the effectiveness of the biological control complex that beetle populations declined. Economic damage to plants has declined greatly in the Middle Atlantic States, and severe damage often is limited to isolated areas in that region. There has been some resurgence of the beetle.

Avoiding Adult Injury to Plants

Plant damage was avoided by growing crops and ornamentals that were immune or seldom attacked by the adult beetle. Some varieties of preferred species were resistant to injury. Much corn damage was avoided by so regulating the planting that silking occurred before or after beetles were abundant.

Reducing Adult Beetle Populations

The density of adult beetle populations on crops and ornamentals was reduced by adequate control of other insect pests and plant diseases and the elimination of favored weeds.

For several years large-scale traps were used to reduce beetle populations. The search for an effective chemical lure has been carried on for many years. The first one recommended, a mixture of geraniol and eugenol, was replaced with anethole and eugenol in 1944; with phenylethyl butyrate and eugenol in 1966; and with phenylethyl propionate and eugenol in 1970. The sex pheromone of the virgin female was a potent attractant to male beetles, and lures in traps painted yellow proved the most effective. Although they reduced beetle populations, traps were usually of little value in protecting plants from injury.

A new technique for reducing beetle populations involves the release of sexually sterile male beetles.

A DDT fog or mist, applied two to four times during the summer, kept beetle populations reduced.

For many years, a coarse dilute drenching spray containing oleoresin of pyrethrum flowers and sodium oleate reduced beetle populations. Dilute sprays of DDT, methoxychlor, malathion, rotenone, or carbaryl killed many beetles also.

Reducing Grub Populations

Crop rotation to avoid two successive crops of a plant preferred by the beetle kept grub populations low.

Overwinter flooding controlled grubs in cranberry bogs.

Liming acid soils reduced grub populations.

Grubs in turf and fallow land were destroyed by annual fumigation of the soil with emulsified carbon disulfide, ethylene dibromide, or ethylene dichloride.

Protecting Plants from Adult Beetles

Timely and thorough applications of spray or dust are important in protecting crops and ornamentals from damage by the beetle. Lead arsenate, lime, rotenone, DDT, methoxychlor, carbaryl, and malathion were used in the protective sprays and dusts.

Protecting Lawns, Golf Courses, and Parks from Grubs

Grub injury to established turf was prevented for several years by a topdressing of lead arsenate, DDT, toxaphene, chlordane, dieldrin, aldrin, or heptachlor. *Use of these insecticides has been banned by the EPA.*

With a limited persistence in soil, diazinon was applied annually in the late summer or early fall to protect turf.

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