27 February 1959, Volume 129, Number 3348 SCIENCE

CURRENT PROBLEMS IN RESEARCH

Biological Control of Insect Pests

Insect pests are economically controlled through the utilization of their natural enemies.

Charles A. Fleschner

Biological control is the practice of reducing the numbers of a pest by the use of "beneficial" organisms such as parasites, predators, and diseases. As an applied science, biological control is now some 70 years old, having had its first effective and sustained success in 1888 through the introduction of the vedalia beetle, *Rodolia cardinalis* (Muls.), from Australia for the control of cottony-cushion scale, *Icerya purchasi* Mask., on citrus in California. Since this initial success the biological method of pest control has spread rapidly throughout the world. It has been used effectively against a wide variety of noxious plants and animals. The greatest number of successes, however, have been in the control of insect pests of agricultural crops, and it is this aspect of biological control that is considered here (*1*). Throughout this article, except where otherwise stated, phytophagous mites are grouped with pest insects.

The biological method for insect pest control is based on the knowledge that there exists in nature a balance between plant-feeding insects and their enemies and that this balance may be shifted one way or another through the manipulation of environmental factors. This manipulation may involve one or more ecological approaches: (i) the importation of beneficial organisms, (ii) the mass production and periodic release of beneficial organisms, or (iii) the conservation and augmentation of native or established beneficial organisms.

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Importation of Beneficial Organisms

Plant-feeding insects of no economic importance in their native habitat are likely to become serious pests if moved to new areas free of their natural enemies. Most major insect pests of agricultural crops in the United States today originated in this manner. In many instances such pests have been controlled biologically through the introduction of their natural enemies from the native habitat.

The international movement of beneficial insects for pest control began in 1873 with the shipment of the mite *Rhizoglyphus phylloxerae* (Riley) from the United States to France for control of the grape phylloxera. This was followed in 1874 by the introduction of the lady beetle *Coccinella undecimpunctata* L. into New Zealand from England for the control of aphids. The next recorded movement was that of *Apanteles glomeratus* (L.), a parasite of the cabbage worm, to the United States from England in 1883. These three efforts resulted in establishment of the parasites in their new environment, but in no instance was economic control complete.

As mentioned above, the first example of complete and sustained economic control of an insect pest by a beneficial organism was the control of the cottony-cushion scale by the vedalia beetle. The cottony-cushion scale was accidentally introduced into California from Australia about 1869. It was first found on a species of Australian acacia in a nursery at Menlo Park, near San Francisco. None of the natural enemies of this scale were introduced with it. Free of any effective natural check, the scale spread rapidly over a large portion of the state. It was introduced on lemon trees from the nursery at Menlo Park into southern California, prior to 1876, and soon became a widespread primary pest of citrus. No means of chemical control proved effective against it. By the early 1880's citrus crops were being lost, trees were being ruined, and properties had depreciated in value.

In 1888, C. V. Riley, chief entomologist of the United States Department of Agriculture, arranged for Albert Koebele to go to Australia in search of enemies of the cottony-cushion scale. Within a few months, Koebele sent two species of insect enemies of the scale to California. These were the vedalia beetle and the parasitic fly, *Cryptochaetum iceryae* (Will.). Both species became established, but the vedalia beetle proved to be the more effective of the two. Within a year, orchards in which vedalia beetles were first released were practically free of the scale, and within two years the cottony-cushion scale ceased to be of economic importance in California.

Since the establishment of biological control of the cottony-cushion scale, many insect pests in various countries have been controlled by the biological method. The purposeful introduction into various parts of the world of certain entomophagous insects brought about full commercial control of their hosts. It is significant that in each case only one species of natural enemy was primarily responsible for control (*2*). The following list includes some of these insects:

Anaphoidea nitens Gir., a parasitic wasp (egg parasite), introduced from Australia to the Union of South Africa to control the eucalyptus snout beetle, *Gonipterus scutellatus* Gyll.

Apanteles solitarius (Ratz.), a parasitic wasp, from Europe to Canada and parts of the United States, to control the satin moth, *Stilpnotia salicis* (L.), a pest of certain forest and shade trees.

Aphelinus mali (Hald.), a parasitic wasp, from the eastern United States to New Zealand, Australia, and elsewhere, to control the woolly apple aphid, *Eriosoma lanigerum* (Hausm.), a pest of apple trees.

Cyrtorhinus mundulus Bredd., a predaceous bug, from Fiji to Hawaii, to control the sugar-cane leaf hopper, *Perkinsiella saccharicida* Kirk.

Cryptognatha nodiceps Mshll., a lady beetle, from Trinidad to Fiji, to control the coconut scale, *Aspidiotus destructor* Sign.

Eretmocerus serius Silv., a parasitic wasp, from Malaya to Cuba, to control the citrus black fly, *Aleurocanthus woglumi* Ashby.

Prospaltella smithi Silv., a parasitic wasp, from China to Japan, to control the spiny blackfly, *Aleurocanthus spiniferus* Quaint., a pest of citrus.

Ptychomyia remota Aldr., a tachinid fly, from Malaya to Fiji, to control the coconut moth, *Levuana iridescens* B.-B.

Rodolia cardinalis (Muls.), a lady beetle, from Australia to California and to many other countries, to control the cottony-cushion scale, *Icerya purchasi* Mask., a pest of citrus.

Tretacnemus pretiosus Timb., a parasitic wasp, from Australia to California, to control the citrophilus mealy bug, *Pseudococcus gahani* Green, a pest of citrus.

Introduction of a parasite obtained from a pest species other than that to be controlled. It has been demonstrated in several instances that parasites obtained from a host species other than that to be controlled may be successfully utilized. An example of this is the control of the coconut moth, *Levuana iridescens,* in Fiji, through the introduction of a tachinid fly, *Ptychomyia remota,* a parasite of *Artona catoxantha* Hmps., a moth of a different subfamily. This highly successful biological control project has been reported in detail by Tothill *et al.* (*3*). In this instance the native home of the coconut moth was in question. However, *Artona,* a different moth pest of the coconut palm, was known to be controlled by parasites in Indo-Malaya. Consequently, two parasites of *Artona,* a tachinid fly and an ichneumonid wasp, were introduced into the Fiji Islands from Indo-Malaya. The tachinid *Ptychomyia* proved to be a very effective parasite of the coconut moth in Fiji. Field control of the pest was accomplished in many areas within six months after release of the parasites, and economic control was general throughout the islands within 2 years.

Biological races of parasites. Experience has shown that in many instances a single species of parasite may be represented by two or more races which are morphologically indistinguishable and yet show marked biological differences.

The parasitic wasp *Comperiella bifasciata* How. offers an outstanding example of a single parasite species comprising at least two morphologically indistinguishable races. Through a series of attempts to establish *C. bifasciata* as a parasite of the California red scale, *Aonidiella aurantii* (Mask.), a pest of citrus in California, it was learned that stocks introduced from China differed biologically from these introduced from Japan. Both races oviposit readily in the California red scale, but only the Chinese race of *C. bifasciata* can reproduce upon it; the Japanese race rarely completes its development in this scale. However, both the Chinese and the Japanese races of *C. bifasciata* reproduce readily in the closely related yellow scale, *Aonidiella citrina* (Coq.), which is also a pest of citrus in California (*4*).

The biological control program on the olive scale, *Parlatoria oleae* (Colvée), in California, serves as a more recent illustration of the importance of biological races of parasites in pest control. In this instance stocks of *Aphytis maculicornis* (Masi) imported in 1951 from the area extending from India through the Middle East to the Mediterranean proved to be indistinguishable morphologically, yet biological studies by Hafez and Doutt (*5*) revealed the existence among them of three races which have been designated as the Indian, Persian, and Spanish forms, and which show distinct biological differences. Under field conditions in California the Persian form has proved to be the most effective in the control of the olive scale. It is apparent that the success of a biological control project may depend on the importation of stocks of a beneficial species from the various parts of its geographic range; limitation of importation to a single source may preclude success.

Importation Procedures

The success of a biological control project involving the importation of beneficial insects requires the cooperative efforts of several well-trained entomologists. The work is generally divided into three phases: (i) importation, (ii) reception, and (iii) colonization.

The first step in the importation phase is the determination of the native habitat of the pest species, this being the most logical place to begin a search for its effective natural enemies. This involves assembling information on the distribution of the pest, of the plants on which it feeds, and of its natural enemies throughout the world. The sources of such information include agricultural journals, scientific publications, collections—those in museums and those of specialists—and files of unpublished data.

The foreign explorer, in order to ensure the proper handling of imported material, sends with each shipment all of the information he may have obtained regarding the environmental conditions under which the material was found and collected, the kind of host, and the relation of the material to other insects.

The reception phase involves the segregation and analysis of the entomophagus forms under quarantine conditions and the determination of their host relations. Properly constructed quarantine facilities and specially trained entomologists are essential for this phase of the work. Suitable quarantine housing is insect-proof and sturdy. It includes proper facilities for preventing the escape of insects, as well as facilities for the incineration of all introduced host-plant materials. All rearing areas are air-conditioned to ensure optimum conditions for rearing the insects. Space is available for housing all supplies and equipment needed to determine the host relations of the imported species and for their propagation in numbers sufficient for breeding stocks, pending their release from quarantine. The entomologist in charge should have the services of competent taxonomists for the gross identification of material. He should have special knowledge of insect biologies and rearing techniques and the ability to segregate and maintain cultures of biological races of parasites which are morphologically indistinguishable.

The colonization phase includes (i) the propagation of the selected species

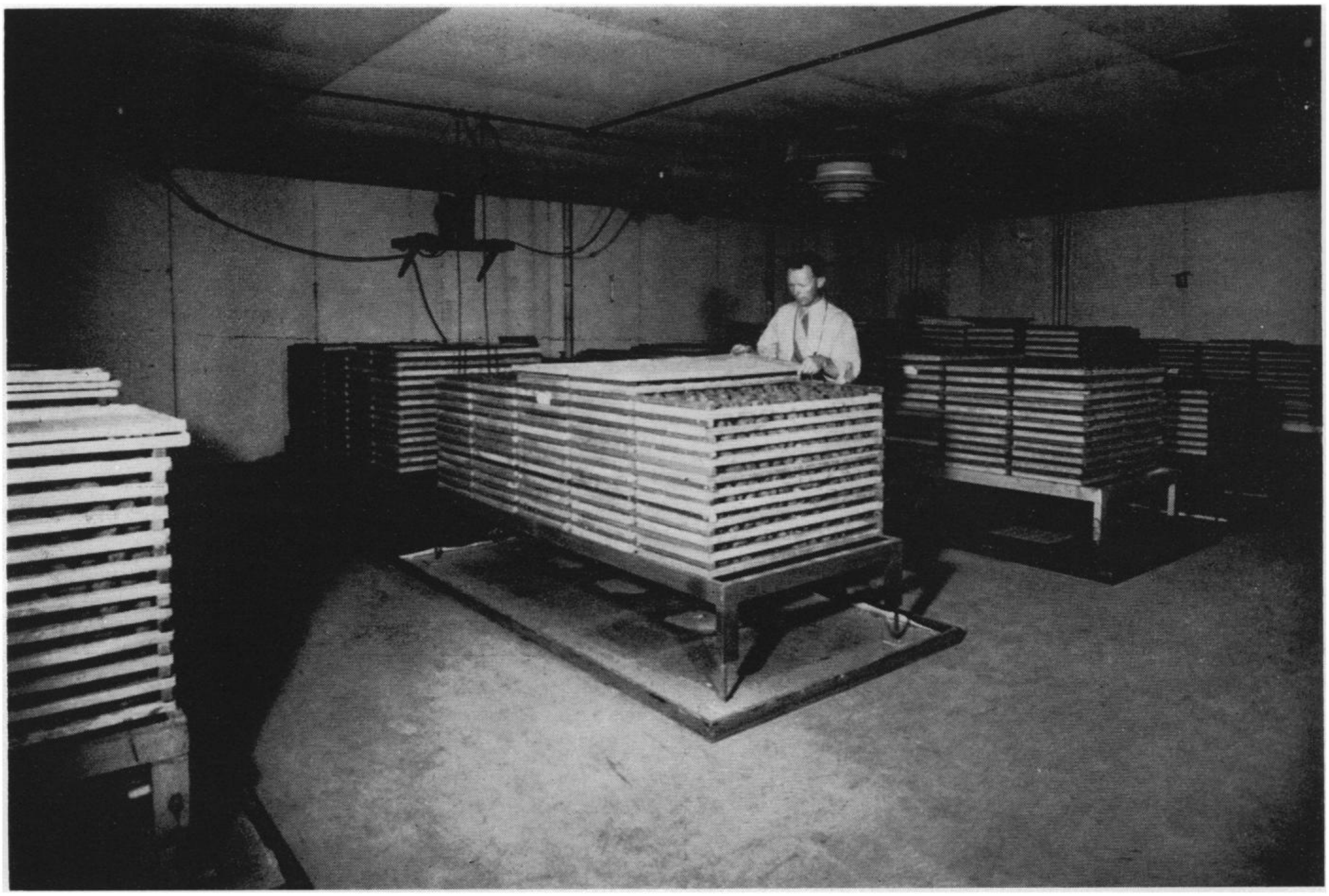

Fig. 1. Insectary room containing 50 stacks of wire trays, each tray holding 20 pounds of potatoes infested with tuber moth larvae that have been subjected to parasitization by *Macrocentrus ancylivorus* Roh. When the White Rose variety of potato is used, 75 to 80 percent of the host larvae are parasitized, the average pound of potatoes yielding 200 adult parasites. [After Finney, Flanders, and Smith]

in large numbers subsequent to release from quarantine; (ii) the selection of favorable spots for field release in all climatic areas where the pest occurs; and (iii) the ascertainment, should the beneficial species establish itself, of its effect on the population density of the host.

Mass Production and Periodic Release

It is reported that for centuries Chinese citrus growers have made a practice of placing colonies of predaceous ants in their orchards to protect the trees from the ravages of certain insect pests. The growers place bamboo poles from tree to tree to provide runways for these ants, and they feed them during certain periods when their hosts are scarce. In areas where it is too cold for the ants to overwinter, nests of these insects are purchased each spring from tradesmen in warmer areas who earn their livelihood by rearing these beneficial insects for fruit growers. In a discussion on the use of beneficial ants in China, Groff and Howard (*6*) cite a publication by Pei Wan Chai, dated 1708, which states that the kumquat is attacked by a "black ant" and that, in order to combat this ant, the people purchase "yellow ants" which they place in the trees. The "yellow ants" attack the "black ants" and kill them, and the trees thrive thereafter.

It was reported by Forskål in 1775 (*7*) and by Botta in 1880 (*8*) that predaceous ants were used in Yemen in southwestern Arabia to protect date palms from harmful ants. Each year the date growers of Yemen brought down from the mountains colonies of the beneficial ants and placed them in the palms to control the harmful ants.

In the United States, field-collected lady beetles have for many years been released for control of aphids infesting agricultural crops. The species of lady beetle that has been used almost exclusively in this work is *Hippodamia convergens* Guer. The beetles hibernate in compact colonies consisting of millions of individuals, in mountain valleys and canyons, and consequently can be collected in almost unlimited quantities at a low cost. The largest numbers of these lady beetles have gone to melon growers in the Imperial Valley of California. Recently, attempts have been made to utilize them on a large scale against the pea aphid, *Macrosiphum pisi* (Harris), in the eastern states, and against the green bug, *Toxoptera graminum* (Rond.), in the Middle West. However, in tests on the melon aphid, *Aphis gossypii* Glov., in the Imperial Valley, little or no benefit resulted from this practice, for the beetles dispersed widely immediately after release and generally appeared in the fields of their own accord as soon as the aphid infestation became sufficient to maintain them.

Predators and parasites. The instances in which naturally occurring populations of beneficial organisms can be collected and distributed periodically for economic pest control are rare. Of much more importance to the science of biological control has been the development of methods for the mass culture of beneficial organisms to be used in periodic release programs for pest control. The purpose of such programs is primarily to increase the efficiency of native or established beneficial species which, for various reasons, are not fully effective in the field.

Mass-produced beneficial insects may also be used in the inundative method of pest control. In this technique, which is practicable only under exceptional circumstances, sufficient numbers of the beneficial species are released at one time to control the pest by the first field generation. In such cases the numbers released per unit area may far exceed the host population, as frequently occurred when the wasp *Macrocentrus ancylivorus* Roh. was used to control outbreaks of the oriental fruit moth in California during the period from 1944 to 1946 (*9*).

In the mass culture of any organism the basic problem is usually the economic mass production of its food. In the culture of beneficial insects, an obvious solution to this problem is the production of suitable quantities of host insects. The discovery at Sacramento, California, in 1916, that mealy-bug pests of citrus could be grown on potato sprouts paved the way for the first successful mass culture and periodic release of insectary-produced entomophagous insects (*10*). In this project the lady beetle *Cryptolaemus montrouzieri* Muls. was reared by the millions on mealy bugs grown on potato sprouts. The beetles were released in California citrus orchards at critical periods to control the mealy bug on citrus. The use of this beetle is today a part of the citrus pest control program in certain parts of California.

The potato has proved useful in other mass-culture projects. The sprouts have served exceptionally well for the production of black scale (a pest of citrus and other plants), permitting the economical production of millions of a series of imported parasites. The potato tuber itself is an excellent host on which to produce California red scale (a primary pest on citrus in California) and other related scales used in parasite production. The potato tuber also provided a means whereby many millions of the wasp *Macrocentrus ancylivorus* were produced for the control of the Oriental fruit moth outbreak in California (Fig. 1). This production was possible because the potato tuberworm proved to be an acceptable host for the parasite, although the latter is not known to attack the tuberworm in the field (*9*).

Ripe oranges, citron melons (*Citrullus* spp.), and banana squash have been used as food in the mass-rearing of several species of tetranychid mite pests, which, in turn, are used in the production of natural enemies of mites (*11*).

The first mass production of a parasitic hymenopteran for periodic release was that developed for propagating species of *Trichogramma* parasitic on the eggs of moths and butterflies (*12*).

In the early work on this project corn was used for rearing the host insect, the Angoumois grain moth, *Sitotroga cerealella* (Oliv.). From large numbers of moths economically produced by this method, eggs were obtained for the mass rearing of *Trichogramma*. With various modifications, such as the use of wheat instead of corn for rearing *Sitotroga*, this method of mass-producing *Trichogramma* is now being used by private insectaries in several countries.

In a number of instances artificial media have been used successfully in the mass culture of host insects, parasites, or predators. Hagen (*13*) found that egg deposition of the predator *Chrysopa californica* (Coq.) was greatly increased by adding an enzymatic hydrolysate of brewer's yeast to the honey solution fed to adults.

Hagen and Finney (*14*) recently developed an artificial food medium for the mass production of the oriental fruit fly, *Dacus dorsalis* Hendel, in Hawaii, which greatly expedited the parasite-production program. The use of fruit for this purpose was uneconomical, and it was impracticable for several other reasons. A preparation of squash, later replaced by carrot, supplemented with an enzymatic protein hydrolysate of soy to induce increased fecundity, proved highly satisfactory for large-scale production of the fly.

House and Traer (*15*) found that the larvae of the sarcophagid fly, *Pseudosarcophaga affinis* (Fall.), parasitic in the spruce budworm, *Choristoneura fumiferana* (Clem.), could be reared on an artificial medium. They showed that a proper mixture of pork liver and fish was fully acceptable to the parasite larvae and that a much higher proportion of the larvae reached maturity on this medium than on the natural insect host. This development permitted year-round production of the parasite in any desired quantity.

Insect pathogens. Mass-produced pathogenic microorganisms are also used in "mass-release" programs to control noxious insects. When employed in this manner the pathogens may be colonized in the field, or they may be mixed with a suitable diluent and applied as dusts or sprays. Such insect pathogens, being fairly specific, are harmless to other forms of life and thus have no adverse effect on the biological balance of other pest species in the area where they are used.

In 1911 the artificial distribution of a bacterium, *Coccobacillus acridiorum* d'Her., apparently controlled migratory locusts (*Schistocerca* spp.) in Mexico, Argentina, and Tunisia (*16*). This was the first well-publicized instance in which bacteria were used in an attempt to control insects.

The most outstanding example of insect pest control by mass-produced dis-

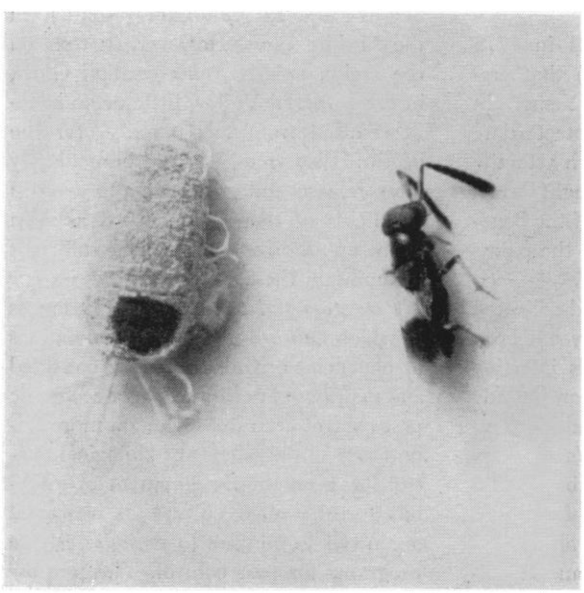

Fig. 2. Mummy of a long-tailed mealy bug (left) which was parasitized by *Anarhopus sydneyensis* Timb. (right). The circular opening in the mummy is the exit hole through which the parasite emerged. *Anarhopus sydneyensis*, introduced into California from Australia, controls the long-tailed mealy bug on avocado, citrus, and other plants.

Fig. 3. Predatory mite, *Typhlodromus* sp. Mites belonging to this beneficial genus prey on many species of injurious plant-feeding mites.

ease organisms is the use of *Bacillus popilliae* Dutky, the causative agent of milky disease, against the Japanese beetle, *Popillia japonica* Newm., in the eastern United States. In 1939, members of the Bureau of Entomology and Plant Quarantine of the U.S. Department of Agriculture devised methods for preparing spores of *B. popilliae* for field distribution (*17*). In this preparation spores of *B. popilliae* cultured in Japanese beetle larvae are mixed with a suitable carrier, such as talcum powder, at a concentration of approximately 100 million spores per gram. This spore-dust mixture is applied to the soil, and the spores are disseminated throughout the area. The Japanese beetle larvae, which subsequently ingest the spores, are then destroyed by the well-known milky disease.

Insect pathogens, as well as parasites and predators, may be mass-produced on artificial media. The famous Russian zoologist Elie Metchnikoff was probably the first to produce an insect pathogen on an artificial medium. In 1880 he utilized sterilized beer mash for the production of spores of the green-muscardine fungus *Metarrhizium anisoplae* (Metch.). The spores thus produced were used experimentally in the control of several insect pests (*18*). The bacterium *Coccobacillus acridiorum,* used by d'Herelle to control locusts, was produced on nutrient agar. In the 1920's and early 1930's several European workers used aqueous suspensions and dusts of the bacterium *Bacillus thuringiensis* Berliner with varying degrees of success in controlling the European corn borer, *Pyrausta nubilalis* (Hbn.). In California, in 1950, spores of *B. thuringiensis* produced on nutrient agar were used in field experiments on the biological control of the alfalfa caterpillar, *Colias philodice eurytheme* Bdv. (*19*). The results of these experiments and of experiments involving the use of *B. thuringiensis* to control other lepidopterous pests were so promising that this material is now being produced commercially in aerated nutrient broth by several firms.

Although at present the number of beneficial organisms which can be produced on artificial food media is limited, it is apparent that in the study of nutrition lies one of the greatest frontiers in the science of biological control.

Conservation and Augmentation of Native Beneficial Organisms

Economic importance. Plant-feeding insects everywhere are subject to attack by parasites, predators, and diseases. In some cases the influence of these beneficial organisms on pest populations is merely superficial; in other cases their influence is of great economic importance. These beneficial organisms control many pest insects which, in their absence, would cause serious economic loss. In fact, the vast majority of plant-feeding insects throughout the world are under satisfactory natural balance. Control measures such as the use of insecticides are necessary only where effective beneficial organisms or other natural control factors are either lacking or unable to maintain pest species below the level of economic importance.

Results of long-term field studies on the biological balance in California avocado groves will serve to illustrate the great economic importance of native parasites and predators and the problems involved in their conservation.

Pest-control treatment is seldom necessary in California avocado orchards. Each year only a fraction of 1 percent of the total avocado acreage receives chemical pest-control treatment. Field studies now in progress have shown that, despite the seeming freedom from destructive pests, there are many species of insects of potential economic importance present in avocado orchards throughout southern California, but that in general they are in a state of almost perfect biological balance (*20*). Some of the potential pests—such as the long-tailed mealy bug, *Pseudococcus adonidum* (L.), the black scale, *Saissetia oleae* (Bern.), and the soft (brown) scale, *Coccus hesperidum* L.—are controlled by imported parasites, but most are controlled by native parasites and predators (Fig. 2). Numerous experiments have shown that when parasites and predators are excluded from avocado trees in any area, damaging populations of various mite and insect pests soon develop.

In one experiment, for a period of 84 days all parasites and predators were removed by hand from a portion of an avocado tree in an orchard in the coastal area of San Diego County. During this time the omnivorous looper, *Sabulodes caberata* Gn., the six-spotted mite, *Eotetranychus sexmaculatus* (Riley), the long-tailed mealy bug, the avocado brown mite, *Oligonychus punicae* (Hirst), and the latania scale, *Hemiberlesia lataniae* (Sign.), developed to high populations on the portions of the tree from which the beneficial insects were removed. The three first-named species developed to seriously damaging proportions (*21*).

To save the leaves on the experimental portion of this tree, it became necessary to remove the larvae of the omnivorous looper, whose population also had been released from the repressive action of natural enemies. A careful study of the natural balance of the looper larvae at this time disclosed that over 90 percent of the very young larvae were parasitized by one or the other of two species of small wasps, *Apanteles caberatae* Mues. and *Meteorus tersus* Mues. These two native parasitic wasps were largely responsible for the excellent natural control of the loopers that was maintained in the orchard during these studies.

Throughout the entire experimental period there were no observed pest problems on the remainder of the test tree or on any other tree in the grove.

In this instance, predatory *Typhlodromus* mites (Fig. 3), a small black lady beetle (*Stethorus picipes* Casey), and a small staphylinid beetle [*Oligota oviformis* (Casey)]—all native predators—were primarily responsible for the control of the avocado brown mite and the six-spotted mite.

This simple experiment clearly demonstrated that except for the protective action of native parasites and predators the damage caused throughout the grove by the pests mentioned would have been truly disastrous.

Other such studies showed that when beneficial insects were removed by hand from certain castor-bean plants, the plants soon lost most of their leaves as a result of feeding damage by the two-spotted mite, while the surrounding plants remained relatively free of mites and showed practically no mite damage. Similarly, when predators of citrus red mites were removed by hand from certain citrus trees, those trees were much more seriously damaged by the mites than were surrounding trees to which the predators had access (*22*).

At Riverside, in the interior avocado-growing area of California, *Amorbia* (see Fig. 4) may quickly build up to seriously damaging populations when parasites and predators are excluded by the use of screen tree cages or cloth sleeve cages. Upon removal of such barriers excellent natural balance is attained in a surprisingly short time.

Ants. There are many species of ants associated with agricultural crops. Some of the ants prey on harmful insects and thus are beneficial; others inhibit the activity of beneficial insects or damage plants and thus are harmful.

The use of predaceous ants in China to control various citrus pests and in Arabia to control ants destructive of date palms has already been discussed.

In the forests of Germany, ants of the genus *Formica* are colonized in artificial nests and protected for their aid in controlling insect pests of the trees. There are many other species of predaceous ants which, in the aggregate, destroy vast numbers of noxious insects; the economic value of ants in this respect seems to have been generally underestimated.

The species of ants that are harmful to agricultural crops are mainly those that feed on honeydew secreted by scale insects, mealy bugs, white flies, aphids, and leaf hoppers. Their activities emphasize the importance of entomophagous insects in pest control. In gathering honeydew, ants surround these pest species and attack other insects that attempt to reach them. In this way they protect the harmful species from their insect enemies and make it possible for the former to thrive and increase to the point of causing severe damage. This protective effect is not limited to honeydew-producing species but is often extended to associated phytophagous species such as mites and diaspidine scale insects, when such forms happen to be within the area of ant activity.

In avocado orchards in California the Argentine ant, *Iridomyrmex humilis* Mayr, while gathering honeydew from colonies of long-tailed mealy bugs, soft (brown) scale, and black scale, protects these pests from their natural enemies and thus is frequently responsible for the development of damaging populations of the pest species. This same ant also disturbs or kills natural enemies of other pest species in the vicinity and is therefore frequently responsible for increasing the populations of such non-honeydew-secreting pests as six-spotted mites, avocado brown mites, and *Latania* scale. The Argentine ant has a similar influence on insect pests in California citrus groves. Therefore it is essential to eliminate ants from orchards where biological control measures are practiced.

It is becoming increasingly clear that the presence of honeydew-feeding ants may greatly reduce the effectiveness of beneficial insects that might otherwise be capable of controlling major pest species, regardless of the pest or the plant species concerned.

Insecticides. Just as the removal of beneficial insects by hand-picking or through the use of mechanical barriers may result in the development of heavy infestations of their harmful insect hosts, so may a similar result follow the use of insecticides which are toxic to beneficial species. In this manner a given insecticidal treatment may result in (i) an increase in numbers of the pest species against which control is directed, or (ii) serious outbreaks of other insects and mites, which, prior to the treatment, were so rare as to be of no economic importance.

In the first case, the pest increase occurs because the insecticide that effectively controls the pest for a given period of time has an even more drastic and longer-lasting effect on the beneficial species which formerly gave partial control of the pest. Thus, freed of natural enemies, the pest species rapidly increase to much higher populations than occurred before treatment.

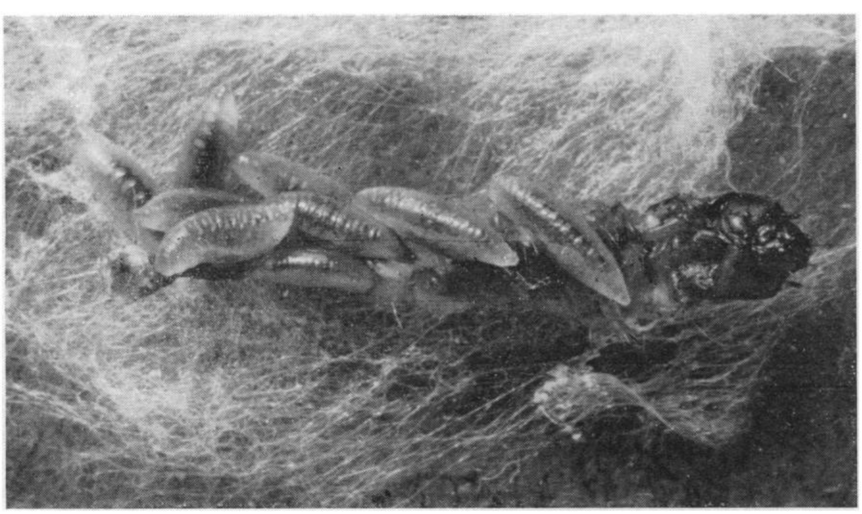

Fig. 4. Larvae of a parasitic wasp, *Elachertus proteoteratis* Howard, devouring a caterpillar of *Amorbia essigana* Busck, a pest of avocado in California. This native parasite, along with several other native parasites, effectively controls *A. essigana*.

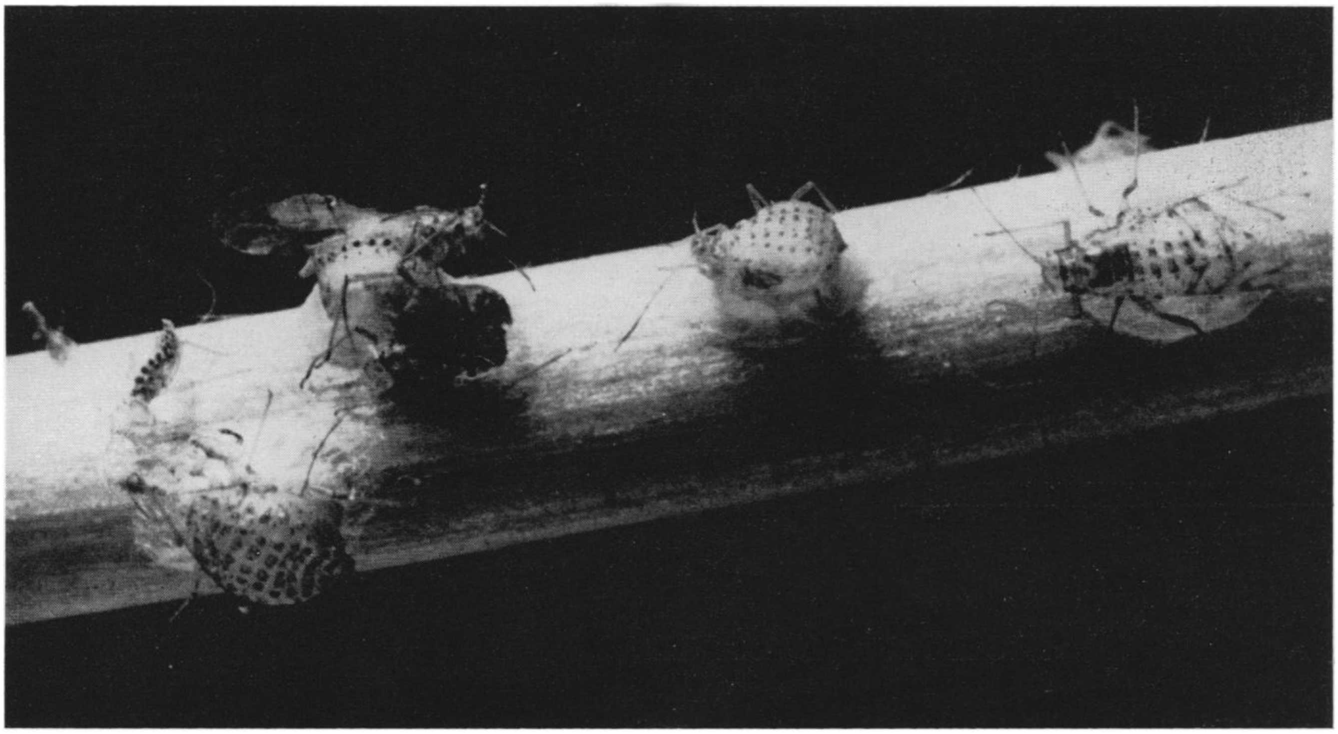

Fig. 5. Spotted alfalfa aphids parasitized by the wasp *Praon palitans* Mues. Cocoons of the wasp may be seen securely attached between the dead aphids and the alfalfa stem. *Praon palitans* was introduced into California from the Middle East.

In the second case, the pest species may increase in numbers either for the same reason as given in the first case or because the treatment killed certain beneficial species but was innocuous to the pests which these species had controlled. Entomological literature contains many examples of these several effects of insecticides on biological balance.

Biological upsets following the use of insecticides have been especially common since the relatively recent development and widespread use of highly toxic insecticides having long residual action. DDT was the first of the new insecticides to attract attention in this respect. The extensive and indiscriminate use of DDT destroyed harmful and beneficial insects alike and resulted in a subsequent increase in numbers of phytophagous insects and mites. For example, DDT readily killed all arthropod enemies of certain plant-feeding mites but did not kill the mites; consequently, many agricultural crops developed injurious mite populations following the use of DDT for the control of various insect pests.

An excellent example in this connection was the severe damage caused by six-spotted mites in California avocado orchards following the use of DDT for control of the greenhouse thrips, *Heliothrips haemorrhoidalis* (Bouché). DDT gave excellent control of the thrips, but it also killed the natural enemies which had previously controlled the six-spotted mites. Thus freed of their natural check, the mites, which were not harmed by the DDT, rapidly increased in numbers and severely damaged the trees. This particular danger is now avoided by the use of a modified spray program.

In addition to the potent new insecticides, there are various other pest-control materials which have long been known to cause biological upsets. In a recent review of the effects of pesticides on arthropod populations, Ripper (*23*) states that in spite of a good initial kill at the time of treatment, chlorinated hydrocarbons, parathion, para-oxon, sulfur, lime sulfur, copper carbonates, calcium arsenate, derris, zinc sulphate, thiuram, and even supposedly inert materials used on orchard or field crops at times bring about a tremendous increase of the pest species against which they have been applied or of other phytophagous species present in small numbers at the time of treatment. Upsets of this sort have been recorded in temperate, subtropical, and tropical climates for many species of arthropods belonging to the families of Tetranychidae, Euophyidae, Tarsonemidae, Coccidae, Aphididae, Aleyrodidae, Cicadellidae, Noctuidae, Tortricidae, Olethreutidae, Tephritidae, Agromyzidae, and Collembola.

Because the indiscriminate use of insecticides frequently results in the destruction of beneficial insects and thus in increased rather than in decreased pest activity, and because both insecticides and beneficial insects play important roles in pest control, more and more attention is being given to the development of integrated pest-control programs. The aim of such programs is the development of insecticidal treatments which will least inhibit the activity of beneficial insects. Considerable progress is currently being made in this respect through the use of selective insecticides, proper timing of application, and proper insecticidal dosage.

The recent program developed for control of the alfalfa aphid, *Therioaphis maculata* (Buckton), in California, offers an excellent example of integrated pest control (*24*). In this program the use of Systox—a selective systemic insecticide—with proper timing and a low dosage, offered a minimum of resistance to a complex of native and introduced beneficial organisms, including parasites (see Fig. 5), predators, and diseases. The activity of beneficial organisms in this integrated pest-control program now saves millions of dollars annually for California alfalfa growers.

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CURRENT PROBLEMS IN RESEARCH

Electroluminescence

New light sources, having theoretical as well as practical interest, are created by electroluminescence.

K. H. Butler

The art of producing light has gradually evolved from the original volume sources, typified by a bonfire or a lamp flame, through line sources, represented by incandescent filaments, to point sources, such as the concentrated arc lamp, and finally to a plane source, the electroluminescent lamp.

This newest member of the large family of lamps generates a sheet of light, not more than a few thousandths of an inch thick, by direct electrical excitation of a phosphor embedded in a dielectric layer. This light-emitting surface can be applied directly to a thin piece of metal, giving a lamp no thicker than half a dozen pages of a magazine, with two fine wires leading to a source of power. The simplicity and mechanical strength of the electroluminescent lamp thus presents a striking contrast to the complex supporting structure and fragile glass envelopes of practically all other electrical lamps.

While natural phosphorescent materials must have existed for many thousands of centuries, no known record exists prior to A.D. 980, when it was noted by the Japanese that calcinated oyster shells could store up light by day and give it off at night. After several more centuries other materials were recognized which would convert ultraviolet radiation, or other special sources of energy, into visible fluorescent light immediately. The systematic studies by Becquerel, Lenard, and Nichols between 1860 and 1920 laid the foundations for the modern development of phosphors.

While phosphors are generally excited by bombardment with high-speed electrons, as in television tubes, or by ultraviolet radiation, as in the fluorescent lamp, many other methods can be used to make them luminesce. However, the results are usually only of scientific interest and have no practical value.

In the early 1920's Gudden and Pohl made some noteworthy studies of the luminescence and photoconductivity of zinc sulfide phosphors. In the course of these investigations they found that if a phosphor were excited by ultraviolet radiation, the application of a strong electric field during the phosphorescent decay gave a temporary increase of light emission. Further studies by Schmidt, Hinderer, and Destriau confirmed and extended this observation. Destriau reported also that a strong field applied to certain phosphors, without previous ultraviolet excitation, would give a transient light emission and that if the field were alternating, the light emission would be sustained.

This scientific observation remained essentially dormant until 1950, with some scientists doubting the existence of the effect, until Payne, Mager, and Jerome announced the development of a practical electroluminescent lamp in their report to the Illuminating Engineering Society. Commercial production of the lamp followed immediately.

The potential importance of this unique light source was obvious, and there has been a rapid burgeoning of interest in electroluminescence for the last ten years, with a proliferation of papers in many journals.

In the present article an attempt is made to winnow out and present the more significant facts on electroluminescence from the extensive literature.

Lamp Construction

Basically, the commercial electroluminescent lamp is a flat-plate condenser with the dielectric medium between the two electrodes containing a phosphor in suspension. When alternating current in the audiofrequency range is supplied, power consumption by the suspended particles results in excitation of the phosphor with emission of visible light. Since the light is generated in the dielectric phosphor layer, at least one of the electrodes of the condenser must be transparent or translucent to give a useful lamp.

Figures 1A, 1B, and 1C show three types of construction which have been used in manufacture during the last eight years. In type A, a sheet of glass is

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