HILGARDIA

A Journal of Agricultural Science Published by the California Agricultural Experiment Station

VOLUME 29 OCTOBER, 1959 NUMBER 2

THE INTEGRATION OF CHEMICAL AND BIOLOGICAL CONTROL OF THE SPOTTED ALFALFA APHID

The Integrated Control Concept

Vernon M. Stern, Ray F. Smith, Robert van den Bosch, and Kenneth S. Hagen

Field Experiments on the Effects of Insecticides

Vernon M. Stern and Robert van den Bosch

Impact of Commercial Insecticide Treatments

Ray F. Smith and Kenneth S. Hagen

UNIVERSITY OF CALIFORNIA · BERKELEY, CALIFORNIA

Chemical and biological control are regarded as two main methods of suppressing insects and spider mites. These two methods are often thought of as alternatives in pest control. This is not necessarily so, for with adequate knowledge they can be made to augment one another.

Biological control is part of the permanent natural control of population density. Chemical controls involve only immediate and temporary decimation of localized populations and do not contribute to natural control. Natural control may keep a pest species from ever reaching the economic-injury level or it may permit economic outbreaks. The frequency of these pest outbreaks varies from a regular to an occasional occurrence depending upon the level of the general equilibrium position in relation to the economic injury level and the types of fluctuations about the general equilibrium position.

Integrated control combines and integrates biological and chemical controls. Chemical control is used as necessary and in a manner which is least disruptive to biological control. Integrated control may make use of naturally occurring biological control as well as modified or introduced biological control. Thought must be given to the biological control of not only the primary pest under consideration but also other potential pests.

Integrated control is most successful when sound economic thresholds have been established, rapid sampling methods have been devised, and selective insecticides are available. In some situations, the development of integrated control requires the augmentation of biological control through the introduction of additional natural enemies or modification of the environment.

Integrated control of the spotted alfalfa aphid has been achieved in California. Economic thresholds were established so that insecticides are applied only when damage is imminent. Native predators, introduced parasites, and entomogenous fungi now keep the spotted-alfalfa-aphid populations below the economic threshold for most of the year. When population counts in the individual field clearly demonstrate that a field is threatened, Systox is applied at low dosages. These chemical treatments give adequate control, but do not necessarily eradicate the aphids. Most of the predators and parasites survive and persist on the remaining aphids.

HILGARDIA

A Journal of Agricultural Science Published by the California Agricultural Experiment Station

VOL. 29 | OCTOBER, 1959 | NO. 2

THE INTEGRATED CONTROL CONCEPT[1]

VERNON M. STERN, RAY F. SMITH, ROBERT van den BOSCH, and KENNETH S. HAGEN[2]

ALL ORGANISMS are subjected to the physical and biotic pressures of the environments in which they live, and these factors, together with the genetic make-up of the species, determine their abundance and existence in any given area. Without natural control, a species which reproduces more than the parent stock could increase to infinite numbers. Man is subjected to environmental pressures just as other forms of life are, and he competes with other organisms for food and space.

Utilizing the traits that sharply differentiate him from other species, man has developed a technology permitting him to modify environments to meet his needs. Over the past several centuries, the competition has been almost completely in favor of man, as is attested by decimation of vast vertebrate populations, as well as populations of other forms of life (Thomas, 1956). But while eliminating many species, as he changed the environment of various regions to fit his needs for food and space, a number of species, particularly among the Arthropoda, became his direct competitors. Thus, when he subsisted as a huntsman or foraged for food from uncultivated sources, early man was largely content to share his subsistence and habitat with the lower organisms. Today, by contrast, as his population continues to increase (Hertzler, 1956) and his civilization to advance, he numbers his arthropod enemies in the thousands of species (Sabrosky, 1952).

The increase to pest status of a particular species may be the result of a single factor or a combination of factors. In the last century, the most significant factors have been the following.

First, by changing or manipulating the environment, man has created conditions that permit certain species to increase their population densities

[1] Received for publication October 24, 1958. This investigation (including those parts reported in the other two papers of this issue) was supported in part by research grants nos. E 885 and E 2192 from the National Institute of Allergy and Infectious Diseases of the National Institutes of Health, Public Health Service.

[2] Mr. Stern is Assistant Entomologist in Entomology, Citrus Experiment Station, Riverside; Mr. Smith is Associate Professor of Entomology and Associate Entomologist in the Experiment Station, Berkeley; Mr. van den Bosch is Associate Entomologist in Biological Control, Citrus Experiment Station, Riverside; and Mr. Hagen is Associate Entomologist in Biological Control in the Experiment Station, Berkeley.

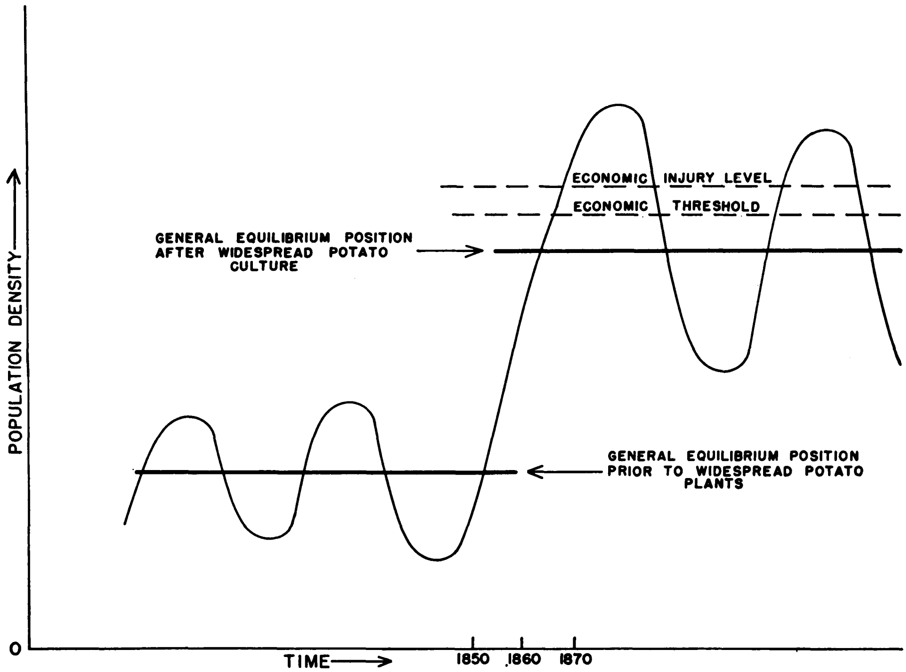


Fig. 1. Schematic graph of the change in general equilibrium position of the Colorado potato beetle, *Leptinotarsa decemlineata* following the development of widespread potato culture in the United States. For a discussion of the significance of economic-injury levels and economic thresholds in relation to the general equilibrium position, see p. 89.

(Ullyett, 1951). The rise of the Colorado potato beetle, *Leptinotarsa decemlineata* (Say), to pest status occurred in this manner (see fig. 1). When the potato, as well as other solanaceous plants, was brought under widespread cultivation in the United States, a change favorable to the beetle occurred in the environment, which enabled it to become very quickly an important pest (Trouvelot, 1936). Similarly, when alfalfa, *Medicago sativa* L., was introduced into California about 1850, the alfalfa butterfly, *Colias philodice eurytheme* Boisduval, which had previously occurred in low numbers on native legumes, found a widespread and favorable new host plant in its environment, and it subsequently became an economic pest (Smith and Allen, 1954).

A second way in which arthropods have risen to pest status has been through their transportation across geographical barriers while leaving their specific predators, parasites, and diseases behind (Smith, 1959). The increase in importance through such transportation is illustrated by the cottony cushion scale, *Icerya purchasi* Maskell (see fig. 2). This scale insect was introduced into California from Australia on acacia in 1868. Within the following two decades, it increased in abundance to the point where it threatened economic disaster to the entire citrus industry in California. Fortunately, the timely importation and establishment of two of its natural ene-

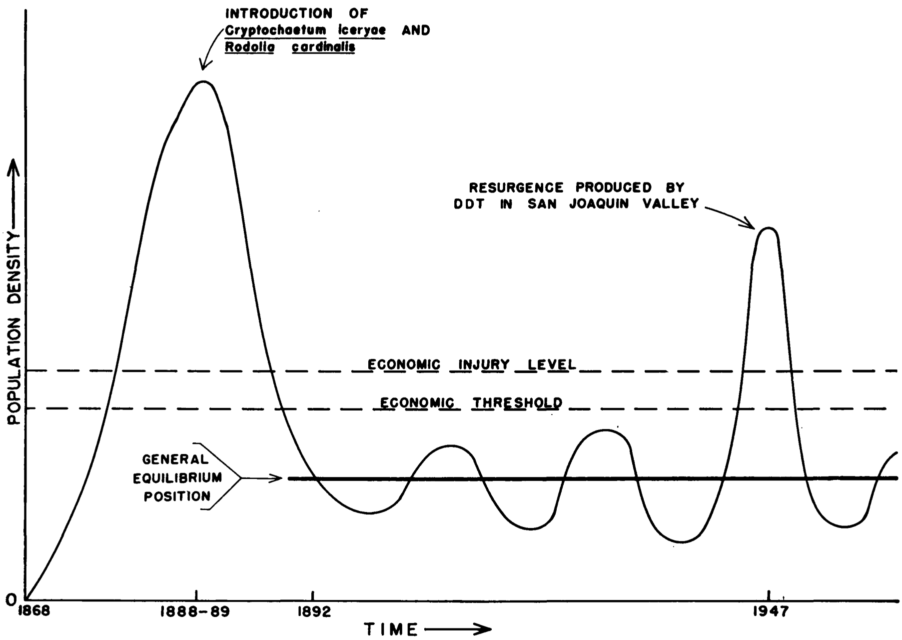


Fig. 2. Schematic graph of the fluctuations in population density of the cottony cushion scale, *Icerya purchasi,* on citrus from the time of its introduction into California in 1868. Following the successful introduction of two of its natural enemies in 1888 this scale was reduced to noneconomic status except for a local resurgence produced by DDT treatments.

mies, *Rodolia cardinalis* (Mulsant) and *Cryptochaetum iceryae* (Williston), resulted in the complete suppression of *I. purchasi* as a citrus pest (Doutt, 1958).

The cottony cushion scale again achieved the status of a major pest when the widespread use of DDT on citrus in the San Joaquin Valley eliminated the vedalia (Ewart and DeBach, 1947).

A third cause for the increasing number of pest arthropods has been the establishment of progressively lower economic thresholds (see p. 89 for definition and discussion). This can be illustrated by lygus bugs (*Lygus* spp.) on lima beans. Not too many years ago the blotches caused by lygus bugs feeding on an occasional lima bean were of little concern, and lygus bugs were considered a minor pest on this crop. However, with the emphasis on product appearance in the frozen-food industry, a demand was created for a near-perfect bean. For this reason, economic-injury thresholds were established and lygus bugs are now considered serious pests of lima beans.

In the face of this increased number of arthropod pests man has made remarkable advances in their control, and economic entomology has become a complex technical field. Of major importance have been new developments in pesticide chemistry and application.

The discovery of the insecticidal properties of DDT, and its spectacularly successful application to arthropod-borne disease and agricultural pest problems, spurred research in chlorinated hydrocarbon chemistry and stimulated the development of other organic pesticides. On a national scale, the experiment stations, state and governmental agencies, and commercial companies, all searching for new or better answers to old insect-pest problems, eagerly accepted the new chemicals. Within a short period many became an integral part of public health and agricultural pest-control programs. Without question, the rapid and widespread adoption of organic insecticides brought incalculable benefits to mankind, but it has now become apparent that this was not an unmixed blessing. Through the widespread and sometimes indiscriminate use of pesticides, the components and intricate relations of crop environments have been drastically altered, and as a result a number of serious problems have arisen (Wigglesworth, 1945; Michelbacher, 1954; Pickett, 1949; Pickett and Patterson, 1953; Solomon, 1953; and others). Among these new problems and old ones which have been aggravated are:

1. Arthropod resistance to insecticides. This phenomenon relating to the genetic plasticity of the arthropods has been reviewed by Metcalf (1955), Hoskins and Gordon (1956), Crow (1957), Brown (1959), and others. In many cases, resistance is already drastic enough to have eliminated certain insecticides from important pest-control programs. There are today in excess of 70 demonstrated cases of arthropod resistance. Actually, a much larger number of pest species exist which are developing resistance or have already done so, but there has not been time to evaluate these cases.

2. Secondary outbreaks of arthropods other than those against which control was originally directed (Massee, 1954; DeBach and Bartlett, 1951; Ripper, 1956; and others). These outbreaks usually result from the interference of the insecticide with biological control (Lord, 1947; Bartlett and Ortega, 1952; Michelbacher, 1954; Michelbacher and Hitchcock, 1958; and others). This may also occur through the effect of the insecticide on the plant, which, in turn, affects the development of the secondary pest (Fleschner and Scriven, 1957). An example is the increase in mites on plants growing in soil receiving certain chemical treatments (Klostemeyer and Rasmussen, 1953).

3. The rapid resurgence of treated species necessitating repetitious insecticide applications (Holloway and Young, 1943; Bovey, 1955; Schneider, 1955; Stern and van den Bosch, 1959; and others). These flarebacks occur from individuals surviving treatment or from individuals migrating into the treated area, where they can reproduce unhindered because their natural enemies have been eliminated.

4. The toxic insecticide residues on food and forage crops (Brown, 1951; Linsley, 1956). This problem may result from two sources. First, untimely applications or accidental increases in dosage may result in residues above the tolerance limits. Second, the first three problems mentioned above are interrelated and by aggravating one another may lead to excessive treatment and a residue problem. For example, where the level of resistance is increasing, it requires either more frequent applications or higher insecticide dosages to control the pest, or both. This increased insecticide program may in turn have a drastic effect on the ecosystem, which frequently results in outbreaks of secondary pests or rapid resurgence of the resistant pest

for which control was originally intended. Often, under such conditions, where insects threaten the crop or marketability of a crop close to harvest, the grower is faced with the problem of suffering a severe monetary loss or of making an insecticide application closer to harvest than is ordinarily permissible. In many instances, the end result is a residue far above the accepted tolerance limit at harvest time.

5. Hazards to insecticide handlers and to persons, livestock, and wildlife subjected to contamination by drift (Hayes, 1954; Petty, 1957; Upholt, 1955).

6. Legal complications from suits and other actions pertaining to the above problem.

Unquestionably, some of these problems have arisen from our limited knowledge of biological science; others are the result of a narrow approach to insect control. Few studies have included basic investigations on the effects the chemicals might have on other components of the ecosystems to which the pests belong. The entomologist may recognize the desirability of a thorough investigation of these aspects, but because of the need for immediate answers to pressing problems and because of other pressures, he does not have the necessary time. In other instances because fundamental knowledge is lacking, the investigator may be unaware of the intricate nature of the biotic complex with which he is dealing, and of the destructive potential that many chemicals in use today have on the environment of the pests. Finally, and most unfortunately, there are workers who are highly skeptical that biotic factors are of any consequence in the control of pest population densities and thus choose to ignore any approach to pest control other than the use of chemicals.

Whatever the reasons for our increased pest problems, it is becoming more and more evident that an integrated approach, utilizing both biological and chemical control, must be developed in many of our pest problems if we are to rectify the mistakes of the past and avoid similar ones in the future (DeBach, 1951, 1958*a*; Pickett, Putman, and Roux, 1958; Ripper, 1944; Huffaker and Kennett, 1956; Wille, 1951; Michelbacher and Middlekauff, 1950; and others).

TERMINOLOGY

To clarify the discussion in other parts of this paper some definitions and explanations of terms are here given:

Biological control. *The action of parasites, predators, or pathogens on a host or prey population which produces a lower general equilibrium position than would prevail in the absence of these agents.* Biological control is a part of natural control (*q.v.*) and in many cases it may be the key mechanism governing the population levels within the framework set by the environment. If the host or prey population is a pest species, biological control may or may not result in economic control. Biological control may apply to any species whether it is a pest or not, and regardless of whether or not man deliberately introduces, manipulates, or modifies the biological-control agents.

Biotic insecticide. *A biotic mortality agent applied to suppress a local insect pest population temporarily.* The effects of the agent usually do not persist and they are similar to those resulting from the use of a chemical insecticide in that they do not produce a permanent change in the general equilibrium position. A polyhedrosis virus applied as a spray to control the alfalfa caterpillar is a typical example of a biotic insecticide. Preparations of microörganisms used in this manner are sometimes referred to as *microbial insecticides.* Predators, such as lady beetles, or parasites, when they are released in large numbers, can also act, in some instances, as biotic insecticides.

Biotic reduction. *Deaths or other losses to the population* (e.g., *dispersal, reduced fecundity*) *caused or induced by biotic elements of the environment in a given period of time.*

Economic control. *The reduction or maintenance of a pest density below the economic-injury level* (q.v.).

Economic-injury level. *The lowest population density that will cause economic damage.* Economic damage is the amount of injury which will justify the cost of artificial control measures; consequently, the economic-injury level may vary from area to area, season to season, or with man's changing scale of economic values.

Economic threshold. *The density at which control measures should be determined to prevent an increasing pest population from reaching the economic-injury level.* The economic threshold is lower than the economic-injury level to permit sufficient time for the initiation of control measures and for these measures to take effect before the population reaches the economic-injury level.

Ecosystem. *The interacting system comprised of all the living organisms of an area and their nonliving environment.* The size of area must be extensive enough to permit the paths and rates of exchange of matter and energy which are characteristic of any ecosystem.

General equilibrium position. *The average density of a population over a period of time* (*usually lengthy*) *in the absence of permanent environmental change.* The size of the area involved and the length of the period of time will vary with the species under consideration. Temporary artificial modifications of the environment may produce a temporary alteration of the general equilibrium position (*i.e.*, a temporary equilibrium).

Governing mechanism. *The actions of environmental factors, collectively or singly, which so intensify as the population density increases and relax as this density falls that population increase beyond a characteristic high level is prevented and decrease to extinction is made unlikely.* The governing mechanisms operate within the framework or potential set by the other environmental elements.

Integrated control. *Applied pest control which combines and integrates biological and chemical control.* Chemical control is used as necessary and in a manner which is least disruptive to biological control. Integrated control may make use of naturally occurring biological control as well as biological control effected by manipulated or introduced biotic agents.

Microbial control. *Biological control that is effected by microörganisms (including viruses).*

Natural control. *The maintenance of a more or less fluctuating population density within certain definable upper and lower limits over a period of time by the combined actions of abiotic and biotic elements of the environment.* Natural control involves all aspects of the environment, not just those immediate or direct factors producing premature mortality, retarded development, or reduced fecundity; but remote or indirect factors as well. For most situations, governing mechanisms (*q.v.*) are present and determine the population levels within the framework or potential set by the other environmental elements. In the case of a pest population, natural control may or may not be sufficient to provide economic control.

Natural reduction. *Deaths or other losses to the population caused by naturally existing abiotic and biotic elements of the environment in a given period of time.*

Population. *A group of individuals of the same species that occupies a given area.* A population must have at least a minimum size and occupy an area containing all its ecological requisites to display fully such characteristics as growth, dispersion, fluctuation, turnover, dispersal, genetic variability, and continuity in time. The minimum population and the requisites in occupied area will vary from species to species.

Population dispersion. *The pattern of spacing shown by members of a population within its occupied habitat and the total area over which the given population may be spread.*

Selective insecticide. *An insecticide which while killing the pest individuals spares much or most of the other fauna, including beneficial species, either through differential toxic action or through the manner in which the insecticide is utilized (formulation, dosage, timing, etc.).*

Supervised insect control. *Control of insects and related organisms supervised by qualified entomologists and based on conclusions reached from periodically measured population densities of pests and beneficial species.* Ideally, supervised control is based on a sound knowledge of the ecology of the organisms involved and projected future population trends of pests and natural enemies.

Temporary equilibrium position. *The average density of a population over a large area temporarily modified by a procedure such as continued use of insecticides.* The modified average density of the population will revert to the previous or normal density level when the modifying agent is removed or expended (*cf.* "general equilibrium position").

THE NATURE AND WORKING PRINCIPLES OF BIOLOGICAL AND CHEMICAL CONTROL

Biological Control. Biological controls are part of natural control which governs the population density of pest species. On the other hand, with certain exceptions, chemical controls involve only immediate and temporary decimation of localized populations and do not contribute to permanent density regulation. This distinction is not always clearly made, and biological control is often thought of as being similar in its action to chemical control. Perhaps one reason for the misunderstanding is that in spectacular instances a biotic agent may act in the manner of a chemical in eliminating a local pest population. For example, this may occur when weather conditions are favorable and disease pathogens eliminate a localized pest population. Parasites and predators may sometimes act in a similar manner. However, the important prevailing characteristic of biological control is one of permanent population-density regulation. Usually these governing mechanisms occur over such a large area and are so subtle or intricate in their action that they are not easily observed and recorded; thus they tend to be overlooked.

A principal phase of applied biological control is the importation and establishment of natural enemies of pests that accidentally gain entry into new geographical regions. These new pests frequently escape the natural enemies that help to regulate their densities in the areas to which they are indigenous (Elton, 1958). Under satisfactory conditions in the new environment, the pest may flourish and reach damaging abundance. As a counter measure, the natural enemies are obtained from the native home of the pest and transplanted into the new environment to increase the biotic resistance of the environment to the pest.

Biological control is thus utilized to permanently increase environmental resistance to an introduced pest. The hope is that the introduced enemies will lower the general equilibrium position of the pest sufficiently to maintain it permanently below the economic threshold. Most often the introduction of a biotic agent is not so spectacular, and it is an exception when the general equilibrium position of the introduced pest is lowered sufficiently to prevent its occasionally or even commonly reaching economic abundance at certain times or places (Clausen, 1956; Simmonds, 1956). This, of course, is precisely the status of a native pest which, though attacked by a complex of parasites and predators, still has a general equilibrium position high enough to permit it occasionally to cause damage of greater or lesser severity. Thus, in any geographic area the governing mechanisms in the environment are constantly at work to counteract the inherent natality of plant and animal pest species. In terms of crop protection, these regulating factors actually keep thousands of potentially harmful arthropod species permanently below economic thresholds. Moreover, these environmental pressures tend to localize the outbreaks of those forms which on occasion are capable of rising above economic thresholds. A biological control agent is self-perpetuating and capable of response to fluctuations in the population density of the pest it attacks. Biological controls, whether imported or native, are permanent characteristics of a given environment.

Chemical Control. Chemical control of an arthropod pest is employed to reduce populations of pest species which rise to dangerous levels when the environmental pressures are inadequate. When chemicals are used, the damage from the pest species must be sufficiently great to cover not only the cost of the insecticidal treatment but also the possible deleterious effects, such as the harmful influence of the chemical on the ecosystem. On some occasions, the pest outbreak may cover a wide area; in other instances, damaging numbers occur in very restricted locations. These outbreaks occur during the season favorable to the pest, with the relaxed environmental pressures occurring some time before the outbreak. Chemical control is only needed at those times and places where natural control is inadequate. Chemical control should act as a complement to the biological control.

An insecticide must always be manipulated by man, who adds it to a restricted segment of the pest's environment to decimate a localized pest population. Because chemical insecticides are nonreproductive, have no searching capacity, and are nonpersistent, they constitute short-term, retricted pressures. They cannot permanently change the general equilibrium position of the pest population nor can they restrain an increase in abundance of the pest without repeated applications. Therefore, they must be added to the environment at varying intervals of time.

In certain pest-control programs, the insecticide is applied over extensive geographical areas. In some areas, after application, the pest population density may be far below the economic threshold and below its general equilibrium position; but since the insecticide is not a permanent part of the environment, the pest may return to a high level when the effects of the insecticide are gone.

The effectiveness of a chemical insecticide or a biotic insecticide is measured in per cent of kill or in per cent of clean fruits, uninjured cotton bolls, and so forth, in the area of application. Such applications have little influence on the pest in adjoining areas except as localized population depressants. In general, this contrasts sharply with the role of the permanent biotic mortality agent, whose effectiveness is best measured by its influence on the general equilibrium position of the pest species over an entire geographical region or a long period of time.

ECONOMIC THRESHOLDS AND THE GENERAL EQUILIBRIUM POSITION

Chemical control should be used only when the economic threshold is reached and when the natural mortality factors present in the environment are not capable of preventing the pest population from reaching the economic-injury level. The economic-injury level is a slightly greater density than the economic threshold. This difference in densities provides a margin of safety for the time that elapses between the detection of the threatening infestation and the actual application of an insecticide. The economic threshold and the economic-injury level of a pest species can vary depending upon the crop, season, area, and desire of man; the general equilibrium position, on the other hand, barring "permanent" changes in the environment, is a fixed population level (Griffiths, 1951; Strickland, 1954).

A species population is plastic and is undergoing constant change within the limits imposed upon it by its genetic constitution and the characteristics of its environment. Typical fluctuations in population and dispersion are shown in figure 3. The population dispersions shown at the three points in time A, B, and C are not static but rather are instantaneous phases of a continuously changing dispersion.

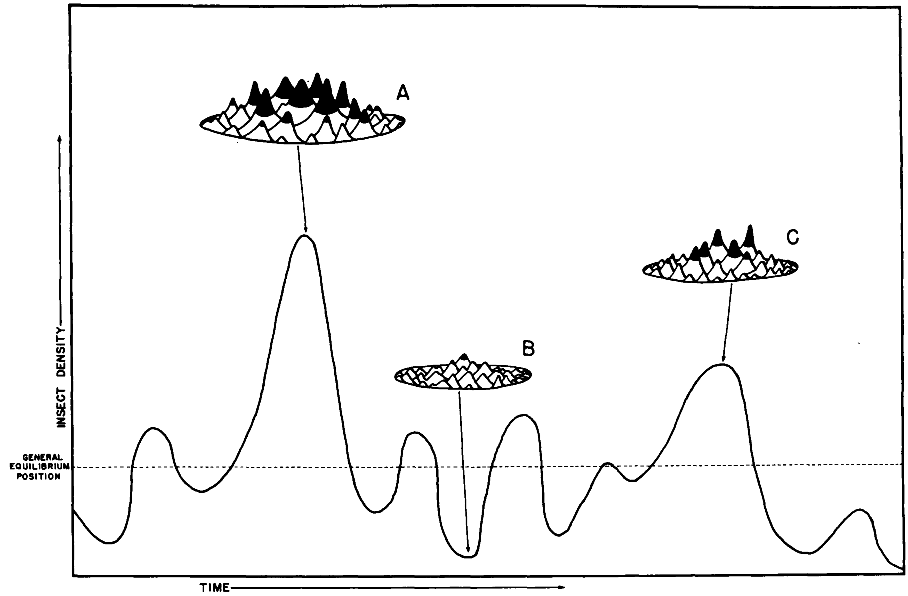


Fig. 3. Schematic graph of the population trend and population dispersion of a pest species over a long period of time. The solid line depicts the fluctuations in the population density with time. The broken line depicts the general equilibrium position. The population dispersion is indicated at the specific times *A*, *B*, and *C*. The basal area of these models reflects the distributional range, the height indicates population density. Population densities above the economic threshold are black.

Thus at point A, when the population is of greatest numerical abundance, it also has its widest distributional range (as depicted by the maximum diameter of the base of the model), and is of maximum economic status (as depicted by the number and magnitude of the blackened pinnacles representing penetrations of the economic threshold). At point B, on the other hand, when the species population is at its lowest numerical abundance, it is also most restricted in geographical range and is of only minor economic status. Point C represents an intermediate condition between points A and B.

In order to determine the relative economic importance of pest species, both the economic threshold and general equilibrium position of the pests must be considered. It is the general equilibrium position and its relation to the economic threshold, in conjunction with the frequency and amplitude of fluctuations about the general equilibrium position, that determine the severity of a particular pest problem.

In the absence of permanent modifications in the composition of the environment, the density of a species tends to fluctuate about the general equilibrium position as changes occur in the biotic and physical components of the environment. As the population density increases, the density-governing factors respond with greater and greater intensity to check the increase: as the population density decreases, these factors relax in their effects. The general equilibrium position is thus determined by the interaction of the species population, these density-governing factors, and the other natural factors of the environment. A permanent alteration of any factor of the environment—either physical or biotic—or the introduction of new factors may alter the general equilibrium position.

The economic threshold of a pest species can be at any level above or below the general equilibrium position or it can be at the same level. Some phytophagous species may utilize our crops as a food source but even at their highest attainable density are of little or no significance to man (see fig. 4, *A*). Such species can be found associated with nearly every crop of commercial concern.

Another group of arthropods rarely exceeds the economic thresholds and these consequently are occasional pests. Only at their highest population density will chemical control be necessary (see fig. 4, *B*).

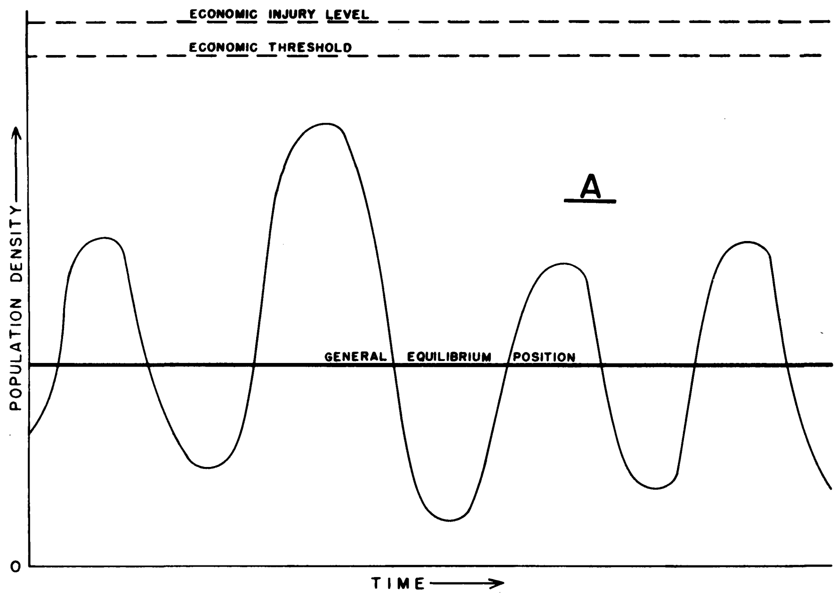
When the general equilibrium position is close to the economic threshold, the population density will reach the threshold frequently (see fig. 4, *C*). In some cases, the general equilibrium position and the economic threshold are at essentially the same level. Thus, each time the population fluctuates up to the level of the general equilibrium position insecticidal treatment is necessary. In such species the frequency of chemical treatments is determined by the fluctuation rate about the general equilibrium position, which in some cases necessitates almost continuous treatment.

Finally, there are pest species in which the economic threshold lies below the general equilibrium position; these constitute the most severe pest problems in entomology (see fig. 4, *D*). The economic threshold may be lower than the level of the lowest population depression caused by the physical and biotic factors of the environment, *e.g.*, many insect vectors of viruses. In such cases, particularly where human health is concerned, there is a widespread and almost constant need for chemical control. This produces conditions favorable for development of insecticide resistance and other problems associated with heavy treatments.

One solution to pest problems and particularly those in this last category is to change the environment permanently so that the general equilibrium position will be lowered. For example, this might be accomplished through the introduction of a new biological control agent or through the permanent modification of a large portion of a required habitat. This has been done in certain areas with malaria-vector mosquitoes and similar pests by the draining of swamps and the destruction of other favorable habitats. Such methods may completely eliminate the species from some areas.

Environmental changes unfavorable to the pest may also be made through the use of plants and animals resistant to the pest species. This control method may involve three different aspects—tolerance, preference, and antibiosis (Painter, 1951). If tolerance alone is involved, the general equilibrium position may not be changed but the economic threshold is raised. Where preference or antibiosis is involved, the ability of the pest to reproduce upon the host is reduced, so that the general equilibrium position is lowered.

The lack of a sound measure of economic thresholds, in many cases, has been a major stumbling block to the development of integrated pest-control programs. Our changing economy, variations in natural governing mecha-



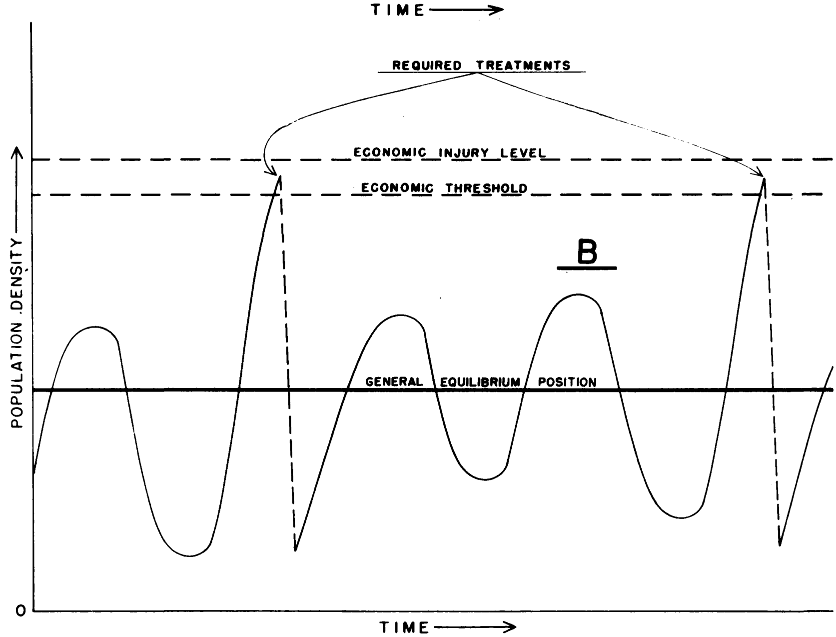
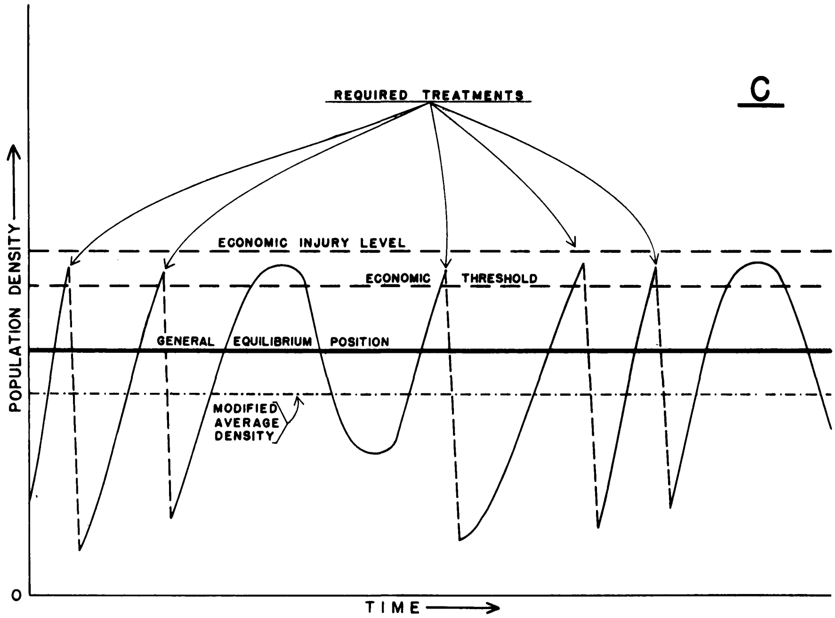
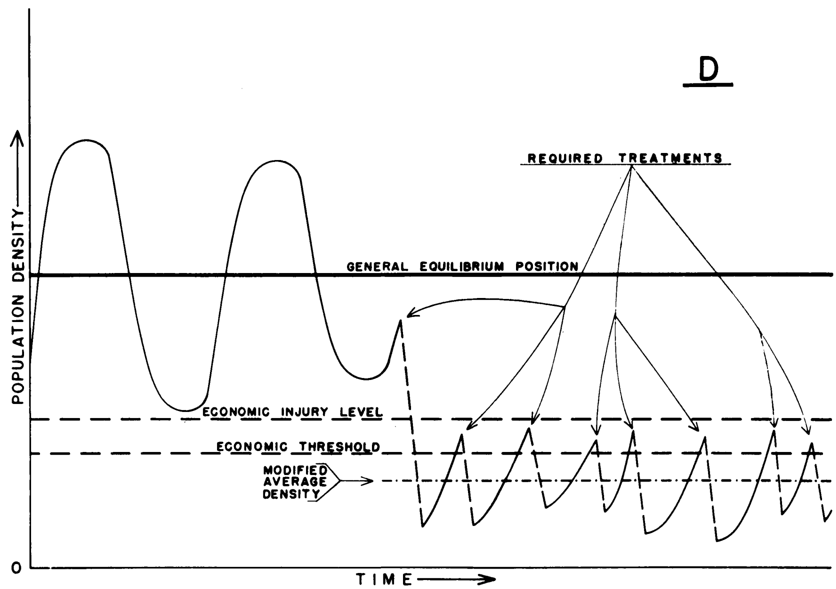


Fig. 4. Schematic graphs of the fluctuations of theoretical arthropod populations in relation to their general equilibrium position, economic thresholds, and economic-injury levels. *A*, Noneconomic population whose general equilibrium position and highest fluctuations are below the economic threshold, *e.g.*, *Aphis medicaginis* Koch on alfalfa in California. *B*, Occasional pest whose general equilibrium position is below the economic threshold but whose highest population fluctuations exceed the economic threshold, *e.g.*,





Grapholitha molesta Busck on peaches in California. *C,* Perennial pest whose general equilibrium position is below the economic threshold but whose population fluctuations frequently exceed the economic threshold, *e.g., Lygus* spp. on alfalfa seed in the western United States. *D,* Severe pest whose general equilibrium position is above the economic threshold and for which frequent and often widespread use of insecticides is required to prevent economic damage, *e.g., Musca domestica* in Grade A milking sheds.

nisms from one geographical area to another, differences in consumer demands, and the complexity of measuring the total effect of insects on yield and quality often make the assessment of economic damage extremely difficult. Yet the economic threshold and the economic-injury level must be determined reasonably and realistically before integrated pest control can develop to its fullest. Success in any well-balanced pest-control program is dependent on the aim of holding insect populations below experimentally established economic levels rather than attempting to eliminate all the insects.

THE INTEGRATION OF BIOLOGICAL AND CHEMICAL CONTROL

Biological control and chemical control are not necessarily alternative methods; in many cases they may be complementary, and, with adequate understanding, can be made to augment one another. One reason for the apparent incompatibility of biological and chemical control is our failure to recognize that the control of arthropod populations is a complex ecological problem. This leads to the error of imposing insecticides on the ecosystem, rather than fitting them into it. It is short-sighted to develop a chemical control program for the elimination of one insect pest and ignore the impact of that program on the other arthropods, both beneficial and harmful, in the ecosystem. On the other hand, this approach is no worse than the other extreme which would eliminate chemicals to preserve the biological control even in the face of serious economic damage. For we must recognize that modern agriculture could not exist without the use of insecticides. The evidence that biological and chemical control can be integrated is mounting. It has come from many sources involving many kinds of pests in various situations: see Ullyett (1947), Pickett and Patterson (1953), Ripper (1956), Huffaker and Kennett (1956), DeBach (1958*a*), Stern and van den Bosch (1959), and many others.

In approaching an integrated control program, we must realize that man has developed huge monocultures, he has eliminated forests and grasslands, selected special strains of plants and animals, moved them about, and in other ways altered the natural control that had developed over thousands upon thousands of years. We could not return to those original conditions if it were desirable. We may, however, utilize some of the mechanisms that existed before man's modifications, to establish new balances in our favor.

Recognition of the Ecosystem. To establish new, favorable balances, it is first necessary to recognize the "oneness" of any environment, natural or man-made. The populations of plants and animals (including man) and the nonliving environment together make up an integrated unit, the ecosystem. If an attempt is made to reduce the population level of one kind of animal (for example, a pest insect) by chemical treatment, modification of cultural practices, or by other means, other parts of the ecosystem will be affected as well. For this reason, the production of a given food or fiber must be considered in its entirety. This includes simultaneous consideration of insects, diseases, plant nutrition, plant physiology, and plant resistance, as well as the economics of the crops (Forbes, 1880; Ullyett, 1947; Pickett, 1949; DeBach, 1951; Solomon, 1953; Pickett and Patterson, 1953;

Glen, 1954; Michelbacher, 1954; Huffaker and Kennett, 1956; Simmonds, 1956; Balch, 1958; Decker, 1958; and others).

In most agricultural ecosystems, some potentially harmful organisms are continually held at subeconomic levels by natural controlling forces. In others, the pests are held below economic levels only part of the time. A pest species may be under satisfactory biological control over a large area or a long period of time, but not in all individual fields or during all periods. In a single field or orchard, or during a portion of a year, the pest population may rise to economic levels, while elsewhere or at other times the pest may be subeconomic. It is in such situations that integrated control programs are especially important. These intermittently destructive populations must be reduced in a manner that permits the biological control which prevailed before or prevails elsewhere to take over again. If a chemical treatment destroys the biotic agents without eradicating the pest, then repeated treatments may become necessary.

Population Sampling and Prediction. The sampling methods utilized by most research investigators for experimental plots are usually too time-consuming and tedious to be of practical value in establishing pest population levels in commercial crops. Special index methods are needed that are rapid and simple to use. Ideally, these should be of such nature that they can be easily utilized by the person examining the crop. But in many cases the grower is not able to evaluate all situations because of the difficulties and complexities involved in determining the status of some pest populations at the times of the year when they must be controlled. Then qualified entomologists will be required to evaluate the populations (Ripper, 1958).

One answer to this problem has been the development of supervised control in California, Arkansas, Arizona, and elsewhere. In a supervised control program the farmer, or a group of farmers, contracts with a professional entomologist who determines the status of the insect populations. On the basis of his population counts, other conditions peculiar to each situation, and his knowledge of the ecology of the pests and their biological controls, the entomologist makes predictions as to the course of the population trends and advises as to when controls should be applied and what kind. For instance, in the case of the alfalfa caterpillar, *Colias philodice eurytheme*, when economic thresholds are reached, the recommended procedure may involve immediate cutting of the hay crop without treatment, application of the polyhedrosis virus (Steinhaus and Thompson, 1949; Thompson and Steinhaus, 1950), or treatment with an insecticide. The course to be taken depends on the characteristics of the particular infestation (Smith and Allen, 1954).

Wherever possible, knowledge must be developed so that we can predict the times when occasional pests will be present in outbreak numbers. This will eliminate unnecessary and environment-disturbing "insurance" treatments. When this is not possible, the treatments can be timed according to the actual pest population levels, as is now done with many field-crop pests.

With those crops that do not yet have fixed chemical control schedules, every effort should be made to plan programs dependent upon pest population levels and to avoid dependence upon insurance and prophylactic treatments. If this is not done there is real danger that on these crops, too, pest-control problems will become increasingly complex.

Augmentation of Natural Enemies. In some situations, the development of integrated control requires the augmentation of the natural-enemy complex (DeBach, 1958*a*). The introduction of additional natural enemies is usually the simplest and best solution. This may not be possible or effective with some pest species, and methods of overcoming the inefficiency of the natural-enemy complex must be sought. This can be done by periodic colonization of parasite or predators (Doutt and Hagen, 1950; DeBach, Landi, and White, 1955), artificial inoculation of the host at times of low density (Smith and DeBach, 1953; Huffaker and Kennett, 1956), modification of the environment, or selective breeding of parasites and predators.

The modification of the environment may involve changes in irrigation, introduction of a covercrop, or development of greater plant heterogeneity. Refuges for beneficial forms can be produced by strip treatments with chemicals (DeBach, 1958*a*) or by the development of uncultivated and untreated areas (Grison and Biliotti, 1953). Modification of the environment may also involve the control of ants or other organisms which curtail parasite and predator activity (Flanders, 1945; DeBach, Fleschner, and Dietrick, 1951). The selective breeding of parasites and predators may be directed toward increased or modified tolerance ranges to physical conditions (DeBach, 1958*b*) or insecticides (Robertson, 1957).

Where prophylactic treatments are proved to be necessary for a perennial pest, selective materials must be developed and utilized to foster biological control both of other pests and of the pest of direct concern at other times.

Selective Insecticides. Chemical control programs are limited by the nature of the available materials. In the past, nonselective insecticides applied for one insect in a pest complex often have eliminated the biotic factors holding other pests in check. More recently, we have had available a greater variety of materials, some of them selective in their action (Ripper, 1956).

The selective use of insecticides may be accomplished in at least four ways. First, the insecticide itself may be selective in its toxicological action. Narrow-range toxicants may be utilized to reduce a pest of concern and at the same time spare the beneficial forms (Ripper, 1944; Ripper, Greenslade, and Hartley, 1951). A particular material may be selective in one situation and not in another; or it may be selective at low dosages but not at high dosages. Furthermore, the manner of application (Ripper, 1956) and especially the type of carrier and residue deposit may produce differential effects on the insect complex (Flanders, 1941; Holloway and Young, 1943; DeBach and Bartlett, 1951).

Second, we can produce a selective action on a pest-parasite complex by treating only those areas where the pest-parasite ratio is unfavorable. This method is one of the bases of supervised control of the alfalfa caterpillar in California (Smith and Allen, 1954). Population levels of both the host caterpillar and its parasite, *Apanteles medicaginis* Muesebeck, are determined at appropriate intervals in all fields. A prediction of possible damage is made on the basis of these population levels, and only those infestations which are potentially damaging are treated. In this way, on an area-wide basis, the balance is shifted in favor of the parasites, even though parasite adults and parasite larvae within the host caterpillars are often destroyed in the treated fields. The success of such programs will depend on the exact nature of the local problem and the quality of supervision. The rates of dispersal of parasites, predators, and pests are complicating factors.

Third, proper timing of insecticides can produce a selective action on the pest and natural-enemy complex (Ewart and DeBach, 1947; Michelbacher and Middlekauff, 1950; Bartlett and Ewart, 1951; Jeppson, Jesser, and Complin, 1953; Massee, 1954; DeBach, 1955). In such situations, an intimate knowledge of the behavior patterns of the pests and their natural enemies is required.

Fourth, nonselective materials with short residual action may be used if the beneficial forms can survive in a resistant stage or in an untreated reservoir area. Stern and van den Bosch (1959) have demonstrated that parasites of the spotted alfalfa aphid can survive nonselective treatments if they are in the more resistant pupal stage. DeBach (1958*a*) reports successful integration of biological and chemical control of purple scale on citrus where alternate pairs of tree rows were sprayed at 6-month intervals with a nonselective oil treatment.

For some pests a disease pathogen may be used as a selective insecticide (Steinhaus, 1954; 1956). For example, under supervised control in the Dos Palos area of California, the polyhedrosis virus affecting the alfalfa caterpillar has been used successfully either alone or in combination with a selective insecticide to avoid the use of a nonselective treatment. More recently, interest has developed in the commercial use of virulent strains of *Bacillus thuringiensis* Berliner, for the control of certain truck- and field-crop pests in California. The use of disease pathogens as selective insecticides is in its infancy, but can be expected to increase in importance with additional research (Steinhaus, 1951, 1957).

The ideal selective material is not one that eliminates all individuals of the pest species while leaving all of the natural enemies. Use of such a material would force the predators and parasites to leave the treated area or starve (Clausen, 1936; Flanders, 1940). The ideal material is one that shifts the balance back in favor of the natural enemies (Boyce, 1936; Ripper, 1944; Wigglesworth, 1945).

Future of Integrated Control. If our knowledge were adequate today to outline an ideal integrated control program for a crop now utilizing an intensive fixed spray program, it would not be possible to switch to such a program immediately. The effects of the previous treatments may last several years. In some instances, effective biological control no longer exists and would have to be reëstablished. This may be a slow process (DeBach, 1951; DeBach and Bartlett, 1951; Pickett and Patterson, 1953; and others).

It should be emphasized also that the development of integrated control is not a panacea that can be applied blindly to all situations, for it will not work if biotic mortality agents are inadequate or if low economic thresholds preclude utilizing biological control (Barnes, 1959). However, it has worked so well in some appropriate situations that there can be no doubt as to its enormous advantages and its promise for the future.

LITERATURE CITED

BALCH, R. E.
1958. Control of forest insects. Ann. Rev. Ent. **3**:449–68.

BARNES, M. M.
1959. Deciduous fruit insects and their control. Ann. Rev. Ent. **4**:343–62.

BARTLETT, B., and W. H. EWART
1951. Effect of parathion on parasites of *Coccus hesperidum*. Jour. Econ. Ent. **44**: 344–347.

BARTLETT, B. R., and J. C. ORTEGA
1952. Relation between natural enemies and DDT-induced increases in frosted scale and other pests of walnuts. Jour. Econ. Ent. **45**(5):783–85.

BOVEY, PAUL
1955. Les actions secondaires des traitements antiparasitaires sur les populations d'insectes et d'acariens nuisibles. Schweiz. Landw. Monatsh. **33** (9/10):369–79.

BOYCE, A. M.
1936. The citrus red mite, *Paratetranychus citri* McG. in California, and its control. Jour Econ. Ent. **29** (1):125–30.

BROWN, A. W. A.
1951. Insect control by chemicals. John Wiley & Sons, Inc., New York, N.Y. 817 pp.
1959. Spread of insecticide resistance. Adv. Pest Control Res. **2**:351–414. Interscience Publishers, Inc., New York, N.Y.

CLAUSEN, C. P.
1936. Insect parasitism and biological control. Ent. Soc. Amer. Ann. **29**:201–23.
1956. Biological control of insect pests in the continental United States. U.S. Dept. Agr. Tech. Bul. 1139. 151 pp.

CROW, J. F.
1957. Genetics of insect resistance to chemicals. Ann. Rev. Ent. **2**:227–46.

DEBACH, P.
1951. The necessity for an ecological approach to pest control on citrus in California. Jour. Econ. Ent. **44**(4):443–47.
1955. Validity of the insecticidal check method as a measure of the effectiveness of natural enemies of diaspine scale insects. Jour. Econ. Ent. **48**(5):584–88.
1958*a*. Application of ecological information to control of citrus pests in California. Tenth Internatl. Congr. Ent. Proc. **3**:185–97.
1958*b*. Selective breeding to improve adaptations of parasitic insects. Tenth Internatl. Congr. Ent. Proc. **4**:759–67.

DEBACH, P., and B. BARTLETT
1951. Effects of insecticides on biological control of insect pests of citrus. Jour. Econ. Ent. **44**(3):372–83.

DEBACH, P., C. A. FLESCHNER, and E. J. DIETRICK
1951. A biological check method for evaluating the effectiveness of entomophagous insects. Jour. Econ. Ent. **44**(5):763–66.

DEBACH, P., J. H. LANDI, and E. B. WHITE
1955. Biological control of red scale. California Citrog. **40**:254, 271–72, 274–75.

DECKER, G. C.
1958. Don't let the insects rule. Agr. Food Chem. **6**(2):98–103.

DOUTT, R. L.
1958. Vice, virtue and the vedalia. Ent. Soc. Amer. Bul. **4**(4):119–23.

DOUTT, R. L., and K. S. HAGEN
1950. Biological control measures applied against *Pseudococcus maritimus* on pears. Jour. Econ. Ent. **43** (1):94–96.

ELTON, CHARLES S.
1958. The ecology of invasions by animals and plants. 181 pp. Methuen & Co. Ltd., London; John Wiley & Sons Inc., New York, N.Y.

EWART, W. H., and P. DEBACH
1947. DDT for control of citrus thrips and citricola scale. California Citrog. **32**:242–45.
FLANDERS, S. E.
1940. Environmental resistance to the establishment of parasitic Hymenoptera. Ent. Soc. Amer. Ann., **33**:245–53.
1941. Dust as an inhibiting factor in the reproduction of insects. Jour. Econ. Ent. **34**(3):470–1.
1945. Coincident infestations of *Aonidiella atrana* and *Coccus hesperidum,* a result of ant activity. Jour. Econ. Ent. **38**:711–12.
FLESCHNER, C. A., and G. T. SCRIVEN
1957. Effects of soil-type and DDT on ovipositional response of *Chrysopa californica* (Coq.) on lemon trees. Jour. Econ. Ent. **50**(2):221–22.
FORBES, S. A.
1880. On some interactions of organisms. Illinois State Lab. Nat. Hist. Bul. **3**:3–17.
GLEN, R.
1954. Factors that affect insect abundance. Jour. Econ. Ent. **47**:398–405.
GRIFFITHS, J. T.
1951. Possibilities for better citrus insect control through the study of the ecological effects of spray programs. Jour. Econ. Ent. **44**:464–68.
GRISON, P., and E. BILIOTTI
1953. La signification agricole des "stations refuges" pour la faune entomologique. Acad. d'Agr. de France Compt. Rend. **39**(2):106–9.
HAYES, W. J.
1954. Agricultural chemicals and public health. U. S. Public Health Reports **69**(10): 893–98.
HERTZLER, J. O.
1956. The crisis in world population. 279 pp. Univ. Nebraska Press, Lincoln.
HOLLOWAY, J. K., and T. ROY YOUNG, JR.
1943. The influence of fungicidal sprays on entomogenous fungi and on the purple scale in Florida. Jour. Econ. Ent. **36**(3):453–57.
HOSKINS, W. M., and H. T. GORDON
1956. Arthropod resistance to chemicals. Ann. Rev. Ent. **1**:89–148.
HUFFAKER, C. B., and C. E. KENNETT
1956. Experimental studies on predation: Predation and cyclamen-mite populations on strawberries in California. Hilgardia **26**(4):191–222.
JEPPSON, L. R., M. J. JESSER, and J. O. COMPLIN
1953. Timing of treatments for control of citrus red mite on orange trees in coastal districts of California. Jour. Econ. Ent. **46**:10–14.
KLOSTERMEYER, E. C., and W. B. RASMUSSEN
1953. The effect of soil insecticide treatments on mite populations and damage. Jour. Econ. Ent. **46**:910–12.
LINSLEY, E. G., editor
1956. Evaluation of certain acaricides and insecticides for effectiveness, residues, and influence on crop flavor. Hilgardia **26**(1):1–106.
LORD, F. T.
1947 The influence of spray programs on the fauna of apple orchards in Nova Scotia: II. Oystershell scale, *Lepidosaphis ulmi* (L.) Canad. Ent. **79**:196–209.
MASSEE, A. M.
1954. Problems arising from the use of insecticides: effect on the balance of animal populations. 6th Commonwealth Entomol. Conf. Rept. Pp. 53–57. London, England.
METCALF, R. L.
1955. Physiological basis for insect resistance. Physiol. Rev. **35**:197–232.
MICHELBACHER, A. E.
1954. Natural control of insect pests. Jour. Econ. Ent. **47**(1):192–94.

MICHELBACHER, A. E., and S. HITCHCOCK
1958. Induced increase of soft scales on walnut. Jour. Econ. Ent. **51**(4):427–31.

MICHELBACHER, A. E., and W. W. MIDDLEKAUFF
1950. Control of the melon aphid in northern California. Jour. Econ. Ent. **43**(4): 444–47.

PAINTER, R. H.
1951. Insect resistance in crop plants. xi + 520 pp. Illus. Macmillan Company, New York, N.Y.

PETTY, C. S.
1957. Organic phosphate insecticide poisoning; an agricultural occupational hazard. Louisiana St. Med. Soc. Jour. **109**(5):158–64.

PICKETT, A. D.
1949. A critique on insect chemical control methods. Canad. Ent. **81**(3):67–76.

PICKETT, A. D., and N. A. PATTERSON
1953. The influence of spray programs on the fauna of apple orchards in Nova Scotia. IV. A Review. Canad. Ent. **85**(12):472–78.

PICKETT, A. D., W. L. PUTMAN, and E. J. LE ROUX
1958. Progress in harmonizing biological and chemical control of orchard pests in eastern Canada. Tenth Internatl. Congr. Ent. Proc. **3**:169–74.

RIPPER, W. E.
1944. Biological control as a supplement to chemical control of insect pests. Nature **153**:448–52.
1956. Effect of pesticides on balance of arthropod populations. Ann. Rev. Ent. **1**:403–38.
1958. The place of contracting organizations and professional supervision in the application of pest control methods. Tenth Internatl. Congr. Ent. Proc. **3**:93–97.

RIPPER, W. E., R. M. GREENSLADE, and G. S. HARTLEY
1951. Selective insecticides and biological control. Jour. Econ. Ent. **44**(4):448–59.

ROBERTSON, J. G.
1957. Changes in resistance to DDT in *Macrocentrus ancylivorus* Rohw. Canad. Jour. Zool. **35**(5):629–633.

SABROSKY, C. W.
1952. How many insects are there? Pp. 1–7 *in:* Insects, 1952 Yearbook of Agriculture. 780 pp. U. S. Dept. Agr., Washington, D.C.

SCHNEIDER, F.
1955. Beziehungen zwischen nützlingen und chemischer Schädlingsbekämpfung. Deutsche Gesell. f. Angw. Ent. Verhandl. (13[te] Mitglied versamm.). **1955**:18–29.

SIMMONDS, F. J.
1956. The present status of biological control. Canad. Ent. **88**(9):553–63.

SMITH, H. S., and P. DEBACH
1953. Artificial infestation of plants with pest insects as an aid in biological control. Seventh Pacific Sci. Congr. Zoology (1949) Proc. **4**:255–59.

SMITH, RAY F.
1959. The spread of the spotted alfalfa aphid, *Therioaphis maculata* (Buckton), in California. Hilgardia **28**(21):647–91.

SMITH, R. F., and W. W. ALLEN
1954. Insect control and the balance of nature. Sci. Amer. **190**(6):38–42.

SOLOMON, M. E.
1953. Insect population balance and chemical control of pests. Chem. and Indus. **1953**: 1143–47.

STEINHAUS, E. A.
1951. Possible use of *Bacillus thuringiensis* Berliner as an aid in the biological control of the alfalfa caterpillar. Hilgardia **20**(18):359–81.
1954. The effects of disease on insect populations. Hilgardia **23**(9):197–261.
1956. Potentialities for microbial control of insects. Agr. Food Chem. **4**(8):676–80.
1957. Concerning the harmlessness of insect pathogens and the standardization of microbial control products. Jour. Econ. Ent. **50**(6): 715–20.

STEINHAUS, E. A., and C. G. THOMPSON

1949. Preliminary field tests using a polyhedrosis virus in the control of the alfalfa caterpillar. Jour. Econ. Ent. **42**(2):301–5.

STERN, V. M., and R. VAN DEN BOSCH

1959. Field experiments on the effects of insecticides. Hilgardia **29**(2):103–30.

STRICKLAND, A. H.

1954. The assessment of insect pest density in relation to crop losses. 6th Commonwealth Ent. Conf. Rept., pp. 78–83. London, England.

THOMAS, W. L., JR., EDITOR

1956. Man's role in changing the face of the earth. 1193 pp. Univ. Chicago Press, Chicago, Ill.

THOMPSON, C. G., and E. A. STEINHAUS

1950. Further tests using a polyhedrosis virus to control the alfalfa caterpillar. Hilgardia **19**(14):411–45.

TROUVELOT, B.

1936. Le doryphore de la pomme de terre (*Leptinotarsa decemlineata* Say) en Amerique de Nord. Ann. Epiphyt. (n.s.) **1**:277–336.

ULLYETT, G. C.

1947. Mortality factors in populations of *Plutella maculipennis* (Tineidae: Lep.) and their relation to the problem of control. South African Dept. Agr. and Forestry Ent. Mem. **2**(6):77–202.

1951. Insects, man and the environment. Jour. Econ. Ent. **44**(4):459–64.

UPHOLT, W. M.

1955. Evaluating hazards in pesticides use. Agr. Food Chem. **3**(12):1000–6.

WILLE, J. E.

1951. Biological control of certain cotton insects and the application of new organic insecticides in Peru. Jour. Econ. Ent. **44**:13–18.

WIGGLESWORTH, V. B.

1945. DDT and the balance of nature. Atlantic Monthly **176**(6):107–13.

The journal *Hilgardia* is published at irregular intervals in volumes of about 600 pages. The number of issues per volume varies.

Subscriptions are not sold. The periodical is sent as published only to libraries, or to institutions in foreign countries having publications to offer in exchange.

You may obtain a single copy of any issue free, as long as the supply lasts; please request by volume and issue number from:

Agricultural Publications
207 University Hall
University of California
Berkeley 4, California

The limit to nonresidents of California is 10 separate issues on a single order. A list of the issues still available will be sent on request.