THE INTEGRATION OF CHEMICAL AND BIOLOGICAL CONTROL OF ARTHROPOD PESTS

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The desirability of integrating chemical and biological control of arthropod pests is not a new idea in the field of applied entomology. Recurrently over the years, investigators have expressed a need for the preservation, augmentation, and utilization of entomophagous and entomogenous organisms in overall pest control programs involving chemical control (14, 34, 63, 69, 70, 76, 77, 88, 109, 116, 117, 119). However, these were sporadic pleas and it was not until the last decade that the call for integrated control swelled to a chorus. Now, a band wagon of rather respectable proportions seems to have developed in support of this approach to arthropod pest control. As a point of illustration, in the most recent numbers of the Journal of Economic Entomology, a significant percentage of the articles have dealt with or alluded to integrated control. (Six of 51 papers in Volume 54, No. 1.)

The factors contributing to this trend seem directly related to the manifold secondary problems associated with the extensive use of the new, widely toxic synthetic organic insecticides. Prior to the organic insecticide era, entomologists working with the arsenicals, botanicals, petroleum oils, lime sulfur, and the few other materials available to them, inadvertently effected large-scale integrated control. This came about because the methods of entry and chemical and physical characteristics of these materials limited their toxicity to a relatively small number of arthropods, and they did not have the disruptive effects to arthropod ecosystems that the new broad spectrum synthetic chemicals do. As a result, the problems of insecticide resistance, pest flarebacks, and secondary pest outbreaks that have come to plague the organic insecticides were not nearly as severe and general as they are today. Consequently, there was no great concern over, or even awareness of the potential disruptiveness of insecticides to arthropod ecosystems.

Thus, with little reason for apprehension other than matters related to mammalian toxicity, pollinator mortality, and possibly resistance, the organic insecticides were almost universally accepted as unmixed blessings. With rare exceptions, those persons associated with arthropod pest control crossed

1 The survey of the literature pertaining to this review was concluded in April, 1961.
2 The common names and abbreviations for insecticides in this chapter follow the usage of the Committee on Insecticide Terminology of the Entomological Society of America, as presented in the J. Econ. Entomol., 52, 361–62, 1032 (1959).
the organic insecticide threshold largely innocent of the pitfalls that lay ahead.

It would be redundant at this time to point out the problems associated with the use of the new organic insecticides. This information can be obtained from the papers of Pickett (69, 70), Ripper (77), Linsley (50), Smith & Hagen (91, 92), Stern et al. (106), Metcalf (56), Franz (36), Brown (12), and many others.

These are problems that are inherent in the use of the widely toxic, synthetic organic insecticides. They cannot be ignored or wished away, but must be attacked and, wherever possible, corrected. There seems little question that the fullest possible integration of chemical and biological control will aid materially in attaining this objective.

**THE TERM “INTEGRATED CONTROL”**

The term “integrated control” is generally synonymous with the terms “complementary control” (18), “coordinated control” (18, 31), “harmonic control” (32, 33, 72), and “modified spray program” (69, 72). To our knowledge, the term “integrated control” was first used in a publication by Bartlett (8). It has since been used by a number of authors and thus seems to be gaining widespread acceptance (19, 21, 22, 35, 37, 52, 75, 78, 79, 91, 92, 106, 108).

Stern et al. (106) define integrated control as “pest control which combines and integrates biological and chemical control.” They state that in this approach chemical control is used as may be necessary and in a manner which is least disruptive to biological control. This interpretation essentially limits integrated control to the biological (natural enemy) and chemical (insecticidal) aspects of arthropod pest control. However, Franz (37) suggests that integrated control in concept and application be broadened to embrace the integration of all artificial pest control measures and cultural practices with biological control. This is a sound suggestion, for if we are to expand our emphasis on the ecological approach to pest control, then no factor which impinges upon the agricultural ecosystem can be overlooked in the integrated control program.

The current discussion is not one in semantics and we shall restrict our remarks largely to factors affecting the integration of chemical and biological control. We shall also concern ourselves for the most part with integrated control of agricultural pests, although there is undoubtedly need for development of this approach in other areas of arthropod pest control (7, 61, 62). Finally, we shall draw heavily upon our own experiences and those of certain of our colleagues in California for much of our illustrative data.

**THE INTEGRATED CONTROL CONCEPT**

The integrated control concept is no longer a hypothetical one. Investigations and pest-control programs such as those on the diamondback moth, *Plutella maculipennis* (Curtis), in South Africa (116, 117); on the alfalfa caterpillar, *Colias eurytheme* Boisduval, in California (1, 3, 49, 58, 88, 90,
104); on cotton insects in Peru (39, 123); on apple pests in Nova Scotia (51, 52, 69 to 72); on the newly introduced spotted alfalfa aphid, Therio-
aphis maculata (Buckton), in California (91, 106); on the cyclamen mite, Steneotarsonemus pallidus (Banks), on strawberries in California (2, 44, 45) and other cases, have clearly demonstrated the long-term and even permanent benefits that derive from such programs. Moreover, currently in California, a statewide research program is underway to bring the entire pest complex of field crops (cotton, alfalfa, alfalfa seed, cereal grains, sugar beets, sorghums, and field corn) under an integrated pest-control program. Similar long-range research projects are being initiated for vegetable crops and deciduous fruits in that state.

In Europe, deciduous fruit pest problems are being attacked from the integrated control approach in a number of countries (16, 32, 33, 35, 36, 85, 93, 120). This approach is also seemingly being given careful consideration in the U.S.S.R. (86). The Canadians are continuing their intensive investigations in Nova Scotia and are also carrying on expanded programs in other provinces. Unquestionably, there are a number of other areas in which such investigations have been underway, or are contemplated.

In recent years, there have been several comprehensive publications dealing with the general subject of integrated control (8, 13, 18, 19, 36, 69, 70, 71, 76, 77, 78, 82, 91, 92, 106, 116). These papers collectively cover the broad principles of this approach to pest control and many of the phenomena related to it.

In the limited space available in the present paper it is impossible to present a meticulous review of the numerous specific instances in which integrated control is, or has been suggested, implied, or utilized. It is felt rather that it is more important at the present time to examine thoroughly and discuss those factors which hinder and those which favor effective application of this pest-control technique.

BIOLOGICAL AND CHEMICAL CONTROL

Before proceeding it seems desirable that the phenomena of biological and chemical control be briefly discussed since there are differing opinions concerning them, their scope and characteristics. Some persons hold that the term "biological control" applies only where there is manipulation or direct utilization of entomophagous and entomogenous organisms by man to attempt suppression of pest species (30, 37, 87). Others, including the authors, believe biological control to include the action of naturally existing unmanipulated biotic mortality agents, as well as those utilized directly and deliberately by man (28, 46, 106, 115, 119). We also feel that biological control occurs whether or not a pest species is involved (106). There could be considerable discussion on this conflict of viewpoints. However, this is not the concern of the present paper. It is important here only that it be understood that the authors consider biological control in the broadest sense.

Biological and chemical control, though both involved in the suppression
or alleviation of pest arthropod problems, are in no way similar phenomena. Biological controls are a part of the natural control which governs the population density of a pest species (106). On the other hand, with certain exceptions as in insect eradication programs (73), chemical controls involve only immediate and temporary decimation of localized populations and do not contribute to permanent density regulation. Where this distinction is not always made clear, biological control is 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 and rapidly decimate a local pest population. However, an important characteristic of a biological control agent as compared to a chemical control agent is that it is self-perpetuating and responsive to fluctuations in the population density of the pest it attacks. Biological controls, whether imported or native, usually are permanent characteristics of a given environment (106).

Obviously, if biological controls were perfect there would be no pests and chemical control would be unnecessary. Thus, characteristically, chemical control is needed and should be used to reduce numbers of pest species which rise to dangerous levels when or where the suppressive environmental pressures are inadequate. It derives from this that an essential function of chemicals is to complement biological control at the times and places where it weakens or is inadequate. These same chemicals, especially if used indiscriminately or improperly, can be antagonistic to biological control rather than complementary, and this can lead to many secondary problems (20, 70, 77).

In essence, then, integrated control has as its objective, maximum chemical augmentation of the biological control of a given pest with the least disruptive effect by these chemicals on the ecosystem to which the pest belongs.

THE ECOSYSTEM

Stern et al. (106) define ecosystem as follows: "The interacting system comprised of all the living organisms of an area and their non-living environment. The size of the area must be extensive enough to permit the paths and rates of exchange of matter and energy which are characteristic of any ecosystem.” This is also essentially the definition used by Odum (67).

An agricultural region may be comprised of one or more ecosystems, depending on the flora, fauna, and physical features of the region. The ecosystem may cover a considerable area as in the huge monocultures of wheat, other cereal grains, and cotton, while in highly intensified farming areas with a variety of crops, tree plantings, and cropping systems, the individual ecosystem is frequently more restricted. Each agricultural ecosystem may vary in its degree of complexity but all are complex. The lack of appreciation of this factor has had much to do with the complications that have arisen from the widespread use of the organic insecticides.

The fantastic complexity of an agricultural ecosystem is illustrated by
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the unpublished data of our colleague, E. I. Schlinger (University of California, Riverside), who has been conducting a faunistic survey of arthropods in alfalfa fields in southern California. This investigation, which is being implemented by a mechanical suction-type collector and a modified Berlese separator system (23, 24), has already revealed over 600 identified arthropod species to exist in alfalfa. Schlinger estimates that this total will approximate 1000 species when his study is completed. The complex interrelationships of the components of such a diverse arthropod fauna and other components of the ecosystem are almost incomprehensible. It takes little imagination to visualize the catastrophic effects of a widespread generally toxic insecticide program on such a fauna.

For example, during the height of the emergency chemical campaign against the spotted alfalfa aphid, 1955 through 1957 in southern and central California, we, and other workers, noted unprecedented numbers of a leaf miner, *Liriomyza* sp.; spider mites, *Tetranychus* spp.; pea aphid *Macrosiphum pisi* (Harris); beet armyworm, *Spodoptera exigua* (Hübner); and a leaf roller, *Platyptota stultana* Walsingham, in alfalfa. Circumstantially, at least, these pest upsurges seemed to have been correlated with the widespread and repeated use of the broadly toxic materials, parathion and malathion. Certain of these pests caused considerable damage to alfalfa and one, *P. stultana*, spread to cotton where, for the first time, it caused serious damage to this crop in southern California (4, 5). Since the emergency parathion and malathion spray campaign has given way to an integrated control program in which low dosages of Demeton are used selectively (107), this pest has subsided to very minor status in cotton.

Recognition of the concept of the ecosystem and its complexity is fundamental to an understanding of integrated control. In developing an integrated control program, it is the entire ecosystem and its components that are of primary concern and not a particular pest. This latter point is one that is particularly easy to overlook. For instance, even Ripper, one of the pioneer proponents of integrated control, seemingly tends to do this. In his prerequisites for integration (78) he states that, "... Integration of biological and chemical control is possible if (a) a suitable low-density natural enemy is available (b) a selective insecticide exists which controls the pest but not the low density-dependent natural enemies, and (c) the maximum population density of the pest which does not produce economically significant damage to the crop is not lower than the population density of the pest needed to retain the low-density natural enemy." Here, Ripper apparently overlooks the complete ecosystem and emphasizes only the pest of interest, its low density-acting natural enemies, and selective insecticides to be used on these organisms. Actually, the "selective" materials he suggests could conceivably have adverse effects on other components of the ecosystem and defeat the purpose of integration. Though digressing somewhat, we cannot agree either with the viewpoint that low density-active natural enemies are essential to the development of integrated control. In
direct contrast to this contention, Stern & van den Bosch (107) and Smith & Hagen (91), successfully utilized coccinellids, high density-active predators, in developing an integrated control program for the spotted alfalfa aphid. A similar program has been developed for control of the pea aphid, on alfalfa, again utilizing coccinellids (Stern, unpublished data).

Stability of the ecosystem.—The relative stability of the ecosystem is an important factor in the development of an integrated control program. Where a planting is of a permanent or semipermanent nature, phytophagous arthropods and their natural enemies tend to establish relatively stable relationships. Thus, the possibilities of directly utilizing biological control agents are generally much better in orchards, forests, rangelands, and perennial field and forage crops than they are in short-term plantings such as vegetable crops, cut flower plantings, and the like, where stable host-natural enemy relationships hardly have time to develop before the crop matures. It is not implied though, that integrated control should be ignored in such crops. In many cases significant natural enemy populations do develop in them as on *Liriomyza* sp. in melons and lettuce (42) and *Liriomyza pictella* (Thomson) in melons (66) and on the diamondback moth, *P. maculipennis*, and the cabbage aphid, *Brevicoryne brassicae* (Linnaeus), in crucifers (77, 78, 116). In fact, Ripper (77, 78) and Ullyett (116) both have developed integrated control programs in cruciferous crops. Furthermore, regardless of the complexity or relative stability of the ecosystem, the search in applied entomology should wherever possible be directed toward discovery of the most selective and least environmentally disruptive chemical treatment.

**Selectivity in Insecticides**

Expansion of integrated control programs is limited in part by the nature of available control materials. Among commercially utilized synthetic insecticides there is no absolutely selective material (i.e., selective for a given arthropod species) and most materials in general use today are rather broadly toxic in their action. However, within the great variety of materials now available for pest-control purposes, there are a number which show considerable selectivity and these, along with more broadly toxic materials used with special techniques, have been and can be incorporated into integrated control programs.

It has been said that the ideal selective material is not necessarily one that eliminates all individuals of the pest species while leaving all of the natural enemies (14, 68, 69, 77, 91, 106). Use of such a material would force the predators and parasites to leave the treated area or starve. This, however, would only hold true if natural enemies were significantly affecting a given pest at the time the selective material was applied. Thus, where natural enemies are scarce or ineffective, anything but essentially complete kill of the hosts with the selective material could lead to disastrous pest resurgences (106). On the other hand, where parasites and predators are
abundant or effective, a chemical treatment which would shift the balance back in favor of the natural enemies would be ideal (11, 77, 106). There are situations, however, where despite the absence of effective natural enemies partial chemical kill of a pest does not entail the danger of pest resurgence. This can occur with a univoltine species or one that passes but a single generation in a crop cycle. For example, in recent experiments involving the Egyptian alfalfa weevil, *Hypera brunneipennis* (Boheman), we have found that kills of approximately 90 per cent produced by low (selective) dosages of methoxychlor are adequate for economic control of this univoltine species. With this pest, which is without effective natural enemies in the desert valleys of southern California, there is no danger of resurgence because essentially all oviposition and larval eclosion has occurred by the time chemical treatment is initiated.

Ripper (77, 78, 79) breaks selectivity down into two categories, physiological selectivity and ecological selectivity. Physiological selectivity occurs where certain groups of arthropods or certain species are inherently more susceptible to a given material than are arthropods as a whole. This type of selectivity is also involved where a normal broadly toxic material is so treated, as with a protective coating over the particles, that it loses its contact toxicity and becomes toxic only when the protective coating is lost through mastication or digestion. Ripper (78, 79) has demonstrated this principle through the coating of DDT particles with zein. A particular material may be physiologically 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 (74, 78) and especially the type of carrier and residue deposit may produce differential effects on the insect complex (20, 74, 78).

Ecological selectivity occurs where the timing or placement of a material reduces its overall disruptiveness to the ecosystem. This may be done in a number of ways. First, it can be accomplished by treating only those areas where the pest natural enemy ratio is unfavorable. This method is one of the bases of supervised control of the alfalfa caterpillar in California (88, 89). In this program, population levels of both the host caterpillar and its parasite, *Apanteles medicaginis* Muesebeck, are determined at appropriate intervals in all fields under supervision. 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 the parasite adults as well as those parasite larvae within the host caterpillars are largely 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.

Proper timing of treatments has been used repeatedly to gain a degree of selective action in insecticides (10, 26, 27, 29, 35, 36, 53, 57, 59, 77). In such
situations, intimate knowledge of the behavior patterns of the pests and their natural enemies is required. In other situations, selectivity might also be attained by using insecticides in the manner described for control of the melon fly, *Dacus cucurbitae* Coquillet, in Hawaii (64, 65). In this case, ecological studies had shown that the fly habitually roosts on field edge vegetation during most of the day and excellent chemical control was effected by treating this vegetation instead of the cropplantings themselves. In California, the ovipositional habits of the alfalfa butterfly are helpful in localizing treatments of this pest. The butterfly females oviposit in alfalfa that is less than one-quarter grown and as the alfalfa in an area is mowed they concentrate and ovipost only in such fields. The entomologist or farmer, by keeping close watch on these "oviposition fields" can essentially localize all the danger spots during a given cutting and treat those fields which break away from biological controls (89, 90).

The flight habits of the may beetle, *Melolontha vulgaris* Fabricius, have been useful in the development of selective treatment for this pest in Switzerland. It has been found that in their vernal flight the beetles rise from the ground, circle about and then direct themselves towards the point of highest average elevation on the horizon, where they eventually alight. By mapping these concentration areas and restricting chemical treatments to such sites the Swiss entomologists have eliminated the need for area wide chemical treatment (82, 84).

It is quite probable that expanded ecological studies will reveal many more arthropod behavioral patterns such as those just described. This information will be of great advantage in integrated control programs, for treatment of the places in which pest insects rest or otherwise concentrate would save broader areas from insecticidal coverage.

A fourth way in which ecological selectivity can be attained is through the proper use of widely toxic materials with short residual action (14, 77). Thus, with such materials as Phosdrin® (1-methoxycarbonyl-1-propen-2-yl dimethyl phosphate), TEPP, Dylox®, (also known as Dipterex) (0,0-dimethyl 2,2,2-trichloro-1-hydroxyethyl-phosphonate), nicotine, etc., a degree of selectivity can be attained if the beneficial forms survive initial application in resistant stages, protected places, or untreated reservoirs. Bartlett (9) and Stern & van den Bosch (107) have demonstrated that parasites of the spotted alfalfa aphid can survive normally non-selective treatments if they are in the pupal (mummy) stage. Nicotine has long been known to have little or no residual effect on beneficial forms (60, 77, 118). It would seem particularly important that the factor of residual toxicity be given serious consideration where repopulation of treated areas by entomophagous species is critical. Thus, we found that Phosdrin, a highly toxic non-residual phosphate had advantages over parathion or malathion as a control of spotted alfalfa aphid because it produced no mortality to parasites emerging from mummified aphids or coccinellid larvae hatching from eggs (107). Similarly, commercial dosages of Dylox and Phosdrin
though they eliminate about 85 per cent of the adults of the egg parasite, *Trichogramma semifumatum* (Perkins), in treated areas, are essentially harmless to the parasite stages contained within the host eggs. Parasites emerging from these eggs suffer no mortality because Dylox and Phosdrin leave no toxic residues. On the other hand, Sevin® (1-naphthyl-N-methylcarbamate), a residual material, largely eliminates the free-living *T. semifumatum* adults at the time of treatment and its residue remains sufficiently long in the field to kill the adult parasites as they emerge from the host eggs (unpublished data of the authors). The same situation undoubtedly occurs with other egg and pupal parasites.

Still another way in which selectivity can be increased is by the lowering of dosages of normally rather toxic materials. This was demonstrated by Ripper (77) in the use of reduced dosages of schradan in cabbage aphid control. This principle has also been used successfully in control programs for several forage and field crop pests in California (102, 105, 107).

A sixth way in which ecological selectivity can be attained is by strip, spot, or otherwise restricted treatment of a planting. DeBach (19) and DeBach & Landi (21) report successful integration of biological and chemical control of purple scale, *Lepidosaphes beckii* (Newman), on citrus where alternate pairs of tree rows were sprayed at 6-month intervals with a nonselective oil treatment. Spot treatment is a frequently used technique for control of colonial insect species which otherwise tend to build up in scattered places in a planting (116).

Lawson et al. (48) have employed restricted treatment of a somewhat different type. These workers have found that when the tobacco budworm, *Heliothis virescens* (Fabricius), and hornworms, *Protoparce* spp., are concurrently infesting tobacco, top treatment of the plants will give good control of these pests in the upper leaves where they are most abundant. This restricted treatment spares the lower leaves from heavy insecticidal residues and permits significant predation of the lighter hornworm populations in the lower plant parts by *Polistes* wasps.

Another important way in which selectivity can be obtained is through the application of otherwise widely toxic materials as soil dressings, seed treatments, in granulated form, etc. (74, 77). Finally, selectivity of highly toxic materials can be attained when they are used in baits or with attractants (55). Used in this manner, such materials as DDT, toxaphene, endrin, dieldrin, the arsenicals, etc., can be highly effective and accomplish their insecticidal purpose without the generally disturbing effects on the environment that would occur when the same materials are applied in broadcast spray or dust formulations. Even the more or less widely broadcast fruit-fly bait sprays seem to have generally less detrimental effects on beneficial insects than do conventional insecticide sprays or dusts involving the same toxicants (95, 96).

**Microbial insecticides.**—For some pests, a disease pathogen may be used as a selective insecticide (36, 99, 111). For example, under supervised con-
control in the Dos Palos area of California, the nuclear polyhedrosis virus affecting the alfalfa caterpillar has been used successfully either alone or in combination with a selective chemical insecticide to avoid the use of a non-selective treatment. Highly specific virus diseases would appear to offer considerable promise in integrated control programs particularly against lepidopterous pests (36, 99, 111). Recently, widespread 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 the United States and elsewhere (36, 99). The use of disease pathogens as selective insecticides is in its infancy, but can be expected to increase in importance with additional research.

Factors Which Affect the Development of Integrated Control Programs

It is evident from the foregoing discussion that there are practical and effective means of integrating chemical and biological controls. As mentioned previously, this concept is no longer a hypothetical one, and it is being accepted and practiced on a rapidly widening scale. However, integrated control is not a panacea for there are a number of factors that inhibit its universal application to pest control problems. These factors, together with certain of those which favor integrated control, will be discussed in the following pages.

Insecticides and chemical control practices.—Perhaps the major factor currently limiting greater application of integrated control is the essential lack of truly selective organic insecticides. This condition would seem to derive in considerable measure from the philosophy of pest control prevailing during the past two decades which has emphasized the development and utilization of broadly toxic residual insecticides. The agricultural chemical industry, research entomologists, pest-control advisors, and insecticide users have generally shared this philosophy. Industry has quite understandably looked to widely toxic, highly residual materials, for these offer the best opportunities for wide markets and rapid economic returns to amortize high research and development costs (41). This is a legitimate consideration, and it must be realized that the development of highly specific insecticides will often be precluded by economic factors. An additional barrier to the development of highly specific materials is the technological difficulty of developing specific insecticides for even a fraction of the world's arthropod pests. Economics aside, this is probably a nearly impossible task.

The solution to the over-all problem outlined above may lie largely in the development of more materials toxic to certain taxonomic groups of arthropods. Thus, one compound may be toxic only to lepidopterous larvae, another to aphids, a third to mites, a fourth to weevils, etc. These materials could then be used at proper dosages, formulations, timing, etc., to bring on further selectivity in particular situations.
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There is also a general desire among growers for widely toxic, highly residual materials and this, too, has an economic as well as a strong psychological basis. When his livelihood is threatened, the farmer quite understandably looks to that material which will kill the most insects quickly and with long-lasting effect. By and large, he cannot be expected to be familiar with the concept of the agricultural ecosystem or the intricate points of arthropod population dynamics. He wants "dead bugs" and he is quite often disturbed when any living creature stirs about in his fields following treatment.

Cost of insecticides is also a factor which affects the growers choice of materials. It is difficult to persuade a person to use a selective but more costly material when as an alternate choice he has available to him a cheaper broadly toxic insecticide. Even when it is argued that the long-term costs to him will be less with the initially more expensive selective material he will still be inclined to use that which is immediately less costly to him.

Nature of the pest complex.—In many cases almost all prerequisites exist in a given crop or pest complex for the development of integrated control except for the existence of a key species whose habits, insecticide tolerance, type of injury, or other characteristics, require frequent insecticide treatments. Often only a widely toxic residual material can effect its control. Many cases of this sort can be enumerated but among those familiar to most of us are the boll weevil, Anthonomus grandis Boheman, on cotton in southern United States; the codling moth, Carpocapsa pomonella (Linnaeus), on pome fruits in many parts of the world; the California red scale, Aonidiella aurantii (Maskell), on citrus in California; the Colorado potato beetle, Leptinotarsa decemlineata (Say), on potatoes in Europe, etc.

The key species often varies from area to area. But for the existence of such key species, pest problems in these crops would be much more adaptable to integrated control. However, the use of such widely toxic materials such as DDT, toxaphene, dieldrin, endrin, parathion, malathion, etc., precludes such possibilities, and this aggravates the overall pest control picture (18, 70, 77). One answer to this type of problem, particularly where the economic threshold is necessarily low, would appear to lie in the development of pest-resistant, host-plant varieties (68).

Restrictions on insecticide residues and insect parts in foodstuffs.—Regulations governing insecticide residues and insect parts in foodstuffs are necessary to safeguard the public health. However, such regulations can be somewhat self-defeating for, at times, they lead to increased use of broadly toxic materials. This, in turn, has had an adverse effect on integrated control as well as other complications. For example, recently, heptachlor, a highly selective chemical control for Egyptian alfalfa weevil, Hypera brunneipennis (Boheman), in southern California (102) had to be abandoned when it was found that this material converts to a toxic epoxide as a degradation product. As a substitute, growers reverted to the use of
more broadly toxic organic phosphates. This shift threatened the integrated control program in alfalfa and, in addition, endangered honey bees which forage heavily in alfalfa in the early part of the year.

In certain cases, at least, regulations or marketing standards that limit insect parts in processed foods to miniscule amounts have a particularly ironic twist, for in meeting such exacting requirements growers can be forced into heavy insecticidal programs. This, of course, jeopardizes chances for integrated control. But integrated control considerations, notwithstanding, it would seem that the hazards to human health associated with such heavy use of insecticides are infinitely greater than those posed by a few thrips tarsi or aphid antennae in frozen asparagus, peas, and spinach, or canned corn.

*Economic thresholds.*—In many pest problems, economic thresholds are necessarily low and this presents a serious but largely unavoidable obstacle to integrated control. Problems involving arthropod disease vectors fall in this category (77, 106). So, too, do those problems in which fruit-feeding species attack crops of high economic value or high market standards. In these cases, heavy insecticidal treatment is usually initiated early in the crop cycle and frequently maintained nearly to harvest time.

In many other crops, however, treatment is often invoked prematurely or unnecessarily because economic thresholds are unrealistically low, poorly defined, erroneously derived, or non-existent. Rectification of this situation through careful development of soundly-based economic thresholds could lead to better possibilities for integrated control, especially where the economic thresholds can be substantially raised. Unquestionably, the higher the economic threshold the greater will be the possibility for biological control agents to come into play and hence the greater the possibilities for integrated control. Of course, under any circumstance, whenever repetitious treatments are needed, the most selective materials should be sought in order to give maximum protection to the other biotic components of the ecosystem.

*Biological control agents.*—The development of any integrated control program will normally be enhanced by the existence of a complex of natural enemies attacking the key pest species. However, the presence of natural enemies, even in abundance, is not necessarily an indication that they will effectively reduce the economic status of a pest in a given planting. Their activity may simply not be sufficient to preclude the necessity for frequent chemical treatments. The careful and thorough study of Jaynes & Marucci (47) shows that the codling moth populations in untreated orchards commonly suffer very heavy mortality from a complex of natural enemies. Yet, as we all know, economic production of apples cannot be generally attained without insecticidal control of this pest despite this heavy natural mortality. The corn earworm, *Heliothis zea* (Boddie), is frequently heavily attacked by predators and parasites but even in these cases severe injury
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... to sweet corn can ensue. Larvae of the Oriental fruit fly, *Dacus dorsalis* Hendel, may be heavily parasitized by opiine wasps but the very presence of these parasitized larvae in the fruits makes them inedible and unmarketable. There are, of course, many cases of this sort where the economic threshold is so low or pest injury of such a nature, that natural enemies are not capable of altering the pest's economic status in a given planting.

Under modern agricultural or otherwise largely artificial circumstances, there are certain pests that simply do not have important natural enemies capable of giving economic control. The house fly, *Musca domestica* Linnaeus, many species of mosquitoes, termites, ants, many weevils, borers, etc., are examples. Other insects seem completely free of attack by parasites (i.e., parasitic arthropods) as is apparently the case with the wooly balsam aphid, *Adelges piceae* (Ratzeburg), (6). In a recent intensive survey of aphid parasites in Europe and the Middle East conducted by one of the writers, no evidence of parasitism could be found in heavy and widespread populations of *Boernerina depressa* Bramstedt, *Cryptura grassii* Silvestri, *Callaphis juglandis* (Goeze), and *Ctenocallis* spp. in the Callaphididae. Needless to say, where natural enemies are essentially lacking or highly ineffectual the difficulties in developing integrated control programs will be greatly increased.

At times biological control can be augmented by man and this, of course, tends to reduce the need for chemical control. Such a shift reduces the chances for disruption of the various ecosystems to which the pests belong and this, as stated earlier, is a major objective of integrated control. Over the years this goal has been attained repeatedly through the introduction of exotic natural enemies of immigrant pests (15, 36, 110, 125). In certain cases, the augmentation of natural enemy activity has also been attained through the mass release of cultured or otherwise accumulated natural enemies. The familiar use of *Trichogramma* spp. against a variety of pests (36) and the similar use of natural enemies of scales and mealybugs on citrus (25) and egg parasites against Senn pest, *Eurygaster integriceps* Puton (128), are examples of this sort.

Natural enemy efficacy may also be augmented through modification of cultural practices such as mowing (40, 81), weed control (17, 112, 126, 127), and irrigation (18), or the provision of artificial nesting sites (38, 48).

*Fundamental studies of insect ecology.*—An inescapable prerequisite to the broadening of integrated control is an increase in the painstaking, long-term study of insect ecology (18, 70, 106, 116). It is very difficult to attain this objective, especially where understanding of the need is lacking, funds are short, personnel is limited, or where there is constant pressure for quick answers to a multitude of urgent problems.

This condition constitutes an important obstacle to broadened integrated control. However, when one analyzes the known cases of successful integrated control, it becomes strikingly evident that all were attained only after
thorough ecological studies were made of the pest species involved and the environments in which they lived.

As an illustration of the nature and scope of study that may be necessary to develop an integrated control program, it seems appropriate to analyze that which has been developed for the alfalfa caterpillar, *C. eurytheme*, in California. Initial biological investigation on this pest dates back to the studies of Wildermuth (121, 122, 123). Michelbacher & Smith (58) carried out further biological investigations and made a preliminary evaluation of natural enemies in the biological control of the butterfly. Smith (88) followed these studies with investigations that established a sound economic threshold and methods for utilizing natural enemies in a supervised control program. Interfield movements of butterflies were reported by Smith et al. (90). Stern & Smith (105) reported on the reproductive mechanisms, ovi-position, and population dynamics of the butterfly, while Leigh & Smith (49) published findings on the flight activity, dispersal and response of *C. eurytheme* to physical factors in the environment. Studies of the biology and effectiveness of the larval parasite, *Apanteles medicaginis* Muesebeck, and its relationship to the alfalfa caterpillar have been published by Allen (1), Allen & Smith (3), and by Michelbacher & Smith (58). Additional studies of the biology, effectiveness, dispersal habits, and population dynamics of the egg parasite, *Trichogramma semifumatum* (Perkins), and its association with the alfalfa caterpillar will be published shortly by Stern & Bowen (103). Extensive investigations of the nuclear polyhedrosis virus, *Borrelina virus campeoles* Steinhaus, attacking *C. eurytheme* have been reported by Steinhaus (97), Steinhaus & Thompson (101), Thompson (113), and Thompson & Steinhaus (114). Further investigations utilizing spore material of *Bariillus thuringiensis* Berliner to control the alfalfa caterpillar have been published by Steinhaus (98) and by Stern et al. (104), and the utilization of selective insecticides has been reported by Reynolds et al. (74) and Stern et al. (108). A vast amount of additional data has been gathered on this insect but has not as yet been published.

These investigations of a single pest insect and its environment have given enormous insight into the pest's behavior, population dynamics, economic status, the nature, timing, and efficacy of natural enemy attack and selective chemical control. This information has been used in a supervised control program, in effect for fourteen years on the "Westside" of the San Joaquin Valley. In this program the growers contract a professional entomologist, who follows population trends in commercial alfalfa fields, predicts when and where butterfly outbreaks will occur and utilizes biological control to maximum advantage. When chemical treatments are necessary, selective chemicals are applied. Still, despite this long-term and intensive investigation of *C. eurytheme* and its natural enemies and the years of practical application of this research information in California, investigations continue today.
IMPLEMENTATION OF INTEGRATED CONTROL PROGRAMS

It is obvious that complex programs of the type described above require trained, experienced professional entomologists for their effective implementation. In the United States, as in most areas, the general lack of such personnel would constitute a formidable obstacle to broadened integrated control programs even were the techniques for such programs to be developed. Unquestionably, the existence of such a corps of professional consulting entomologists would greatly alleviate many of our present pest-control problems at every level. It is not likely, however, that this corps will soon evolve, and for this reason adoption of integrated control will probably be a slow process.

Perhaps the key to the widespread adoption of the integrated control concept in agriculture lies with the attitudes and desires of the man who needs it most—the grower. If insecticide resistance problems continue to increase at their currently alarming rate, if secondary pest problems burgeon, if legal entanglements increase, and if the cost of pest control mudrooms because of these factors, then it seems inevitable that growers and others will demand relief, and that they will come to perceive the advantages of integrated control in contributing to this end.

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