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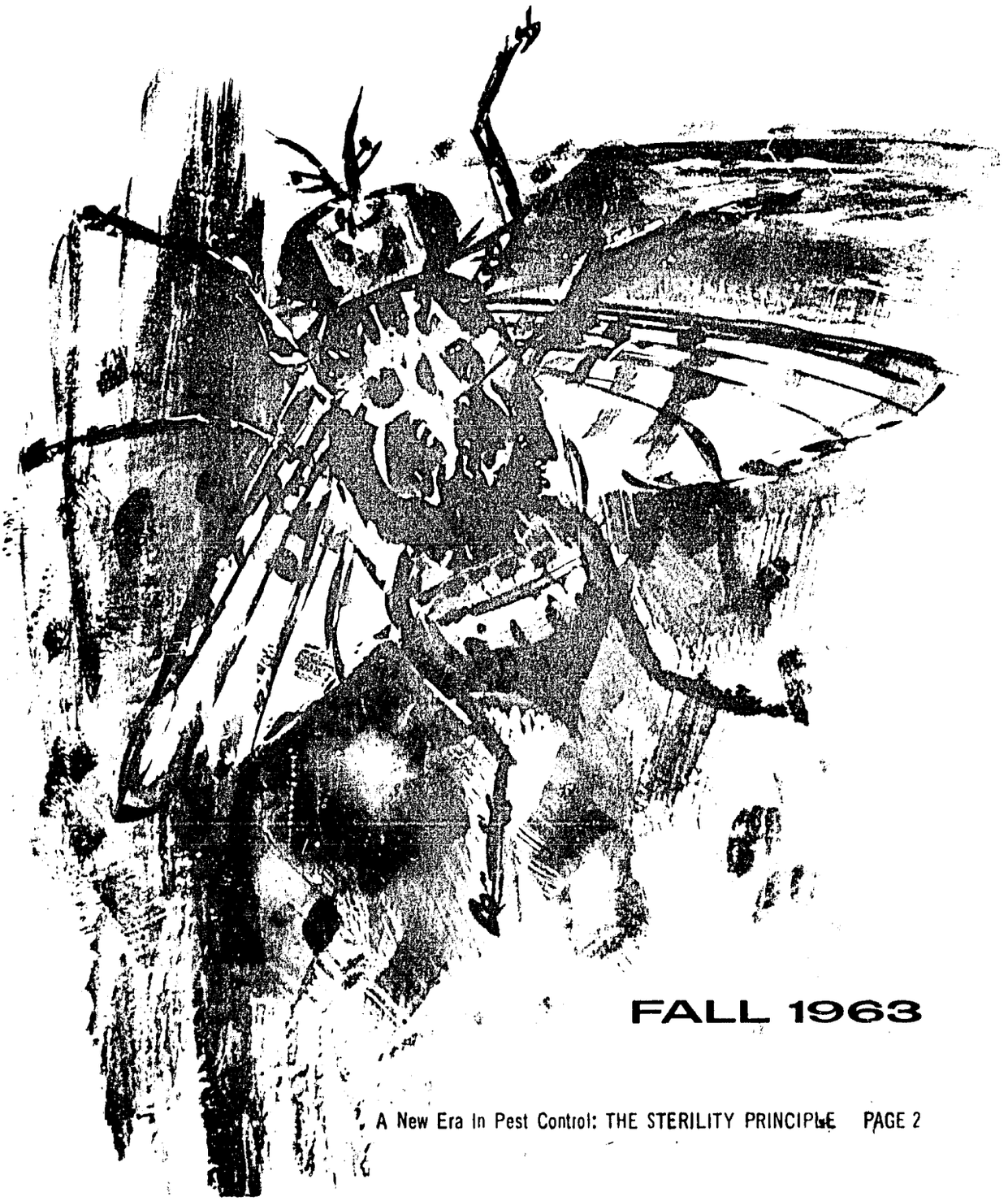

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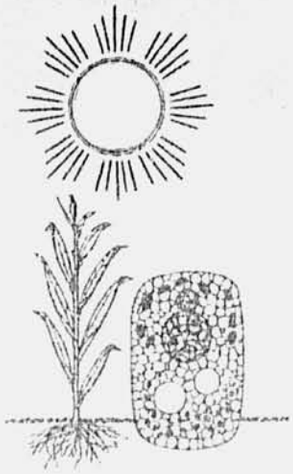

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EDITOR: WARD W. KONKLE

The Language of Science

Probably no other form of communication faces greater innovations in the years ahead than does the language of science. True, its traditional characteristics—pure objectivity, lavish use of technical terms, and symbolic statement of fact—are likely to remain, or perhaps become even more dominant when scientists are sharing knowledge among themselves. But because science and its product affect interest groups outside the realm of the laboratory, its communications patterns will, at times, need to be modified.

Of highest priority is the need for a better public understanding of science knowledge. Surveys have revealed wide areas of ignorance about modern technological concepts. Such ignorance is detrimental both to the public welfare and to the scientific community itself. Much of the burden for correcting this situation rests with scientists themselves. Only when they learn to adapt their language at the right time and in the right way can the myths and misunderstandings surrounding the research laboratory be dispelled.

Almost equally important is the need to establish a more effective crossfire of disciplines; that is, the interaction of every branch of science with other branches. This interdisciplinary communication depends heavily on the use of a language geared to the premise that every science author is somewhat of a layman for articles in fields other than his own.

Finally, the language of scientists must be adaptable to the language of professional documentalists—those who are skilled in the mechanical techniques of information transfer. Authors will need to assume more responsibility for the final links in the dissemination process by preparing manuscripts, abstracts, and titles that enable documentalists to store and retrieve the information quickly and accurately. The benefits such cooperation affords are too valuable to be overlooked.

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A New Era In Pest Control:

THE STERILITY PRINCIPLE

E. F. Knipling

USING the sterility principle for the self-destruction of insects represents a method of control that could be tremendously important in meeting insect pest problems in the future. Thus far the principle has been considered primarily for controlling or eliminating insect populations. It should offer similar opportunities for regulating vertebrate pests.

The release of sterile insects has been used successfully only for controlling the screw-worm, which was eliminated from the island of Curaçao in a pilot eradication effort by the Entomology Research Division. Results of the basic laboratory and field studies have been reported in various publications by R. C. Bushland, A. W. Lindquist, A. H. Baumhover, and their associates in the Insects Affecting Man and Animals Research Branch. A successful eradication program in the Southeast by the U.S. Department of Agriculture and the Florida Livestock Board followed the Curaçao experiment. An extensive and more difficult program sponsored by the U.S. Department of Agriculture and the Southwest livestock interests is currently underway to eliminate the screw-worm from its normal range in southwestern United States. If the eradication phase is successful, efforts will be made to prevent its reestablishment by the continuous release of sterile flies in a barrier zone along the Mexico-United States border.

The Entomology Research Division, ARS, has intensified its research efforts during the past decade—largely at the expense of other phases of research—to explore the potentialities of the sterility principle for controlling or eliminating certain other insect pests. Despite limited research resources for such work, progress has been excellent. Results to date on several important insect species have shown sufficient promise to suggest that research on this approach to pest control warrants major attention and support.

Research is underway on two ways of utilizing the sterility principle—the rearing and release of large numbers of sterile insects which compete with normal insects in the population, and producing sterility in the natural population. This latter method would obviate the need for rearing and releasing sterile insects.

Each method involves the use of insects for their own destruction, but there are important differences between the two methods in the way that the sterile insects affect population trends. Much research must be conducted and many problems must be resolved to realize the full potential that the two sterility methods hold. Basic information is needed

on many aspects of the biology, ecology, behavior, genetics, rate and distance of spread, and population dynamics of insects that formerly seemed to be of little consequence, and hence is now generally lacking. This is true even for some of our most destructive species that have been the subject of extensive research for many years. Moreover, our entire concepts of how to deal with pest problems must change if we are to take advantage of the methods. We must give primary attention to the pest population when it is at its lowest level rather than when it is at its highest level. We must think in precise quantitative terms in regard to such pest populations. We must think in terms of the total pest population in a community, region, or nation, and not just segments of the population on individual farms.

The sterility principle will not be applicable for all insects or even a majority of the destructive species. It could, however, play a vital role in meeting many of our major insect problems. There are indications now that the method may be feasible to help eradicate or control a number of key insects and future developments should broaden its potential usefulness.

BASIC PRINCIPLES IN STERILE-MALE RELEASE METHOD

Theoretical Aspects

THE effective use of sterile insects for release depends on our ability to rear enough insects to overflood the natural population. The insects to be released must be made sterile without seriously affecting the ability of the released males to compete with normal males in the natural environment. The number of insects required, the allowable cost of rearing them, and the required ratio of sterile to fertile insects—all depend on the species and the circumstances. Where both the natural population density and the biotic potential for the species are high, billions of insects may be needed. The natural population, initially, would have to be overflooded by a factor of 25 or more. For the procedure to be practical under such circumstances, it will of course be necessary to develop very low cost methods of rearing and distributing the many insects required. In many situations, however, the natural population density of the pest may be low. Here, relatively few sterile insects might be adequate and the allowable cost for rearing them may be high.

If fully competitive sterile insects are released, we can make a reasonably valid estimate of the effect such releases will have on population trends, provided that we know the natural population density level and the normal rate of increase from one generation to the next. Table 1 shows the theoretical trend of an insect population subjected to the release of a constant population of sterile insects each generation.

The assumption is made that the normal uncontrolled population is increasing at the rate of fivefold per generation, which is probably fairly realistic for many insect species even though the biotic potential is much higher. It would be necessary, therefore, to overflood the natural population by at least 4 to 1 to prevent an increase in the natural population. To start a downward trend, the initial release rate would have to exceed 4:1. To start a downward trend with a chemical, the level of kill must exceed 80 percent. The model provides for an overflooding ratio of 9:1 for the initial generation so that a downward trend in the population will result. The degree of control with the insecticide is assumed to be 90 percent each generation. Thus, the effect on the reproductive potential of both populations would be the same for the first generation.

Note, however, that with the sterile male method, a constant release rate will result in a higher and higher ration of sterile to fertile insects as the population declines. The effect on the population trend becomes progressively greater each generation. On the other hand, the effect of each insecticide treatment on the population trend remains constant regardless of the population density. When the population density is high, the insecticide treatment is highly efficient in terms of the actual number killed. But the efficiency of each treatment becomes lower and lower as the population declines. These are features of major significance in considering the role that insecticides and the release of sterile organisms might play in meeting pest problems.

In most situations, the natural population of a pest, even at the lowest level in the population density cycle, may be so high that it would not be practical to rear and release enough sterile organisms to start a downward population trend. In

TABLE 1.—THEORETICAL MODEL SHOWING THE TREND OF INSECT POPULATIONS SUBJECTED TO 3 TREATMENTS

Generation	No treatment	Insecticide treatment that kills 90 percent each generation	Release of constant number of sterile insects that initially overflood the natural population by a ratio of 9:1			
			Natural population	Sterile population	Ratio: Sterile to fertile	Progeny
	Number	*Number*	*Number*	*Number*		*Number*
Parent	1,000	1,000	1,000	9,000	9:1	500
F_1	5,000	500	500	9,000	18:1	132
F_2	25,000	250	132	9,000	68:1	10
F_3	[1] 125,000	125	10	9,000	900:1	0
F_4	125,000	62	0			
F_5	125,000	31				
F_6	125,000	16				
F_7	125,000	8				
F_8	125,000	4				
F_9	125,000	2				
F_{10}	125,000	1				

[1] An uncontrolled population of any insect will reach a maximum population level that the environment will maintain. For this model, it is assumed that 125,000 would represent the maximum.

such event the prior use of an insecticide or some other method of control would be more efficient and practical than the release of sterile organisms. However, the release method should become more practical than insecticides at some point in the natural population density level. We may illustrate this by citing some hypothetical figures. A 90-percent kill of a million insects in a population by an insecticide would mean the destruction of 900,000 insects the first treatment. In terms of numbers killed, this would be highly efficient. The second treatment, however, would destroy only 90,000; the third, 9,000; the fourth, 90; the fifth only 9. Thus, as the population declines each insecticide treatment becomes less efficient in terms of the number of individuals killed.

At some point in the population density level, the rearing and release of sterile insects should become more efficient and perhaps more desirable than the continued use of an insecticide. The density level at which the rearing and release of sterile insects will become more efficient than insecticides will depend on the cost of producing the insects.

In general, we might conclude that a combination of the two systems of insect control in many situations would be highly complementary and more effective, more economical, or more desirable than either system alone. Once the population of an insect reaches the manageable level with sterile insects, each sterile male insect is not only a survey tool but also a lethal weapon. If an area under treatment is subject to reinvasion of normal insects, relatively low level releases of sterile insects on a continuing basis may be adequate to prevent reestablishment and thus provide continued control more economically than the routine use of chemicals.

Keep in mind that the effect on population trends as depicted in the model is hypothetical. Research on several insect species, however, has confirmed the principle.

Progress and Problems

As previously indicated, the screw-worm is the only insect in which the release of sterile insects has been actually employed for insect eradication. Substantial progress has been made, however, in developing the principle for other insects. We now face several problems. First, a suitable method of inducing insect sterility must be developed. Presently, the Entomology Research Division is conducting extensive research on gamma radiation and chemosterilants. Studies with radiation sterilization have shown wide variation in the effect of gamma rays on different insect species. In all insects, substantial reduction in sexual vigor and competitiveness due to radiation is apparent. With some insects, however, vigor is reduced to such degree that the males are of little value. The screw-worm, tropical fruit flies, the codling moth, and certain other insects can be radiated in the pupal stage without serious adverse effects. Radiation effects are severe on the boll weevil, the sugarcane borer, the gypsy moth, and the European corn borer. The adverse radiation effect on the pupal stage of some insects is largely morphological, as in moths that emerge from pupae with deformed wings. In such species, radiation of the adult stage may reduce the serious damage to the wings.

Although atomic radiation may prove to be the most desirable way to sterilize certain insects, chemosterilants seem to achieve sterility in insects with less adverse effects on the competitiveness of the males. The Orlando, Fla., laboratory has pioneered the early investigations on insect chemosterilants that will produce sterility in both sexes of insects. The Pesticide Chemicals Research Branch has given major attention to the chemical aspects of research on chemosterilants. In addition, the Division's laboratories at Mexico City, Mexico; Kerrville, Tex.; and Corvallis, Oreg., as well as a number of other locations have evaluated chemosterilants on a wide range of insect species.

Research thus far indicates that chemosterilants could be used to sterilize such insects as the house fly, several species of mosquitoes, all of the species of tropical fruit flies, Drosophila fruit flies, codling moth, pink boll worm, boll weevil, tobacco budworm, tobacco horn worm, as well as others. Much remains to be done on all of these insects and other species. But the ability to release reasonably competitive sterile insects does not appear to be a major obstacle to the development of the sterility principle for practical use.

Mass Rearing of Insects

The ability to rear insects in sufficient numbers and at a cost that will be practical appears to be feasible for many insects. During recent years the Entomology Research Division has given high priority to research in this area, not only in relation to the sterility method of control but also for other reasons. Remarkable progress has been made in the mass production of such insects as the screw-worm, four species of tropical fruit flies, Drosophila fruit flies, the tobacco hornworm, and several species of biting flies and mosquitoes. Although much additional research is needed, excellent progress has been made in developing mass rearing methods for such insects as the boll weevil, pink bollworm, cabbage looper, tobacco budworm, codling moth, European corn borer, and other species.

Currently the cost of producing screw-worm flies in the Mission, Tex., rearing plant probably is within the range of $250-$300 per million insects. Tropical fruit flies such as the oriental, Mexican, Medfly, and melon fly probably could be mass produced at a cost ranging from $100-$200 per million. A cost factor ranging from $1,000 to $5,000 per million may be practical for a number of insects. This depends on the situation under which sterile males might be used as an adjunct to other methods of control.

One of the essential requirements in appraising the feasibility of utilizing sterile male insects is knowledge of the natural population density of the insects to be controlled. Such information must be available on a quantitative basis. For well-established insects, we can assume that the natural population density in most areas will be too high, even at the lowest density level, to utilize sterile male releases alone for practical control. However, a pertinent question is: To what extent is it feasible to lower the population by other methods of control to a level that could then be dealt with by the release of sterile insects? Research has been undertaken on a number of insects to obtain such information.

It seems entirely possible that the boll weevil population can be reduced readily to a level of 5 to

10 adults per acre by the use of insecticides in a spring or fall treatment program. At this low level, it should become entirely feasible and practical to overflood the natural male population with sterile males by a ratio of from 25 to 50 times at a cost that would be no higher than the cost of continued use of insecticides to further reduce or prevent the buildup of boll weevil populations. If the natural population of boll weevils is reduced to 5 males per acre, the addition of 200 sterile males per acre per week would cost only $1 per acre if a production cost of $5,000 per million insects could be achieved. This would be a lower cost than the application of insecticides each week.

Research on population densities, the expected rates of increase from one generation to the next, the dispersion habits, the ecological requirements, and many other aspects of insect population dynamics and insect ecology which are of vital importance in applying the sterile male principle is difficult and costly. But only through such research will it be possible to appraise the potential possibilities of the sterile male release method for controlling or eliminating insects that are already well established.

Status of Research

ASIDE from the screw-worm, the greatest advance in research on the sterile male release method has been made on tropical fruit flies. A pilot experiment to eradicate oriental fruit flies on the island of Rota was not successful, because it was not possible to achieve and maintain the desired ratio of fully competitive sterile to fertile flies with the research resources available. There are circumstances in which the method would undoubtedly be entirely feasible and advantageous alone or in combination with other methods.

An experiment just completed on Rota with sterile melon flies has led to the eradication of this important vegetable pest. Eradication was achieved within about 3-4 months after releases began. The natural population was first reduced by applying bait sprays to restricted areas of high population densities. A ratio of about 15 sterile to 1 fertile insect was achieved within a month; this quickly rose to over 100 to 1 in about 2 months. Eradication soon followed. This is the first multiple-mating species in which eradication has been demonstrated by the release of sterile male insects.

A pilot experiment on the island of Hawaii, conducted in a semi-isolated area, demonstrated that Medfly population could be reduced by the sustained release of sterile males. Research has advanced to a stage that practical eradication experiments on the Mediterranean fruit fly are justified.

Several pilot experiments in semi-isolated areas in Mexico have shown that Mexican fruit fly populations can be held down by the release of sterile males. Practical eradication experiments in completely isolated areas are indicated and are planned.

Canadian workers have shown in laboratory and caged tree experiments that the reproductive potential of the codling moth can be greatly reduced by the presence of sterile male codling moths. Research on methods of mass producing codling moths and various ways of sterilizing the insect is underway at the Division's Yakima, Wash., laboratory.

Studies show that a high ratio of sterile to fertile boll weevils will eradicate an artificially induced infestation in the field. A pilot eradication effort will be undertaken within 1 or 2 years. Prior reduction of the natural population with insecticides will be required. Much research is still needed on the boll weevil to develop better methods of inducing sterility. However, the practical use of sterile boll weevils to eradicate low level populations seems encouraging.

Research on the tobacco hornworm indicates that the sterile-male method might have a place in the control of this insect. Several islands in the West Indies have been surveyed and plans are underway to initiate a pilot eradication effort within the next year.

Research on Drosophila fruit flies has shown that the natural population can be reduced by the release of sterile males. Pilot experiments are planned to determine if field control can be achieved by sterile male releases.

Research on the pink bollworm has advanced to a stage that a pilot eradication experiment in an isolated area is warranted for this important cotton pest.

Additional research is still needed on various aspects of the problem before it can be determined that sterile insect releases will be effective as a means for controlling or eradicating low level populations of the various insects mentioned. However, excellent progress has already been made and the outlook

is encouraging for developing practical ways to use sterile insects for such purposes.

EXAMPLES OF POSSIBLE APPLICATION

OUR numerous insect problems and the many and varied circumstances when eradication is necessary or desirable will suggest many situations where the release of sterile insects should prove advantageous over existing eradication methods.

1. **The Mexican fruit fly** is a continuing threat to California fruit and vegetable interests because of the spread from the border city of Tijuana in Mexico. The threat results largely from flies emerging from infested market fruits grown in other areas in Mexico where the fly is established. The total number probably does not exceed 1,000 each year. If periodical releases of sterile Mexican fruit flies totaling 1 million flies were made each year along the United State-Mexican border, a ratio of perhaps 1,000 sterile to 1 fertile fly could be maintained at all times. There is every reason to believe that such high ratio of sterile to fertile insects would provide adequate security against establishment of the insect in southern California. The cost of rearing 1 million Mexican fruit flies probably would not exceed $200. The current method of applying sprays is not only many times more costly, but for various reasons frequent application of insecticides over a period of years has several undesriable features.

2. A recent establishment of **pink bollworms** in Arizona necessitated a costly eradication program in a 75,000-acre area. Pink bollworms were numerous in much of the area before the eradication began; intensive use of insecticides during the first year greatly reduced the size and extent of the infestation. During the second year about 32,000 acres were treated at a cost of about $700,000. However, the number of pink bollworms found and moths trapped totaled less than 100. The natural population density of the pink bollworm is unknown, but for the first generation during the second year the number may not have exceeded 1 million.

If the sterile-male method had been perfected for pink bollworm eradication, as few as 100 million sterile-male moths might ha ' been adequate to eliminate the low level infestations during the second and subsequent years. If mass production of pink bollworms could be perfected at a cost of $1,000 per million which should eventually be possible the use of sterile males in such situations would have cost only $100,000. Not only would such cost be less than that of current methods, but it would obviate the need for high accumulative rates of insecticides in the treated area. The sterile-male method might make it more feasible and practical to eventually initiate a program to eradicate the pink bollworm from the United States by using both chemical and cultural methods to reduce the populations to levels that can be managed with sterile males.

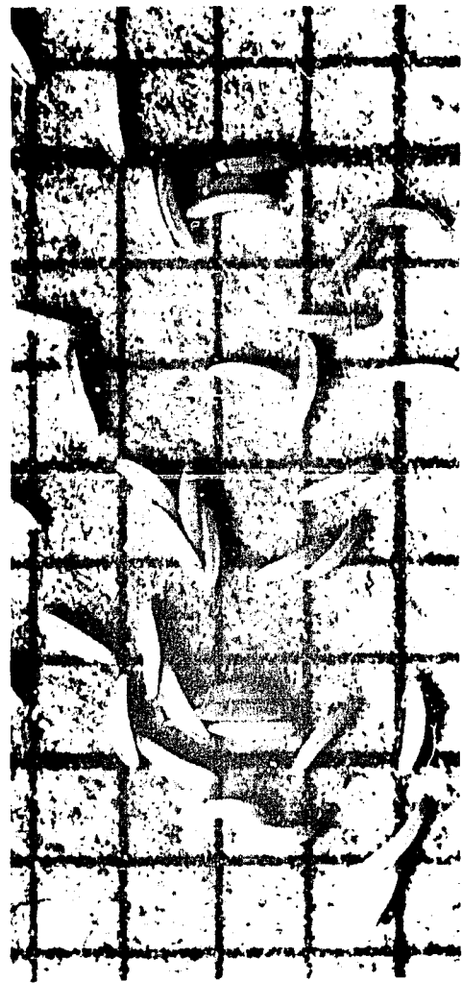
3. A recent **Mediterranean fruit fly** introduction in Florida was discovered when the natural population probably did not exceed 1 million. A total of 64 adults were caught in traps. Again, it is not possible on the basis of current knowledge to translate such trap collection figures in terms of total population in the area. However, the estimate of 1 million is probably conservative. If the sterile-male method were fully perfected, it is possible that the infestation could have been eradicated by releasing several hundred million flies over a period of a year or so. The bait spray treatment now used was applied on about 80,000 acres over 700,000 accumulative acre applications. The total cost was about $800,000. Mediterranean fruit flies could no doubt be

produced at a cost of about $200 per million. Even if 1 billion sterile flies would have been required, the estimated cost of $200,000 for sterile flies would be substantially less than the current bait spray method.

4. The **Japanese beetle** poses a difficult problem of eradication when infestations are discovered in new areas, even though the total acreage affected and the number of beetles present generally are small.

No research has been undertaken on ways to induce sterility in Japanese beetles, and mass production methods for the insect have not been developed or investigated. New beetle infestations, however, are often detected when the number of insects does not exceed more than a few thousand. If rearing costs could be developed at a figure of $10,000 per million a cost figure which probably could be readily achieved 1 million sterile Japanese beetles might suffice over a period of a few years to eliminate many small initial infestations that would cost much more to eliminate with insecticides. Moreover, the undesirable side effects of current eradication procedures could be avoided. Liberating adult Japanese beetles might pose some threat to certain crops, but the number required might be below the level that would cause significant crop damage. When new infestations cover rather large areas, such as the current one in Michigan, the use of insecticides in the more heavily infested areas and the use of sterile-male beetles in fringe areas might substantially reduce the area requiring insecticide treatment. Also, following the use of insecticides, low-level populations may survive. These are difficult to deal with and may require extensive surveys and followup treatments with insecticides. The release of a few million sterile males in such areas could mean the difference between success and failure.

5. Sugarcane growers in Louisiana annually spend about $1 million to control the **sugarcane borer.** Under normal circumstances the population density of the insect in the spring is probably too high to use sterile insects alone for control or eradication. During 1962 63, however, cold weather reduced the population to about 50 larvae per acre. If satisfactory methods of inducing sterility could be achieved, and if rearing methods could be developed at a cost of about $1,000 per million, the sterile-insect method of control might be set



up under similar circumstances at an overall cost less than that generally required for insecticidal control. Once virtual elimination is achieved, continued release of sterile males at very low levels each year might prevent reestablishment of damaging populations. The 1963 spring population of moths in the 300,000 acres of sugarcane in Louisiana probably did not exceed 25 per acre, or 7½ million moths. If 100 million sterile moths were required for each of three generations, it would be necessary to produce and release 300 million moths the first year. This number of insects may seem large, but at an estimated production cost of $1,000 per million, the cost of producing the insects would be $300,000. The cost of insecticides for the control of sugarcane borers amounts to about $4.50 per acre per year or about $1,350,000 for 300,000 acres.

6. Insecticide sprays are highly efficient for the destruction of **gypsy moths.** In actual eradication efforts against isolated infestations, it is common to find a very light infestation surviving either in

the treated area or just outside of the treated area. The number of moths responsible for the continuing infestation may not exceed more than a few thousand. Yet, it may be necessary to treat thousands of acres the second year to complete eradication. If moth rearing and ways of providing sterility could be perfected, sterile males should prove useful for final eradication and perhaps for fringe-infested areas and buffer areas with substantial reduction in the acreage requiring treatment with insecticides. It would seem reasonable to estimate a cost of $10,000 for the rearing and release of 1 million sterile-male gypsy moths.

An eradication effort now underway in New Jersey is an example where the sterile-male method might have been useful. According to discussions with the Plant Pest Control Division, ARS, the infestation of gypsy moths currently present in New Jersey may require spray treatments on about 70,000 acres at a cost of over $100,000.

Trapping and egg mass surveys have yielded less than 100 moths and egg masses. Again, it is not possible on the basis of current knowledge to translate survey records into natural population density estimates. However, if we assumed that the total moth population in the area would not exceed 10,000 (5,000 males and 5,000 females) and if the release of 1 million sterile males each year for several years would assure the elimination of such light infestation in the 70,000-acre area, the cost would be substantially less than the insecticide treatment. Moreover, the sterile-male method would also avoid the objections that arise from insecticidal application.

If the 10,000 estimate for the natural population density is reasonably valid, the release of 1 million male moths would constitute an initial ratio of 200 sterile males to 1 fertile male. Such ratio of reasonably competitive sterile moths should substantially reduce the infestation the first year. If releases were continued for 1 or 2 years, the moths should be eradicated. Entomologists with the Forest Service are conducting investigations on the sterility method for gypsy moth eradication. The eradication problems posed by this insect would seem to fully justify a major research effort to explore the feasibility of using sterile males in future situations such as that in New Jersey.

Other examples could be cited where the sterile-male method could prove advantageous over current methods of control or eradication, or where it could provide an important supplementary method. The insect problems cited are realistic. But the feasibility of using sterile insects to meet them is still speculative. Nevertheless, there is good reason to believe that the principle of using sterile insects could be developed if research were adequately supported.

It is obvious that extensive and costly research will be required to develop the sterile-male release method for each insect where the method may be practical alone or integrated with existing control methods. However, in view of the growing concern over the potential adverse effects of some of the current methods of meeting many of our major insect problems and the continuing economic loss caused by many of our major pests, there is every justification for enough research support to fully appraise the feasibility and merits of the sterility method for all of the major insect pests where there is any indication that success could be achieved.

BASIC PRINCIPLES IN USE OF CHEMOSTERILANTS

THE production of sexual sterility in both sexes of an insect or other animal population by any method which does not adversely affect sexual behavior and mating competitiveness of the males and perhaps to a lesser extent females will exert greater effect in reducing the biotic potential of the population than can be achieved by killing or removing a like number of individuals of the population. This is a biological principle advanced by the writer in 1959. It should have great possibilities for meeting pest control or eradication problems. Research, however, has not yet advanced to a stage that it can be applied in practical operations.

But we are making progress. As the result of USDA research, several chemicals are now available which will induce complete and irreversible sterility in both males and females of a wide variety of insect species. For most insects, sterility can be achieved without serious adverse effects on the length of life and sexual vigor of the males. Chemicals that produce sterility in both sexes of insects are known as alkylating agents; they belong to the ethylene amine group.

If we can develop practical and safe ways to achieve sterility in insects as readily and as efficiently

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TABLE 2.—THEORETICAL EFFECT ON REPRODUCTION OF INSECT POPULATIONS SUBJECTED TO 3 TREATMENTS

Generation	No control (fivefold increase)	Control by killing (90 percent kill each generation)	Control by inducing sterility (90 percent sterility in both sexes each generation)
	Number	*Number*	*Number*
Parent	1,000	1,000	1,000
F_1	5,000	500	50
F_2	25,000	250	0
F_3	125,000	125	

as we can control them with insecticides, the impact on the reproductive potential of the population would be much greater than that produced by insecticides. The same relative effect should be possible for controlling or regulating vertebrate pests.

Theoretical Aspects

TABLE 2 shows the theoretical trend in a hypothetical insect population subjected to (1) no control, (2) control by killing, and (3) control by inducing sterility. We can assume, as for table 1, that the normal population in the absence of control efforts would increase fivefold each generation. Surviving insects not killed and those that mate successfully as fertile pairs would also result in a fivefold increase in population. We can further assume that the males sterilized are fully competitive with normal males in mating.

On the basis of the model, theoretical elimination would be achieved by treating two generations with a chemosterilant if 90 percent sterility of the population was achieved each generation. On the other hand, it would be necessary to treat at least eight generations to achieve theoretical elimination by applying insecticides, which would kill 90 percent of the insects each generation.

If a parent population of 1,000 insects were treated with a chemosterilant that produced sterility in 90 percent of the population, 900 of the insects could not reproduce by virtue of the direct effect of the sterility agent. This would be equivalent to killing, so far as reproduction is concerned. However, if the sterility does not adversely affect competitiveness of the males, each sterile male would have the same opportunity as a normal male to mate with the normal females. Since the sterile males, theoretically, outnumber the fertile males by ninefold, chance would provide for only 10 fertile matings. In the population treated with an insecticide, 900 would be killed but the remaining 100 could all mate successfully. Thus, the sterility method, theoretically, provides a bonus effect equivalent to the initial effect of the killing agent.

The relative degree of effect of a sterility agent versus a killing agent in population control depends on the level of kill or sterility achieved. In terms of the number reproducing successfully, a 50-percent sterility level is theoretically two times as effective as a 50-percent kill level. A 75-percent sterility level is four times as effective as a 75-percent kill level. A 90-percent sterility level is 10 times as effective as a 90-percent kill level. A 99-percent sterility level is 100 times as effective as a 99-percent kill level.

The bonus effect referred to is not the only potential advantage of the sterility method over the killing system. In comparing the two systems of popula-

tion control, we might say that the sterility principle has a four-dimensional effect, whereas the killing principle has only a single-dimensional effect.

When individuals in an animal population are killed, the only effect on the population is the elimination of those actually destroyed. When animals are sexually sterilized, without adversely affecting sexual competitiveness, the following effects are possible: (1) Those sterilized cannot reproduce—an effect equivalent to killing. (2) Sterile organisms compete with the fertile organisms and further reduce the reproductive potential of the population. This is the bonus effect already referred to. (3) The sterility method has a potential time effect.

In the model shown is table 2, the assumption is made that there are no carryover effects from one generation to the next with either the sterility agent or the killing agent. However, for insects or animals which live for long periods and overlap generations, the *time* effect is a *disadvantage* in population control when the killing system is employed, but is an *advantage* when the sterility system is employed.

In table 2, for example, if we assumed that one-half the parent population not killed survived and reproduced along with the F_1 progeny and if this happened each generation, the decline in the population would not be as great as indicated. On the other hand, for the population subjected to the chemosterilant treatment, if half of both the sterile insects and the fertile insects survived and overlap the subsequent generations, the effect on reproduction would be greater each generation by virtue of the survival of the sterile insects of the preceding parent population.

The *time* effect, theoretically, would be of major significance among vertebrate pests, which may survive for a number of years. For long-lived vertebrate pests, a 95-percent sterility level achieved only in a parent generation could theoretically result in complete elimination of the entire population in about 9 years. This is based on the assumption that one-half of the original population survived each year, and the normal successful reproduction rate for all reproducing pairs amounted to 2 reproducing progeny. In contrast, for a population subjected to a 95-percent kill, the population would theoretically return to the original level in about 9 years.

The fourth effect resulting from the sterility procedure is a *space* effect. In other words, animals made sterile have the ability to move and affect the reproductive capacity of the population throughout the range of dispersal. This could be a factor of vital importance for controlling both invertebrate and vertebrate pests.

Status of Research on Chemosterilants

A NUMBER of promising chemicals will produce sterility in insects. Original selections of materials for evaluation were made from compounds known to possess antitumor activity in animals. The Division's Pesticide Chemicals Research Branch, which has synthesized a number of other chemicals, is cooperating closely with the National Institutes of Health in the procurement of candidate chemosterilants. Those that are among the most effective are also among the chemicals that are promising as anticancer agents. Thus, the research on insect

sterilants and antitumor agents may be mutually complementary.

Little is known about the toxicological effects of the more promising chemisterilants. They are regarded as mutagenic in action and are also regarded as highly toxic to man and animals. Consequently, most of the research to date has been limited to laboratory investigations.

Laboratory experiments conducted by the Orlando laboratory with house flies in cages have, in general, supported the hypothetical effects of chemosterilants on insect population trends as depicted in table 2. Also, tests on small islands in Florida and around a Florida poultry farm have shown that fly populations can be effectively controlled with fly baits containing chemosterilants. Thus, the principle of insect control by this means has been established. However, in view of the lack of information on the hazards of chemosterilants to other organisms, every effort will be made to develop specific ways of exposing chemosterilants to insects in the natural environment.

Progress in the identification and synthesis of sex attractants that occur naturally in insects may be of vital importance in the potential use of chemosterilants. A high percentage of the males in an insect population may be attracted to highly active and specific sex attractants derived from females of the species. Perhaps it will be feasible in some cases to use the living virgin females of the species to lure males to a trap or to the female insect itself so that the males can be sterilized on contact with a chemosterilant. Success in controlling an insect by killing males may be very difficult, because the males of most or perhaps all insects are polygamous and a high percentage of kill may be required to achieve a high degree of reduction in reproduction. The sterilization of a high level of males could have a direct and proportionate effect on the reproductive potential of the females in the population.

The possibilities of using the natural population of pests for their own destruction through chemosterilants or other means cannot be fully appraised on the basis of current knowledge. But the practical development of this principle of pest control offers real opportunities for scientists of the future.

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Goals For Pesticide Research

IN order to develop safer, more specific controls of pests, it is recommended that Government-sponsored programs continue to shift their emphasis from research on broad spectrum chemicals to provide more support for research on: (*a*) Selectively toxic chemicals, (*b*) nonpersistent chemicals, (*c*) selective methods of application, and (*d*) nonchemical control methods such as the use of attractants and the prevention of reproduction.

In the past few years, the Department of Agriculture has shifted its programs toward these specific controls. The Panel believes this trend should be continued and strengthened. Production of safer, more specific and less persistant pesticide chemicals is not an unreasonable goal; but its attainment will require extending research efforts beyond empirical approaches to more fundamental studies of subjects such as: The mode of action of pesticides; comparative toxicology; the metabolism of compounds in insects, plants, and higher animals; and the processes of chemical degradation and inactivation in nature. Such studies will also provide the information necessary to control those pests which are rapidly becoming resistant to currently available chemicals.

Only by stimulating training and basic investigation in the fields of toxicology and ecology are research needs likely to be met. An increased output of basic research data and a continuing supply of capable research personnel could be insured by a system of grants and contracts. Training grants, basic research grants, and contracts to universities and other nongovernmental research agencies funded by the Departments of Agriculture, Interior, and Health, Education, and Welfare would stimulate this research. In order to accelerate immediate progress, it might prove useful to explore the contributions which can be made by competent research people and their facilities in other countries.

From "The Use of Pesticides," a report from the President's Science Advisory Committee. May 1963. Washington, D.C.