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ABSTRACT

A simultaneous equation model of the behavior of a mosquito abatement district based on biological and economic data is presented. Results indicate high long term costs if heavy reliance on chemical pesticide control methods continues, due to a pesticide resistance buildup in the mosquito populations. Physical source reduction methods were shown to be more efficient both in the short and long run. A linear programming model is presented which optimizes the mix of chemical and physical control methods. Results indicate increasing costs of mosquito abatement as pesticide effectiveness declines. Simulation results of narrow spectrum pesticide manufacturing firms indicate negative returns to research, development and marketing for most firms even with significant subsidies.

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SUMMARY AND CONCLUSIONS

The purpose of this study is twofold: (1) To examine the responsiveness of the population levels of four mosquito species, *Aedes nigromaculis*, *Culex tarsalis*, *Culex pipiens quinquefasciatus*, and *Anopheles freeborni*, to various control methods and environmental factors and (2) to examine the chemical industry's past investment in narrow-spectrum pesticides (e.g., minor-use pesticides for mosquito control) and to explore the impact of public regulations on the industry's investment decisions regarding these pesticides. In this analysis, the primary focus is on the direct costs of pesticides and other methods used in abatement activities. Although the externalities involved are acknowledged to be important to the problems encountered in this study, they are clearly beyond the scope of this research.

A. Summary of Principal Findings

1. *The mosquito abatement relationships:* The data base includes abatement relationships for the period from 1955 to 1975 in the San Joaquin Valley in Delta Vector Control District and Kern Mosquito Abatement District and in the Sacramento Valley in the Butte Mosquito Abatement District. Only Kern district is discussed in detail here. Two types of simultaneous equation models, a monthly-data model and an annual-data model, were developed and estimated. The empirical estimates thus obtained outline the effects of environmental and control factors on mosquito populations and provide a description of the control district's past behavior and decision-making processes. If the district's behavior is assumed to be consistent over time, the models can also be used to predict the

effect of future actions. Simultaneous equation models provide a positive economic analysis.

A linear programming (LP) model also developed for the Kern district involved using coefficients from the simultaneous equation model and additional data from the district's reports. The LP model provided a normative approach to the problem, i.e., what ought to be considered an optimal cost minimization economic solution for mosquito control. The LP model also provided information on the value of having an effective chemical pesticide for mosquito control - that is, simulated market signals to the chemical industry.

a. The regression models. The important findings are as follows:

(1) The monthly-data models are more reliable than the annual-data models in estimating the effect of environmental factors and previous mosquito population levels on the average current population as measured by the number of mosquitoes captured per light-trap night.

(2) Both the annual and monthly models showed that the mosquito control districts in California are not environmentally homogeneous and that the effects of the variables differ from one mosquito species to another within a district and within the same species between districts. Therefore, it is not reasonable to make general statements for a vast geographical area regarding control of mosquitoes or their responsiveness to the environment.

(3) Pesticide treatments of spot locations were generally more effective in reducing the average number of mosquitoes than was broad spraying of large areas.

(4) Source reduction activities generally reduced mosquito population levels.

(5) High temperature, rain, and high river levels were important factors in increasing the number of mosquitoes.

(6) The pesticide effectiveness index (or resistance of mosquitoes to pesticides) is an important factor in the long-run indirect effect of pesticide control measures.

(7) Past exposure to pesticides was directly correlated with higher resistance to pesticides in mosquitoes (lower pesticide effectiveness).

(8) Source reduction activities were associated with lowered resistance of mosquitoes to pesticides.

(9) In Kern control methods for A. nigromaculis ranked in order of efficiency are: (1) ditch construction, (2) construction of fills, levees, etc., and (3) locations treated with pesticides. The cost of a 1 percent reduction in A. nigromaculis numbers is 4.85 times higher for spot spraying than for constructing ditches, and 1.04 times higher than for constructing fills, levees, etc. In 1975-76 cost conditions the rank remains the same and the cost of a one percent reduction in average numbers A. nigromaculis would be 6.05 times higher for spot spraying than for constructing ditches, and 1.46 times higher than for constructing fills, levees, etc. For C. tarsalis efficiency rankings are:

(1) ditch construction, (2) locations treated with pesticides, (3) construction of sumps, ponds, etc., and (4) construction of fills, levees, etc. The cost of a 1 percent reduction in the average number of C. tarsalis mosquitoes by construction of fills, levees, etc., is 18.02 times higher than that for constructing ditches, 7.72 times higher than for treating locations with pesticides and 1.53 times higher than for construction of sumps, ponds, etc.

b. The linear programming model. The principal findings are:

(1) The optimal mosquito control plans for three standards dictating the maximum acceptable number of A. nigromaculis and C. tarsalis mosquitoes indicate that source reduction activities can be substituted for pesticide control measures.

(2) The total number of hours of labor involved in control activities, and hence the costs, increase in inverse proportion to the number of A. nigromaculis and C. tarsalis mosquitoes defined as being acceptable.

(3) As the effectiveness of pesticides decreases, more source reduction activities must be operated in order to keep A. nigromaculis and C. tarsalis mosquito population levels at or below the specified acceptable standard.

(4) When high river flow (i.e., 2.5 times higher than the average) is present, more source reduction is allowed, and pesticide effectiveness declines from 100 to between 75 percent and 50 percent, labor hours and costs must be increased drastically in order to keep the number of mosquitoes at or below the

level defined as acceptable. When pesticide effectiveness is 25 percent or below, no feasible control plan has been developed that can operate within specified restraints and resources. Also, as river flow increased, the preferable method of pesticide usage is spraying large areas rather than treating spot locations.

2. The chemical industry's investment in pesticides: A computer simulation model was developed to examine the effect of various regulations, patent-right periods, subsidies and interest rates on the chemical firm's investment decisions under risk and uncertainty. The important findings are:

(1) Complying with government regulations has lengthened the time and thus the production costs for all sizes of firms from discovery of a pesticide to marketing date.

(2) The market for narrow-spectrum mosquito pesticides is so limited that only the smallest firms are likely to be willing to produce them without substantial subsidies.

(3) Even with three hypothetical subsidy levels, investment in narrow-spectrum pesticides is generally unprofitable for firms of any size under present regulations, patent-right periods, and 6 or 8 percent discount rates. The few exceptions to this conclusion are in the cases of small firms under less stringent government regulation (i.e., conditions in or prior to 1967) which have a 6 percent discount rate, the highest subsidy level (i.e., $4,013,518, or $2,829,129 when discounted) and both 17-year and 20-year patent

rights; and for large firms under the same conditions as above but with only 20-year patent rights.

B. Inferences and Recommendations

1. The findings of the abatement models lead us to infer that even though pesticides can generally reduce mosquito population levels, their use has been overemphasized. Although source reduction activities are generally more economically efficient in controlling mosquitoes, the effect of these activities has been underestimated and they have not been efficiently substituted for chemical control. We therefore recommend that pesticides be de-emphasized by mosquito control districts and various source reduction activities be substituted for them as appropriate. However, in such emergency situations as epidemics, pesticides must still be used in order to reduce mosquito population levels immediately.

2. Study results also show that the continued use of pesticides has led to heightened resistance to chemicals among the mosquito species treated. Moreover in the past, replacement pesticides were more readily available than they are at the present time or will be in the future. We therefore again stress the recommendation that the use of pesticides be de-emphasized in favor of source reduction activities whenever possible.

3. Among other benefits, such a measure should help to preserve the effectiveness of pesticides by reducing the amount of selection pressure on mosquitoes.

The regression models did not consider the value of an effective and immediate control method in case of crisis, but the LP model showed that spraying is necessary in the case of high river flows. Therefore, although there is no single solution to this question, it appears that an effective pesticide should be available at all times.

4. Data from the National Agricultural Chemical Association and the results of the simulation model for three sizes of chemical firms showed that the cost and time required for discovery, R&D and registration of pesticides have increased with the addition and enforcement of government regulations. Because costs associated with producing and marketing broad- and narrow-spectrum pesticides are the same the potential market is much smaller for the latter, conditions do not favor their unsubsidized production. However, the model did not indicate economic grounds for the State of California alone to subsidize the industry's production of pesticides to be used only for mosquito control. Limited data and time constraints did not allow us to investigate the feasibility of a subsidy by out-of-state users of pesticides which were developed for California use.

INTRODUCTION AND OBJECTIVES

The Problem

The world, in general, and the United States, in particular, have become increasingly concerned about pollution of the environment. One area of major concern focuses on pesticides, primarily those persistent pesticides that circulate through and accumulate in certain parts of the environment. Pesticides, and the benefits and costs associated with their usage, have therefore been a controversial topic for more than a decade.

In addition, since the early 1950's mosquito control agencies in California have noted that mosquitoes were becoming increasingly resistant to traditional pesticides [Gillies et al. 1973]. This biological situation has forced control districts to use new and often more expensive chemicals or to shift to nonchemical control methods, which are aimed at creating conditions unfavorable to mosquito production by altering their environment, thereby reducing their potential abundance and spread of the insects. However, nonchemical methods are geared for long term rather than immediate effects, they do not provide sufficiently prompt results for use in the event of emergency situations. Many mosquito control agencies therefore argue that development of new, effective chemicals is a necessity for adequate control, especially in the case of malaria or encephalitis epidemics.

Although nonchemical control methods were not widely used by mosquito abatement agencies in the past, integrated control[1/] programs have been suggested and used by many districts in recent years. Many abatement district managers and entomologists argue that pesticides used in such programs should be toxic to only mosquitoes and that they must not cause important damage to the environment. If such pesticides were used only for mosquito control, they might remain effective for long periods. In the past, however, many broad-spectrum pesticides were widely used for both mosquito control and agricultural pest control, with the result that mosquitoes developed resistance to pesticides. Thus, the broad-spectrum pesticides were not effective as long as might be desired.

Under today's regulatory conditions, chemical firms must invest large sums of money to develop new compounds before the first dollar is received from sales. In addition to ever-rising costs of research and development for new, effective pesticides, registration[2/] costs have rapidly increased [Ernst and Ernst 1971, 1973; Little 1975]. In the past, registration of a new pesticide hinged on its efficacy and safety, with contamination of food stuffs and danger to workers having contact

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1/ Integrated control is used here to mean that biological, chemical and physical techniques for controlling pests are coordinated or "integrated," and are used simultaneously in such a way that each method is compatible with the other [Mulhern 1973].

2/ The registration of pesticides begins when the manufacturer submits a request to the regulatory agencies (e.g., EPA) to produce a certain pesticide. Manufacturers are required to submit detailed biological, toxicological and ecological data in order to obtain permission for final development and sale, and this registration stage of production takes several years to complete [Lever and Strong 1973; Little 1975].

with the product being major concerns. Recent legislation requires manufacturers to supply technical data on the environmental impact of all pesticides [Djerassi, Shih-Coleman and Diekman 1974; Hunter 1973]. Because of the large investment required, a firm must be assured of a substantial market potential for a new chemical before attempting to produce it [Fitzsimmons 1972].

While costs to the pesticide producer escalate, public health, abatement district and other officials insist that new and effective materials to replace those of waning usefulness should be forthcoming and available to the mosquito control agencies. These officials argue that without immediate effective control, major events such as floods or earthquakes could cause mosquito densities to greatly increase. Such situations may very well result in epidemics, substantial losses in livestock production, and continuous public complaints of annoyance caused by mosquitoes. However, economic incentives for chemical companies to produce pesticides in general, and narrow-spectrum[3/] insecticides in particular, have been reduced to the point where those products, which might be urgently needed to meet short-run emergency situations, may no longer be forthcoming. For this reason, the U.S. Congress, the chemical firms and their customers, and particularly, the California abatement agencies, have shown an interest in the possibility of public subsidy of the research development and registration costs for minor-use insecticides [Brady 1972; Djerassi, Shih-Coleman and Diekman 1974; Fitzsimmons 1972].

[3/] "Narrow-spectrum" insecticides, by definition in contrast to "broad-spectrum," are less harmful to nontarget species and organisms. The latter are more profitable to a firm, however, since they have a larger potential market. The former may become unavailable because of their small potential markets, even though they may provide benefits to society which are not reflected in their market value.

Objectives

The overall objectives were to: (1) Examine the responsiveness of the population levels of the predominant California mosquito species to alternative abatement methods and environmental factors and (2) examine the profit potential of narrow-spectrum pesticides for a chemical company and analyze the impact of public regulations on chemical industry investment decisions. The following procedures were involved in the study:

1. To collect and summarize information regarding mosquitoes and abatement operations in California.
2. To identify and estimate the physical and biological mosquito abatement relationships, including factors which influence the effectiveness of pesticides.
3. To use an economic efficiency criterion to determine whether the control agencies were making optimal resource allocation decisions among alternative control methods.
4. To examine the chemical industry's investment in pesticides during the past two decades and the impact of public regulations on the industry's investment decisions.
5. To develop a model for the chemical industry's investment in pesticides. To provide information on the industry's future investment situation and to determine the potential profit for firms investing in pesticides - particularly in narrow-spectrum pesticides.

METHODS AND PROBLEMS OF MOSQUITO CONTROL IN CALIFORNIA

Economic and Social Significance of Mosquitoes

Although there are many species of mosquitoes in California, Culex tarsalis, Culex pipiens quinquefasciatus, Anopheles freeborni and

Aedes nigromaculis are of particular concern to this research. Culex tarsalis is the most important vector (carrier) of encephalitis in California. Aedes nigromaculis, "the irrigated pasture mosquito," may adversely affect livestock production and is a nuisance to humans and other animals. Culex pipiens quinquefasciatus, "the southern house mosquito," attacks man, invades homes, and is considered a great nuisance. It also is a vector of St. Louis encephalitis virus in some parts of its range. Anopheles freeborni, the "western malaria mosquito," an efficient malaria vector and nuisance, poses a continual threat of malaria epidemics in parts of California.

(1) Economic losses in the agricultural sector. Three decades ago agricultural losses in California were attributed to mosquitoes as a result of the reduced weight gain of meat animals and reduced milk production of dairy cows. In spite of early recognition of the problem, there has been no economic evaluation of the full impact of mosquitoes on beef cattle or dairy and poultry production in California. The primary reason for this is the difficulty involved in obtaining basic data showing quantitative cause-and-effect relationships.

A few studies have been conducted elsewhere. Hoffman and McDuffie, [1963], estimated that cattle producers lost $231,250 due to mosquitoes during the midpoint of the 1962 mosquito season in Cameron Parish, Louisiana. Sanders, Rieme and McNeil [1968] reported that Texas Gulf Coast cattlemen who attempted summer grazing observed a reduced feed intake by their cattle as a result of the continuous irritation and blood losses from mosquito attacks. Deaths caused by suffocation from inhalation of mosquitoes were also reported in both young and weak cattle. Steelman, White and Schilling

[1972, 1973] determined that mosquitoes had a substantial effect on the average daily weight gain of steers fed various energy rations in Southern Louisiana. However, this study was carried out under controlled indoor conditions [MacClelland 1975].

Husbands [1973], suggested that the agricultural losses can vary and include:

"(1) Weight losses by beef cattle
(2) Reduced survival in calves (abortion)
(3) Reduced milk production
(4) Reduced poultry production (survival, weight, eggs)
(5) Reduced efficiency of farm employees
(6) Economic losses through:
    a. Taxes needed for mosquito control
    b. Reduced land values
    c. Indirect losses in tax monies resulting from community losses due to sick leave, etc.
    d. Losses due to fees charged for veterinarian services
(7) Recreational and aesthetic values lost in rural areas."

Another item can be added to this list: the difficulty which farmers may encounter in hiring workers in areas with high mosquito infestation. Crop losses can occur due to the inability to handle perishable crops at the proper time. This was a difficulty faced by peach growers in Sutter and Yuba counties before the formation of a mosquito abatement district in 1946.

(2) Mosquitoborne diseases in California. Although the effect of mosquitoes on public health is generally thought of in terms of transmission of disease agents, such as viruses, protozoa, and helminths, there are also indirect health effects caused by annoyance as well as impacts on economic and food production losses. The causative agents of malaria, yellow fever, dengue fever, encephalitis and filariasis are transmitted by mosquito bites. Western equine (WEE) and St. Louis encephalitis (SLE) and malaria threaten the human population in California, and WEE may significantly affect the state's horse population.

In California, excessive rainfall and snowpack in the Sierra Nevada mountains may result in extensive flooding in the Central Valley of California [Sudia et al. 1969], thereby creating conditions favorable to a rapid increase in *C. tarsalis* populations. Reeves [1968] reported a positive correlation between excess river flow, high *C. tarsalis* populations, and increased risk of encephalitis virus transmission to people and horses in Kern County.

WEE and SLE have been endemic in California at least since 1933 and are occasionally epidemic. Approximately 800 human cases were reported in California during the 1952 epidemic. Human cases range in severity from those with inapparent infections to serious illness resulting in stupor or coma, and severe fulminating illness and death in 24 to 48 hours.

Malaria is a major cause of death worldwide. In California, *A. freeborni* and *A. punctipennis* can transmit the disease [Mulhern 1973], which was introduced into the state in the early 1800's. A major epidemic occurred in the Central Valley in 1883 and minor local epidemics occurred near Lodi in 1934-1935 and near Winters in 1938 [Brady 1972]. Bailey [1972] reported a great increase in the number of recorded cases of malaria during the 1950's and 1960's, due largely to imported cases among veterans from Korea and Vietnam. These cases were scattered throughout the state, but the majority occurred in metropolitan areas or locations lacking mosquito species which could carry malaria. Bailey therefore concluded that the potential for a major malaria epidemic in California is not great.

Although human malaria is no longer endemic in California, imported cases occasionally serve as a source for localized outbreaks, as evidenced by the recent ones in Butte, Yuba and Sutter counties [Enterprise, 1974]. In 1974 and 1975 malaria outbreaks were documented in these counties (11 and 19 cases, respectively).

It is evident that a demand for relief from annoyance caused by mosquitoes does exist. Murray's records [Murray 1972], kept since 1948, show a correlation between the number of complaints regarding _A. nigromaculis,_ "the pasture mosquito," and the number of female mosquitoes (only females bite). Reeves [1965] submitted that the health of the population studied was adversely affected by the presence of mosquitoes.

The above discussion of the social significance of mosquitoes clearly illustrates the negative effects of mosquitoes on the health and welfare of human and domestic animals.

Due in large part to the activities of mosquito abatement districts, mosquito population levels have been kept low and there has not been a large outbreak of mosquitoborne disease in California for the last several years. However, Hardy and Reves [1973], Reeves [1965, 1970] and Sudia et al. [1971], among others, believe that there is a continuing threat of an encephalitis epidemic in California. This is particularly true in the Central Valley, which provides habitats favoring the development of large populations of mosquitoes and avian hosts for the viruses.

It should also be emphasized that the small probability of a malaria epidemic in California is a valid assumption only in the context of the present situation. An epidemic could occur in the wake of a disaster, such as an earthquake, flood, or any other major disturbance which would expose the human population to large numbers of _Anopheles_ mosquito bites, and reduced medical surveillance.

Ecology of Mosquito Species Under Consideration

Several environmental variables have a direct effect on the growth, life cycle and abundance of mosquitoes. The most important are temperature, humidity, water[4/], topography[5/], food supply and shelter. Each variable may have a different effect on different species.

Excess water increases the likelihood of survival of immature mosquitoes being associated with a decreased density of predators, an increased availability of food, and less effective action of mosquito abatement districts [Moon 1975]. The food supply of larvae affects their mortality rate and also the size of the adults. Topography, irrigation water and shelter greatly affect both the growth of mosquitoes and the effectiveness of mosquito abatement.

All mosquitoes develop in four stages: egg, larva, pupa and adult. However, the biology of different mosquito species varies and individual species must be considered when discussing their control.

Methods of Mosquito Control

Mosquito abatement programs are aimed at reducing known breeding sources and killing mosquitoes. Control methods can be classified into two main categories: (1) Short-term control methods (primarily chemical) and (2) long-term control methods (primarily nonchemical). For the past quarter century, mosquito control agencies of California emphasized

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[4/] Meaning the amount of water; particularly excess flooding and standing water.

[5/] Topography, i.e., the smoothness or unevenness of the fields or areas, can range from deep, to numerous undulations, to no undulations. When these undulations are deeper and more numerous, the mosquito potential is greater [Davis 1961].

chemical control of mosquitoes far more heavily than nonchemical methods. However, nonchemical methods have been used more frequently in recent years.

Short-term control: Short-term control of mosquito populations primarily involves the use of chemicals in liquid, dust, or granular form applied from the air or ground depending on topography and other conditions. Chemicals usually are used as larvicides or adulticides.[6/] Chlorinated hydrocarbons, organophosphorus, and carbamate compounds have been used extensively in California both in agriculture and for public health purposes.

In recent years a new class of chemicals acting as insect growth regulators has been developed. These are chemical analogues of hormones, and other chemicals which mimic hormonal action. When a growth regulator which mimics the effect of the juvenile hormone[7/] is applied during an insect's tissue maturation when endogenous juvenile hormones are low, lethal deformities result [Bradleigh and Plapp 1974].

Although chemicals provide only temporary control, they are useful in both rural and urban areas when immediate results are necessary. Short-term control may be warranted in the suppression of mosquitoes during epidemics, the treatment of flooded areas, or in answering frequent

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[6/] Larvicides are chemicals applied primarily to kill larvae and/or pupae and can be synthetic insecticides or oil larvicides. Adulticides are chemicals applied to kill the adults.

[7/] The juvenile hormone is one of three primary hormones necessary for an insect's growth and development. The other two are the brain hormone and the molting hormone [Bradleigh and Plapp 1974].

complaints of annoyance. Chemical control is also used to treat mosquito breeding sites in agricultural or urban areas where occurrence is so infrequent that other methods of control are not justified [Mulhern, 1973].

Long-term control: Nonchemical methods of control generally alter the environment and reduce mosquito breeding sources. These methods are effective in the long run, but may not have as immediate an effect on mosquito population levels as do chemicals.

Nonchemical methods of control include:

(1) Biological control.
(2) Physical control (source reduction).
(3) Mechanical barriers, including bed nets and screening of buildings.

Recent studies concerning nonchemical methods of control in California are by Hoy and Reed [1970], Hoy, Kauffman and O'Berg [1971, 1972] and Murray [1972]. Although nonchemical control methods are essential for effective comprehensive mosquito control, they sometimes are not sufficiently effective to completely substitute for chemical control.

Georghiou [1965] summarizes the situation as follows: "However plausible the new methods (biological control) may be, and they undoubtedly are, they do not obviate the need for insecticides." Thus, even though pesticides may play a diminishing role in future pest control strategies, chemicals are likely to remain the primary tools and an important element of integrated control for some time [Brady 1972; Spiller 1968].

The Problem of Mosquito Resistance to Chemical Pesticides

The Central Valley and other parts of the state have become ideal mosquito breeding places because of complex agricultural enterprises and the continuously expanding acreage of irrigated land. In these areas there has been extensive use of insecticides for control of mosquito larvae and, to a lesser degree, adults. Because each generation may require treatment, 15 to 20 treatments a year may be necessary [Spiller 1968]. Such repeated exposure to insecticides applied for mosquito control and chemicals used to control crop pests has resulted in the biological selection of resistant strains [Kauffman, 1975]. Thus, several economically important mosquito species, including two of the most important species, _C. tarsalis_ and _A. nigromaculis_, have become resistant.[8]

Georghiou [1965, 1966] emphasized that the dynamics of resistance are very complex since they are influenced by many factors including population movement, history of selective pressure on the population, degree of dominance of each resistance factor, background environment, stages in life cycle of the insect exposed to the insecticide, and interaction among resistance mechanisms.

Womeldorf et al. [1972] summarized the history of the problem of mosquito resistance to organophosphorus pesticides as follows:

> "In California, DDT resistance in _Aedes nigromaculis_, the irrigated pasture mosquito, has been known since 1949. By the early 1950's resistance against DDT and other organochlorine compounds had become widespread in _A. nigromaculis_ and in the state's primary vector of St. Louis and western equine encephalitis, _Culex tarsalis_. The organophosphorus compounds were then substituted for the organochlorine materials.

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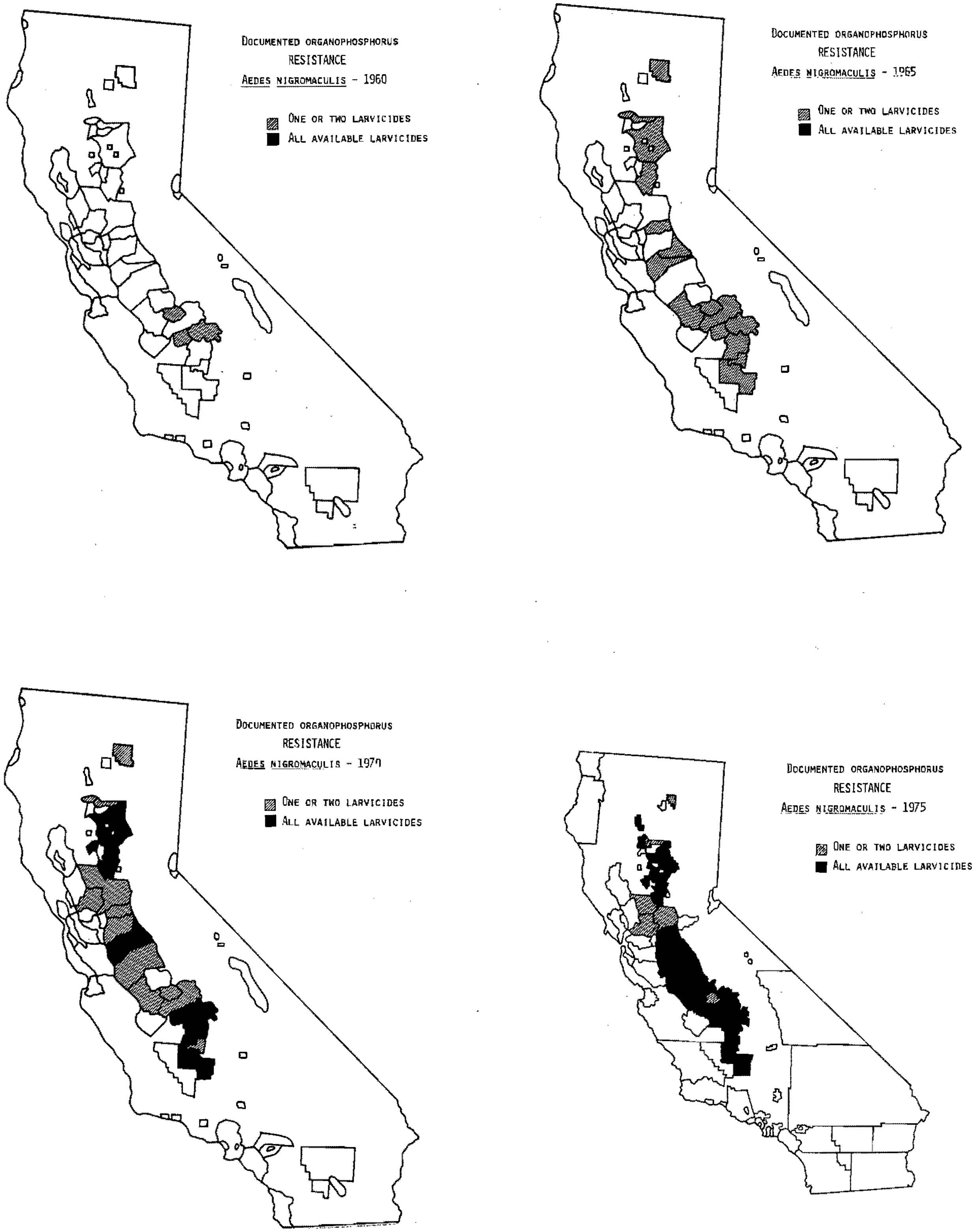
[8] Entomologists usually use the LD_{50} (the lethal dosage for 50 percent of the population) as an indicator for pesticide effectiveness. The LD_{50} is a measure of the degree of toxicity of a pesticide, measured in ppm (parts per million) in larvicide tests and percent concentration in adulticide tests, and is the amount of technical-grade material concentration required to kill 50 percent of the target pest. The higher the LD_{50} coefficient, the less toxic the chemical is to the organism.

> "Parathion resistance in A. nigromaculis was first documented in Kings County in 1958. Within the next few years, parathion and malathion resistance was found in many areas of the Central Valley and methyl parathion resistance also appeared. By 1970, parathion resistance had become commonplace, methyl parathion resistance was not far behind and resistance to fenthion and other organophosphorus compounds had been recorded in several areas of the state in adults as well as larvae. Additionally, problems in obtaining adult control with the carbamate propoxur had begun to develop.
>
> "Malathion resistance in Culex tarsalis was discovered in 1956 in Fresno County. Malathion resistance progressed through the Central Valley and is now common in other parts of the state as well. Resistance against all available organophosphorus larvicides became apparent in the San Joaquin Valley in 1969. Resistance against malathion or against all organophosporus larvicides is now widespread."

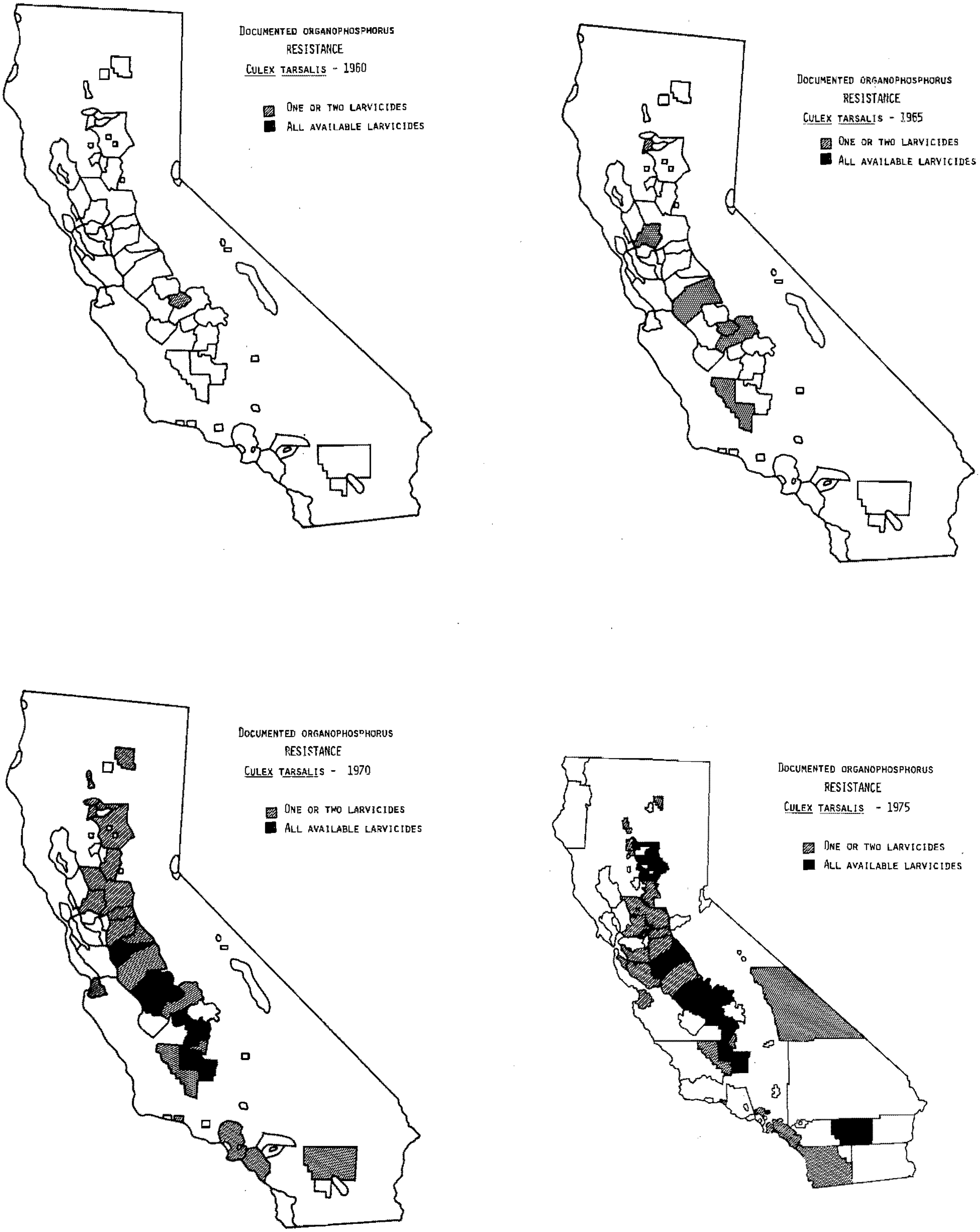
Figures 1 and 2 show the extent of the spread of organophosphorus resistance in A. nigromaculis and C. tarsalis in California, through 1973 [Gillies et al. 1973]. (Inclusion of an agency does not necessarily mean that every mosquito population in it is resistant, but rather that some populations are.) Figure 3 shows the usage patterns of four organophosphorus insecticides for mosquito control in California from 1955-1971. Instances of organophosphorus resistance in important mosquito species in California are summarized in Table 1. Figure 4 shows the usage and replacement of one class of chemical compounds by another.

Figure 1: Documented organophosphorus resistance in Aedes nirgromaculis, California, 1960-1975.



Source: (Gillies, *et al.*, 1976).

Figure 2: Documented organophosphorus resistance in Culex tarsalis, California, 1960-1975.



Source: (Gillies, *et al.*, 1976).

Figure 3: Use of parathion, malathion, methyl parathion and fenthion in mosquito control in California, 1955-1971.

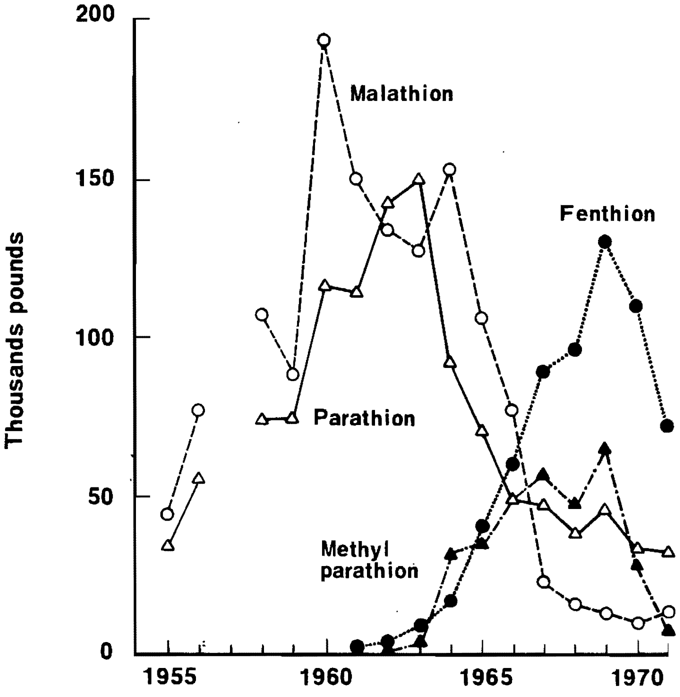
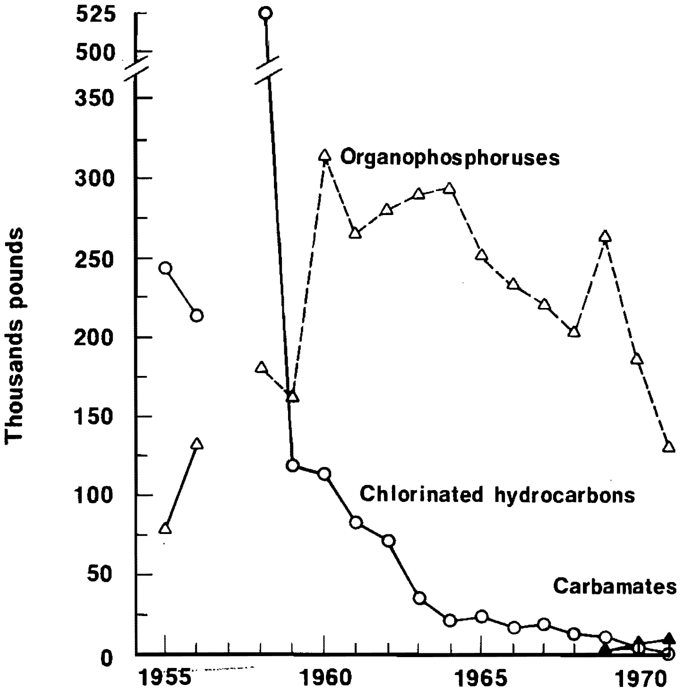


Figure 4: Insecticide use by control districts for mosquito control in California, 1955-1971. *a/*



a/ No data are available for 1957.
Source: (Womeldorf, *et al.*, 1972).

Table 1

Organophosphorus Resistance in California Mosquitoes and Chemical Larvicides, 1971.

	Resistance of Species to Given Chemical Larvicide:						
Species	Malathion	EPN	Parathion	Methyl Parathion	Fenthion	ABATE	Dursban
Aedes nigromaculis	X	X	X	X	X	X	X
Aedes melanimon			X				
Culex tarsalis	X	X	X	X	X	X	X
Culex pipiens	X	X	X		X		
Subspecies *Culex peus*	X		X	X	X		

Source: Womeldorf, Gillies and White 1972.

Because of the increasing insecticide resistance problem and inadequate substitution of other potentially effective alternative methods (i.e., long-term nonchemical controls) by the vector control districts, California is faced with the possibility of uncontrolled mosquito populations.

Mosquito Control Districts

Organization and funding. Attempts were made as early as 1904 to establish agencies for public control of mosquitoes in California; however, the first mosquito abatement district, in Marin County, was not organized until 1915. In 1975 there were 77 mosquito abatement districts and municipal and county control agencies in California which served an area in excess of 40,000 square miles with a total budget of more than $12 million [California 1975; Mulhern 1973].

The districts vary in size and budget. All are publicly organized and administered with a manager and board of trustees. The trustees are responsible for setting the district's fiscal and operational policies, and carry the power to levy taxes and prior to 1978 had limited authority to increase taxes on properties in the district in order to finance abatement operations.

Since state subvention was discontinued in 1967, districts are financed entirely through local funds. Local funds are raised by a levy on taxable properties within a district. The control district's budget trends and the proportion of local and state funds to the total budgets have changed over the years [California 1975]. Table 2 illustrates the changes in and sources of funding from 1954 to 1974.

Monitoring. The major objective of mosquito abatement districts is to control mosquitoes and, to a lesser extent, other insects (e.g., flies and gnats). For vector control districts to decide which control method is the most appropriate they must have a population monitoring system for each mosquito species in the district. However, estimates of the total adult mosquito population of any species within a specific area are not routinely made due to the expense and effort involved. Reasonably accurate methods, based on mark-release-recapture techniques, are available for estimating absolute population densities, but these are impractical except for use in experimental studies and are not essential for effective operation of a control district.

A widely used index of relative abundance is based on light-trap collections, i.e., the number of mosquitoes per light-trap night. Control districts usually operate light-traps in several urban and rural areas. The number of traps operated, the frequency of operation, and their placement may differ from district to district, thus limiting the usefulness of these data for making comparisons between districts. Another drawback to

Table 2

Nominal and Real Value of Local Budget and State Aid for All Reporting California Mosquito Control Districts from 1954-1955 to 1974-1975

	Nominal Budget				Deflated Budget		
Fiscal Year	Local	State Subvention	Total	Deflator[b] Index	Local	State Subvention	Total
1954-55	$ 2,790,553	$342,183	$ 3,132,736	.8770	$3,181,930	$390,174	$3,571,104
1955-56	3,446,851	360,555	3,807,406	.8925	3,862,017	403,983	4,266,001
1956-57	3,445,887	347,480	3,793,367	.9200	3,745,529	377,695	4,123,225
1957-58[a]				.9395			
1958-59	4,114,879	390,368	4,505,247	.9470	4,345,173	412,215	4,757,388
1959-60	4,391,876	104,695	4,496,571	.9485	4,630,338	110,379	4,740,717
1960-61	5,309,808	115,376	5,425,184	.9470	5,606,977	121,833	5,728,810
1961-62	5,132,426	110,612	5,243,038	.9465	5,422,531	116,864	5,539,395
1962-63	5,904,423	143,202	6,050,625	.9465	6,238,164	154,465	6,392,630
1963-64	6,384,199	144,600	6,528,799	.9460	6,748,624	152,854	6,901,478
1964-65	6,673,971	79,660	6,753,631	.9565	6,977,491	83,282	7,060,774
1965-66	7,076,598	50,000	7,126,598	.9820	7,206,311	50,916	7,257,228
1966-67	7,428,742	50,000	7,478,742	.9990	7,436,178	50,050	7,486,228
1967-68	7,818,601	---	7,181,601	1.0125	7,722,075	---	7,722,075
1968-69	8,267,290	---	8,267,290	1.0450	7,911,282	---	7,911,282
1969-70	8,914,503	---	8,914,503	1.0845	8,219,919	---	8,219,919
1970-71	9,713,372	---	9,713,372	1.1215	8,661,053	---	8,661,053
1971-72	9,879,474	---	9,879,474	1.1650	8,480,235	---	8,480,235
1972-73	10,225,437	---	10,225,437	1.2690	8,057,869	---	8,057,869
1973-74	11,089,851	---	11,089,851	1.4735	7,526,196	---	7,526,196
1974-75	12,925,425	---	12,925,425	1.6000	8,078,390	---	8,078,390

a. Data for fiscal 1957-58 were not available.

b. Consumer Price Index, U.S. Department of Commerce.

Source: Calculated from information obtained from the California Mosquito Control Association, Yearbooks, Annual Issues.

using the light-trap index is that not all mosquito species are equally attracted to light. Other sampling techniques must be used to measure the relative abundance of certain species. For example, it would be unreasonable and ineffective to develop a control strategy for A. nigromaculis based solely on light-trap indices. Landing counts[9] are probably the most accurate index for this species. Complaints by residents reflect the degree of mosquito annoyance in an area and hence are an indirect measure of mosquito population levels. Both landing counts (for A. nigromaculis) and complaints (for all species) are often used to supplement the light-trap index in deciding on which abatement activity to implement and at what level.

Pesticides and source reduction control efforts. Until recently vector control districts emphasized chemical control far more than biological control and source reduction methods. From 1962 to 1974, on the average, vector control districts increased their source reduction budgets from 21.2 to 25.6 percent of the total budget. The pesticide resistance problem, environmental and safety requirements, and circumstances such as weather and mosquito intensity may have contributed to the increase. The number of districts reporting source reduction activities increased from 27 in 1962 to 39 in 1974.

The abatement district's emphasis on chemical pesticides has helped them to reduce mosquito populations, but it has also contributed to the problem of mosquito resistance to chemicals. Resistance, in turn, has

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9/ In a "landing count," a person stands in a selected area and allows mosquitoes to land on him while he counts the number landing per unit of time.

required a continuous substitution of one pesticide for another or of one class of chemicals for another. In any case, whether these chemicals are used in a manner similar to or different from that in the past, they will be produced under more difficult conditions of shrinking potential markets and expanding public safety regulations.

MOSQUITO ABATEMENT RELATIONSHIPS: ANALYTICAL FRAMEWORK AND DEVELOPMENT OF THE MODELS

Introduction

Essentially, the problem of mosquito control is similar to that of pest management in the agricultural sector. The aim in both cases is to minimize a pest population subject to a variety of conditions or constraints. With crop pests, the problem is to find an optimal control strategy which minimizes the pest population at minimum cost so that an optimum crop yield is produced. With noncrop pests (e.g., mosquitoes) the common objective is to find a minimum cost strategy which reduces the pest population to a level at which the incidence of diseases they transmit and the annoyance they cause to humans are tolerable.

Studies on the economic impact of mosquitoes and other pests of public health importance have been relatively few. Economic studies of pest management have been dominated by interest in agricultural pests, with only minor studies concerning nonagricultural pests (e.g., mosquitoes and gnats). Most of these studies are based on theoretical approaches to the problem; few are empirically applied.

An empirical study in the United States on mosquito abatement was done in 1974 by D.V. DeBord [1974] in which he investigated the demand for and cost of salt marsh mosquito abatement for 30 East Coast mosquito abatement agencies. DeBord used a four-equation simultaneous pest management model to examine the responsiveness of mosquito density to abatement activities by the agencies and to examine the incentives to collect taxes for mosquito control purposes. The four components or submodels were mosquito abundance, temporary control (chemical), permanent control (source reduction), and abatement demand. Another model was utilized to check for possible economies of scale in the control operations.

Analysis of 30 abatement agencies from 1959 through 1971 revealed that mosquito populations were reduced significantly with both chemical and nonchemical control measures. There were economies of scale with respect to the construction of source reduction measures but not with pesticide spraying activities. Study results indicated that the use of pesticides was three to four times more effective in reducing mosquito density than permanent control measures. Finally, results showed that demand for abatement (as measured by local per capita expenditure on control measures) is affected by income and population of the district, state grants for abatement, tourism and mosquito population levels.

However, DeBord's study did not take into account the important variations in environmental conditions and control activities within the season by taking the time unit for observation to be one year. Also, the study failed to take into account the buildup of chemical resistance in mosquitoes and made the assumption that the entire area studied, which included regions in five states, is environmentally homogeneous.

Mosquito Control Districts Studied

In evaluating mosquito abatement relationships in California we should recognize that mosquito life cycles and breeding habitats and the effects of mosquitoes on humans and domestic animals vary according to the mosquito species involved. In addition, the environmental characteristics encountered by different abatement agencies may differ in climate, population, important mosquito species and agricultural background.

The choice of districts was limited by the quality and availability of organized, reliable data needed for the empirical research and the number of districts chosen was limited by time. The three districts selected are the Delta Vector Control District (VCD) of Tulare County, the Kern Mosquito Abatement District (MAD) located in Kern County in the San Joaquin Valley and the Butte Mosquito Abatement District of Butte County in the Sacramento Valley. These districts operate as public agencies for both rural and urban areas. However, no distinction was made between rural and urban activities because there was no clear separation in the districts' reports covering the period of this study.

Types of Models for the Mosquito Control Agencies

A theoretical model of the underlying biological, economic and physical relationships should be defined which relates abatement strategies with policy decisions. Empirical estimation of these relationships could be used either directly to describe the control district's behavior and decision-making processes, which is a positive economic approach (as in DeBord's study), and/or the coefficients can be used in constructing a programming decision model, which is a normative economic approach.

The two types of models developed and estimated for Delta VCD and Kern MAD [Sarhan 1976] were a monthly-data model and an annual-data model. These two types differ in their structure and number of equations and in the definition and nature of effect of their variables on the abatement relationships and activities. For example, the annual models include variables which are hypothesized to have a long-run influence on mosquitoes (e.g., source reduction). For Butte MAD, the limited data available and the relatively few years for which these data are available led to developing only the monthly-data type of model. Only the Kern annual model is discussed in detail here but we include a brief summary of the important results and implications from other models. It should be emphasized at the outset that the model specification was selected after several others were tested and eliminated due to statistical or theoretical problems and limitations.

Kern MAD: Annual-Data Model

Kern annual-data model consists of the following 10 equations:

(1) $K_1 = h_1(K_{1t-1},K_2,K_3,K_4,K_5,K_6,K_7,K_8,K_9)$ (*Aedes nigromaculis* population)

(2) $K_{10} = h_2(K_{10t-1},K_2,K_3,K_4,K_5,K_6,K_7,K_8,K_{11})$ (*Culex tarsalis* population)

(3) $K_{12} = h_3(K_{12t-1},K_2,K_5,K_{13},K_{14})$ (*Culex p. quinquefasciatus* population)

(4) $K_4 = h_4(K_{4t-1},K_1,K_3,K_{10},K_{15},K_{16})$ (Acres treated with pesticides)

(5) $K_5 = h_5(K_{5t-1},K_1,K_{10},K_{12},K_{16})$ (Locations treated with pesticides)

(6) $K_7 = h_7(K_4,K_{16},K_{17})$ (Sumps, ponds, etc., constructed)

(7) $K_8 - h_8(K_1,K_{10},K_4,K_{16},K_{18})$ (Ditches constructed)

(8) $K_9 = h_9(K_1,K_{17},K_{18},K_{19},K_{20})$ (Effectiveness index-*A. nigromaculis*)10/

10/ See Appendix B for a detailed explanation of method used to estimate the effectiveness index.

(9) $K_{14} = h_{11}(K_{12},K_{20})$ (Effectiveness index- _C. p. quinquefasciatus_)

(10) $K_{14} = h_{11}(K_{12},K_{20})$ (Effectiveness index- _C. p. quinquefasciatus_)

where $K_1, K_{10}, K_{12}, K_4, K_5, K_7, K_8, K_9, K_{11}$ and K_{14} are endogenous variables and all other variables are assumed to be predetermined. The definition of the variables can be summarized as follows:

K_1 = average number of female _A. nigromaculis_ mosquitoes per light-trap night in the year

K_{1t-1} = average number of female _A. nigromaculis_ mosquitoes per light-trap night in the previous year

K_2 = total number of days in the year when temperatures equaled or exceeded 100° Fahrenheit

K_3 = total amount of river flow during the year (the sum of flows of Kern and Tule rivers)

K_4 = total number of acres treated with pesticides (larvicides and adulticides applied by air and ground spray) in the year

K_5 = total number of locations spot-treated with pesticides (larvicides and adulticides) in the year

K_6 = number of cubic yards of dams and levees constructed in the year

K_7 = number of cubic yards of sumps, ponds, etc., constructed in the year

K_8 = number of miles of ditch construction in the year

K_9 = average effectiveness index of pesticides used during the year per average application with a standard dosage (a proxy for the _A. nigromaculis_ species' resistance to pesticides)

K_{10} = average number of female _C. tarsalis_ mosquitoes per light-trap night in the previous year

K_{10t-1} = average number of female C. tarsalis mosquitoes per light-trap night in the previous year

K_{11} = average effectiveness index of pesticides used during the year per average application with a standard dosage (a proxy for the C. tarsalis species' resistance to pesticides)

K_{12} = average number of female C. p. quinquefasciatus mosquitoes per light-trap night in the year

K_{12t-1} = average number of female C. p. quinquefasciatus mosquitoes per light-trap night in the previous year

K_{13} = total number of inches of rainfall from January to October in the year

K_{14} = average effectiveness index of pesticides used during the year per average application with a standard dosage (a proxy for the C. p. quinquefasciatus species' resistance to pesticides)

K_{15} = total number of irrigated crop acres considered important to mosquito production during the year

K_{16} = total deflated budget for the year

K_{17} = the accumulated sum of cubic yards of sumps, ponds, etc., constructed in the past 10 years

K_{18} = the sum of the number of miles of ditch construction for the past 10 years (stock)

K_{19} = the sum of acres treated with pesticides for all mosquito species in the past

K_{20} = the sum of the number of locations spot-treated with pesticides in the past.

Estimation Procedures and Data Sources

In this section we describe the sources of data and the procedures used in the empirical estimation of the regression model's parameters, which are the basis for Kern MAD's linear programming model.

The periods selected for this study were 1955 through 1974. The length of the time period is important because it allows a greater range in variation for both mosquito population levels and the important environmental factors which affect mosquitoes. A longer period also permits the effectiveness of long-term abatement activities (source reduction) to enter the analysis.

Estimates for the parameters of the model developed were derived from time-series data for the district studies. The relationships presented, because of their general interdependent nature, required the specification of simultaneous equation models. Each equation contains one or several endogenous variables which also occur in other equations. The exogenous variables are assumed to be stochastically independent of the disturbances of the system.

Due to the simultaneous nature of the model specification, the two-stage least-square method is used to estimate the parameters.11/ Application of the omitted variable identification test to each of the equations shows that the order condition for identification is satisfied and each equation is overidentified.

In this study we relied on a number of sources to obtain data needed for the empirical application of the model already described. Environmental and climatological data were obtained from the relevant publications of the U.S. Department of Commerce [1971, 1973]. River-flow data were obtained from the files of the State of California Department of Water Resources and from official bulletins of that Department [DWR, 1974].

11/ Given the model specified, it is quite probable that some degree of serial correlation exists which would lead to inconsistency. However, reliable detection methods for serial correlation in the presence of lagged endogenous variables are only just being developed and were not available to the authors.

Mosquito population index data were obtained from monthly reports of the mosquito abatement district or from the data bank of the School of Public Health, University of California, Berkeley. Data for the abatement operations' input amounts and costs were obtained from the control districts' monthly reports, interviews with the manager and the California Mosquito Control Association, Inc., Yearbooks.

Results

With 54 nonzero coefficients in the model, discussion of the expected signs on individual coefficients is precluded. The anticipated coefficient signs are presented concisely in Appendix C. For detailed discussion of the expected signs see Sarhan [1976].

The results of the Kern MAD annual-data theoretical model are presented in Table 3. A brief analysis is presented below.

(1) *Aedes nigromaculis* population: The estimated equation indicated that the average number of A. nigromaculis per light-trap night in any year was influenced by river flow and number of days when temperatures were of at least 100°F. Both had positive effects, as expected. The number of acres sprayed and such source reduction activities as the construction of sumps were not significant influences and had incorrect positive signs. The number of locations treated and ditches constructed had the expected negative effects, but not at significant levels. Average pesticide effectiveness and construction of fills, levees, etc., were not satistically significant factors but carried the expected negative signs. The average number of A. nigromaculis in the previous year was not significant and had a negative sign. These results indicate that in Kern MAD the quality of pesticides and the number of fills, etc., constructed were the most

Table 3

Estimated Results of the Annual Abatement Model Data Base - Kern County Mosquito Abatement District

Equation number	Endogenous Variables / Normalized Endogenous Variables	Constant Term	*A. nigromaculis* numbers	*C. tarsalis* numbers	*C.p. quinquefasciatus* numbers	Acres treated with pesticides	Locations spot-treated with pesticides	Sumps, ponds, etc., constructed in the year	Ditches constructed in the year	Effect on *A. nigromaculis*	Effect on *C. tarsalis*	Effect on *C.p. quinquefasciatus*	*A. nigromaculis* numbers in the previous year	*C. tarsalis* numbers in the previous year
		K_0	K_1	K_{10}	K_{12}	K_4	K_5	K_7	K_8	K_9	K_{11}	K_{14}	K_{1t-1}	K_{10t-1}
1	*A. nigromaculis* (K_1) (numbers)	150.75				.0285 (.35)a/	-.00369 (-.23)	.0109 (.16)	-.0339 (-.23)	-1.559* (-1.50)			-.2137 (-.94)	
2	*C. tarsalis* (K_{10}) (numbers)	228.30				.0071 (.15)	-.0245*** (-2.71)	-.1065*** (-2.33)	-.1110* (-1.38)		-2.0748*** (-3.51)			-.3999* (-1.62)
3	*C.p. quinquefasciatus* (K_{12}) (numbers)	11.4110					-.00063 (-.95)					-.1072** (-2.15)		
4	Acres treated (K_4) with pesticides	127.480	2.035** (1.76)	1.276 (1.03)										
5	Locations treated with pesticides (K_5)	-348.019	-5.390* (1.72)	-1.488** (-1.76)	9.9054* (1.51)									
6	Sumps, ponds, etc., (cubic yards) (K_7)	74.380				.0925 (.78)								
7	Ditches (miles) (K_8)	127.240	1.424 (1.07)	1.505* (1.69)		-.1853 (-.78)								
8	Effect on *A. nigromaculis* (K_9)	100.20	-.0135 (-.21)											
9	Effect on (K_{11}) *C. tarsalis*	99.68		-.2366** (-1.90)										
10	Effect on *C.p.* (K_{14}) *quinquefasciatus*	100.16			-1.687* (-1.50)									

(Continued)

a/ t-ratios are given in parentheses below the respective coe-ficient estimate.
***, ** and * designate the level of significance equal to 1%, 5% and 10%, respectively.

Table 3--Continued

Equation number	Predetermined Variables / Normalized Endogenous Variables	*C.p. quinquefasciatus* numbers in the previous year	Acres treated with pesticides in the previous year	Locations treated with pesticides in the previous year	Number of days of temperatures ≥ 100° F	River Flow	Levees, etc., constructed in the year	Rainfall	Acres of crops	Budget	Stock of sumps, ponds, etc.	Stock of ditches	Sum of acres treated with pesticides in the past	Sum of locations spot treated with pesticides in the past
		K_{12t-1}	K_{4t-1}	K_{5t-1}	K_2	K_3	K_6	K_{13}	K_{15}	K_{16}	K_{17}	K_{18}	K_{19}	K_{20}
1	*A. nigromaculis* (K_1) (numbers)				.1208 (1.03)	.0071* (1.61)	-.1310 (-1.26)							
2	*C. tarsalis* (K_{10}) (numbers)				-.0912* (-1.51)	.000014 (.006)	-.1110** (-1.88)							
3	*C.p. quinquefasciatus* (K_{12}) (numbers)	-.1865 (-.84)			-.00985* (-1.53)			.0336 (.79)						
4	Acres treated with pesticides (K_4)		.1172 (.75)			.0252** (2.30)			-.0273** (-1.987)	.0118 (.08)				
5	Locations treated with pesticides (K_5)			.4386** (1.75)						1.6259*** (2.67)				
6	Sumps, ponds, etc., (cubic yards) (K_7)									-.0752 (.96)	-.2473*** (-2.63)			
7	Ditches (miles) (K_8)									-.3213*** (-3.55)		.0613 (.98)		
8	Effect on *A. nigromaculis* (K_9)										.00015 (.009)	-.00146 (-.17)	-.00186 (-.70)	-.000466 (1.03)
9	Effect on *C. tarsalis* (K_{11})										.0161 (.96)	-.0073 (-.89)	-.00046 (-.19)	-.00051 (1.29
10	Effect on *C.p. quinquefasciatus* (K_{14})													-.00064** (-2.42)

important factors in lowering the A. nigromaculis population levels during the year. Also, the negative effect exerted by the previous year's population on that of the current year could mean that the district's activities during the year were sufficient to reduce the density of mosquitoes overwintering. Or that the overwintering habitat was limited in extent and higher populations decreased over wintering success. Simple *a priori* population growth reasoning which would anticipate a positive relationship shown in Appendix C is borne out in the monthly model (see Appendix D) where the coefficients for the lagged endogenous population variables are all significant and positive. Current source reduction activities (except for fills, levees, etc.) were not significant, probably because they were large projects which took several years to complete. Therefore, the effects of the stock of these source reduction constructions, entering the equation through the effectiveness index rather than through current activities, were the significant factors in source reduction control.

(2) *Culex tarsalis* population: The average number of C. tarsalis mosquitoes per light-trap night in a given year was influenced significantly by the locations treated, construction of fills, levees, etc., sumps, ponds, etc., effectiveness of the pesticides and the number of days when temperatures were at least 100°F in the district. All coefficients of these factors carried negative signs, indicating that both source reduction activities and pesticide treatment (locations) were effective in reducing the average number of C. tarsalis mosquitoes in the Kern MAD study.

The fact that the number of hot days exerted a negative effect on the C. tarsalis population levels in this district may result from the adverse physiological effect of heat on mosquito growth or to the district's effective control program during the summer months. The number of acres treated was not significant and had an unexpected positive sign. The directional effect of river flow was positive, as expected; but at a nonsignificant level. The average number of C. tarsalis in the previous year had a negative effect on the average number in the current year, which can be explained in the same way as in the A. nigromaculis population equation.

(3) *Culex p. quinquefasciatus* population: The estimated equation indicated that the number of locations treated, the average pesticide effectiveness and the number of days with temperatures over 100°F were negatively related to the average number of C. p. quinquefasciatus mosquitoes per light-trap night. The coefficient of the previous population was negative as were the corresponding coefficients for the other two species; the explanation of this effect is similar to that given for the A. nigromaculis equation.[12/] The amount of rain did not exert a significant effect on C. p. quinquefasciatus population levels, but the direction of the effect was predictably positive, as expected.

(4) Acres treated with pesticides: Empirical estimation of the equation indicated that the average number of A. nigromaculis and C. tarsalis mosquitoes per light-trap night influenced decisions on the number of acres sprayed. The directions of the relationships were positive, as expected, but the coefficient of the C. tarsalis population was not

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[12/] It should be pointed out that the dimensional relationship between populations in period t and t-1 was positive when monthly data were used for the three species.

significant. This may be due to the district's policy of responding to A. nigromaculis populations by massive spraying, whereas they respond to C. tarsalis on a smaller scale.

The number of acres treated in the previous year exerted a positive, but not significant, effect on the number treated in the current year. This implies that the district's decisions were not highly dependent on past experience and may indicate some kind of response to the current situation rather than to the established pattern in that district. River flow (a proxy for irrigation) was statistically significant and carried a positive sign. The budget factor did not have a significant effect on acres treated, but it was positive.

(5) Locations treated with pesticide: The estimated equation indicated that the factors which significantly and positively influenced the number of spot locations treated in a given year were the average number of C. p. quinquefasciatus mosquitoes per light-trap night, the number of locations treated in the previous year and the district's budget. The average numbers of A. nigromaculis and C. tarsalis mosquitoes were significant factors, but carried negative signs. It can be inferred from the estimation that Kern MAD's decision on the number of spot locations to treat in any year was not influenced by the densities of pasture or encephalitis mosquitoes, but by the density of the southern house mosquito.13/

13/ This inference does not contradict the policy of Kern MAD, which places primary interest in A. nigromaculis and C. tarsalis mosquitoes for their control programs of treating acres with pesticides. Spot locations treated is only a small part of their pesticide usage.

(6) Construction of sumps, ponds, etc.: Empirical estimation indicated that the only significant factor affecting the amount of these source reduction activities was the stock of sumps, ponds, etc. This is shown by the negative coefficient of the stock variable, K_{17}. In particular, the regression equation showed that an increase of one unit (1000 cubic yards) in the stock of sumps, ponds, etc., constructed in the district one year, decreases construction in the next year by 247.3 cubic yards, with all other factors held constant. In other words, the more sumps, ponds, etc., a district has accumulated, the fewer it will construct in the current year.

The budget was not a significant factor and carried a negative sign which can be explained on the basis that budget priorities were allocated to other activities or that an increased stock of source reduction constructions made it possible to use uncommitted funds for other purposes.

(7) Ditch construction: The estimated equation indicated that in any given year the number of miles of ditch construction was positively influenced by mosquito populations and the stock of ditches. In particular, the average number of *C. tarsalis* mosquitoes per light-trap night was significant, but carried the expected directional relationship. The stock of ditches was not significant and the direction of its effect could mean that the district did not have a large enough stock of ditches in the period of this study to justify reducing current ditch construction. This effect may also be a result of depreciation of the stock or an increasing need for new ditches in new agricultural areas.

The number of acres treated with pesticides exerted a negative effect on the miles of ditches constructed in a given year, which may indicate that the district ranked ditch construction as secondary in importance to pesticide use. This could be particularly true where a high density of mosquitoes causes a shift in the district's efforts to fast, immediately effective control methods (i.e., pesticides), while construction of source reduction projects may be stopped until mosquito populations are down. Also, effective chemical control could appear to reduce the need for other means of control.

(8) Average pesticide effectiveness indices: The estimated equations indicated that the effectiveness of pesticides had a negative effect on the average number of mosquitoes per light-trap night. That is, as pesticide effectiveness decreased, the average number of mosquitoes per light-trap night increased. This was true for all three species studied in Kern MAD: *A. nigromaculis, C. tarsalis* and *C. p. quinquefasciatus.* The influence of population density was statistically significant for the two *Culex* species.

The stock of sumps, ponds, etc., did not have statistically significant effects on the average effectiveness of pesticides used for control of *A. nigromaculis* and *C. tarsalis;* however, its coefficients carried the expected positive signs, indicating that these source reduction activities made it possible for Kern MAD to reduce pesticide selection pressure on mosquitoes, thereby decreasing mosquito resistance (i.e., increasing the per-application average effectiveness of pesticides). The stock of ditches was not significant in the *A. nigromaculis* and *C. tarsalis* average pesticide effectiveness equations and carried negative signs. This could mean that there were not enough ditches or that they were not effective in indirectly reducing the pressure of pesticides on these species, thereby reducing resistance.

The selection pressure of pesticides had the expected negative effects on the average effectiveness indices for all three mosquito species (i.e., increasing the mosquitoes' pesticide resistance). The coefficients of the sum of acres treated in the past were not significant. Those of the sum of spot locations treated in the past were not significant, except in the *C. p. quinquefasciatus* effectiveness index equation. The negative directional relationships indicated by the results are in agreement with entomological studies which indicate a positive correlation between intensity of pesticide selection pressure and the build-up of mosquito resistance. However, the coefficients' low degree of significance may indicate that outside pressure, i.e., agricultural spraying for crop pests, may have been more important in exerting selection pressure on mosquitoes (a nontarget pest for the agricultural spray).

Implications of the empirical results. We are aware of the limitations and drawbacks of using the light-trap index as a measure of *A. nigromaculis* and *C. p. quinquefasciatus* population levels. However, the light-trap index was used in this study because there was no other measure available. Although the districts have tried to use other counting methods, the results are less reliable. Therefore, the results presented in this report and any conclusions or implications, should be interpreted in light of the acknowledged, but unavoidable, limitations.

The results of the empirical estimations of the models supported our hypothesis that the time period of the observations is an important element in analysis of mosquito abatement relationships. The monthly-data models showed ~~the~~ importance of some variables more clearly than the annual-data models. In the monthly-data models for Delta VCD and Kern MAD, for example, the effects of the temperature, rainfall and previous population factors were generally more significant in explaining the variation in the number of mosquitoes within any season than they were in the annual-data models [see Appendix D]. Factors which have a long-run effect on mosquitoes, i.e., source reduction activities, were included only in the annual-data models for the Kern and Delta districts since it was believed that their effects would not be significant in the monthly-data models.

Comparison of the relative efficiency of control methods. The results of Kern MAD's annual-data model showed the differential effects of environmental and control factors on the number of mosquitoes per light-trap night. The response of *Culex tarsalis* density to the number of locations treated with pesticides was 6.6 times that of *Aedes nigromaculis* and 38 times that of *Culex p. quinquefasciatus.* It was further shown that the response of *A. nigromaculis* population levels to new fills, levees, etc., was 35.5 times greater than was its response to spot locations treated, while the response of *C. tarsalis* numbers to fills, levees, etc., was 4.53 times that of its response to locations treated.

Table 4 summarizes the effects on mosquito populations resulting from independent changes in the control factors. The table provides data needed for comparison between various control methods under two cost levels and shows the effects when one- and ten-year periods are considered for source reduction activities.

Table 5 summarizes the various abatement activities and shows their rank in terms of physical and economic efficiency in controlling *A. nigromaculis* and *C. tarsalis* mosquitoes in Kern MAD.

Table 4

Results of Independent 10 Percent Increases in Acres Sprayed, Locations Treated and Source Reduction Activities (1- and 10-year Effects) in Kern MAD for *A. nigromaculis* and *C. tarsalis* and Two Cost Levels[a]

	A. nigromaculis Mosquitoes				*C. tarsalis* Mosquitoes					
			Ditches				Sumps, Ponds, Etc.		Ditches	
Item	Locations treated	Fills levees, etc.	1-year effect	10-year effect	Locations treated	Fills, levees, etc.	1-year effect	10-year effect	1-year effect	10-year effect
(1) Average value of control factors	338,220	27.93	22.26	22.26	338,220	27.93	16.38	16.38	22.26	22.26
(2) 10% increase from the average (1)	33,822	2.79	2.23	2.23	33,822	2.79	1.64	1.64	2.23	2.23
(3) New level of control factors (1) + (2)	372,042	30.72	24.49	24.49	372,042	30.72	18.02	18.02	24.49	24.49
(4) Average light-trap number (all factors at mean values)	4.1821	4.1821	4.1821	4.1821	5.2003	5.2003	5.2003	5.2003	5.2003	5.2003
(5) New light-trap nos. from 10% increase in control variable	4.0573	3.8160	4.1068	3.7952	4.3717	4.8906	5.0258	4.3033	4.9530	3.9305
(6) Percent reduction in light-trap numbers	2.9%	8.75%	1.8%	9.25%	15.93%	5.96%	3.36%	17.25%	4.75%	24.4%
(7) Cost$_a$/ unit[b]	$4/1000 locations	$140/ 1000 c.y.	$40/ mile	$40/ mile	$4/1000 locations	$140/ 1000 c.y.	$450/ 1000 c.y.	$450/ 1000 c.y.	$40/ mile	$40/ mile
(8) Total cost$_a$ for 10% increase in control variable (2) x (7)	$135.23	$391.00	$ 88.80	$ 88.80	$135.28	$391.00	$738.00	$738.00	$ 88.80	$ 88.80
(9) Cost$_a$ per 1% reduction in mosquito light-trap index (8) ÷ (6)	$ 46.65	$ 44.68	$ 49.33	$ 9.60	$ 8.49	$ 65.61	$219.64	$ 42.78	$ 18.69	$ 3.64
(10) Cost$_b$/unit[c]	$6/1000 locations	$150/ 1000 c.y.	$43/ mile	$48/ mile	$6/1000 locations	$150/ 1000 c.y.	$480/ 1000 c.y.	$480/ 1000 c.y.	$48/ mile	$48/ mile
(11) Total cost$_b$ for 10% increase in control variable (2) x (10)	$202.93	$418.50	$106.84	$106.84	$202.93	$418.50	$787.20	$787.20	$106.84	$106.84
(12) Cost$_b$ per 1% reduction in mosquito light-trap index (11) ÷ (6)	$ 69.97	$ 47.83	$ 59.35	$ 11.55	$ 12.74	$ 70.22	$234.28	$ 45.63	$ 22.49	$ 4.38

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[a] It should be understood that the changes in the control factors are not simultaneous, but each factor changes while all others are held at their mean values.

[b] Average cost during the last two decades.

[c] Average cost under 1975-76 conditions.

Table 5

Rank in Physical and Economic Efficiency of Control Activities in Kern MAD[a]

	A. nigromaculis					*C. tarsalis*				
	Physical Efficiency		Economic Efficiency			Physical Efficiency		Economic Efficiency		
Rank	Activity	% reduction in light-trap index	Activity	Past cost of 1% reduction	1975-76 cost of 1% reduction	Activity	% reduction in light-trap index	Activity	Past cost of 1% reduction	1975-76 cost of reduction
1	Ditches	9.25%	Ditches	$ 9.60	$11.55	Ditches	24.4%	Ditches	$ 3.64	$ 4.38
2	Fills, levees, etc.	8.75%	Fills, levees, etc.	$44.68	$47.83	Sumps, ponds, etc.	17.25%	Locations treated (pesticides)	$ 8.49	$12.74
3	Locations treated (pesticides)	2.9%	Locations treated (pesticides)	$45.60	$68.10	Locations treated (pesticides)	15.93%	Sumps, ponds, etc.	$42.78	$45.63
	---	---	---	---	---	Fills, levees, etc.	5.96%	Fills, levees, etc.	$65.61	$70.22

[a] The coefficients of acres sprayed were not included in the comparison because their unexpected signs would result in meaningless conclusions. Only the 10-year extended effects are considered in the calculations for the source reduction control methods.

The unit cost basis is calculated for both the average cost over the past two decades and for the current 1975-76 cost; in no case does this change the efficiency ranking. The ranking comparison indicates that for both species of mosquitoes, the economic efficiency of two source control activities exceeded the efficiency of localized specific pesticide applications. Clearly, the efficacy of source reduction methods can only be assessed accurately in long-term evaluations because their effectiveness is depreciated over a ten-year horizon. However, even for example, when the results from ditch improvement are restricted to a two year payoff horizon, the cost of a 1 percent reduction in the light-trap index results in lower costs for A. nigromaculis ($29.67) and C. tarsalis ($11.24) than that associated with a 1 percent reduction in the cost of pesticides used at specific locations. These direct marginal costs ignore the associated user costs of pesticide use and source reduction which enter the model through the effectiveness equations in Table 3 and emphasize the cost effectiveness of nonpesticide control methods by resulting in a positive user cost for pesticides and a negative user cost for sumps and ditches.

While it is difficult to directly infer policy conclusions from the structural form of the model, the reduced form of the model can be used to show the different impacts of comtemporary and cumulative measures of different control methods. In particular, the effect of a unit change in the stock of past sumps, ponds, etc., or the stock of past pesticide treatments can be calculated.

Expressing the structural form as:

(1) $By_{(t)} + \Gamma_1 y_{(t-1)} + \Gamma_2 x_{(t)} = 0$

where y(t) is the vector of current endogenous variables

x(t) is the vector of exogenous variables

the reduced form is:

(2) $y_t = \Pi_1\ y(t-1) + \Pi_2\ x\ (t)$ where $\Pi_1 = -B^{-1}\Gamma_1$

$\Pi_2 = -B^{-1}\Gamma_2$

The coefficients of Π_2, often referred to as impact multipliers,[14/] show the effect of a unit change in any given exogenous variable on the expected value of a contemporaneous endogenous variable after all the simultaneous effects of the system have been worked through. In the abatement model, a change in the stock of sumps, ponds, etc. (K_{17}), or the sum of locations treated with pesticides (K_{20}) will occur with changes in the corresponding endogenous variables (K_7) and (K_5), respectively. The impact multipliers for the exogenous variable K_{17} and K_{20} on the endogenous light-trap index variables K_1, K_{10}, K_{12}, thus show the immediate indirect effect through the effectiveness equations of source reduction and pesticide use control methods.

Of greater impact are the longer-term indirect effects of control methods. The recursive form of equation (2) clearly recognizes that pesticide resistance is genetically transmitted to future generations; and likewise a source reducing pond or sump will show positive results for a number of years. This intertemporal effect has been noted in the context of a user cost earlier in the report.

The effect of a unit change in an exogenous variable sustained for a period of time on the expected value of an endogenous variable is

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[14/] For a review of impact and t period dynamic multipliers see Goldberger [1964], pp. 374-375 or Dhrymes [1970], pp. 521-525.

termed a T period dynamic multiplier and is obtained by solving the reduced form stochastic difference equation (2) for a given time horizon. If a unit addition to a source eradication has an effective life of T years, the resulting matrix of multipliers is shown as:

$$(3) \quad D_T = (I + \Pi_1 + \Pi_1^2 + \cdot \cdot \cdot \cdot \Pi^T{}_1)\Pi_2.$$

Mindful of the effective life of sumps and ponds, T was set at eight years for an empirical comparison. In Table 6, the direct effect and immediate and long-term indirect effects are compared for a pesticide using control method K_5. All three mosquito species are tabulated despite the change in sign on the eight-year indirect effect coefficient for K_5 on *A. nigromaculis*. For *C. tarsalis* and *C. p. quinquefasciatus,* the direct effect for the pesticide control method is negative as would be expected. The indirect effects, however, show dramatic differences. After one year the indirect effects of pesticide use (K_5) increase the change in light-trap index for *C. tarsalis, C. p. quinquefasciatus,* and *A. nigromaculis*. The net result of direct and indirect effects of the control method, while being beneficial in the short run, diverge drastically in the long run with the long-term costly indirect effects of pesticide use on *C. tarsalis* greatly outweighing the short-term beneficial effects.

It is clear from Table 5 that the decision-makers represented by the abatement model are aware of the inequality of the marginal cost per unit population reduction factors associated with different control alternatives. For example, for *C. tarsalis,* the marginal cost of mosquito abatement using physical control methods is approximately 1/10 that of using pesticides. Physical efficiency shows similar advantages for source reduction

Table 6

Comparison of Direct Controls (and Short-Run and Long-Run Indirect Effects)

Change in light-trap index of mosquito	Location treatment with pesticides (K_5) (thousands)		
	Direct effect	1 year indirect	8 years indirect
A. nigromaculis	−0.00369	0.00077	−0.002661
C. tarsalis	−0.0245	0.00609	0.53202
C. p. quinquefasciatus	−0.00063	0.00009	0.00067

methods but at a lower magnitude. Consideration of the indirect effects in Table 6 exacerbates the problem. Given these suboptimal decisions from an economic viewpoint, a normative constrained optimization model of mosquito control may be of value in setting policies.

Linear Programming Model

A linear programming (LP) model was constructed for a cost-minimizing mosquito control district by making use of the reduced form regression results adjusted for the exclusion of the lagged endogenous and intercept terms and constraints based on the experience of the control district.

The normative approach is concerned with what ought to be, rather than a description of phenomena as they exist (i.e., a positive analysis). The purpose, then, is to develop a linear programming model for cost minimization. In the LP form, the model simultaneously selects the minimum cost combination values for the control factors and assures that the number of mosquitoes will not exceed a specified population level.

Constraint Equations: The coefficients of the constraint equations (a_{ij}'s) and the constraining right hand side values (b_i's) are obtained from the reduced form (2) by expressing the mosquito growth relations as constraints. In matrix notation the set of constraints is expressed as:

$$\underset{\sim}{A}\underset{\sim}{x} \leq \underset{\sim}{b}$$

where $\underset{\sim}{x}$ is a vector of activity levels of mosquito populations, control actions by the abatement district and exogenous variables such as rainfall and river flow. The model has eight main structural features to be explained: (1) Mosquito populations, (2) specifications for maximum acceptable number of mosquitoes per light-trap night, (3) upper and lower bounds on the total number of acres sprayed with pesticides, (4) the upper bound on the number of locations treated with pesticides, (5) upper limits on source reduction activities, (6) specification of the annual river flow, (7) specification of the objective function (operating costs) to be minimized, and (8) total labor availability to the district.

The mosquito population relationships with respect to environmental and man-made control activities must be satisfied. Preliminary solutions suggested that the equation for C. p. quinquefasciatus be omitted because its inclusion led to an infeasible solution. However, Kern Mosquito Abatement District annual reports indicate that control activities which succeed in keeping A. nigromaculis and C. tarsalis mosquito populations below certain levels simultaneously keep C. p. quinquefasciatus at an acceptable level of control. Therefore, since the specification of the mosquito populations allowed for control activities to apply to all species, the omission of C. p. quinquefasciatus will not affect the optimal solution.

Objective Function: A theoretical economic model would suggest that decision-makers optimize over a demand function for the output, in this case mosquito abatement. However, interviews with M.A.D. managers in California [Sarhan, 1976] revealed that the district officers do not operate as if they had hypothetical demand functions for mosquito abatement in their minds. Rather, they have a very inelastic standard of mosquito nuisance they were prepared to tolerate from the principal species, under a given control technology. Under these conditions, the socially efficient objective function for the LP model is one that minimizes the sum of variable costs of control facing the M.A.D. Since the levels of the alternative control actions are a subset of the activities vector $\underset{\sim}{x}$, the objective function can be expressed in vector notation as:

$$\text{Minimize } \underset{\sim}{C}'\underset{\sim}{x}$$

where the vector $\underset{\sim}{C}$ has nonzero elements equal to the variable cost per unit for each control activity.

Clearly the maximum permissible mosquito population standards crucially affect the outcome of the LP. The district managers were twice confronted with the standards used, which were based on the mean of the lowest ten years observed in a 20-year period and concurred with their levels. Subsequently, these standards will be varied to assess their sensitivity on total district control costs. The other constraints, except river flow which was set at its 20-year mean, were set at the maximum observed level in the district.

To assess the sensitivity of the LP model to changes in the maximum allowable mosquito densities, the standards used in the basic model were first cut in half and subsequently doubled. Table 7 displays the results of this sensitivity analysis. Under Plan 2, even though the population density was reduced by 50 percent, the total direct costs increased only slightly. The major change occurring was a more than threefold increase in the miles of drainage ditches constructed.

By doubling the allowable mosquito density standard, Plan 3, direct costs were reduced slightly below the basic least-cost solution. To meet these more relaxed standards, the annual level of ditching was reduced to zero and fewer locations were sprayed which required less labor input.

Table 7

Results of the Programming Model at Original, One-Half Original and Double Original Maximum Acceptable Mosquito Numbers per Light-Trap Night[a]

Activities/items in the optimal solution	Annual level of activities/items under:		
	Plan 1 (original)[b]	Plan 2 (50% below Plan 1)[c]	Plan 3 (100% above Plan 1)[d]
Acres sprayed with pesticides	5,000	5,000	5,000
Locations treated with pesticides	500,000	500,000	418,067
Fills, levees, etc., constr. (1000 c.y.)	49.45	48.31	48.76
Sumps, ponds, etc., constr. (1000 c.y.)	0	0	0
Ditches constructed (miles)	5.50	18.72	0
A.n. mosquitoes per light-trap night	.589	.29	1.17
C.t. mosquitoes per light-trap night	2.67	1.33	5.34
Hours of labor	2,198	2,277	2,083
Total direct costs ($)	24,832	25,295	23,973

[a] All other parameters are held at their original levels.

[b] A. nigromaculis light-trap numbers $\leq .589$; C. tarsalis numbers ≤ 2.67.

[c] A. nigromaculis light-trap numbers $\leq .29$; C. tarsalis numbers ≤ 1.33.

[d] A. nigromaculis light-trap numbers ≤ 1.17; C. tarsalis numbers ≤ 5.34.

The loss of pesticide effectiveness through a resistance buildup and and a lack of new pesticides appearing on the market are a serious concern to control agencies. To estimate the impact on the district of increasing pesticide resistance, the pesticide effectiveness coefficient was varied in discrete steps from 100 percent down to 5 percent. The results of these runs are presented in Table 8 for the basic mosquito population control standard. These results are also shown graphically in Figure 5, along with traces depicting the effect of increasing the control standard one-half the original mosquito density standard (double the original allowable population).

It should be recognized that since the LP model did not allow for an extended effect of source reduction activities the actual total benefits of those activities are underestimated in the results. However, it was shown that even with the one-year effect of these source-reduction activities it is possible to achieve the desired control level (i.e., to keep mosquito poplation levels at or below the specified standard) by substituting such activities for use of pesticides as the effectiveness of pesticides declines or by combining them with pesticide use in an integrated program.

THE CHEMICAL INDUSTRY AND PESTICIDE PRODUCTION

Background

Until 1945, pesticide production was limited and the chemicals were applied almost exclusively on high-value crops. Since 1945 when DDT was introduced and since the development of the new synthetic organic pesticides, spraying and dusting operations spread to most agricultural crops and many public health activities.

Table 8

Results of the Programming Model under Five Levels of Pesticide Effectiveness[a] and the Original Standards of Mosquito Numbers[b]

Activities/items in the optimal solution	Annual level of activities/items under: Pesticide effectiveness on acres and locations 100%	75%	50%	25%	5%
Acres sprayed with pesticides	5,000	5,000	5,000	5,000	5,000
Locations treated with pesticides	500,000	500,000	381,501	500,000	500,000
Fills, levees, etc., constr. (1000 c.y.)	49.45	41.83	47.40	48.73	50.24
Sumps, ponds, etc., constr. (1000 c.y.)	0	0	2.32	29.65	55.99
Ditches constructed (miles)	5.50	60	60	60	60
A. nigromaculis mosquitoes per light-trap night	.589	.589	0	0	0
C. tarsalis mosquitoes per light-trap night	2.67	2.67	2.67	2.67	2.67
Hours of labor	2,198	2,406	2,663	4,303	5,384
Total direct cost ($)	24,832	25,594	28,251	41,570	51,441

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[a] In this table different effectiveness levels were generated from sensitivity tests on the coefficients of acres sprayed and locations treated in the mosquito population relations. The changes in the coefficients were assumed to be linear, e.g., the coefficients of acres sprayed and locations treated at 75 percent pesticide effectiveness were in each case equal to .75 x the original coefficient.

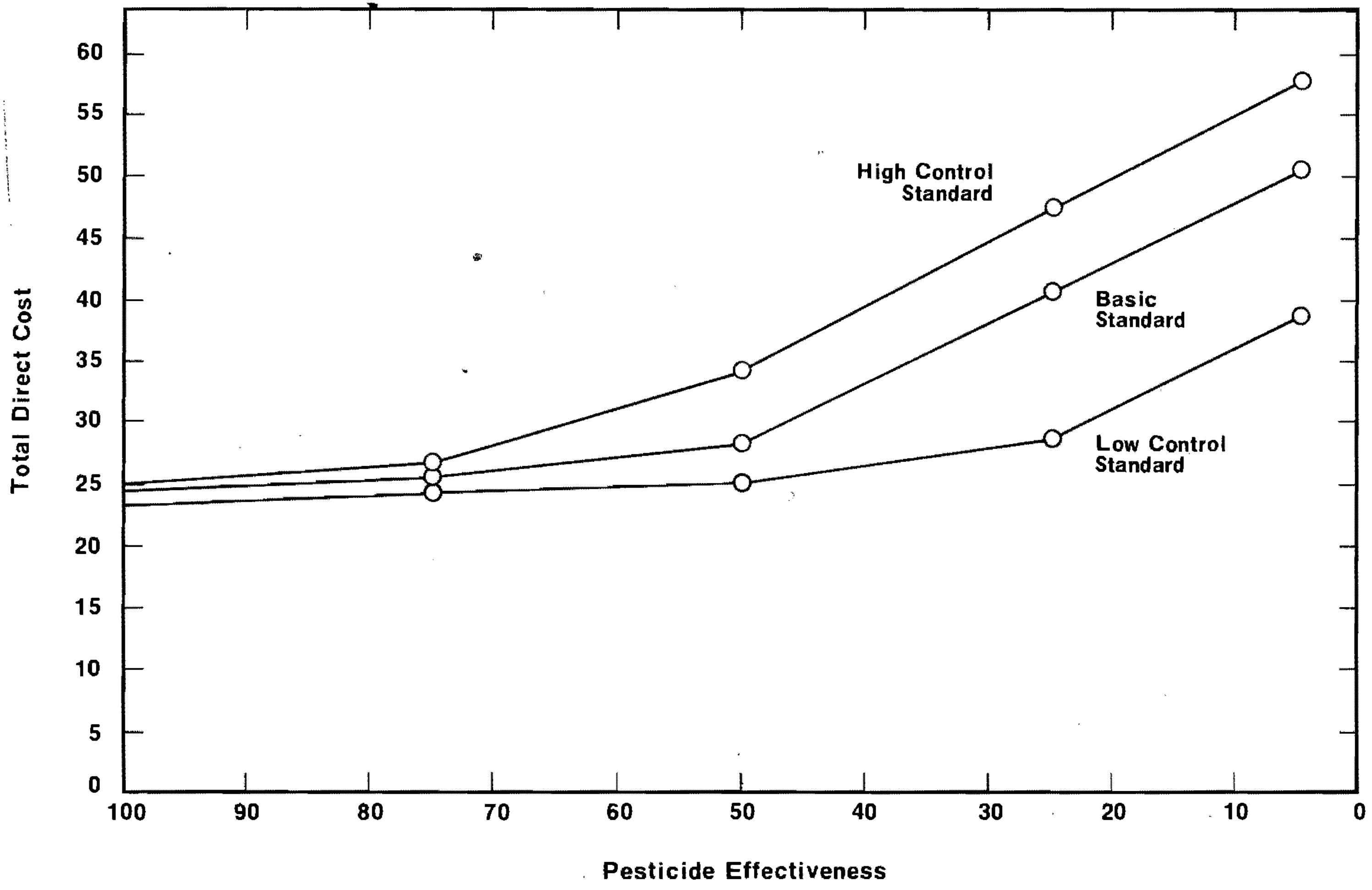
All parameters were held at their levels of the original model except those for acres sprayed and locations treated with pesticides.

[b] *A. nigromaculis* $\leq$ .589 per light-trap night and

C. tarsalis $\leq$ 2.67 per light-trap night.

FIGURE 5

EFFECT OF DECLINING PESTICIDE EFFECTIVENESS ON DISTRICT CONTROL COST AT THREE MOSQUITO CONTROL LEVELS



Since the late 1940's there has been a dramatic increase in the production and sales value of pesticides sold to domestic and international markets. From 1954 to 1972, pesticide production in the United States almost tripled, from 419,274,000 pounds in 1954 to 1,157,698,000 pounds in 1972. These figures are shown in Appendix Table 1. The total sales value for the domestic market and exports increased dramatically by more than eightfold, from $124.5 million in 1954 to over $1 billion in 1972 [USDA 1973].

Of the many U.S. companies involved in the formulating, manufacturing, distributing and selling of pesticides, about 35 are considered to be major innovators which conduct extensive research and development programs [Little 1975]. Most of these companies are multiproduct firms, with less than 20 percent of total sales attributed to pesticides. Two-thirds of the companies with sizable research and development (R&D) efforts are large chemical-or petroleum-based firms; several are multiproduct pharmaceutical companies. Of the smaller firms also involved in pesticide production, pesticides account for as little as 20 percent to as much as 100 percent of their total sales.

The USDA and other public agencies also have a role in developing new chemical pesticides [Klassen and Schwartz 1973; Kramer 1969]. The USDA, particularly the Entomology Research Division of the Agricultural Research Service (ARS), assists in assuring the continuing availability of pesticides for major and minor uses and markets [Klassen and Schwartz 1973]. Two main areas in which the USDA could provide more assistance are:

(1) Generating toxicological, residue and efficacy data needed for registration of candidate pesticides.

(2) Conducting research which complements R&D by the industry, thereby greatly reducing the industry's R&D costs.

Historically, the chemical industry has played the primary role in R&D and pesticide production. All but a few pesticides have been synthesized first in the laboratories of chemical companies [Djerassi, Shih-Coleman and Diekman 1974]. It is possible to assume that private industry will continue to be the primary source, developer and manufacturer of new chemical pesticides because it has the necessary experimental and production facilities and the experienced personnel. However, future pest control efforts will require greater research and development input from public agencies than in the past.

Environmental and Health Regulations on Pesticide Use

In California, laws stipulating enforcement procedures and controls over the sale and use of pesticides can be traced as far back as 1901 [Post 1972]. Various old regulations attempted to protect the agricultural industry from the harmful effects of substandard insecticides. Since 1919, the California Department of Food and Agriculture has been in charge of setting such regulations.

The principal national legislative actions that have affected pesticide research and development in recent years have been the Federal Insecticide, Fungicide and Rodenticide Act (FIFRA), in 1947; the Miller (1954) and Delaney (1962) Amendments to the Federal Food, Drug and Cosmetic Act; the policy changes in pesticide residue requirements enacted during 1966-67; PR Notice 70-15 in 1970; the Federal Environmental Pesticide Control Act (FEPCA) in 1972; and finally the regulations proposed and promulgated under FEPCA since its enactment [Djerassi et al. 1974; Hunter 1978; Little 1975].

The first important act, FIFRA, passed in 1947, called for USDA registration of economic poisons prior to their interstate transport and sale. FIFRA required that all product labels contain instructions for use and warnings about safety hazard to humans, animals and plants. The Miller Amendment (1954) required the Food and Drug Administration (FDA) to establish tolerance limits for pesticide residues. The Delaney Amendment (1962) prohibited the presence of any known carcinogen in food products and increased data requirements for approval.

Data requirements for pesticide registration under FIFRA increased slowly but at a steady pace from 1947 to the 1970's. An Arthur D. Little, Inc., study [1975] summarized the provisions that have had the greatest impact on pesticide R&D as follows.

1. The data requirements for pesticide registration and labeling, for example toxicity tests and data including safety, physical/chemical properties, efficacy and labeling information.
2. Data required for the establishment of tolerances on agricultural commodities, e.g., chemical, toxicological, biochemical, reproduction studies, etc.
3. The experimental use permit program, which required additional data permits for field testing of potential pesticide products.

In 1970, the Environmental Protection Agency (EPA) was created and was granted full regulatory powers over economic poisons. Under the EPA, new regulations shifted the emphasis in USDA and FDA registration and data requirements from efficacy and safety to safety, health and environmental aspects. The industry believes that this shift has had a great impact on the R&D of pesticides [Farm Chemicals 1970; Hunter 1973; Little 1975].

Industrial Research and Development Costs

The costs of R&D associated with the discovery and development of a commercially viable pesticide have increased dramatically in the last several years. In order to gain some insight into the industry's cost we should consider the stages involved in R&D and registration [Lever and Strong 1973; Little 1975].

The four stages of R&D and registration are (1) synthesis and screening, (2) advanced tests, (3) field evaluation and (4) registration. In the synthesis and screening stage, compounds are screened for useful biological pesticidal activity. In stage two, some selected compounds which passed stage one are subjected to advanced screening (laboratory and greenhouse tests are included). In the field evaluation stage, ecological and biological evaluation of products selected from stage two is carried out under various conditions in order to uncover any likely problems and/or limitations. This stage requires the acquisition of use permits from federal and state agencies. The registration stage, which may take three or more years to complete, detailed biological toxicological and ecological studies for final development and obtaining a use and safety label from the EPA.

Time required for the development of new agents varies and largely depends on the regulations and data requirements. For example, the average time expended from synthesis and screening through approval has increased as registration requirements have increased. This can be seen in Table 9.

Several studies and reports have been concerned with the cost of developing a pesticide. In 1969, Wellman [1969] estimated the total cost at \$4.1 million, whereas the National Agricultural Chemical Association (NACA)

Table 9

History of Last Two New Pesticide Chemical Products Cleared for the U.S. Market by Each Participating Chemical Company, by Date of Approval[a]

	Prior to 1963	1963-1967	1967-1971
Number of products reported:	10	22	25
	Average elapsed time (months)		
Stage:			
First screening to decision to commercialize	39	33	32
Decision to commercialize to first registration submission	16	21	19
First registration submission to approval	6	7	18
Average total from screening to approval	61	61	69
	Average Time (Man-years)		
Average R&D man-years expended from screening to approval:	49	34	65

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[a] Composite analysis of all reporting companies [Little 1975].

Source: 1970 Industry Profile Study [Ernst and Ernst 1971].

estimated the same costs to range from \$2.5 to \$6 million.[15] Johnson and Blair [1972] reported in 1972 that costs of R&D increased from \$1.2 million in 1956 to \$4.1 million in 1969. Lever and Strong [1973] reported that these costs increased from \$1.2 million in 1956 to over \$10 million in 1972. In 1975, Arthur D. Little, Inc. [1975] reported the estimated cost for discovery and development of pesticide was about \$7.5 million.

A new industry profile report was published in 1975 by NACA [Ernst and Ernst 1975]. A comparison with previous studies indicates that there has been a consistent increase in cost of discovery and commercialization, from \$3.4 million in 1967 to \$5.5 million in 1970 and to \$6.1 million in 1973.

Investment Decisions for the Pesticide Industry: A Simulation Model

A model for investment under risk and uncertainty should permit the firm to calculate the expected net value of a project from a simulated joint probability density.

The structure of the proposed model, which is concerned with the industry's investment in narrow-spectrum pesticides for mosquito control in California, can be divided into four elements. The first is the criterion function. In this study the discounted net present value of the project will be used. The second element is the variables specified and their interrelationships. The third is the parameters (e.g., the mean and standard deviation of probability distributions). The fourth element is the development of the computational techniques to simulate the net present

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[15] This figure is calculated excluding the opportunity cost of development capital. With an 8 percent interest rate, the development cost would be \$11 million [Djerassi, Shih-Coleman and Diekman 1974].

value of distribution. These four elements of the model's structure are described below.

a. The criterion function - The net present value (NPV) formula consists of two segments: the discounted present value of the sequence of returns (DPVR) and the discounted present value of costs (DPVC), where NPV = DPVR - DPVC. In general, the discounting formula (assuming a constant discount rate over time) can be written as:

$$NPV = \sum_{t=0}^{T} \frac{(R_t - C_t)}{(1 + r)^t}$$

where R_t and C_t are returns and expenditures over time and r is the discount rate.

b. Specification and relationships of variables - The key variables that management is assumed to consider in this model are: (1) the total annual revenue from the sale of a pesticide to all California mosquito abatement agencies,16/ (2) the time spent by the typical pesticide-producing firm (or a firm in the small, medium, or large firm in this category) from first discovery of the product to marketing and (3) the total cost of developing a new pesticide (including R&D, cost of unsuccessful

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16/ For estimation of this segment in equation form, the base market size is initially taken to be the state of California; however, it can increase if we include the possibility of exports to other states. Data for the revenues were calculated from the quantity of malathion used by all mosquito control agencies in California. Malathion, an organophosphorus pesticide, was chosen for the estimation because it was used throughout the state and seemed to be a representative pesticide and because there was sufficient information available regarding its use [Sarhan 1976].

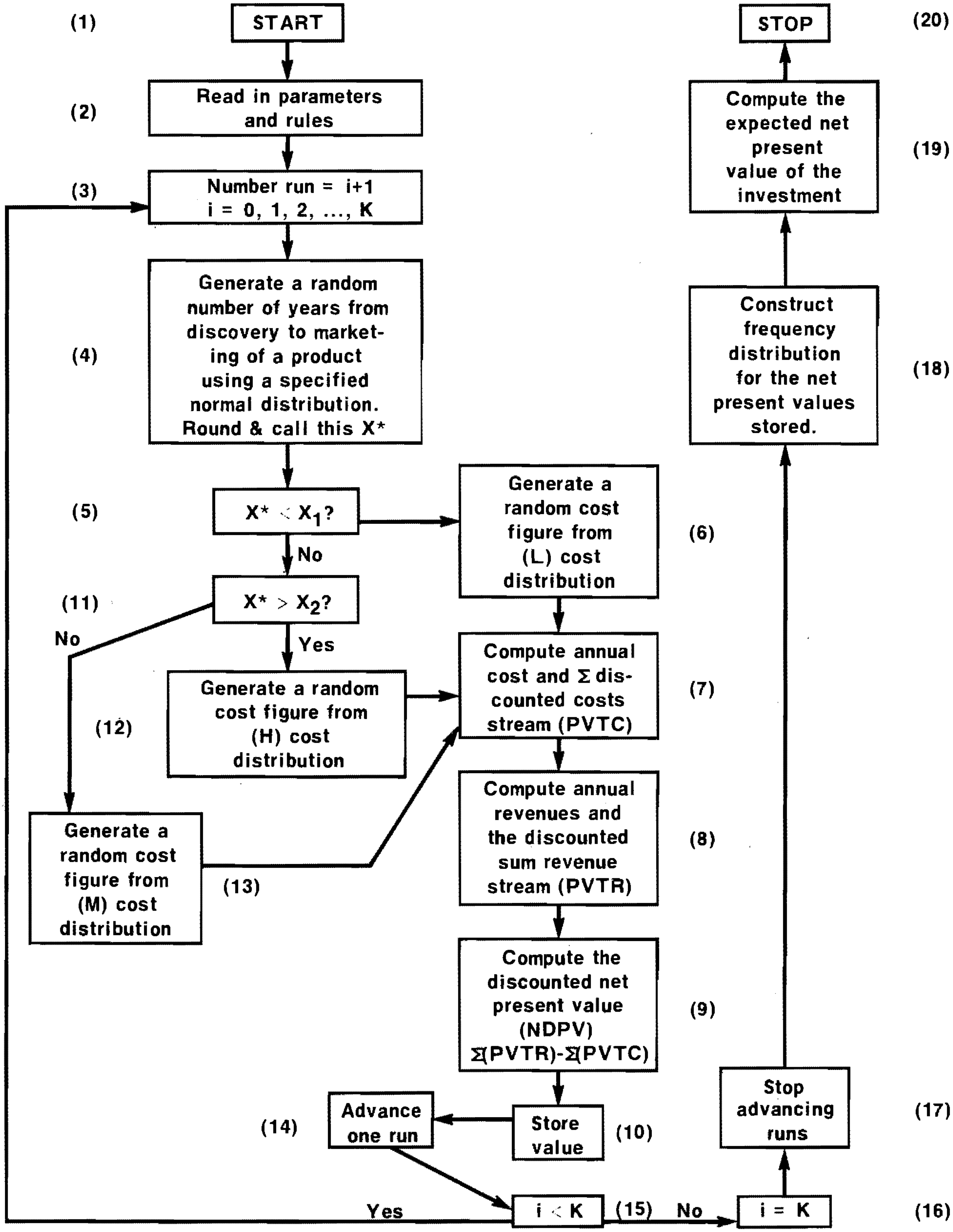
products, etc.). These factors must be determined and combined to obtain a measure of the attractiveness of the proposed investment.

c. The parameters. These are the constants of the system. There are three types: (1) the coefficients of the revenue equation, (2) the parameters of the different probability distributions, i.e., under normal conditions the mean and variance, and (3) the assignment of fixed values. The third category includes assigning a constant value to the length of the useful life of the product or to the period of the potential rights from the firm's viewpoint. It also includes the constant value assigned to the revenue from the first year's sales, which is needed to calculate the second year's sales. Finally, it includes assigning a constant value to the interest rate used in the discounting procedure.

d. Development of computational techniques. The calculations necessary to simulate the various values in the model are outlined in Figure 6.

The program begins by reading in values of constants and rules. The computer generates random variables from a time-from-discovery-to-sale distribution and then generates a random total cost figure from a cost distribution. The choice of a cost distribution depends on the value of the time variable. It is assumed that the lower the number of years spent from first discovery to marketing, the lower the cost. Therefore, it is assumed that management develops a number of probability distributions of the costs, each corresponding to a different

Figure 6: Flow chart of calculations required to simulate net present value for investment proposal



range of values for the time required. In this model it is assumed that there are three cost distributions, with high, medium and low means corresponding to high, medium and low ranges in number of years, respectively. Next, the computer divides the total cost figure by the number (rounded) of years chosen and derives the annual cost.[17/]

The cost stream is then discounted to compute and store a present value of total cost (PVTC).

Calculation of the annual revenue streams then begins. The revenues are computed according to the relationships specified for each of the fixed market horizons. The revenues then are discounted and summed to give a present value of total revenue (PVTR), which is stored. Next, a net discounted present value of the investment (NDPV) is computed by simply subtracting the sum of the present value of total costs (PVTC) from the sum of the present value of the total revenues: NDPV = PVTR - PVTC. The NDPV is then stored and the above procedure is repeated the desired number of times.

The stored NDPV's are then used to derive a frequency distribution, mean and variance of NDPV. In the last step, the values and their relative frequencies are used to compute the expected net present value of the investment.

[17/] The assumption of even annual costs is important to simplify the discounted cost stream calculations. In addition, no other production costs are assumed after the marketing begins.

RESULTS OF THE SIMULATION MODEL

The investment model simulates the pesticide industry's uncertain net present value (NPV) for an investment in a narrow-spectrum pesticide for mosquito control. The total revenues, costs and time required from discovery to marketing of a pesticide were estimated for three different firm-size groups. One run of the model simulates an estimate of the NPV and a total of 100 runs were made for each of several conditions.

The estimated equation for total revenue (TR) from the sales of pesticides to mosquito abatement districts in California is:

$$TR_t = 25{,}894 + \underset{(2.25)^{**}}{1.002}\ TR_{t-1} + \underset{(.30)}{2{,}265.8}\ t - \underset{(-.56)}{193.13}\ t^2 - \underset{(-.88)}{.04186}\ TR_{t-1} \cdot t \qquad \bar{R}^2 = .77$$

where the numbers in parentheses are the t-ratios.

All coefficients of the estimated equation carried the expected signs.

The first year's revenue (FYR) was estimated to approximately equal the average volume of sales ($30,000) of several pesticides in the first year they were used by California mosquito control agencies. Revenues from out-of-state sales were assumed to equal twice as much as California's revenue, while revenues from exports to other countries were assumed to be equal to California's revenue. In calculating the total revenue stream, two (6 percent and 8 percent) discount rates were used.

The total number of years (N) which the firm assumed in calculating its expected net revenue, i.e., $N = P - X^*$ varied for each run according to the specified value of the patent rights (P) and the rounded number of years elapsed from discovery to marketing of the product (X^*). Two values for P were used to compare the effect of different institutions on the industry's investment decisions: the current 17-year patent rights and projected 20-year rights.

A subsidy in the form of a lump sum of money distributed over a number of years would add to the firm's gross revenue. The effect of subsidy on the firm's investment decision depends on the amount and method of payment. Therefore, several subsidy amounts and two payment schedules were used in the calculations.

Results from the Kern MAD's LP model provided information on a potential subsidy level. The results were extended to include direct mosquito control cost estimates under several levels of pesticide effectiveness. It was then assumed that the control district can substitute source reduction for pesticides as the effectiveness of available pesticides declines and can utilize all available labor hours to keep mosquito numbers at or below the specified levels, i.e., A. nigromaculis $\leq$ .5893 and C. tarsalis $\leq$ 2.67 female mosquitoes per light-trap night.

If we consider three hypothetical low levels of effectiveness for a pesticide or group of pesticides available to a district, we can calculate how much the district would be willing to pay[18/] to have more effective materials available. Three subsidy levels ($107,066, $430,313 and $4,013,518) under two payment policies, one paid in a lump sum payment and

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[18/] In other words, the amount the district would save if a more effective pesticide were available or the opportunity cost of not having effective pesticides.

the other divided over four years,[19] were calculated from Kern MAD's simulation model. The aggregate subsidies potentially available from the State of California were calculated by assuming that the value obtained by Kern MAD was equal to 5.5 percent of the total potential value of control cost savings to the state if effective pesticides were available. (This proportion was used because 5.5 percent was the average proportion of Kern MAD's budget to the total budgets of all control districts [CMCA, 1975]). Therefore, it was assumed that the total potential state subsidy is equal to 18.18 times the level for Kern MAD.

Hypothesizing that only one pesticide is available to a mosquito control district, with no replacement and that the pesticide is 80 or 60 or 40 percent effective, the amount of money the district would save if a 100 percent effective pesticide were available is equal to the sum of saving in their direct control costs over an extended period equal to the number of years needed for the 100 percent effective pesticide to reach the effectiveness level of the district's current pesticide.

The number of years required for the effectiveness to drop from 100 to 40 percent is assumed to be proportional to the historical time interval used in calculating the effectiveness indices (see Appendix B) for several pesticides.

With six years as a conservative estimate of the period required from discovery to marketing of a pesticide, the subsidies must be paid to the

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[19] Preliminary runs showed that a lump-sum subsidy given at the time of discovery always added more to the total revenue, and thus to the NPV, than did the total discounted payments divided over four years. The lump-sum subsidy is therefore superior and only the results of the calculations under the policy are reported.

chemical industry six years before the time that a 100 percent effective pesticide will be available. The subsidies then enter the firm's calculations as revenues received in the beginning of year seven and therefore must be discounted.

The NACA reports also provided material upon which to base three different probability distributions for the cost of discovery, development and production of a pesticide. These three distributions, which correspond to the cost conditions in 1967, 1970 and 1973, are designated as low, medium and high cost distributions. After a time distribution is specified (for any firm size), a random number of years can be drawn and its value determines which of the three cost distributions is to be used by the program to draw a cost figure. All time and cost probability distributions were assumed to be normal with known means and standard deviation. Appendix Table A-2 summarizes the different time and cost distributions. The results will be discussed in the following section.

For each firm size, 100 simulated net present values were obtained from computer runs under two discount rates for two patent-right periods. These data were then used to construct a frequency distribution for the NPV's and to calculate the relative frequency distribution for each of the outcomes in an interval. (The interval used was $250,000.) The expected net present values were calculated from the relative frequency distribution and the values of the mid-points of the intervals. The results of the calculations are presented in Appendix A tables.

The 96 computed combinations of the NPV frequency distributions which resulted in the expected net present values will not be reproduced here. However, representative illustrations of the computer output are given in Appendix Tables A-5 through A-8.

Discussion and Implications of the Simulation Results

The results indicate that investment in narrow-spectrum pesticides is unprofitable with or without the specified subsidy levels, except in the following cases:

(1) For small firms with low time requirements (i.e., conditions in 1967), a 6 percent discount rate, the highest discounted subsidy level (i.e., $2,829,129) and 17-year patent rights.

(2) For small firms under the same conditions as above but with 20-year patent rights.

(3) For large firms under the same conditions as above and with 20-year patent rights.

The NPV is positive in all three of these cases, with the highest value for (2) above. At the 8 percent rate of discount, which is a more reasonable rate under today's conditions, there were no cases in which investment in narrow-spectrum pesticides is profitable.

It should be remembered that the NPC is a random variable rather than a constant and when a proposed investment is evaluated the usual procedure is to examine the expected value of the NPV. If the expected NPV is greater than zero the investment would be made since this would increase the expected total wealth of the firm more than an investment of the same money elsewhere at the same interest rate used in the calculation.

In addition to distributions of the NPV's the model simulated distributions for discounted costs and returns. The mean discounted costs ranged from $4.9 million to $5.4 million, with the simulated costs tending to be higher when the time requirement was higher, i.e., after government regulations increased.

The mean discounted simulated revenues ranged from less than $2 million to a little over $5 million. The subsidy always increased the mean value of the simulated revenues because it was specified to add to the cash inflow: the higher the subsidy and the longer the patent life, the higher the simulated revenue. However, examination of both discounted costs and revenues indicates that the mean simulated costs exceeded the mean simulated revenues with very few exceptions (for example, large firms under less restricted conditions).

The results of the pesticide industry's investment model therefore imply that if present cost conditions persist for both narrow-spectrum and broad-spectrum pesticides, it is not profitable, either with or without subsidy and with either patent-rights period, for a firm to invest its capital in a pesticide to be used only for mosquito control. The results indicate that the expected loss would be lower if the industry invested in the development of narrow-spectrum pesticides under the time requirements which existed before the more rigorous government regulation of pesticide production and that a higher subsidy level would provide more incentive for the industry to invest in these products. However, with insufficient data available regarding the social costs of disease, epidemics, etc., it is difficult to justify a higher subsidy.

Conclusions

The outlook appears bleak for a future supply of new narrow-spectrum pesticides, especially those targeted for minor uses such as the control of mosquitoes. The results of this study indicate that increased governmental regulations arising from environmental and safety concerns have eliminated most of the financial incentive for undertaking research and development of such a product. Although the revenue potential for narrow-spectrum pesticides remains about the same, governmental regulations have significantly increased the costs of bringing a new product to market by increasing the length of time from discovery to marketing, requiring additional testing for efficacy and environmental impacts on nontarget species and increasing registration costs. From this study it appears that subsidies, of up to $4 million, would not make investment in a narrow-spectrum mosquitocide financially feasible for commercial firms.

Loss of new narrow-spectrum mosquitocides to the California mosquito control industry would reduce the flexibility now enjoyed by abatement districts in controlling mosquitoes. However, the results of this study indicate there may be some real but less obvious benefits from this situation. The results presented in the first section of this report strongly indicate an overdependence on chemical control methods especially when the long-term costs of pesticide resistance is taken into account. It was shown that physical source reduction was much more cost-effective in areas where drainage and ditching were feasible. Therefore, except during emergencies such as epidemics, the loss of chemical control alternatives will increase the pressure for abatement districts to shift to nonchemical controls and to develop a more optimal mosquito control strategy.

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APPENDIX A

Appendix Table A-1

Synthetic Organic Pesticide Production and Sales in the U.S., 1954-1972[a]

Year	Production Quantity 1000 pounds	Production Change from Previous Year - %	Sales[b] (Domestic & Exports) Value 1000 $	Sales[b] (Domestic & Exports) Change from Previous Year - %
1954	419,274	--	124,501	--
1955	506,376	20.8	152,772	22.7
1956	569,927	12.6	172,908	13.2
1957	511,552	-10.2	178,039	3.0
1958	539,396	5.4	196,149	10.2
1959	585,446	8.5	225,469	14.9
1960	647,795	10.6	261,789	16.1
1961	699,699	8.0	302,955	15.7
1962	729,718	4.3	346,301	14.3
1963	763,477	4.6	369,140	6.6
1964	782,749	2.5	427,111	15.7
1965	877,197	12.1	497,066	16.4
1966	1,013,110	15.5	583,802	17.4
1967	1,049,663	3.6	787,043	34.8
1968	1,192,360	13.6	849,240	7.9
1969	1,104,381	-7.4	851,166	.2
1970	1,034,075	-6.4	870,314	2.2
1971	1,135,717	9.8	979,083	12.5
1972	1,157,698	1.9	1,091,708	11.5

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[a] Includes a small quantity of soil conditions.

[b] Value of sales is not equal to value of production since it is assumed that not all production is sold in the same calendar year. The values in the table are nominal; inflation is not taken into account.

Source: The Pesticide Review [USDA, 1973], 1963-64, 1971 and 1973. United States Department of Agriculture, Agricultural Stabilization and Conservation Service.

Appendix Table A-2

The Chemical Industry's Time and Cost Distributions for Three Firm Sizes

	Time from Discovery to Marketing Distribution Statistics			Total Cost Distribution Statistics[c]	
Time Base[a]	Mean Number of Years Elapsed	Standard Deviation	Cost[b] Condition	Mean	Standard Deviation
S_{t1}: Small firms and low time requirements	4.66	.166	L	$2,905,000	$1,042,000
			M	4,365,000	1,667,000
			H	6,112,963	1,420,000
S_{t2}: Small firms and higher time requirements	6.08	.500	L	$2,905,000	1,042,000
			M	4,365,000	1,667,000
			H	6,112,963	1,420,000
M_{t1}: Medium firms and low time requirements	5.42	.667	L	$3,505,000	916,800
			M	5,479,000	1,250,200
			H	6,112,963	1,420,000
M_{t2}: Medium firms and higher time requirements	6.75	.556	L	$3,505,000	916,800
			M	5,479,000	1,250,200
			H	6,112,963	1,420,000
L_{t1}: Large firms and low time requirements	4.75	.333	L	$4,071,000	600,100
			M	6,112,963	1,420,000
			H	7,285,000	1,417,000
L_{t2}: Large firms and higher time requirements	6.50	.667	L	$4,071,000	600,100
			M	6,112,963	1,420,000
			H	7,285,000	1,417,000

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[a] A time base designated by the subscript "t1" corresponds to conditions with less governmental regulation. A time base designated by the subscript "t2" corresponds to conditions under more regulation.

[b] "L," "M" and "H" represent low, medium and high cost distributions, respectively.

[c] Note from the flow chart in Figure 6 the distribution from which the total undercounted cost is drawn is conditional on the number of years from discovery to marketing (X*). After both these parameters are established the annual cost (and thus the present value of total cost for a particular sized firm) is calculated.

Appendix Table A-3

Expected Net Present Values of Investment in a Narrow-Spectrum Pesticide, with and without Subsidy, for Three Chemical Firm Sizes under 17- and 20-Year Patent Rights and a 6 Percent Discount Rate

Firm Size and Time Requirement from Discovery to Marketing	Patent Rights = 17 Years				Patent Rights = 20 Years			
	Expected NPV When Subsidy = 0 (millions)	Expected NPV When Subsidy a/ Is: $75,471 (millions)	$303,328 (millions)	$2,829,129 (millions)	Expected NPV When Subsidy = 0 (millions)	Expected NPV When Subsidy a/ Is: $75,471 (millions)	$303,328 (millions)	$2,829,129 (millions)
Small firms and lower time	- $ 2.8	- $ 2.7	- $ 2.5	+ $ .017	- $ 2.7	- $ 2.6	- $ 2.3	+ $ .185
Small firms and higher time	- $ 3.4	- $ 3.3	- $ 3.1	- $ .57	- $ 3.2	- $ 3.1	- $ 2.9	- $ .357
Medium firms and lower time	- $ 3.1	- $ 3.1	- $ 2.9	- $ .325	- $ 3.0	- $ 2.9	- $ 2.7	- $ .140
Medium firms and higher time	- $ 3.3	- $ 3.2	- $ 3.0	- $ .445	- $ 3.0	- $ 2.9	- $ 2.7	- $ .212
Large firms and lower time	- $ 2.8	- $ 2.7	- $ 2.5	- $ 0.00	- $ 2.7	- $ 2.6	- $ 2.4	+ $ .155
Large firms and higher time	- $ 3.6	- $ 3.5	- $ 3.2	- $ .733	- $ 3.3	- $ 3.2	- $ 3.0	- $ .057

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a/ These values are lump-sum subsidies and are equal to the discounted (at 6%) sum which the mosquito control agencies would be willing to pay for an effective pesticide to replace materials which are ineffective.

Appendix Table A-4

Expected Net Present Values of Investment in a Narrow-Spectrum Pesticide, with and without Subsidy, for Three Chemical Firm Sizes under 17- and 20-Year Patent Rights and an 8 Percent Discount Rate

Firm Size and Time Requirement from Discovery to Marketing	Patent Rights = 17 Years				Patent Rights = 20 Years			
	Expected NPV When Subsidy = 0	Expected NPV When Subsidy a/ Is:			Expected NPV When Subsidy = 0	Expected NPV When Subsidy a/ Is:		
		$68,522	$275,400	$2,568,651		$68,522	$275,400	$2,568,651
	(millions)	(millions)	(millions)	(millions)	(millions)	(millions)	(millions)	(millions)
Small firms and lower time	- $ 3.1	- $ 3.0	- $ 2.8	- $ .470	- $ 2.9	- $ 2.9	- $ 2.7	- $ .360
Small firms and higher time	- $ 3.5	- $ 3.5	- $ 3.3	- $ .96	- $ 3.4	- $ 3.4	- $ 3.2	- $ .80
Medium firms and lower time	- $ 3.3	- $ 3.3	- $ 3.1	- $ .710	- $ 3.2	- $ 3.2	- $ 3.1	- $ .60
Medium firms and higher time	- $ 3.4	- $ 3.4	- $ 3.2	- $ .77	- $ 3.2	- $ 3.2	- $ 3.0	- $ .63
Large firms and lower time	- $ 3.1	- $ 3.0	- $ 2.8	- $ .45	- $ 3.0	- $ 2.9	- $ 2.7	- $ .30
Large firms and higher time	- $ 3.7	- $ 3.6	- $ 3.4	- $ .960	- $ 3.5	- $ 3.5	- $ 3.3	- $ .85

a/ These values are lump-sum subsidies and are equal to the discounted (at 8%) sum which the mosquito control agencies would be willing to pay for an effective pesticide to replace materials which are ineffective.

Appendix Table A-5

NPV Frequency Distributions for Small Firms and Low Time Requirements at a 6 Percent Discount Rate

	Freq	CRF	RF	Mid Pt		Freq	CRF	RF	Mid Pt
Patent	1	.01	.01	-6.345 *	Patent	1	.01	.01	-3.625 *
Rights =	0	.01	.00	-6.125	Rights =	0	.01	.00	-3.375
17 Years	0	.01	.00	-5.875	17 Years	0	.01	.00	-3.125
	1	.02	.01	-5.625 *		2	.03	.02	-2.625 **
	1	.03	.01	-5.375 *		2	.05	.02	-2.375 **
Subsidy =	2	.05	.02	-5.125 **	Subsidy =	3	.08	.03	-2.125 ***
zero	3	.08	.03	-4.875 ***	$2,829,129	3	.11	.03	-1.875 ***
	4	.12	.04	-4.625 ****		5	.16	.05	-1.625 *****
	5	.17	.05	-4.375 *****		7	.23	.07	-1.375 *******
	6	.23	.06	-4.125 ******		4	.27	.04	-1.125 ****
	8	.31	.08	-3.875 ********		10	.37	.10	-0.875 **********
	6	.37	.06	-3.625 ******		2	.39	.02	-0.625 **
	7	.44	.07	-3.375 *******		12	.51	.12	-0.375 ************
	12	.56	.12	-3.125 ************		7	.58	.07	-0.125 *******
	2	.58	.02	-2.875 **		5	.63	.05	0.125 *****
Mean =	8	.66	.08	-2.625 ********	Mean =	5	.68	.05	0.375 *****
-$2,937,038	3	.69	.03	-2.375 ***		4	.72	.04	0.625 ****
	3	.72	.03	-2.125 ***	-$ 107,909	4	.76	.04	0.875 ****
	4	.76	.04	-1.875 ****		3	.79	.03	1.125 ***
	4	.80	.04	-1.625 ****		2	.81	.02	1.375 **
	1	.81	.01	-1.375 *		2	.83	.02	1.625 **
Standard	3	.84	.03	-1.125 ***	Standard	3	.86	.03	1.875 ***
Deviation =	3	.87	.03	-0.875 ***	Deviation =	3	.89	.03	2.125 ***
$1,605,242	2	.89	.02	-0.625 **	$1,605,242	1	.90	.01	2.375 *
	1	.90	.01	-0.375 *		2	.92	.02	2.625 **
	2	.92	.02	-0.125 **		0	.92	.00	2.875
	1	.93	.01	0.125 *		3	.95	.03	3.125 ***
Expected NPV =	4	.97	.04	0.375 ****	Expected NPV	3	.98	.03	3.375 ***
	1	.98	.01	0.625 *	= $ 17,500	0	.98	.00	3.625
-$2,802,500	0	.98	.00	0.875		1	.99	.01	3.875 *
	2	1.00	.02	1.125 **		1	1.00	.01	4.125 *

Note: Abbreviations used in Appendix Tables A-5 through A-8 are as follows:

Freq = Frequency
CRF = Cumulative Relative Frequency
RF = Relative Frequency
Mid Pt = Midpoints of Intervals of the NPV's

Appendix Table A-6

NPV Frequency Distributions for Small Firms and Low Time Requirements at a 6 Percent Discount Rate

	Freq	CRF	RF	Mid Pt			Freq	CRF	RF	Mid Pt	
	1	.01	.01	-6.375	*		1	.01	.01	-3.375	*
Patent	0	.01	.00	-6.125		Patent	0	.01	.00	-3.125	
Rights =	0	.01	.00	-5.875		Rights =	0	.01	.00	-2.875	
20 Years	1	.02	.01	-5.375	*	20 Years	1	.02	.01	-2.625	*
	3	.05	.03	-5.125	***		1	.03	.01	-2.375	*
	2	.07	.02	-4.875	**		2	.05	.02	-2.125	**
Subsidy =	2	.09	.02	-4.625	**	Subsidy =	3	.08	.03	-1.875	***
zero	3	.12	.03	-4.375	***	$2,829,129	4	.12	.04	-1.625	****
	6	.18	.06	-4.125	******		5	.17	.05	-1.375	*****
	8	.26	.08	-3.875	********		6	.23	.06	-1.125	******
	11	.37	.11	-3.625	***********		8	.31	.08	-0.875	********
	1	.38	.01	-3.375	*		6	.37	.06	-0.625	******
	9	.47	.09	-3.125	*********		8	.45	.08	-0.375	********
	11	.58	.11	-2.875	***********		11	.56	.11	-0.125	***********
	4	.62	.04	-2.625	****		3	.59	.03	0.125	***
	5	.67	.05	-2.375	*****		7	.66	.07	0.375	*******
Mean =	2	.69	.02	-2.125	**	Mean =	3	.69	.03	0.625	***
-$2,777,503	7	.76	.07	-1.875	*******	-$ 51,625	4	.73	.04	0.875	****
	2	.78	.02	-1.625	**		3	.76	.03	1.125	***
	2	.80	.02	-1.375	**		4	.80	.04	1.375	****
	2	.82	.02	-1.125	**		1	.81	.01	1.625	*
	4	.86	.04	-0.875	****		4	.85	.04	1.875	****
Standard	3	.89	.03	-0.625	***	Standard	3	.88	.03	2.125	***
Deviation =	1	.90	.01	-0.375	*	Deviation =	1	.89	.01	2.375	*
$1,595,240	1	.91	.01	-0.125	*	$1,595,240	1	.90	.01	2.625	*
	1	.92	.01	0.125	*		2	.92	.02	2.875	**
	3	.95	.03	0.375	***		1	.93	.01	3.125	*
	3	.98	.03	0.625	***		4	.97	.04	3.375	****
Expected NPV =	0	.98	.00	0.875		Expected NPV =	1	.98	.01	3.625	*
-$2,662,500	1	.99	.01	1.125	*	$ 185,000	0	.98	.00	3.875	
	1	1.00	.01	1.375	*		2	1.00	.02	4.125	**

Appendix Table A-7

NPV Frequency Distributions for Small Firms and Higher Time Requirements at a 6 Percent Discount Rate

	Freq	CRF	RF	Mid Pt			Freq	CRF	RF	Mid Pt	
Patent	1	.01	.01	-6.375	*	Patent	1	.01	.01	-3.625	*
Rights =	0	.01	.00	-6.125		Rights =	0	.01	.00	-3.375	
17 Years	0	.01	.00	-5.875		17 Years	0	.01	.00	-3.125	
	2	.03	.02	-5.625	**		0	.01	.00	-2.875	
	1	.04	.01	-5.375	*		3	.04	.03	-2.625	***
Subsidy =	3	.07	.03	-5.125	***	Subsidy =	2	.06	.02	-2.375	**
zero	3	.10	.03	-4.875	***	$2,829,129	4	.10	.04	-2.125	****
	5	.15	.05	-4.625	*****		3	.13	.03	-1.875	***
	7	.22	.07	-4.375	*******		7	.20	.07	-1.625	*******
	8	.30	.08	-4.125	********		8	.28	.08	-1.375	********
	12	.42	.12	-3.875	************		8	.36	.08	-1.125	********
	3	.45	.03	-3.625	***		8	.44	.08	-0.875	********
	10	.55	.10	-3.375	**********		14	.66	.14	-0.375	**************
	13	.68	.13	-3.125	*************		4	.70	.04	-0.125	****
Mean =	4	.72	.04	-2.875	****	Mean =	8	.78	.08	0.125	********
-$3,517,382	7	.79	.07	-2.625	*******	-$ 688,253	4	.82	.04	0.375	****
	5	.84	.05	-2.375	*****		5	.87	.05	0.625	*****
	6	.90	.06	-2.125	******		6	.93	.06	0.875	******
Standard	2	.95	.02	-1.625	**	Standard	1	.94	.01	1.125	******
Deviation	1	.96	.01	-1.375	*	Deviation =	2	.96	.02	1.375	**
$1,127,967	2	.98	.02	-1.125	**	$1,136,307	1	.97	.01	1.625	*
	1	.99	.01	-0.875	*		2	.99	.02	1.875	**
	0	.99	.00	-0.625			0	.99	.00	2.125	
Expected NPV =	0	.99	.00	-0.375		Expected NPV	0	.99	.00	2.375	
-$3,392,500	0	.99	.00	-0.125		-$ 567,000	0	.99	.00	2.625	
	1	1.00	.01	0.125	*		1	1.00	.01	2.875	*

Appendix Table A-8

NPV Frequency Distributions for Small Firms and Higher Time Requirements at a 6 Percent Discount Rate

	Freq	CRF	RF	Mid Pt			Freq	CRF	RF	Mid Pt	
Patent	1	.01	.01	-6.125	*	Patent	1	.01	.01	-3.375	*
Rights =	0	.01	.00	-5.875		Rights =	0	.01	.00	-3.125	
20 Years	0	.01	.00	-5.625		20 Years	0	.01	.00	-2.875	
	2	.03	.02	-5.375	**		1	.02	.01	-2.625	*
	1	.04	.01	-5.125	*		2	.04	.02	-2.375	**
Subsidy =	4	.08	.04	-4.875	****	Subsidy =	3	.07	.03	-2.125	***
zero	3	.11	.03	-4.625	***	$2,829,129	3	.10	.03	-1.875	***
	4	.15	.04	-4.375	****		3	.13	.03	-1.625	***
	7	.22	.07	-4.125	*******		9	.22	.09	-1.375	*********
	9	.31	.09	-3.875	*********		6	.28	.06	-1.125	******
	13	.44	.13	-3.625	*************		10	.38	.10	-0.875	**********
	2	.46	.02	-3.375	**		7	.45	.07	-0.625	*******
	12	.58	.12	-3.125	************		9	.54	.09	-0.375	*********
	10	.68	.10	-2.875	**********		12	.66	.12	-0.125	************
Mean =	4	.72	.04	-2.625	****	Mean =	6	.72	.06	0.125	******
-$3,303,905	8	.80	.08	-2.375	********	-$ 474,776	6	.78	.06	0.375	******
	7	.87	.07	-2.125	*******		5	.83	.05	0.625	*****
	3	.90	.03	-1.875	***		7	.90	.07	0.875	*******
Standard	3	.93	.03	-1.625	***	Standard	3	.93	.03	1.125	***
Deviation	2	.95	.02	-1.375	**	Deviation =	2	.95	.02	1.375	**
$1,128,657	1	.96	.01	-1.125	*	$1,128,657	1	.96	.01	1.625	*
	2	.98	.02	-0.875	**		2	.98	.02	1.875	**
	1	.99	.01	-0.625	*		1	.99	.01	2.125	*
Expected NPV =	0	.99	.00	-0.375		Expected NPV	0	.99	.00	2.375	
-$3,177,500	0	.99	.00	-0.125		-$ 357,500	0	.99	.00	2.625	
	1	1.00	.01	0.125	*		0	.99	.00	2.875	
							1	1.00	.01	3.125	*

APPENDIX B

Derivation of Pesticides' Effectiveness Indices

The pesticide effectiveness indices were included in the mosquito abatement annual-data models for Delta VCD and Kern MAD. The variables were K_9, K_{11} and K_{14} in Kern MAD's model. The average effectiveness functions were used in this study in lieu of resistance functions because of the difficulty in quantifying several variables which affect the resistance of mosquitoes to pesticides.

The effectiveness indices which were generated and used as independent variables in the estimation of the effectiveness functions were based on several simplified assumptions and each generated index represented the average effectiveness of all pesticides used in the district during any year. The indices are measured as the average field percentage control attained by all pesticides rather than the usual laboratory LD_{50} used by entomologists for individual chemicals.1/

The field-percentage measure of pesticides' control is used by the districts studied as a measure of the degree of mosquito resistance (or the effectiveness of pesticides). The percentage of control (or kill) in the field is defined in this study as that number of out of 100 acres sprayed or 100 locations treated which does not require respraying or retreatment. For example, if 10 percent of the acres sprayed must be retreated with pesticides, then the effectiveness of one application of pesticides is 90 percent.

1/ It should be recognized that although there is a correlation between the average field percentage measure of effectiveness and the LD_{50} measurement used in laboratory tests, they are not necessarily the same.

Since data on field percentage control were not kept by the districts for the entire period of this study, it was necessary to generate observations of these measurements. Therefore, the following assumptions were made:

(1) Pesticides applied against one species simultaneously affect other species present in the area.

(2) As the number of mosquito generations subjected to pesticides increases, the average effectiveness of pesticides declines, i.e., resistance to pesticides increases.

(3) The average number of generations per year (March - November) is assumed to be:

		Mar	Apr	May	June	July	Aug	Sep	Oct	Nov
A. nigromaculis	15 generations	1	1	2	2	3	3	2	1	a/
C. tarsalis	12 generations	1	1	2	2	2	2	1	1	a/
C.p. quinquefasciatus	13 generations	1	1	1	2	2	2	2	2	a/

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a/ If a pesticide treatment was reported in November, it was assumed to affect one additional generation.

(4) When a pesticide has been used during a month it is assumed that all mosquito generations of that month have been subjected to its effect.

(5) For each class of pesticides, the average time of use before mosquitoes show signs of resistance will be higher for the first product in the class than for those which follow. (This assumption is accounted for by cross resistance.)

(6) A new pesticide has an effectiveness index of 100, i.e., it is 100 percent effective at the first application.

(7) A pesticide is replaced when repeated field observations show that its effectiveness is less than or equal to 80 percent.

(8) The effectiveness index for a pesticide (e_t) 100 if $t \leq a$
at any generation t is equal to $e_t - b$ if $t > a$

where t is the number of generations affected by the pesticide,

a is the number of generations elapsed when resistance (or a decline in effectiveness) appears (this number will differ from one pesticide to another) and

b is the amount of decline in the effectiveness per period as the number of generations treated with pesticides exceeds the critical number "a". (b will differ from one pesticide to another and from one class to another.)

(9) b is estimated as follows:

b = 20 ÷ total number of generations affected by the pesticide − the number of generations elapsed when resistance is first observed.

Therefore, b, the decline per period, is the same for each period but the rate of decline is increasing. For example, a one-unit decline from an original effectiveness of 95 percent indicates a rate of decline equal to 1.05 percent, but the rate is 1.1 percent if the original effectiveness level was 90 percent. This implies that resistance develops faster as the number of mosquito generations subjected to pesticide selection pressure increases.

(10) The generated average effectiveness index is weighted average of effectiveness of each class of pesticide used during the season. Effectiveness of each class is in turn a weighted average of effectiveness of each product in that class. The following table summarizes the parameters used in calculating the effectiveness index for each pesticide.

Appendix Table B-1

Calculation of Effectiveness Index

Class	Pesticide[a/]	(a) Number of generations before resistance is observed	(c) Maximum number of generations treated or estimated to be treated before replacement	$\frac{20}{c-a}$
			Kern MAD	Kern MAD
Chlorinated hydrocarbons:	DDT	40	b/	b/
		32	b/	b/
	Toxaphene			
	Chlordane	32	b/	b/
Organophosphorus:	Parathion	96	300	.0980
	EPN	96	300	.0980
	M. Parathion	48	142	.2128
	Malathion	48	136	.2273
	Dibrom	48	300	.0794
	Baytex	48	300	.0794
	Dursban	48	300	.0794

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a/ Baygon and Altosid were assumed to be 100 percent effective during the period of this study.

b/ No use reported or data available during the study period.

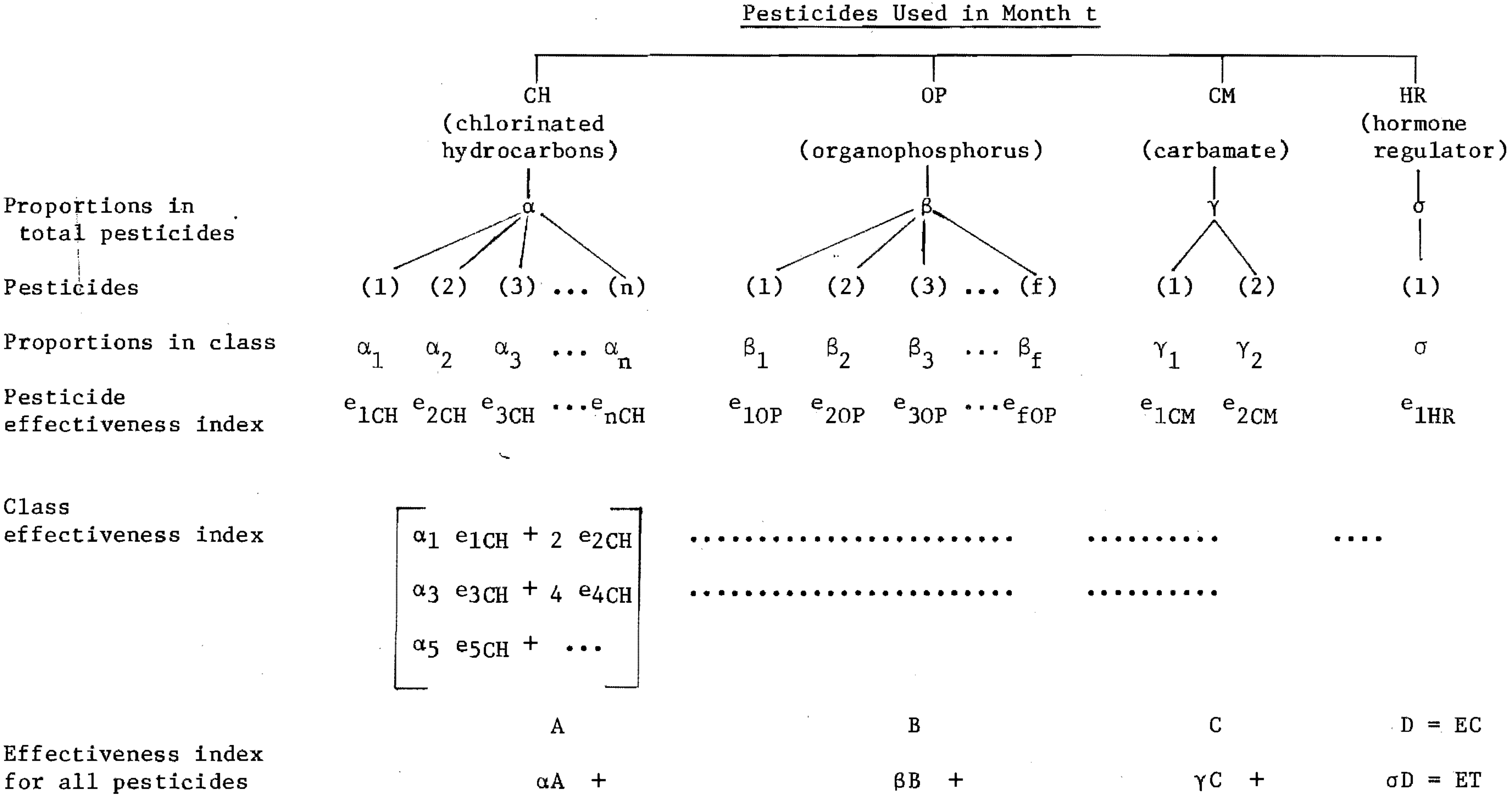
The information shown in the Table[2/] was used to calculate the amount of per-generation decline in pesticide effectiveness for each species after the initial 100 percent effectiveness has begun to decline, i.e., $b = \frac{20}{c-a}$. It should be noted that the number of generations in any year differs from species to species, so the time when one species develops resistance to a pesticide will not necessarily be the same for all species. For example, *A. nigromaculis* will be more likely to develop resistance before *C. tarsalis*. Also, the total decline in effectiveness in one season depends on the number of generations subjected to pesticides' selection pressure, so we expect that the decline or deterioration in effectiveness will be faster for *A. nigromaculis* than for other species.

The above information was then used to calculate annual effectiveness indices for each species and for each pesticide in each class of pesticides. The resulting figures were weighted by the values of each pesticide in the total class (α_i, β_i, γ_i, σ_i) to obtain the average class index, EC. The average class indices were then weighted by each class value in the total pesticides during the year (α, β, σ). An average annual index for pesticides, ET, was then obtained and used as a dependent variable in equations (8), (9) and (10) of the abatement models. (See Figure B-1.)

[2/] This information was based on data obtained from the control districts' reports and from: Mulla, Mir S., "Solution to the Phosphate Resistance Problem," papers and procedures of the 33rd Annual Conference of the California Mosquito Control Association, Inc., 1966, pp. 73-76.

Appendix Figure B-1

Summary of the Calculations of the Effectiveness Index for Each Species



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where n = number of pesticides in CH class and f = number of pesticides in OP class.

APPENDIX C

Appendix Figure C-1

Expected Coefficient Signs - Kern County Mosquito Abatement District (MAD) (Annual Model)

Normalized Endogenous Variables	Expected sign of:																								
	K_1	K_2 [a]	K_3 [b]	K_4	K_5	K_6	K_7	K_8	K_9	K_{10}	K_{11}	K_{12}	K_{13}	K_{14}	K_{15}	K_{16}	K_{17} [c]	K_{18} [c]	K_{19}	K_{20}	K_{1t-1}	K_{4t-1}	K_{5t-1}	K_{10t-1}	K_{12t-1}
K_1		+ or -	+	-	-	-	-	-	-												+				
K_{10}		+ or -	+	-	-	-	-	-			-													+	
K_{12}		+ or -			-								+	-											+
K_4	+		+							+					+	+						+			
K_5	+									+		+				+							+		
K_7				+ or -												+	+ or -								
K_8	-			+ or -						-						+		+							
K_9	+ or -																+	+	-	-					
K_{11}										+ or -							+	+	-	-					
K_{14}												+ or -								-					

[a] Positive up to a specie specific limit, then negative if the number of days above 100° F. is excessive.

[b] The trade-off between K_4 and source reduction may be positive or negative depending on the MAD practices and philosophy.

[c] Indeterminate sign because current activities depend on the extent of the accumulated source reduction and the MAD management philosophy.

APPENDIX D

Appendix Table D-1

Kern MAD Monthly-Data Model: Empirical Estimation Results

		Number of Mosquitoes			Acres treated with pesticides	Locations treated with pesticides
		A. nigromaculis Equa. 17 (k_1)	*C. tarsalis* Equa. 18 (k_9)	*C.p. quinque fasciatus* Equa. 19 (k_{10})	Equa. 20 (k_4)	Equa. 21 (k_5)
				Endogenous Variables		
Constant term:		11.3760	-27.2010	- .4367	1.0142	25.3062
A. nigromaculis numbers	(k_1)				- .0095 (.11)[a]	- .3923 (1.09)
C. tarsalis numbers	(k_9)				.1116 (1.21)	.4796 (.79)
C.p. quinque-fasciatus numbers	(k_{10})					- 8.2138 (-1.03)
Acres treated with pesticides	(k_4)	3.450*** (5.14)	.227 (.50)			
Locations treated with pesticides	(k_5)	- .1156 (-1.03)	- .0982 (1.17)	.0071** (1.78)		

Appendix Table D-1-- Continued

		Number of Mosquitoes			Acres treated with pesticides	Locations treated with pesticides
		A. nigromaculis Equa. 17 (k_1)	*C. tarsalis* Equa. 18 (k_9	*C.p. quinque fasciatus* Equa. 19 (k_{10})	Equa. 20 (k_4)	Equa. 21 (k_5)
				Predetermined Variables		
A. nigromaculis numbers in the previous month	(k_{1t-1})	.1318* (1.59)				
C. tarsalis numbers in previous month	(k_{9t-1})		.4233*** (4.04)			
C.p. quinquefasciatus numbers in the previous month	(k_{10t-1})			.5070*** (6.77)		
Temperature	(k_2)	- .4047 (-1.10)	.4452** (2.11)	.0043 (.42)		
Rainfall	(k_3)	1.4387 (.47)	1.5900 (.90)	.0231 (.21)		
Irrigation water	(k_6)	.0344 (1.28)	.00149 (.084)		.0125** (2.27)	
River flow	(k_7)	-.1631*** (-4.36)	.00054 (.021)		.0367*** (6.53)	
Fills constructed in the previous month	(k_8)	.0832 (.20)	-.2922* (-1.30)			

Appendix Table D-1--Continued

		Number of Mosquitoes			Acres treated with pesticides	Locations treated with pesticides
		A. nigromaculis Equa. 17 (k_1)	*C. tarsalis* Equa. 18 (k_9	*C.p. quinque fasciatus* Equa. 19 (k_{10})	Equa. 20 (k_4)	Equa. 21 (k_5)
				Predetermined Variables		
Acres treated with pesticides in the previous month	(k_{4t-1})			.3710***^{a} (3.93)		
Locations treated with pesticides in the previous month	(k_{5t-1})				561.6*** (6.31)	

a/ t-ratios are given in parentheses below the respective coefficient estimate.
***, ** and * designate the level of significance equal to 1%, 5% and 10%, respectively.

t-ratio is defined as t = b_i/standard error of b_i, where b_i's are the estimated coefficients.