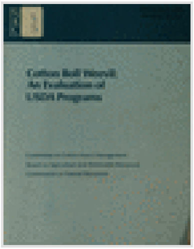

Cotton Boll Weevil: An Evaluation of USDA Programs : a Report (1981)

Pages
144

Size
8.5 x 10

ISBN
0309296315

Committee on Cotton Insect Management; Board on Agriculture and Renewable Resources; Commission on Natural Resources; National Research Council

Cotton Boll Weevil: An Evaluation of USDA Programs

A Report Prepared by the
Committee on Alternative Programs for Beltwide Cotton Insect Management
Board on Agriculture and Renewable Resources
Commission on Natural Resources
National Research Council

NATIONAL ACADEMY PRESS
Washington, D.C. 1981

NOTICE

The project that is the subject of this report was approved by the Governing Board of the National Research Council, whose members are drawn from the councils of the National Academy of Sciences, the National Academy of Engineering, and the Institute of Medicine. The members of the Committee responsible for the report were chosen for their special competences and with regard for appropriate balance.

This report has been reviewed by a group other than the authors according to procedures approved by a Report Review Committee consisting of members of the National Academy of Sciences, the National Academy of Engineering, and the Institute of Medicine.

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This study was supported by the U.S. Department of Agriculture.

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PREFACE

The United States is a major world supplier of cotton. U.S. production of cotton lint plus seed was valued at $5.1 billion in 1979 and $4.7 billion in 1980. Cotton is the fourth most valuable crop in the United States after corn, soybean, and wheat. Because it is grown only in the South, it represents only 6.8 to 8.1 percent of the total crop receipts for the United States. For the 14 cotton-producing states, however, it represents about 18 to 20 percent of the total crop receipts.

The cotton crop is vulnerable to attack from several insects everywhere, but especially in the humid Southeast. The cotton boll weevil, Anthonomus grandis, attacks developing cotton flowers (pinhead squares) and young cotton bolls and causes them to fall off the plant. Insecticides used to control the boll weevil have an effect on other insects found on cotton as well, and as a result work against modern insect pest strategies directed toward encouraging natural predators and parasites of the cotton insects. The cotton boll weevil entered the United States from Mexico in the late 1800s and is now a key pest in about half the cotton acreage in the United States, seriously infesting 7.3 million acres of a total 14 million. It is a marginal pest on an additional 1.7 million acres. For 1970-1972, boll weevils cost cotton farmers nearly $260 million each year in direct crop loss plus control costs (SEA 1981).

In 1958 the National Cotton Council at their annual convention recommended government action to eradicate the boll weevil. The U.S. Department of Agriculture (USDA) set up a Working Group on Boll Weevil Research Programs to respond to this recommendation, and the Working Group proposed that an interdisciplinary research laboratory be established to concentrate on new approaches to boll weevil control. In 1962 the USDA established the Boll Weevil Research Laboratory in Mississippi State, Mississippi.

By 1968, USDA scientists concluded that boll weevil control technology had advanced sufficiently to justify a field trial of the feasibility of eradication, and a boll weevil eradication test was undertaken in southwest Mississippi. The test area selected was considered to be one of the most difficult areas in which to achieve eradication of the boll weevil. The data from the two-year test completed in 1973 did not conclusively demonstrate the feasibility of eradicating the boll weevil. A second large-scale eradication trial was recommended for either northwest Texas or North Carolina and Virginia. In 1978, two large-scale trials, the Boll Weevil Eradication (BWE) trial in Virginia and North Carolina and the Optimum Pest Management (OPM) trial in Mississippi, were initiated by the USDA to assess which boll weevil/cotton insect management system would be most effective, economical, and environmentally acceptable if implemented beltwide, throughout the cotton-producing areas in the United States.

The USDA appointed four evaluation teams to review the data from the BWE and OPM trials. Teams of economists, biologists, and environmentalists and an overall evaluation team were asked to evaluate the data from the two trials, along with data from additional sources, and to assess and compare the impact of different pest control strategies across the Cotton Belt. The reports prepared by these evaluation teams constitute the USDA's evaluations of beltwide boll weevil/cotton insect management programs.

In the winter of 1978-1979, USDA asked the Board on Agriculture and Renewable Resources of the National Research Council to set up a committee of scientists with expertise in program evaluation and technical expertise in cotton production, entomology, economics, ecology, and statistical analysis to study the conduct and results of the two trials that had just gotten under way and to review the USDA's evaluation team reports that were to assess the practicability of alternative programs for beltwide cotton insect management. The NRC Committee was to consider several cotton insect management programs including current insect control (CIC) programs practiced by cotton producers as implemented by the Cooperative Extension Service, USDA, grower organizations, and private consultants; the OPM trial in Mississippi; the BWE program in Virginia and North Carolina; and other programs including combinations of those mentioned above.

At the conclusion of the trials and the overall evaluation, the NRC Committee was asked to appraise the technical effectiveness of the BWE and OPM trials in relation to alternative pest control options and to assess the biological, economic, and environmental implications of implementing the BWE, OPM, and alternative programs in boll-weevil-infested areas of the Cotton Belt.

In undertaking its task the NRC Committee visited the BWE trial in Virginia and North Carolina and the OPM trial in Mississippi and talked with the program management staff, USDA Cooperative Extension Service and research specialists, growers in the programs, and pest control consultants. We met with entomologists from the cotton-producing states as well as private pest control consultants. Members of the NRC Committee also attended meetings of the USDA Interagency Working Group, the environmental, biological, and economic evaluation teams of USDA, the Southern Plant Board, and the

National Plant Board, and meetings on pheromone trapping technology and the Boll Weevil Sterility Program. During the course of the study, I, as chairman, met with the USDA Boll Weevil Policy Group to discuss the status of the Committee's activities and their concerns about certain aspects of the field trials and evaluation plans.

A major difficulty we encountered was the delays in availability of the final evaluation reports from the USDA evaluation teams. Without these final reports we could not proceed effectively with our review and assessment. The final biological, environmental, and economic reports from USDA were delayed three to six months, and the crucial USDA overall evaluation team report was delayed three months--from February 20 until May 19, 1981. We accommodated these delays by adjusting to a more intensive review schedule.

The USDA has also prepared an Executive Overview, dated May 20, 1981. While we approve the efforts in this additional overview to identify and explore new and improved alternatives, these new scenarios cannot be evaluated on the basis of the data from the BWE and OPM trials.

Special appreciation is extended to those who coordinated the research in the trial programs for their cooperation and efforts to maintain appropriate communication with the NRC Committee.

Kenneth R. Keller, USDA Overall Program Coordinator, provided valuable assistance as USDA's liaison to the NRC Committee. We wish to express our appreciation to him.

We also wish to thank Philip Ross, Executive Secretary of BARR, staff officers James E. Tavares and Selma P. Baron, and secretaries Mary Lou Sutton and Sheridan E. Caldwell for their assistance.

Dean L. Haynes and Carter M. Harrison served as consultants and helped in the preparation of this report. We are grateful for their assistance. The content of the report, however, and the views expressed in it remain the sole responsibility of the NRC Committee.

Gordon E. Guyer, Chairman
Committee on Alternative Programs for Beltwide Cotton Insect Management

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SUMMARY

Since the early years of this century, efforts to control the boll weevil and other insect pests of cotton have been the combined responsibility of the federal government, state governments, and cotton growers themselves. In the laboratories of USDA, of state universities in the Cotton Belt states, and of private chemical companies, scientists in a number of disciplines have continually sought better ways of controlling the boll weevil and other cotton pests, placing most of their emphasis on the development of chemical insecticides. As new insecticides have been created in the laboratories and then manufactured on a commercial scale by chemical companies, the USDA and state agricultural extension services have advised cotton growers--often with the assistance of cotton growers' councils--on how to use these insecticides in the most effective and efficient ways, and to supplement them with other tactics such as cultural practices. This method of dealing with cotton pests is referred to in this report as "current insect control," or CIC. This method, of course, has required cotton growers to spend vast sums of money to purchase and apply the insecticides.

One major problem has been that the boll weevil, *Anthonomus grandis*, has shown remarkable ability in developing biological resistance to each new insecticide over a period of time. Although many of the insecticides developed over the last 40 years were able to reduce boll weevil infestations substantially when first used, none has demonstrated the ability to do so indefinitely. A related problem has been that reductions in boll weevil populations through the use of the newest pesticides have often been accompanied by increases in the populations of other cotton plant pests, such as the bollworm and the tobacco budworm. Furthermore, efforts to control these pests and the many others that also attack the cotton plant have been hampered by the practical difficulties involved in carrying out coordinated control programs among thousands of cotton growers spread out over large geographic areas.

As the demand for cotton has gradually declined in the United States, as each new insecticide has lost its effectiveness against the boll weevil, and as the costs of growing cotton have increased, cotton growers and other interested persons from the Cotton Belt states afflicted by the boll weevil have urged the federal government to assume the responsibility of managing the boll weevil on a coordinated national basis. Those in the cotton industry, as well as many members of Congress from the southern states, have generally advocated an all-out effort to eradicate the boll weevil from the entire United States. Others, however, including a substantial number of scientists, have expressed reservations about the probability of success of any attempt to eradicate--that is, to totally eliminate--the boll weevil population in the United States. Their view is that any federal program should be directed at keeping boll weevil populations below the levels at which they cause economically significant damage to cotton.

Between 1978 and 1980, USDA conducted concurrent three-year trials of these two strategies. One, the boll weevil eradication (BWE) program in North Carolina and Virginia, was intended to reduce the boll weevil population to zero. The other, called the optimum pest management (OPM) program, in Panola County, Mississippi was designed to keep the populations of boll weevils and other cotton pests below economically damaging levels. The BWE trial area increased from 15,500 acres in 1978 to 32,500 acres of cotton in 1980, and the OPM trial in Mississippi involved treatment of cotton acreage that increased annually from approximately 32,000 acres in 1978 to 39,000 acres in 1980.

The principal purpose of this report is to review the conclusions reached from the two experiments as to the probable biological, economic, and environmental effects that might result from federal implementation of either a BWE or OPM program throughout the Cotton Belt. Chapter 1 of the report provides an overall description of cotton culture in the United States and of the insect pests which attack cotton, while Chapter 2 summarizes the various efforts that have been made to reduce the economic damage caused by these pests. Chapter 3 has two parts, one reviews the legislative background for publicly supported pest control programs in general, the other concentrates on federal programs toward the control of the boll weevil in particular. Chapter 4 discusses the OPM and BWE trials in more detail and outlines how they would be implemented if a decision was made to use either one throughout the Cotton Belt. It also touches upon alternative control strategies. Chapter 5, the longest chapter in this report, is an extensive appraisal of the two experimental trials themselves--how they were conducted, the conclusions drawn from them, and the extrapolations of those conclusions made by USDA to determine the probable biological, economic, and environmental effects if either an insect management or eradication program was carried out throughout the Cotton Belt. The USDA identified six alternative beltwide boll weevil/cotton insect management programs. The definitions of these alternative programs are given in Appendix A.

CONCLUSIONS

Overview

The NRC Committee applauds the advances in insect control technology and management that have taken place under the direction of the USDA during the course of the trials such as diapause control, pheromone traps for monitoring population of weevils, and plant breeding. The NRC Committee recognizes the important contribution to the understanding of cotton insects made by the technical monograph on cotton insect management (SEA 1981) and also commends USDA for the imaginative approach and creative efforts to project future impacts of the various programs.

More than 80 years of experience with programs intended to eradicate such pests as the gypsy moth, the fire ant, and the mosquitoes that transmit malaria and yellow fever have demonstrated that the future effects and costs of eradication programs cannot be accurately predicted. Eradication programs must therefore remain open-ended. Since difficulties are likely to appear, eradication efforts may have to be intensified, new technologies may have to be used, and legislative action may be required to enforce full participation by cotton producers.

An acceptable beltwide program for managing cotton pests must be one that allows cotton growers to produce cotton efficiently and causes minimum harm to the environment. Since the biological consequences, environmental effects, and economic costs of an eradication program cannot be predicted with any degree of certainty, specific probabilities should be attached to alternative estimates of public costs and benefits. The probability of success of each level of program effort should be stated, and it is necessary to compare a realistic range of potential benefits with a realistic range of possible costs.

After reviewing the USDA evaluation team reports, the NRC Committee came to the following conclusions about the BWE and OPM trials and the USDA evaluation teams' extrapolation of the data from the trials to beltwide programs:

USDA Biological Evaluation Team Report

- The USDA biological evaluation was based only on data from the two trial areas; therefore, the biologists were unable to make probabilistic extrapolations about the possible effects of either method on the entire boll weevil belt. The implicit inference that these data apply to the entire area inhabited by the boll weevil is statistically invalid.

- The cotton insect complex, the environmental characteristics, the cotton production practices, the insect management practices, and perhaps the boll weevil populations vary considerably from year to year across the Cotton Belt. Yet the OPM and BWE trials and the USDA plans for implementing each one on a beltwide basis provide little information on this heterogeneity or how to deal effectively with it.

- The evidence does not demonstrate that migration was the reason for the discovery of an individual weevil or the discovery of a reproducing weevil population in the BWE trial area. Therefore, the BWE trial did not conclusively demonstrate that eradication was achieved. Even if no weevils had been found, the trial as designed could not have proved conclusively that eradication had been accomplished.

- The migration and dispersal potential of the boll weevil are incompletely understood. There are risks in assuming that the boll weevil is incapable of "jumps" of a much longer distance than what is now accepted as the maximum. It is not possible to judge the prospects for eradication and their costs without more knowledge of boll weevil migration.

- The effectiveness of efforts to sterilize male boll weevils has not been demonstrated. Since the original plan of the BWE trial was based on male sterilization as a basic technique, there is a need to reexamine the role of this technique in future boll weevil control and eradication programs.

- The proposed pheromone trap densities and the length of time they would be operational for monitoring the effectiveness of a beltwide eradication program would be inadequate, particularly for detecting low level infestations.

USDA Economic Evaluation Team Report

- The specific costs for full implementation of the OPM program that would be necessary prior to eradication were not included in projecting the overall costs of the eradication program (OPM-BWE, see definitions in Appendix A), and the regulatory and organizational responsibilities in efforts to eradicate were not defined.

- The NRC Committee believes that the net consumer benefits as well as the loss of net income to producers as calculated in the USDA Economic Evaluation Team Report are inflated (See Table 5.2 that reproduces the table from the USDA report, Economics and Statistics Service 1981b).

- The NRC Committee agrees that if eradication of the boll weevil is adopted as a joint policy and financial responsibility of the federal and state governments and cotton growers, the short-range costs of cotton insect control, both economic and environmental, will rise relative to continuation of current insect control practices. However, the long range economic and environmental costs of a BWE program or CIC cannot be predicted from either the trial data, which do not address the heterogeneity across the Cotton Belt, or the Delphi panel data, which are subjective projections and estimates obtained from pest control experts and cotton producers.

- The NRC Committee agrees if an OPM program, implemented area by area, was adopted as a coordinated public responsibility, this strategy would reduce the economic and environmental costs to below the costs of current insect control. The short run management costs of an OPM program could be expected to be much below the short run cost of eradication.

- A decision on which strategy should be implemented beltwide should not be made on the basis of the reported differences among benefit-cost ratios or "normalized" economic predictions. The data generated by the Delphi process and the program cost projections simply are not precise enough and fail to show enough recognition of the risks of changing to a BWE or an OPM program.

USDA Environmental Evaluation Team Report

- The USDA environmental evaluation focused on the two trial areas, and no estimates were made of the changes in environmental quality that might result from beltwide implementation of eradication or optimum pest management programs.

- Since no beltwide data were provided on the existing levels of pesticide residues or on the residues that would be added by implementing either an OPM or a BWE program, the NRC Committee was unable to evaluate the projected environmental impact. Any beltwide conclusions extrapolated from environmental effects during the OPM or BWE trials are unjustified.

- The NRC Committee believes that a BWE or OPM program would increase pesticide concentrations initially by adding substantial amounts of insecticides (5 or more additional applications per season) to the 10 to 12 applications per season now made in some areas. The duration of this intensive application period in any given area cannot be predicted. However, it would obviously have to be continued as long as weevils were captured in traps. At least 16 different insecticides have been employed in the OPM and BWE trials. The environmental effects of some of these insecticides over extended areas and extended periods of time are little known.

- Several important pesticide concentration rates, and the beltwide environmental impacts of the insecticide applications proposed in the USDA's OPM and BWE programs, have not been estimated adequately. Areas of particular concern are: (1) the effects of diflubenzuron on estuarine and coastal crustacea, (2) the effects of inhalation of the highly toxic methyl parathion, EPN, and azinophosmethyl upon human health, (3) the effects of these three insecticides upon honeybees and other pollinators, (4) the general effects of an intensified insecticide load on natural enemies of secondary cotton insect pests and the possible resurgence of these pests as a consequence, (5) the effects of an intensified insecticide load, especially of pyrethroids, on game and cultivated fish populations, and (6) the effects of an intensified insecticide load on endangered species.

- The "modular indices" used in the USDA environmental evaluation are misleading and are based on insufficient or inadequate data. The only wildlife parameter used, for example, was the population of white-tailed deer, estimated from hunter kills. It was also reported that insufficient data were gathered on fish populations in the trial areas to calculate population changes. As a consequence of this paucity of data, no indices were determined for either fish or wildlife in the OPM and BWE trials. Despite this lack of critical information, calculations based entirely on limited spray drift and residue were made and led to the assumption that an eradication program (OPM-BWE as defined in Appendix A) would have much less of an environmental impact than an OPM program or CIC.

- No attempt was made to monitor the effects of either an OPM, CIC, or BWE program upon the health of persons directly exposed to insecticides. An excellent opportunity existed to monitor the impact of the insecticides on the exposed personnel involved in the trials, but no studies appear to have been made. A minimum list of the clinical evaluations that should have been made during the trials would include: (1) excretion of urinary metabolites from parathion, methyl parathion, azinophosmethyl, diflubenzuron, etc.; (2) neurological and behavioral evaluations including blood acetylcholinesterase levels; and (3) blood chemistries for an analysis of pesticide residues.

Operational and Sociological Considerations

- The NRC Committee believes that a precondition for implementation of any eradication program would be a commitment by Cotton Belt states to establish the necessary regulatory authority and to appropriate the necessary financial support. No evidence was presented that such commitments have been made or can be obtained.

- A beltwide appraisal of the attitudes of cotton growers toward an OPM or BWE effort was not undertaken. The NRC Committee believes that such a survey to determine the extent of grower cooperation and opposition would be essential before a federal and state commitment to any kind of program could be made.

- The USDA evaluation did not try to assess the attitude that private pest consultants or agribusiness firms might take toward either an OPM or BWE program. It is the NRC Committee's opinion that the positive support of both groups would raise the probability of success.

- The USDA evaluation fails to include any technical plans for maintaining a barrier along the border with Mexico to prevent a reinvasion of U.S. cotton by the boll weevil. Also missing are plans for coping with plants outside cotton fields which may be boll weevil hosts.

RECOMMENDATION

The NRC Committee unanimously recommends that integrated pest management (IPM) practices--that is, the use of all available technology and methods integrated into a holistic approach to pest control--be the thrust of boll weevil and other cotton pest control programs for the next several years. During the past 10 years, integrated pest management has made tremendous progress in reducing both insecticide use and cotton losses. Through continued research, education, and the adoption of new practices, cotton insect management should continue to improve. The rapid adoption of new techniques in recent years demonstrates that current insect control practices are dynamic. A truly integrated management program is still evolving and probably will vary from year to year and area to area, depending on the variables in each region's cotton crop, ecology, and economy.

As cotton insect control technology continues to evolve, the potential for eradication should be periodically reevaluated. The NRC Committee therefore recommends an indefinite postponement of both the OPM and BWE programs, and we encourage the private sector, the academic community, and government agencies to assist the development and adoption of private integrated pest management so that its potential is more fully realized.

1. COTTON CULTURE AND COTTON INSECT PESTS

COTTON AND COTTON CULTURE IN THE UNITED STATES

The genus *Gossypium*, to which the cotton plant belongs, may be divided into 2 groups, according to chromosome number. One group has a haploid chromosome number of 13, the other 26. Commercial cotton belongs mainly to the group with 26 chromosomes that originated in Central America. This group consists mainly of the cultivated species *G. hirsutum* and *G. barbadense*.

Cotton is generally an annual plant when cultivated, although it can also be grown as a perennial in warm temperate zones. Cotton is cultivated in a wide range of soil types that are well-drained and aerated but retentive of moisture. It can be cultivated between 43° north latitude and 25° south latitude. Successful cultivation requires a mean warm season temperature of over 24°C, an annual rainfall of 400 to 1,200 mm with favorable seasonal distribution, abundant sunshine during the period of boll maturation and harvesting, and a frost-free period longer than 160 days.

The maturation of the boll from the time of fertilization to the time of splitting takes about 50 days. The mature lint is formed by extrusions of the epidermal cells of the testa (seed coat). These are long tubular cells with a heavy cellulose wall. The staple length of the mature lint ranges from 1 to 5 cm or more in different species and varieties.

Cotton has long been a major crop in the United States. Along with tobacco and rice, cotton was an agricultural export of colonial America, and its importance increased during the nineteenth century to the point where the cultivation of cotton became a dominant influence in the social and economic development of the southern states. Ebeling (1980) has described the social and economic changes that accompanied the expansion of cotton culture in the South.

Cotton culture survived the social and economic upheavals of the Civil War, although cotton growers in the southeastern states often suffered economic depression and depletion of soil nutrients eventually resulted in widespread malnutrition in the region (Ebeling 1980). At the beginning of the twentieth century cotton was still the major agricultural crop in the Old South. In recent years, however, cotton cultivation in the southwestern states and California has become important due to the implementation of irrigation projects (Ebeling 1980).

The boll weevil, which appeared in the United States in the last decade of the nineteenth century, was the first important insect pest of cotton (Parencia 1978). The search for measures to control the boll weevil and the development of other significant pest problems have become overriding considerations in cotton cultivation. Recent control technology has included the widespread use of a varied arsenal of synthetic organic chemicals. The history of insecticide development, use, and abuse, and the concomitant changes in cotton cultivation are discussed in later sections of this chapter.

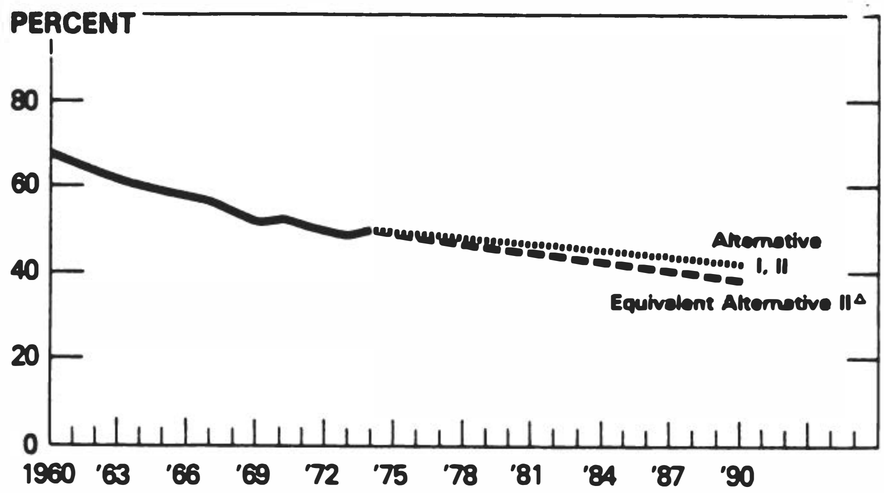
COTTON PRODUCTION

Cotton production in the United States has ranged from 17 to 22 percent of world cotton production since 1974. Russia, China, and the United States together produce about one-half to two-thirds of world cotton. While most cotton seeds are used domestically, about half of U.S. cotton lint is exported. These exports vary sharply from year to year, in contrast to the relatively steady domestic lint consumption of 6 million bales per year. In 1979-1980, for example, 9.2 million bales of U.S. cotton were exported, accounting for more than 40 percent of world cotton trade; in 1980-1981 less than 6 million bales were exported, about 30 percent of world cotton trade. Cotton comprised 6.3 percent of the total value of U.S. agricultural exports in 1979 and 6.8 percent in 1980.

Cotton accounts for half of the fiber used worldwide and for one-quarter to one-third of U.S. fiber consumption. It is an important crop to the world, the United States, the textile industry, the economies of the cotton states, and to several hundred thousand people employed in cotton-related industries.

Cotton's share of the world fiber market has been trending downward, however, and will probably continue to fall, reaching 40 percent by the year 1990 (Figure 1.1). Nonetheless, per person fiber use has been rising about 4 percent a year. Future world fiber consumption may grow 2.5 to 3 percent a year and world cotton use 1.3 to 2 percent a year (Figure 1.2). Worldwide cotton use rose from 45 million bales in the early 1960s to 65 million in 1980-1981 and by 1990 may be 80 million bales (Collins et al. 1979).

The upward trend in use of cotton (Figure 1.3) is relatively smooth compared to the upward trend in worldwide production (Figure 1.4). Production of cotton in the developing and Communist (Central Plan) countries has increased faster than in the United States. Between 1964 and 1977 the largest increases and the greatest rates of increase in both use and production were in the Communist countries (Collins et al. 1979), and the greatest future expansion in cotton use is expected to be in developed countries outside the United States (Collins et al. 1979). Data for 1977 through 1980 show that



ΔTHE LOWER SHARE PROJECTIONS ARE THE SHARES IMPLIED BY DIVIDING THE TOTAL FIBER USE PROJECTIONS OF ALTERNATIVE I INTO THE COTTON USE PROJECTIONS OF ALTERNATIVE II.

FIGURE 1.1 Actual and projected levels of cotton's share of the total fiber market. Cotton's share of the world fiber market declined from 68% in 1960 to 50% in 1974. Alternative I & II (dotted line) projects cotton to have 43% in 1990. Equivalent of Alternative II (dashed line) projects lower share by dividing the more optimistic total fiber use by the least optimistic projection of cotton production.

SOURCE: Collins et al. (1979)

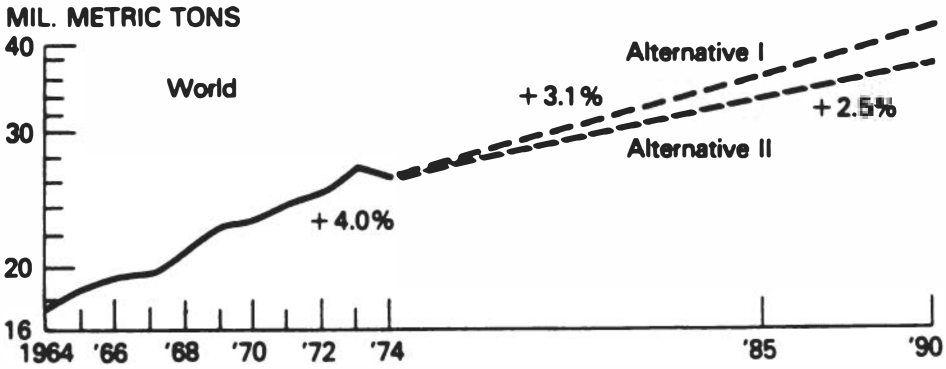


FIGURE 1.2 Actual and projected annual average growth rates of world fiber use. World fiber use grew about 4% per year from 1964-1974. Alternative I projects 3.1% growth to the year 1990 by a more rapid growth of world population and fiber use per capita than Alternative II.

SOURCE: Collins et al. (1979)

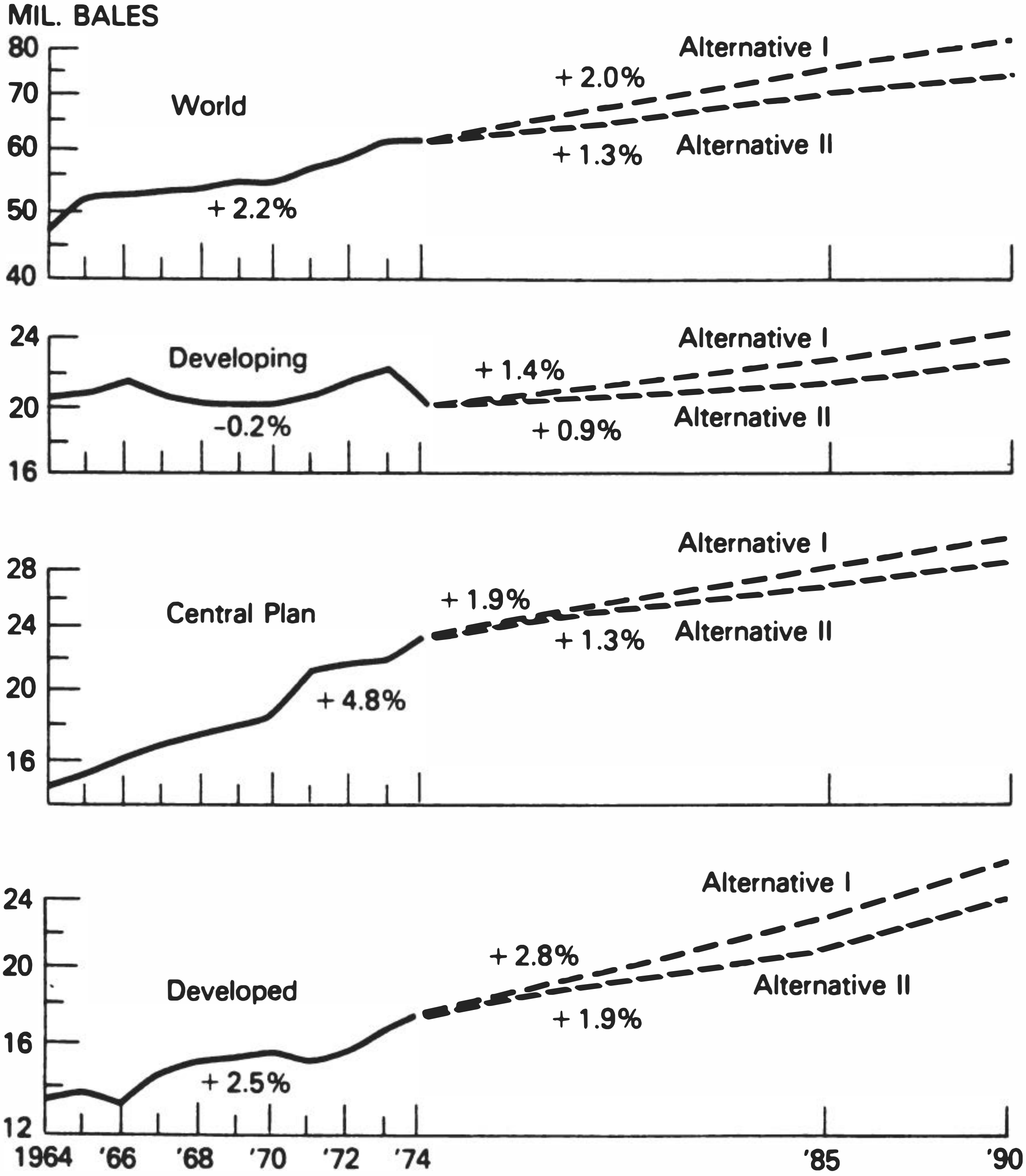


FIGURE 1.3 Actual and projected annual average growth rates of cotton use. World cotton use expanded 2.2% per year up to 1974 which was only half the rate of expansion of total fiber use. Alternative I projects 2% growth to 1990 by anticipating slower growth of total fiber use and a declining share for cotton. Alternative II anticipates the same market share for cotton but lower cotton yields, fewer acres, less people, and lower use of fiber per capita.

SOURCE: Collins et al. (1979)

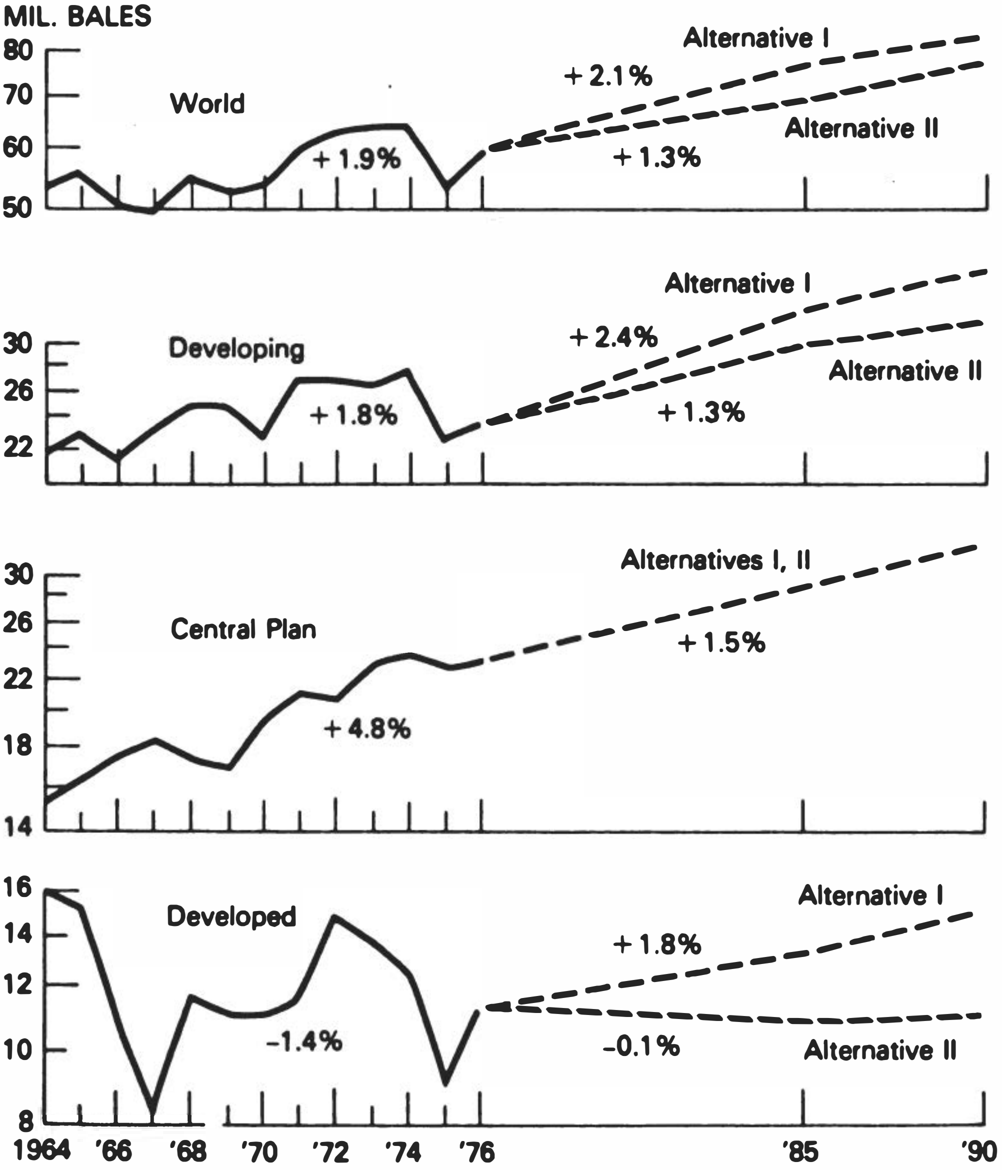


FIGURE 1.4 Actual and projected annual average growth rates of cotton production. Expansion of world cotton production may speed up in the future (Alternative I) in spite of slower growth in Central Plan Countries. Under Alternative II slower yield growth and expansion of acreage is expected in all regions.

SOURCE: Collins et al. (1979)

cotton use in the Communist countries is expanding more rapidly than expected, while production is expanding less rapidly than expected (note dots, Figures 1.3 and 1.4).

Use of cotton in the United States has declined since the early 1960s. Total use of all fibers in the United States grew from 36 pounds per capita in 1960 to 56 pounds in 1980, while domestic cotton use fell from 23 to 14 pounds per capita. Cotton's share of the fiber market fell from 64 to 27 percent between 1960 and 1980 but may decline more slowly to 22 percent by 1990 (Collins et al. 1979). It appears that the extent of the change to man-made fibers may be nearly complete.

Table 1.1 gives the cotton production for the major cotton producing states in the USA. There has been a steady shift of cotton acreage within the United States toward the West. This shift is primarily the result of better cotton-growing conditions--a longer growing season in Arizona and California, a greater number of large flat fields in Texas, and less damage from pests in both areas. These advantages have resulted in lower per bale production costs in the West than in the Southeast or in the hills of the Delta states. In addition, western cotton has usually been sold at slightly higher prices because of its better quality. In 1977 yields were above normal for the Delta and the Southwest and below normal for the Southeast, and the cost differences were very large. Production costs per pound of lint in 1977, excluding land costs, were 50 cents in the West, 46 cents in the Southwest, 56 cents in the Delta, and 99 cents in the Southeast. Regional prices for cotton in 1977 were relatively low (56 cents in the West, 50 cents in the Southwest, 52 cents in the Delta, and 52 cents in the Southeast), but these regional price differences reflected the typical pattern--cotton in the West averaged 4 cents above the national average of 52 cents, and cotton in Texas averaged 2 cents below.

Up to 1974, various government programs retarded the westward movement of cotton. Prior to 1971, marketing quotas discouraged expansion in the West. The quotas were eliminated in 1971, but a program involving a minimum price of 15 cents per pound, with bonuses for small farmers, was maintained until 1974. When the small farmer bonuses were eliminated, cotton acreage dropped in the Southeast (see Figure 1.5).

If the trends shown in Figure 1.5 continue until 1990, the reduction in acreage may be slower in the Southeast and the Delta, and expansion in Texas and Oklahoma may be slower. Some additional expansion of irrigated cotton acreage may take place in Arizona and California, although the increase in production costs associated with irrigation may limit this expansion and spur the trend to dryland cotton in Texas and Oklahoma. The economic return from using water to irrigate cotton--for example, in the Imperial Valley of California--is generally higher than from water used to irrigate grain crops, but it is lower than the return from irrigating off-season vegetable, vine, and tree crops.

National average yield per acre may not rise as much in the future or may even fall if there is a reduction in the Southwest's

TABLE 1.1 Average cotton acreage, yield and production 1975-1979 for 10 major cotton producing states and the total for the United States.

Upland Cotton	Acres harvested (1000 acres)	Yield (lbs. per acre)	Production (1000 bales)
Texas	5593	347	4113
California	1295	957	2515
Mississippi	1232	526	1330
Arizona	483	1019	1020
Arkansas	770	475	753
Oklahoma	463	331	330
Louisiana	477	551	545
Alabama	361	419	311
Tennessee	289	378	222
Missouri	209	447	188
Total U.S.	11,643	481[a]	11,751

[a] Average yield per acre.

SOURCE: USDA (1981b)

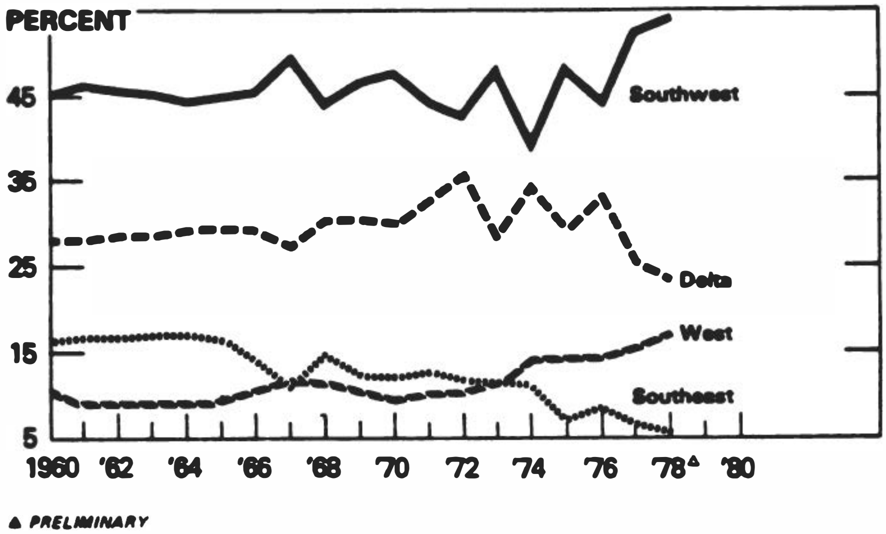


FIGURE 1.5 U.S. harvested cotton acreage by regions. The shift of cotton toward the West accelerated after 1974. The share of cotton in the West outside the boll weevil belt is 17% of acreage but is 35-40% of production.

SOURCE: Collins et al. (1979)

ability to irrigate cotton. An expansion of Texas and Oklahoma dryland cotton production may be large enough to offset any production declines in the Southeast and West.

In the Delta states, which produce 20 to 30 percent of the cotton produced in the United States, future acreage and yield levels are not projected to change significantly. No significant change is expected in these states over the long run in the price ratio between cotton and soybeans, and only moderate increases are expected in rice production.

Cotton acreage and production have fallen in the Southeast. During the early 1960s the amount of acreage used for cotton in this area was about 2.5 million, or one-sixth of U.S. total. In the early 1970s it declined to 1.5 million acres, and was about 600 thousand acres, or one-twentieth of the U.S. total from 1978 to 1980. Cotton production in the Southeast fell from about 2 million bales, or 13 percent of the U.S. total, in the early 1960s to about 1.3 million bales, or 10 percent, in the early 1970s. Between 1978 and 1980 it dropped to 0.6 million bales, or 5 percent.

Cotton production in the Southeast has been dramatically restructured as well. In 1960 some 80 to 90 percent of the cotton there was picked by hand. By 1970 more than 95 percent was picked by machine. Cotton production in the Southeast has a relatively high gross value of $200 to $400 per acre, which is higher than soybeans ($150 per acre) or corn ($200 per acre). Cotton production costs in the Southeast, however, are a high $300 per acre. The average net land rent per acre of cotton is often not larger than the average net land rent for corn and soybeans. Soybeans are less costly per acre and provide a more certain profit. Cotton will probably continue to be competitive with corn and soybeans in the Southeast and the Delta only on larger fields with better soil or in times when the supply of cotton is relatively short.

The trend in the application of insecticides to cotton fields is downward. Cotton growers now have a strong economic incentive to assess the size of insect populations and their potential damage before applying pesticides. The use of scouting procedures allows beneficial arthropods to control cotton insects as long as possible before the application of insecticides. Increases in the costs of insecticides and of applying them, relative to the costs of scouting and pest management consultant services, are leading to the adoption of different techniques.

THE ECOSYSTEM CONCEPT

A growing awareness of the cottonfield as part of the ecosystem has begun to influence cotton pest insect control. Although control programs are still based primarily on insecticide use, systems of pest management utilizing other techniques have begun to be developed. The concept of integrated crop management or agroecosystem management is emerging. The holistic concept of ecosystems, which has become a dominant theme in environmental biology (Odum 1971), has also assumed importance in modern agronomy (Todd 1981). The major precepts of holism are the interconnection of different parts of an ecosystem, beyond the sum of the system's parts, and the existence of homeostatic (self-regulatory) mechanisms.

An agroecosystem has been defined as "a unit composed of the total complex of organisms in a crop-producing area together with the overall conditioning environment and as further modified by various agricultural, industrial, recreational and social activities of man" (Smith and Reynolds 1972). Nutrient cycling processes are altered by the harvesting of agroecosystems. They are also altered by consumer organisms--insects, weeds, and other pests--within the ecosystem, which are controlled with pesticides; by tillage, which incorporates organic matter into the soil, thus increasing decomposition rates and hastening nutrient release from decomposing organic matter; and by the addition of fertilizer nutrients, which often cannot be stored efficiently by the system and are partly lost via leaching. Although agricultural management causes large-scale changes in agroecosystems, ecosystem-level processes continue to operate.

The Cotton Agroecosystem

Extensive reviews of the cotton agroecosystem and its components have been published by Smith and Reynolds (1972) and Reynolds et al. (1975). These reviews discuss in detail the plant system, the complex of invertebrate plant pests, soils, water, fertilizer, and weather that affects the plant system, and the various human influences.

The cotton plant has undergone considerable artificial selection. The varieties currently grown have been selected for fiber quality and yield, insect resistance, fruiting characteristics, and other traits which permit, or may require, changes in cultivation and management. Like many other agroecosystems, cotton fields may contain a variety of weed species. Weeds are considered undesirable because they compete with crop plants for sunlight, water, and fertilizer and may serve as alternate hosts for insect pests. But weeds may also serve as refuges for predaceous and parasitic arthropods of cotton plant pests (Altieri and Whitcomb 1979), and nutrient uptake by weeds may serve to retard nutrient loss from the cotton ecosystem.

The insect complex of cotton fields is a varied one, including not only pest species and their predators but many other arthropod species. The presence of weeds in cotton fields and in surrounding vegetation doubtless has a major influence on the numbers of arthropod species in the cotton fields and may sustain a desirable diversity of arthropod species. Attempts to manage consumer organisms, however, are aimed more frequently at suppressing them than at promoting their predators or parasites.

Future management practice may include using invertebrates as regulators in the decomposition process, although current practice does not attach importance to the decomposition process as a way of recycling nutrients. Nutrients, and frequently water, are provided by artificial methods. Although no-tillage practices conserve soil fertility, using them for cotton probably is not practical at present because of insect pests and disease problems. The most significant difference between the abiotic environments of cotton and natural ecosystems is the number and volume of synthetic organic chemicals--insecticides, herbicides, defoliants--added to cotton ecosystems. The variety of cotton plants, the timing of planting, and the density and size of fields are other human-controlled variables. The cotton ecosystem may be the most chemically altered of all our agroecosystems.

COTTON INSECTS

Cotton fields contain a surprisingly varied and complex population of insect pests and entomophagous (insect-eating) organisms, such as birds, small mammals, and other insects. There is general agreement among entomologists about the importance of entomophagous species for maintaining optimum cotton production over the long term.

Key Cotton Insect Pests

According to Reynolds et al. (1975), there are at least one or two key pests of cotton wherever the crop is grown in the United States. There is also a large array of insect and spider mite species that are considered to be "occasional" or "potential" pests. Damaging populations of the occasional pests occur sporadically, some become problems only when their natural enemies are eliminated by insecticides. Adkisson (1973) listed the key pests in the three major cotton-producing regions in the United States as follows:

- West: pink bollworm (*Pectinophora gossypiella*), tobacco budworm (*Heliothis virescens*), and plant bugs (*Lygus* species).
- Southwest: boll weevil (*Anthonomus grandis*), fleahopper (*Pseudatomoscelis seriatus*), bollworm (*Heliothis zea*), and tobacco budworm.
- Delta and Southeast: boll weevil, plant bug (*Lygus lineolaris*), bollworm, and tobacco budworm.

There is a small area in Arizona subject to boll weevil infestation which is non-contiguous to the main boll weevil region. In the last decade overwintered "stub" cotton which, in effect, lengthens the season, has provided great impetus for this displaced infestation to occur (Bergman et al. 1981).

The boll weevil is considered the key insect pest in the Mississippi Delta despite the current situation, in which the bollworm and the tobacco budworm create larger losses. Prior use of insecticides to control boll weevils accounts for the current problems (Parvin et al. 1977, Clower 1980). The tobacco budworm did not become a serious pest until the synthetic organic pesticides were introduced in the 1940s. Between 1972 and 1978 *H. virescens* was the dominant species of *Heliothis* from August to October in the Delta.

The widespread alteration of the cotton field environment by insecticides has also turned other minor pests into major problems. The cotton leaf perforator (*Bucculatrix thurberillea*) population has reached serious proportions in recent years. Whitefly (*Trialeurodes abutilonea*) was not a problem until damaging populations developed in the Red River Valley in Louisiana in the late 1960s. Whiteflies now extend eastward as far as Georgia (Jones et al. 1976).

Beneficial Arthropods

In the absence of insecticides, populations of arthropod predators of cotton insect pests normally become large and diverse.

Whitcomb and Bell (1964) found over 600 predaceous species of insects, mites, and spiders in Arkansas cotton fields. Gonzalez et al. (1977) reported that total predator populations are generally more abundant in California than elsewhere, which may be a result of the state's numerous alfalfa fields. When the alfalfa is cut about every 30 days, vast numbers of predators are driven out and migrate to surrounding fields. Van den Bosch and Hagen (1966) have published a detailed list of the parasitic and predaceous species more commonly found on cotton.

The overall value of parasites in controlling cotton insect pests is not known, in part because of the complexity of faunal relationships. Attempts have been made to establish biological control of the boll weevil, pink bollworm, and lygus bugs by importing exotic parasites, but these have had no measurable effect. In fact, some of the imported parasite species have failed even to become established. No pathogens that are effective against the boll weevil have been reported.

2. COTTON INSECT CONTROL

HISTORY OF INSECTICIDE USE ON COTTON

Before the boll weevil invaded the United States from Mexico in about 1892 there was relatively little damage to cotton by insect or spider mite pests. Arsenical insecticides--Paris green, London purple, and lead and calcium arsenates--were used to control occasional outbreaks of the bollworm and the cotton leafworm (*Alabama argillacea*). Nicotine sulfate dusts were sometimes employed to control the cotton aphid (*Aphis gossypii*) (Reynolds et al. 1975).

The cotton boll weevil, an invader almost devoid of natural enemies, rapidly changed this placid scene. By 1909 it was reported to be causing at least $200 million in damage annually in the United States (Metcalf et al. 1962), and by 1922 it had spread as far as the coastal regions of North Carolina and Virginia.

The history of insecticide use on cotton insect pests can be divided into four periods, each of which is discussed below.

The Arsenical Period

The first insecticide recommended for control of the boll weevil was a spray utilizing Paris Green, London purple, or lead arsenate in combination with molasses (Townsend 1895, Maley 1902). The techniques for formulating and applying the spray were inadequate, however, and it was not until 1923 that Coad and McNeil (1924) demonstrated the effectiveness of applying undiluted calcium arsenate dust by airplane in controlling the boll weevil. The effectiveness of this method for controlling another pest, the cotton leafworm, had been demonstrated the previous year.

The success of dusting with calcium arsenate from airplanes was repeatedly demonstrated in Georgia and Texas in the period 1925-1927 (Post 1924, Thomas et al. 1929), and aerial dusting became the principal method of applying insecticides to cotton until the early 1950s. The use of calcium arsenate rose from about 3 million lbs. in 1919 to approximately 15 million lbs. in 1925. U.S. production reached 33 million lbs. in 1929, 43 million lbs. in 1935, and a maximum of 84 million lbs. in 1942. The total amount of calcium arsenate applied to domestic cotton fields from 1919 to 1948 has been estimated at about 850 million lbs. (Shepard 1951).

This vast amount of calcium arsenate had substantial effects on the pest fauna of cotton fields and on the environment. Calcium arsenate was toxic to the natural arthropod enemies of the cotton aphid (ladybird beetles, syrphid flies, lacewing flies), and as a result the aphid became a serious threat, requiring the addition of nicotine sulfate to the arsenical dust. Annual production of nicotine sulfate was about 1 million lbs. from 1938 to 1940, most of it used domestically on cotton; consumption reached 1,460,000 lbs. in 1943 (Shepard 1951). The bollworm also became a significant pest in this era because of the destruction of its natural enemies by calcium arsenate, but satisfactory control of this pest was maintained because bollworm larvae themselves are fairly susceptible to calcium arsenate.

Calcium arsenate also had an impact on the natural enemies of the cotton flea hopper and of lygus bugs, particularly in the Southwest and in newly irrigated areas of the West. Sulfur dusts were incorporated into control programs to deal with these pests as well as occasional outbreaks of red spider mites (Tetranychidae) (Reynolds et al. 1975, NRC 1975). During the arsenical period most of the insecticides were applied in boll weevil-infested areas.

The Organochlorine Period

In 1945 the organochlorine insecticide DDT became available for domestic use. DDT brought about a revolution in cotton insect control. It was a persistent contact insecticide, and it was oil-soluble and could therefore be applied as a spray. Improved aircraft spray technology resulted in low volume sprays that almost totally replaced dust applications. Subsequently, benzene hexachloride (BHC) and toxaphene also became major cotton pest insecticides, and they were followed by aldrin, dieldrin, endrin, heptachlor, and DDD (TDE). U.S. production of DDT increased to 164,180,000 lbs. by 1960, benzene hexachloride to 84,599,000 lbs. by 1956, and the aldrin-toxaphene group to 90,671,000 lbs. by 1960. Although statistics are not available, from one-quarter to one-third of the organochlorine insecticides produced between 1945 and 1960 was probably applied to U.S. cotton. These insecticides had two important qualities: (1) high initial effectiveness against a wide variety of cotton pests; and (2) lengthy persistence, which made it possible to control newly emerging insects and insects migrating into treated areas. Spectacular increases in yields were obtained at high profit levels for many years (NRC 1975, Reynolds et al. 1975), and it appeared that complete control over arthropod pests of cotton had been achieved. The use of the organochlorine insecticides also decimated the parasites and predators of cotton pests, however, and often resulted in an increase in red spider mites. Grave problems of environmental pollution also resulted.

The Organophosphorus Period

In 1955 it was discovered that the boll weevil was beginning to become resistant to the organochlorine insecticides. The result of this discovery was a gradual but substantial shift to organophosphorus insecticides--parathion, methyl parathion, azinphosmethyl, malathion, and EPN. These pesticides were effective against the boll weevil at relatively lower rates than the organochlorine insecticides but were not effective in controlling the bollworm and the tobacco budworm, which achieved the status of major pests as their natural parasites and predators were decimated. To control all of the major pests, growers then resorted to various mixtures of DDT, toxaphene, endrin, methyl parathion, azinphosmethyl, malathion, and EPN. These mixtures initially provided control of aphids, fleahoppers, plant bugs, leaf-feeding caterpillars, and spider mites as well as boll weevils, bollworms, and budworms. Growers demanded insecticidal mixtures that would produce cotton fields almost completely devoid of insects (Reynolds et al. 1975, NRC 1975).

By the early 1960s, however, the bollworm and the tobacco budworm had also developed a high degree of resistance to the organochlorine insecticides and the carbamate insecticide, carbaryl (see Table 2.1), and by the late 1960s the tobacco budworm in the lower Rio Grande Valley of Texas and northeastern Mexico developed resistance to the organophosphorus insecticides as well. The use of methyl parathion was increased to 15 to 18 applications per season, but yield losses continued and in some areas the crop was almost totally destroyed. As a result of tobacco budworm resistance, many producers were forced out of business, and cotton production ceased on about 700,000 acres (Adkisson 1971).

The organophosphorus-resistant tobacco budworm then spread to Louisiana and Arkansas, and from there to the cotton states of the Southeast. Tobacco budworm resistance reached such a high level that it became virtually impossible to control this pest with any insecticide. Meanwhile, however, a side effect of the greatly increased use of the organophosphorus insecticides was a dramatic increase in the number of cases of human poisoning from insecticides and the resurgence of pests on other crops, such as citrus, following spray drift from cotton (Adkisson 1971).

Then, in 1973, the U.S. Environmental Protection Agency (EPA) banned the use of DDT to control cotton pests. The EPA action was a marked change in public policy toward insect control by chemicals. DDT plus toxaphene, often with methyl parathion added, had provided satisfactory control of the boll weevil, the bollworm, the cotton fleahopper, and plant bugs in the cotton-producing areas east of Texas, and the ban on DDT resulted in a shift to intensive use of the organophosphorus insecticides, often in combination with toxaphene, sometimes with endrin or chlordimeform (Reynolds et al. 1975). Nonetheless, insect control had become ever more costly and ever less efficient (Reynolds et al. 1975, NRC 1975).

TABLE 2.1 Measures of susceptibility and resistance of *Heliothis* bollworm and budworm to various insecticides. The LD_{50}, measured in micrograms per gram larval weight, was determined 48 hours after topical application to 4th instar larva.

	LD_{50}			
	Susceptible		Resistant	
DDT				
H. virescens	132	(1961-Florida)[b]	16,123	(1962-Texas)[b]
			16,510	(1965-Texas)[b]
H. zea	26	(1960-Texas)[d]	5,680	(1962-Texas)[c]
	28	(1959-Texas)[d]	14,150	(1962-Texas)[c]
	30	(1962-Texas)[c]		
Endrin				
H. virescens	26	(1970-Peru)[i]	3,980	(1970-Colombia)[i]
	34	(1970-Mexico)[i]	12,940	(1965-Texas)[g]
	58	(1961-Texas)[b]		
H. zea	12	(1960-Texas)[d]	130	(1965-Texas)[g]
	20	(1962-Texas)[c]	530	(1970-Nicaragua)[i]
	23	(1970-Mississippi)		
Methyl parathion				
H. virescens	0.53	(1977-Georgia)[a]	2,110	(1970-Texas)[i]
	0.57	(1970-Peru)[i]	3,580	(1969-Mexico)[i]
	2.2	(1969-Mississippi)[i]		
H. zea	2.2	(1970-Texas)[i]	150	(1970-Mexico)[i]
			180	(1970-Nicaragua)[i]
			310	(1970-Guatemala)[i]
Carbaryl				
H. virescens	304	(1961-Texas)[b]	54,570	(1965-Texas)[g]
H. zea	110	(1972-Texas)[c]	540	(1965-Texas)[g]
Permethrin				
H. virescens	0.097	(1974-Texas)[f]	1.64	(1977-Arizona)[e]
	0.12	(1977-Georgia)[a]	3.13	(1976-Texas)[h]
	0.28	(1978-Arizona)[e]	5.4	(1974-Texas)[f]
	0.29	(1976-Texas)[h]		
H. zea	0.47	(1976-Georgia)[f]	1.1	(1974-Texas)[f]

[a] All et al. (1977)
[b] Brazzel (1963)
[c] Brazzel (1964)
[d] Brazzel et al. (1961)
[e] Crowder et al. (1979)
[f] Davis et al. (1975)
[g] Reynolds et al. (1975)
[h] Wolfenbarger et al. (1977)
[i] Wolfenbarger et al. (1973)

The Current Period

The situation during the past five years has been one of growing awareness that, as one author puts it, the entire Cotton Belt has been on an "insecticide treadmill" (Van den Bosch 1978). Although synthetic pyrethroids capable of controlling the tobacco budworm appeared in 1978, there have been other less positive developments. In 1976 chlordimeform was withdrawn from active use because of its carcinogenic properties. In 1978 it was once again permitted to be used, but only under very strict conditions. In 1980 a ban was placed by EPA on the use of endrin east of the Mississippi River because of that chemical's very high toxicity to fish and other aquatic organisms. At the present time some 33 insecticides and acaricides are regularly used to control cotton insect pests, and another four, including the chitin synthesis inhibitor, diflubenzuron, have received conditional registration from EPA for specific uses (USDA 1979).

Overall Chemical Use

It has been estimated several times that from 40 to 50 percent of all crop insecticides in the United States have been used to control cotton insect pests (Pimentel 1973; USDA 1965, 1970, 1974, 1978). In 1971, for example, 73.4 million pounds of active insecticide ingredients were applied to 7.5 million acres of cotton. This was equivalent to 9.8 pounds of active ingredients per acre. In 1976, 64.1 million pounds were applied to 7.0 million acres. This was the equivalent of 9.2 pounds per acre (USDA 1979). This use was also approximately 40 percent of the 162 million pounds of the active insecticide ingredients used by all U.S. farmers that year.

Using 40 percent as an average figure, one researcher has calculated that about 2.3 billion pounds of active insecticide ingredients have been applied to the U.S. cotton crop since 1950. That is an average of more than 200 lbs. per acre (Metcalf 1980).

The estimated quantities of insecticides applied to cotton over the period 1964-1976 are summarized in Table 2.2. The table also shows how insecticidal control of cotton insect pests has changed since accurate records became available in 1964. Control efforts since then have been marked by a steadily increasing proliferation in the number of insecticides used and substantial changes in quantities. From 1964 to 1976 the total amount of organochlorine insecticides decreased by half and the use of DDT came to an end, while toxaphene remained in large-scale use. During that same period the use of organophosphorus insecticides has approximately doubled, with methyl parathion becoming dominant and EPN very widely used.

RESISTANCE OF COTTON PESTS TO INSECTICIDES

The application of insecticides to cotton has demonstrated clearly that natural selection of resistant strains of cotton insect

TABLE 2.2 Use of insecticides on cotton in the United States, 1964-1976.

	Active ingredient (pounds x 1000)				Area treated (acres x 1000)			
Insecticide	1964	1966	1971	1976	1964	1966	1971	1976
Inorganic								
Calcium arsenate	2,518	-	69	-	57	-	23	-
Organic								
I. Organochlorines	55,778	49,703	42,619	27,277	14,252	10,157	6,130	3,762
aldrin	17	123	-	-	-	16	161	-
clordane	-	3	-	-	-	6	-	-
DDT	23,558	19,213	13,158	-	6,901	4,767	2,383	-
DDD (TDE)	191	167	-	-	61	33	-	-
dieldrin	-	11	65	-	-	36	174	-
endosulfan	-	61	-	677	-	56	-	325
endrin	1,865	510	1,068	311	1,194	403	262	325
lindane	540	163	-	-	636	298	-	-
methoxychlor	-	6	-	-	-	6	-	-
strobane	-	2,016	216	-	-	225	18	-
toxaphene	26,915	27,345	28,112	26,289	5,016	3,881	3,275	3,112
other	2,660	65	-	-	428	285	-	-
II. Organophosphates	15,196	13,624	29,376	30,980	10,237	7,865	11,427	12,824
azinphosmethyl	250	200	288	229	641	222	119	-
bidrin	-	1,857	778	251	-	1,416	1,797	378
demeton	47	-	-	-	322	-	-	658
diazinon	-	-	-	36	-	-	-	51
dimethoate	-	-	-	87	-	-	-	237
disulfoton	565	300	225	1,819	619	473	553	1,400
EPN	-	-	-	6,140	-	-	-	1,496
ethion	-	73	6	-	-	26	30	-
malathion	1,811	559	670	43	213	245	273	55
methyl parathion	8,760	7,279	22,988	19,981	5,420	3,577	6,384	6,166
monocrotophos	-	-	-	1,487	-	-	-	1,494
parathion	1,636	2,181	2,560	680	751	860	682	561
phorate	10	-	100	158	35	-	182	115
trichlorfon	-	963	144	-	-	512	191	-
other	2,117	212	1,617	69	2,236	534	1,216	213
III. Carbamates	4,524	1,571	1,291	1,445	1,002	415	294	1,137
aldicarb	-	-	-	470	-	-	-	171
carbaryl	4,510	1,571	1,214	385	-	-	-	177
methomyl	-	-	40	590	-	-	84	789
other organic	6	-	2	-	102	-	24	-
IV. Miscellaneous								
botanicals-biologicals	-	2	-	-	-	8	-	-
chlordimeform	-	-	-	4,437	-	-	-	2,912
Total insecticide used:	78,022	64,900	73,357	64,139				

SOURCE: Data from USDA Agricultural Economic Report No. 131 (1965); No. 179 (1970); No. 252 (1974); No. 418 (1978); and NRC (1975).

pests can occur rapidly. It has also been demonstrated that selection can continue in a single species of pest so that it becomes resistant to several, often unrelated, insecticides. Since 1947, as shown in Table 2.3, at least 21 species of cotton insects and mites have developed resistance to one or more insecticides. Of the 21 principal resistant species, 14 are resistant to at least two groups of insecticides, 6 are resistant to at least three groups, 5 (including the bollworm, the tobacco budworm, the cotton leaf perforator, the cabbage looper, and the beet armyworm) are resistant to four groups, and 1, the tobacco budworm, is resistant to all five groups. Species resistant to some insecticides occur in localized areas of all the cotton-producing states (USDA 1979).

The boll weevil has shown resistance to some insecticides in 10 of the 11 states where it occurs. DDT resistance developed in the boll weevil in 1954 in Louisiana and Mississippi (Roussel and Clower 1955), and the resistant strain of insect subsequently spread rapidly. By 1960, all areas of the South and the Southeast infested by the boll weevil had reported the development of organochlorine-resistant weevils (Brazzel 1961).

Bollworms and tobacco budworms have shown resistance to insecticides in all 12 of the major cotton-growing states. As shown in Table 2.1, the bollworm and particularly the tobacco budworm have developed enormously high resistance to DDT, endrin, methyl parathion, and carbaryl, as well as to toxaphene-DDT mixtures.

Rather surprisingly, as of 1968 no cotton pest had been shown to have acquired resistance to calcium arsenate despite 25 years of heavy application (Newsome and Brazzel 1968). This, however, may have been because scientific techniques for the study of resistance were not well-developed until after the introduction of the organochlorine insecticides, and also because resistance to insoluble stomach poisons like calcium arsenate is very difficult to measure.

If anything, cotton insect pests appear to be developing resistance to new insecticides even faster than before. Two synthetic pyrethroids developed to control cotton insect pests, fenvalerate and permethrin, were given conditional registration by EPA in 1979. Yet, as Table 2.1 shows, there is already evidence that the tobacco budworm has developed resistance to permethrin.

The history of chemical control of cotton insect pests during this century suggests that its future is doubtful. Cotton insect pests--particularly the various worms that feed on the leaves and bolls of the cotton plant--have shown resistance to insecticides in the rest of the world as well, and control is now obtained in some cases only by as many as 50 applications of insecticide per year. In Egypt, for example, more than 811 million pounds of active insecticide ingredients were applied to cotton between 1961 and 1975, primarily to control bollworms and leafworms. The leafworm, however, exhibited resistance to virtually every available insecticide, and in 1977 it was reported that no new insecticide used in Egypt had remained effective for more than 2 to 4 years (El-Sebae 1977).

TABLE 2.3 Multiple insecticide resistance in insect and mite pests of cotton in the United States.

Species	Group I DDT, DDD, methoxychlor dicofol	Group II lindane, cyclodienes	Group III organo-phosphorus	Group IV carbamates	Group V pyrethroids
Banded winged whitefly, *Trialeurodes abutilonea*			x		
Beet armyworm, *Spudoptera exigua*	x	x	x	x	
Boll weevil, *Anthonomus grandis*	x	x			
Bollworm, *Heliothis zea*	x	x	x	x	
Cabbage looper, *Trichoplusia ni*	x	x	x	x	
Cotton aphid, *Aphis gossypiella*		x	x		
Cotton fleahopper, *Pseudatomoscelis seriatus*	x				
Cotton leaf perforator, *Buccalatris thuberiella*	x	x	x	x	
Cotton leafworm, *Alabama argillacea*	x	x			
Lygus bugs, *Lygus hesperus*	x		x		
Pink bollworm, *Pectinophora gossypiella*	x		x		
Saltmarsh caterpillar, *Estigmene acrea*	x	x			
Southern garden leafhopper, *Empoasca solana*	x				
Stink bug, *Euschistus conspersus*	x				
Thrips, *Frankliniella occidentalis*		x			
Thrips tabacci	x				
Tobacco budworm, *Heliothis virescens*	x	x	x	x	x
Red spider mites, *Tetranychus cinnebarinus*	x		x		
T. pacificus	x		x		
T. turkestani			x		
T. urticae	x		x	x	

Holistic Pest Control and Pesticide Use

The tobacco budworm, Heliothis virescens, and the cotton bollworm, Heliothis zea, have effective natural enemies, and as a result they are generally under adequate control over much of the Cotton Belt. The development of reliable techniques to assess the degree of biological control will make it possible to include entomophagous species in pest control plans (Hartstack et al. 1975).

The development of a strategy to preserve intact the parasite and predator species that help to suppress Heliothis is a key to successful pest management. Measures to control the boll weevil must be carefully refined, since the beneficial species holding Heliothis in check can be disrupted by chemical control measures aimed at the boll weevil. If a favorable ecological balance tending to suppress the Heliothis complex is destroyed by the application of insecticides for the boll weevil, there is usually no alternative but to continue applying insecticide until the crop is mature. Such a strategy is both very expensive and ecologically unsound. Far more than half of the cotton losses ascribed to insects and mites may be attributable to the Heliothis complex (DeBord 1977). The crop losses and the increased costs of production caused by Heliothis, and the concomitant load of insecticide in the environment, are enormous.

Careful management of boll weevil control programs can reduce the insecticide load, and careful timing of insecticide applications can avoid the destruction of the beneficial insects that control Heliothis. What this means is using insecticides toward the end of the growing season to minimize the number of boll weevil adults leaving cotton fields to overwinter (diapause control). This reduces the boll weevil population in the following growing season to the extent that insecticide control of the weevil is not needed until late in the growing season after Heliothis is no longer a problem. Various modifications of the diapause supression program have been used effectively in certain areas of the Cotton Belt since 1964 (Cross 1973).

Entomologists do not anticipate that boll weevil management or eradication programs would remove Heliothis as a significant cotton pest. In the southeastern states particularly, continuing problems with Heliothis can be anticipated. Other plants, such as corn, will support Heliothis populations at levels sufficiently high to prevent beneficial insects from keeping them below the level at which they can cause serious economic loss. In certain years this could occur in most production areas as is the case with secondary pests. In-season applications of insecticides keep certain other pest species, such as the plant bugs, below damaging levels.

RECENT DEVELOPMENTS IN COTTON INSECT CONTROL

Plant Breeding and Cultural Management of Cotton

Cotton cultivars from the United States are the main varieties grown in many countries. Much progress has been made in developing cultivars that consistently achieve high yields under good management (Bridge et al. 1971).

Some high-yielding cotton varieties have the ability to adapt to environmental stress, including substantial insect damage. The traits that provide such resilience have been discovered in rare and isolated types of cotton and utilized to confer host plant resistance (HPR) against the major cotton insect pests, including the boll weevil, bollworm, tobacco budworm, pink bollworm, and *Lygus* species. The development of host plant resistance is approached from a holistic viewpoint, i.e., reducing the overall vulnerability of the cotton plant to the entire insect complex.

The traits desired for breeding strains of cotton that are resistant to insects are generally found in otherwise poorly adapted cultivars or in wild relatives of cultivated cotton. As a result, certain adverse effects also occur when traits that improve resistance are transferred into well-adapted cultivars. These agronomically inferior but resistant strains of cotton are useful only under severe or chronic infestations when resistance is more important than yield potential. Cultivars with a specified characteristic that improves resistance often do not yield as well as nonresistant cultivars in the absence of the pest species. In order for any HPR trait to be valuable, the long-term average protection afforded by the characteristic must be greater than the mean yield reduction due to the negative effects of breeding.

Carefully designed experiments have given indications of the reduction in insect damage that various traits can provide, singly or in combination. It does not appear possible to calculate the effects directly, however, because the interactions among pest-resistant plants, the insects themselves, and beneficial species are too complex.

Only insect-resistant cultivars that provide yields comparable to those of standard cultivars in a pest-free environment gain commercial acceptance. After two decades of increasingly intensive efforts to develop host plant resistant cultivars of cotton, only a few are generally accepted. They include Stoneville 825, Coker 413, and Tamcot SP-21S. Each of these incorporates a single trait that gives measurable protection against *Heliothis*. The absence of nectary glands, nectarilessness, in Stoneville 825 provides some additional protection against plant bugs.

Cotton hybrids may offer new opportunities for improving cotton cultivars. It may be more feasible to make an F_1 hybrid from a resistant parent and a high-yielding parent than to try to combine resistance and agronomic performance in a single pure line (Milam et al. 1980). Davis (1979) reported that certain interspecific hybrids have significantly higher yield than the standard commercial varieties. Thus, it may be possible to breed insect-resistant hybrids that are also high-yielding. Preliminary data indicate the possibility of combining high yield and high bollworm resistance in an interspecific hybrid of cotton (Call and Weaver 1980), and other types of resistant hybrids are being sought.

Breeding Strategies for Host Plant Resistance (HPR)

As used here, the word "ambivalent" refers to a trait or characteristic that increases a plant's resistance to one insect species but increases its vulnerability to another. Most of the known resistance characteristics in the various kinds of cotton are ambivalent. According to Lukefahr (1977), red plant color is the only major HPR trait that shows no ambivalence. Because of ambivalence, breeders often seek combinations of HPR traits, a goal called compensated ambivalence. Ambivalence does not have to be compensated for if the insect species to which vulnerability is increased is not a serious pest in a particular region, but there is always the possibility that a species that does no harm to normal cotton may attack modified cotton (Murray et al. 1965). Furthermore, natural selection among cotton insect pests may negate host plant resistance. It took many years for most biologists to realize the ecological impact of insecticides, and it may take a similar period of time to observe the full effects of widespread use of HPR varieties of cotton.

A particularly effective technique for growing cotton is to intersperse a few rows of a susceptible strain at wide intervals in a field primarily planted in an HPR strain. The target insect pest tends to avoid the HPR plants and concentrate on the susceptible plants, which can then be treated with insecticide. This is called "trap cropping," and a number of ways in which it can be used to manage weevil populations have been described (Namken et al. 1981; Jones et al. 1978a, 1978b).

Short-Season Varieties of Cotton

Researchers in Texas have developed a technique for avoiding boll weevil damage by utilizing short-season varieties of cotton. The life span of the boll weevil in southern Texas is such that cotton will escape damage from the first generation of boll weevils to emerge each growing season if overwintered populations are less than 22 weevils per acre. Newly developed short-season strains set fruit rapidly and reduce the amount of crop damage from the second generation of weevils that develop later in that growing season (Walker and Niles 1971).

In one experiment, two applications of insecticide at an early flowering stage in cotton (pinhead square stage) reduced boll weevil population levels below the economic threshold for 59 days, allowing most of the cotton bolls to mature. Use of the short-season technique has reduced in-season insecticide applications by half and has avoided late-season increases in tobacco budworm populations (Heilman et al. 1977). This early application of insecticides does temporarily disrupt the suppression of *Heliothis*, and as a result damage to pinhead squares by *Heliothis* may rise to 25 percent or more. But heavy damage can be endured at the early squaring stage, and if no more insecticide is used the natural enemies of *Heliothis* will recover in time to protect the crop through the main fruiting period

(Walker et al. 1978). Since the size of the boll weevil population is related to the number of generations in a growing season, the elimination of a single generation can greatly reduce economic loss and the need for additional control measures.

Namken et al. (1981) point out the superiority of the early blooming rate of certain new cultivars over the standard full season cultivar, Stoneville 213. They show that a higher number of blooms per acre in the first 20 days of blooming lead to significantly earlier maturity and, in some cases, higher yields.

For full-season varieties the duration of the fruiting period varies and is normally terminated by low temperatures in the fall (Gipson and Joham 1968a, 1968b). This means that in years with long warm fall seasons the use of the short-season varieties involves a deliberate sacrifice of yield (Fisher and Cannon 1981). Reduced yield, however, has proven to be an acceptable tradeoff for reduced vulnerability to insect attack in parts of Texas. Short-season cultivars also reduce the costs of water, labor, and machinery, and the savings in insecticide costs may be highly significant when the short-season technique is coupled with careful selection and timing in the use of insecticides (Walker et al. 1978).

Host Plant Resistance Against the Boll Weevil

Reduced oviposition (egg-laying) by the boll weevil has been found in a number of strains of cotton.

Frego Bract. In the 1960s a large number of trials demonstrated that the modified bract type called frego bract was attacked much less severely by boll weevils than normal cotton (Jones et al. 1977). The boll weevil populations in frego bract fields were one third as large as the populations in cotton fields of other types when no diapause program was applied to either the frego or non-frego fields and in-season treatments for weevils were applied as needed (Jenkins and Parrott 1971). Weevil suppression through the use of frego was variable, depending in part on the size of overwintering populations and on in-season and diapause insecticide applications. Insecticide was not needed in frego fields until 4 weeks after non-frego fields received their first treatment. The resistance shown by frego bract cotton may therefore make it possible to postpone insecticide applications that would otherwise disrupt the beneficial species which hold Heliothis in check.

Four small test plantings of paired frego and non-frego cotton showed that the boll weevil populations on the frego were between 66 and 94 percent less than on the non-frego cotton. Resistance was attributed to the "upsetting of normal patterns of behavior" in the weevil. If natural selection then resulted in altered weevils which preferred frego, normal varieties might then show some resistance (Jenkins and Parrott 1971).

The structure of frego bract cotton allows a much larger amount of insecticide to penetrate to the flower bud. There was significantly higher mortality of boll weevils on frego than on non-frego cotton when both were sprayed with azinphosmethyl (Parrott et al. 1973).

Frego bract varieties, however, have not yet become commercially feasible because of the extreme susceptibility of frego bract varieties to plant bugs. Damage to frego bract strains from plant bugs (Lygus species) may be as much as twice as great as damage to normal bract strains (Jones 1972), and for this reason Meredith (1980) projects that commercial use of frego bract varieties will not occur in the 1980s. J. E. Jones (Louisiana State University, Baton Rouge, personal communication, 1981) is confident, however, that the susceptibility of frego bract to plant bugs can eventually be overcome by combining frego with a compensating trait, such as nectarilessness that confers some resistance to Lygus.

Red Plant Color. There are two HPR strains with red color that exhibit a valuable weevil-resistant trait. A gene that imparts intense red color (R_1) to the entire plant elicits as strong a negative reaction from the boll weevil as frego bract (Jones et al. 1978a, 1978b) but gives a lower yield than a red stem (R_2) type. Cotton plants with the red stem trait are competitive in yield with their normal green counterparts under all but the most favorable conditions (Jones et al. 1977).

Host Plant Resistance Against Other Key Pests

Nectarilessness. A trait that makes cotton partially resistant to attack from both Lygus and Heliothis became available when the genetic factors causing the absence of leaf, bract, and involucral nectary glands were bred into upland cotton from the wild species G. tomentosum. The trait is controlled by two unlinked recessive genes (Meyer and Meyer 1961) and poses no great difficulty in breeding.

Nectariless types have been backcrossed into three major varieties and had no significant effects on yield or fiber properties (Meredith et al. 1973). Significantly reduced Lygus populations have been reported on nectariless varieties (Schuster and Maxwell 1974).

Genetic modification of normal cotton into nectariless cotton has also been reported to result in reduced bollworm egg-laying by several investigators (Davis et al. 1973, Lukefahr et al. 1965, Schuster and Maxwell 1974). This reduction may be close to 50 percent, but there was high variability between trials (Schuster and Maxwell 1974, Davis et al. 1973). Part of the variability may be due to the fact that nectarilessness also suppresses populations of beneficial insects that attack the bollworm (Schuster and Maxwell 1974; J. Ellington, New Mexico State University, Las Cruces, unpublished personal communication, 1981).

Leaf Smoothness. Another modification that significantly affects Heliothis behavior is leaf smoothness. This trait has been transferred into upland cotton from the wild G. armourianum (Meyer 1957). The genes responsible for the trait have also been found in Central American "dooryard" accessions, and in a commercial variety of American upland cotton (Lee 1971). Combinations of two or more of the genes that account for smoothness can produce glabrous or "super smooth" cotton.

The smooth-leaf characteristic is highly ambivalent, however. Glabrousness gave cotton plants (except for North Carolina Smooth) resistance to Heliothis, the cotton fleahopper, and the pink bollworm, but resulted in greater numbers of cabbage loopers and leafhoppers (Lukefahr 1977). The tarnished plant bug (Lygus lineolaris) caused a significantly greater reduction in the number of flower buds and in the lint yield of smooth leaf cotton as compared to pubescent cottons (Meredith and Schuster 1979). Jones et al. (1977) confirmed the increased susceptibility of smooth-leaf types to plant bugs and leafhoppers. The primary value of leaf smoothness is the protection it provides against Heliothis.

Significantly fewer Heliothis eggs were laid on Deltapine smooth leaf cotton than on normally pubescent Stoneville 213. The suppression effect of smoothness on bollworm egg-laying is confirmed by Lukefahr et al. (1965).

Crossing glabrous and frego bract cotton with okra-leaf cotton partially reduced their susceptibility to plant bugs (Jones et al. 1978a). Okra leaf counters potential plant bug damage by enhancing the fruiting rate. High resistance to whitefly was also associated with okra leaf and super okra leaf. Near-glabrousness gave a moderate degree of resistance (Jones et al. 1976).

The smooth-leaf types (except for sm_3) have been reported to have a low percentage of lint and erratic yield (Meredith 1980). Glabrous isolines were slightly lower in yield and significantly later in reaching maturity than their hairy counterparts. The lateness of these glabrous types was associated with susceptibility to an "early season pest complex" involving plant bugs and leafhoppers (Jones et al. 1977).

High Gossypol. There are naturally occurring plant pigments in cotton, notably gossypol, that are toxic to some insects at high concentrations (Lukefahr and Martin 1966). The gene that results in high concentrations of floral bud gossypol confers resistance to Heliothis and Lygus and may suppress leafhoppers, but it has the ambivalent property of leading to severe attack by thrips and whiteflies.

Nonetheless, the excellent protective effect of high gossypol against Heliothis has resulted in intensive efforts to incorporate this trait into commercial cotton (Sappenfield and Dilday 1980). Parrott et al. (1981) reported that certain high-gossypol strains of cotton showed no yield loss when infested with tobacco budworm. Artificial infestation (Parrott et al. 1981) and the withholding of insecticide protection (Bailey et al. 1978) have been used to demonstrate the protective value of high gossypol concentrations.

Breeding strains of cotton with high gossypol content, however, is a lengthy and difficult procedure (Sappenfield et al. 1974). Furthermore, high gossypol has a negative effect on yield (Meredith 1980, Sappenfield and Dilday 1980). Gossypol content has also been reported to be negatively correlated with boll size and the ratio of lint to seed (Wilson and Lee 1976, Dilday and Shaver 1980).

Therefore, the best way to achieve high yield plants with a high gossypol content may be through interspecific hybrids. Singh and Weaver (1972) reported an interspecific cross whose gossypol content was closer to that of the Pima cotton plant parent with high gossypol than to that of the XG-15 upland parent with a lower gossypol content.

The Prospects for Host Plant Resistance (HPR)

Boll weevil-resistant varieties of cotton will not become a reality until breeders are able to combine traits that help cotton plants resist the boll weevil with genetic backgrounds that insure at least a normal level of resistance to other cotton insect pests. Red stem varieties of cotton with a minimum of negative traits will probably be commercially important in the near future, but frego bract's resistance to the boll weevil cannot be exploited until the variety's increased susceptibility to *Lygus* is overcome.

Most of the available HPR traits have been known and used by cotton plant breeders for more than a decade. This is about the length of time needed to breed out the agronomic defects that come from introducing traits from exotic plant varieties. The future of breeding for host plant resistance in cotton holds promise of significant breakthroughs. In addition, integrated pest management programs may accelerate the development of trap cropping systems in which both resistant and susceptible varieties of cotton play a useful role.

Pheromones of Cotton Insect Pests

Much of the fundamental behavior of insects in searching for food, sexual partners, and egg-laying sites is controlled by the release of specific chemical signals, called semiochemicals, produced in the insect environment. Semiochemicals that act interspecifically are called *allomones* if they favor the insect that produces them and *kairomones* if they favor the insect that receives them (Brown et al. 1970). Semiochemicals that act intraspecifically between individuals of the same species are called *pheromones* (Karlson and Butenandt 1959).

In the two decades since the identification of the sex pheromone of the silkworm *Bombyx mori* as *trans*-10-*cis*-12-hexadecadien-1-ol, or bombycol (Butenandt et al. 1959), intensive study has demonstrated the almost ubiquitous presence of these chemical messengers in insect species and their essential role in reproduction. The sex pheromones of many insect pests, including several pests of cotton, have been identified and are now available as synthetic chemicals. Much progress has been made in using these sex pheromones to monitor the environment for the presence of the pest, to trap and destroy large numbers of insects seeking mates, and to suppress mating and reproduction by confusing and disrupting natural pheromone signals. Captures in traps baited with pheromones have been studied as a way of predicting the need for insecticide applications to combat the pink bollworm (Toscano et al. 1974) and the boll weevil (Rummel et al. 1980).

Current knowledge about the chemical identity of pheromones of important cotton insect pests is shown in Table 2.4. The sex pheromones of most Lepidoptera are blends rather than simple chemical compounds, and "fine tuning" of the pheromone blend is essential to elicit maximum insect response. The pheromone of the cabbage looper is apparently an exception to the preceding statement, since it consists of only a single component. Even with Heliothis, however, significant communication response between male and female moths has resulted from employment of a single parapheromone, cis-9-tetradecenyl formate (Mitchell et al. 1975).

Little effort has been made to use pheromones to control either Heliothis or the various kinds of armyworms, but communication between cabbage loopers has been disrupted by using 100 evaporative sources per 0.1 hectare plot (Gaston et al. 1967). Although the sex pheromone blend of Heliothis is used in survey and detection, much research is still needed to improve the use of this "tool."

Boll Weevil

The identification and synthesis of the components of grandlure, the boll weevil sex pheromone (Tumlinson et al. 1971), affords new opportunities for cotton insect pest management. Unlike the sex pheromones of a majority of the lepidoptera, which are produced by females, grandlure is elaborated by the male boll weevil in fecal pellets. Grandlure apparently functions as an aggregating pheromone during early spring and again during the fall, when boll weevil populations migrate. During the cotton plant's fruiting period grandlure functions as a male sex pheromone with a relatively short range.

Grandlure is a combination of two terpenoid alcohols and a cis-trans mixture of aldehydes (Table 2.4). It has been especially useful in monitoring boll weevil infestations. Dispensers containing 25 mg of grandlure are effective for about 4 weeks, and more than 1 million of the dispensers were used in monitoring experiments between 1973 and 1977.

A number of attempts have been made to use traps baited with grandlure to suppress the spring population of boll weevils as it emerges from overwintering sites. In fields of 35 and 73 acres in Mississippi the use of 10 pheromone traps per acre was estimated to have captured 75 percent of the overwintering population (Mitchell et al. 1976). The efficiency of such pheromone traps is inversely related to pest density; hence, trapping is a feasible control measure only when boll weevil populations are already at low levels (Mitchell and Hardee 1974). Knipling (1979) has explored many of the theoretical problems involved in determining the optimum employment of grandlure.

TABLE 2.4 Sex pheromones of insect pests of cotton.

Heliothis zea, cotton bollworm	mixture of: *cis*-11-hexadecenal *cis*-9-hexadecenal *cis*-7-hexadecenal hexadecanal	Klun et al. (1980a)
Heliothis virescens, tobacco budworm	mixture of: *cis*-11-hexadecenal *cis*-9-hexadecenal *cis*-7-hexadecenal hexadecanal *cis*-11-hexadecen-1-ol *cis*-9-tetradecenal tetradecanal	Klun et al. (1980b)
Pectinophora gossypiella, pink bollworm	*cis*-7-*trans*-11-hexadecadienyl acetate *cis*-7-*cis*-11-hexadecadienyl acetate	Hummel et al. (1973)
Spodoptera exigua, beet armyworm	*cis*-9-tetradecenyl acetate *cis*-9-*trans*-12 tetradecadienyl acetate	Brady and Ganyard (1972)
Spodoptera frugiperda, fall armyworm	*cis*-9-tetradecenyl acetate *cis*-9-*trans*-12-tetracadienyl acetate	Sekul and Sparks (1967)
Trichoplusia ni, cabbage looper	*cis*-7-dodecenyl acetate, Looplure	Berger (1966)
Anthonomus grandis, bollweevil	Grandlure, a mixture of: (+)-*cis*-2-isopropenyl-1-methylcyclobutaneethanol *cis*-3, 3-dimethyl-Δ-cyclohexaneethanol *cis*-3, 3-dimethyl-Δ-cyclohexaneacetaldehyde *trans*-3, 3-dimethyl-Δ-cyclohexaneacetaldehyde	Tumlinson et al. (1971)

SOURCE: Data from Georghiou and Taylor (1977), USDA (1979).

Pink Bollworm

Both the natural pheromone gossyplure, or cis-7-cis-11-hexadecadienyl acetate, and hexalure, a less active synthetic parapheromone (cis-7-hexadecenyl acetate) have been studied for use in control programs. The pink bollworm population in the newly infested area of the San Joaquin Valley, California, has been monitored with about 100,000 "delta" traps, each containing about 1,000 micrograms of gossyplure, as part of a male sterilization program (Foster et al. 1977). The use of gossyplure to control the pink bollworm in cotton fields seems to have been evaluated most thoroughly in the People's Republic of China. It has been reported (NAS 1977) that in a 27-hectare cotton field in China baited with 30 traps per hectare containing gossyplure, 290,000 male pink bollworm moths were captured. This was estimated to be about 25 percent of those present.

The disruption of communication between male and female pink bollworms using hexalure also is a practical possibility. In one experiment, the release of about 330 g of hexalure per hectare during the 16-week growing season caused most of the females to remain unmated and thus produced a reduction of 75 percent in the larval population of the next generation (Shorey et al. 1974). It has been estimated that by using the best techniques of microencapsulation and impregnation in hollow microfibers, satisfactory control of the pink bollworm could be obtained by releasing about 15 g of gossyplure per hectare per season.

Male Sterilization

The use of sterile males to control insect pest populations is a relatively new technique. A Russian geneticist named Serebrovsky originally outlined this approach in 1940 (Proverbs 1969, Whitten and Foster 1955). The first significant application of the technique, in which male insects are exposed to radiation, was the eradication of the screwworm fly (*Cochliomyia hominivorax*) from the southeastern United States (Knipling 1960). The technique is now being used to maintain eradication through the annual release of 8 to 10 billion sterilized flies in the southwestern United States and the adjacent area of Mexico (CEQ 1978).

Successful suppression of the codling moth, using both sterile males and sterile males plus sterile females, has also been demonstrated. A release rate of 40 fully sterile insects to one wild insect was sufficient to rapidly reduce the natural population. The cost, however, was considerably higher than the cost of conventional control methods (Proverbs 1970). Programs of less demonstrable success have also utilized sterile males. Approximately 100 million sterile pink bollworm moths have been released annually in the San Joaquin Valley to prevent the establishment of this pest. In a similar program, sterile Mexican fruit flies have been released annually in southern California since 1964, the purpose being to prevent the establishment of flies dispersing from Mexico.

Numerous experiments with male sterilization in other pest species, such as the oriental fruit moth, the melon fly, the Caribbean fruit fly, the cotton bollworm, the horn fly, the stable fly, and several mosquito species have shown favorable results. Diptera species appear to be the most amenable to effective sterilization. Lepidoptera and Coleoptera require larger and more debilitating doses of radiation to effect sterilization and present a complex problem of determining the competitiveness of sterilized insects with unsterilized ones.

Continual improvements in equipment, diet, and technique for the mass rearing of the boll weevil have occurred over the past quarter century (Griffin et al. 1981; J.E. Wright, Mississippi State University, Mississippi State, MS, personal communication, 1981). In 1980, six million adults could be delivered per week to the North Carolina eradication project at a cost of $3 to $4 per thousand (T.B. Davich, Mississippi State University, Mississippi State, MS, personal communication, 1981).

The principal problem in obtaining sterile boll weevils has been the development of a radiation treatment that would achieve full sterility of both sexes. Gamma irradiation was tried initially but had to be rejected because the dose inducing permanent sterility was rapidly lethal (Davich and Lindquist 1962). During the following fifteen years a variety of chemosterilants was tried, but all had at least one major drawback. Either the sterilizing dose was debilitating or fatal, or the dose failed to induce complete sterility, or it proved impossible to sterilize females at the dosage capable of sterilizing males (Wright and Villavaso 1981).

Attempts to discover a new method of sterilization were intensified after the inconclusive Pilot Boll Weevil Eradication Experiment (PBWEE) in 1971 to 1973. The methods used in PBWEE sterilized males only, and the two sexes of the mass-reared insects had to be separated by hand, an obvious and very costly defect in the procedure (Lloyd et al. 1976; Davich 1976).

Recent tests indicate the best method of sterilization now available is to feed weevils for 5 days with diflubenzuron followed by a gamma irradiation treatment in a nitrogen atmosphere (J.E. Wright, Mississippi State University, Mississippi State, MS, personal communication 1981). Reproduction by adults treated by this method is apparently zero, since treated weevils failed to establish a detectable population in a weevil-free area (Mitchell et al. 1980).

The longevity of male weevils sterilized by the gamma irradiation-diflubenzuron process, however, is severely affected. Mortality at day eight was 96 percent in a sterilized weevil population, as compared to 40 percent for unsterilized males (Boll Weevil Research Laboratory 1981a). Studies of the attraction of females to traps baited with sterile males have indicated that the attraction of females to both sterile males and grandlure is greatly reduced by the presence of normal males (Boll Weevil Research Laboratory 1981a).

The most recent studies place the field competitiveness of weevils treated with irradiation and diflubenzuron at 23 percent for the first four days after release. The apparent loss of vigor after day four is supported by day seven mortality figures of 58 percent for sterile males and 6 percent for normal males (Boll Weevil Research Laboratory 1981b). Attempts to increase the longevity of sterile males are continuing (T.B. Davich, Mississippi State University, Mississippi State, MS, personal communication, 1981), and a new technique for the aerial dispersal of weevils demonstrated good dispersal throughout the target field for the first time (Boll Weevil Research Laboratory 1981c).

Unfortunately, there have been no experimental demonstrations of population suppression using fully sterile weevils produced by current technology. In 1980 an extensive test involving two methods for the dispersal of sterile weevils in a test and control area containing comparable weevil populations in North Carolina provided no clear findings (J.E. Wright, Mississippi State University, Mississippi State, MS, personal communication 1981; Boll Weevil Research Laboratory 1981c). Inadequate preliminary monitoring and the seasonal influx of boll weevils from more heavily infested areas are believed to have contributed to lack of success in this experiment.

A large-scale test was also conducted in the Mississippi Delta in 1980, utilizing a 300-acre test site adjacent to a 500 acre control site. This test also failed to give a clear cut indication of suppression. Reduction in egg hatch in the infested squares was considered to be the best criterion, and there was only a slight (3 percent) reduction in egg hatch due to the release of sterile boll weevils. This test was performed under severe climatic stress conditions not favorable to weevil survival and reproduction (T.B. Davich, Mississippi State University, Mississippi State, MS, personal communication 1981). High temperatures on the soil surface are believed to have contributed heavily to mortality among the sterile weevils. Tests scheduled for 1980 in Nebraska to provide more information were apparently scrapped for lack of funds.

In summary, the use of sterile male boll weevils for eliminating natural boll weevil populations suffers from inconclusive data. Total suppression has been attempted in only a few field experiments, and these experiments have failed in one way or another.

Diflubenzuron

Diflubenzuron, or N-(4-chlorophenyl)-(2,6-difluorobenzoyl)-urea*, was originally described (Wellinga et al. 1973) as an insect growth regulator with a novel mode of action--a specific inhibitor of the synthesis of the N-glucosamine polymer, chitin, a critical component of the insect exoskeleton. This specific biochemical inhibition is a common property of an extensive series of substituted benzoyl ureas (Wellinga et al. 1973). Two related compounds, penfluron, or N-(4-trifluoromethylphenyl)-(2,6-difluorobenzoyl)-urea (Olivier et al. 1977), and trifluron, or N-4-(trifluoromethylphenyl)-

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*also named N-(4-chlorophenyl)-aminocarbamyl-2,6-diflurobenzamide.

(2-chlorophenyl)-urea, have been reported to be more effective than diflubenzuron, in some cases, and less effective in others, depending on the insect species. Only diflubenzuron, however, has conditional EPA registration for use on cotton against the cotton boll weevil and on forests for control of the gypsy moth, *Lymantria dispar*. Because of the complexities of the registration process, it seems unlikely that competing products will rapidly displace diflubenzuron.

The chemical structure of diflubenzuron is closely related both to those of the persistent herbicidal ureas--e.g., monuron, or *N*-(4-chlorophenyl) *N*, *N*-dimethylurea--and to that of the herbicide dichlorbenil, or 2,6-dichlorobenzonitrile. All of these herbicides have been widely used in the United States for three decades (Herbicide Handbook 1974).

Degradative Pathways

Studies of the degradation of diflubenzuron have been made with three different radiolabeled moieties (Metcalf et al. 1975). It has been shown that the parent molecule cleaves at both C(O)-N bonds in the -C(O)NHC(O)NH- bridge to form the primary degradation products 2,6-diflurobenzamide and *p*-chlorophenylurea. The 2,6-difluorobenzamide is subsequently converted to 2,6-difluorobenzoic acid and the *p*-chlorophenylurea to *p*-chloroaniline. None of these degradation products was found to be biomagnified extensively in the organisms of the laboratory model ecosystem (Metcalf et al. 1975).

Persistence

Diflubenzuron has a low water solubility of 0.3 to 0.10 ppm, and it has an octanol/water partition coefficient of about 3500. Extensive laboratory studies with three different radiolabeled preparations of diflubenzuron showed that it does not become highly bioconcentrated. The bioconcentration or ecological magnification factors for the parent compound were alga, 18 to 83 times; snail, 86 to 135 times; mosquito larva, 596 to 779 times; fish (*Gambusia*), 14 to 19 times (Metcalf et al. 1975). These factors indicate a decrease in residue concentration through food chains. The levels of bioconcentration are miniscule compared to those for DDT and other organochlorine insecticides under similar test conditions (Metcalf and Sanborn 1975). The relatively high values in mosquito larva reflect the affinity of diflubenzuron for the insect cuticle.

Diflubenzuron has moderate persistence in biological systems. In a laboratory model ecosystem treated with diflubenzuron, the percentages of parent diflubenzuron found in the organisms after 30 days of exposure were alga, 46 to 61; snail, 73 to 90; mosquito larva, 84 to 98; and fish, 5.2 to 6.7. The range of values shows the results with two separate radiolabeled preparations, one labeled in the difluorobenzoyl and the other in the *p*-chloroaniline moieties (Metcalf et al. 1975).

Persistence in Water. Diflubenzuron may persist in water for considerable periods. After 33 days in the water phase of a laboratory model ecosystem, two radiolabeled preparations of diflubenzuron had 24 to 31 percent of the total extractable radioactivity present as the parent compound (Metcalf et al. 1975). The primary hydrolysis products are 2,6-difluorobenzoic acid and p-chlorophenylurea, and their production is photochemically catalyzed through conversion to 2,6-difluorobenzamide and p-chlorophenyl isocyanate intermediates (Metcalf et al. 1975). The half-life of diflubenzuron in water is strongly pH-dependent, ranging from about 1 day under alkaline conditions to 2 weeks or more under neutral or acid conditions (EPA 1979).

Persistence in Soil. As expected from its similarity to monuron, diflubenzuron can be highly persistent in soil. The residues of two radiolabeled preparations placed in the soil of a laboratory model ecosystem showed only about 1 percent decomposition after 4 weeks at 27°C (Metcalf et al. 1975). Verloop and Ferrell (1977) demonstrated that soil persistence of diflubenzuron was related to particle size, with 2 micron-sized particles having a half-life of 0.5 to 1 week and 10 micron-sized particles having a half-life of 8 to 16 weeks. The effect of particle size on the degradation rate of diflubenzuron residues on cotton plants that are shredded and cultivated into the soil after harvesting is not clear. One experiment showed that such diflubenzuron residues showed no appreciable degradation 9 months after being placed in the soil. The content of the residue recovered by solvent extraction was 95 percent intact diflubenzuron (Bull and Ivie 1978). Diflubenzuron was found to bind tightly to soil particles and did not readily leach away.

Toxicology

The action of diflubenzuron in inhibiting chitin synthetase (Verloop and Ferrell 1977, Hajjar and Casida 1978) suggests a high degree of specificity of this insecticide for insects and related arthropods and for crustacea. The concentrations of diflubenzuron that are lethal to aquatic invertebrates are very small, with acute LC_{50} values in ppm for water flea, Daphnia, 0.0015; sand flea, Gammarus, ca 0.040; clam shrimp, Eulimnadia, 0.00015; mysid shrimp, Mysidopsis, 0.002; and brine shrimp, Artemia, 0.002 (LC_{50} is the concentration in water that is lethal to 50 percent of the aquatic organisms in the test population). Chronic reproductive effects over 6 to 30 days were observed in blue crab at 0.0005 ppm and March crab at 0.001 ppm (EPA 1979).

Vertebrate animals are much less susceptible. The LC_{50} value for guppies is 100 ppm, and phytotoxic effects were not observed at levels up to 10,000 ppm. The lethal oral dose (LD_{50}) for laboratory rats and mice is greater than 10,000 mg/kg.

Diflubenzuron per se does not appear to cause tumors, but its primary degradative pathway to p-chloroaniline, which is related to known human bladder carcinogens, has raised questions about diflubenzuron's overall tumor-causing potentiality. P-chloroaniline is mutagenic in the Ames Salmonella assay (EPA 1979).

3. PUBLICLY SUPPORTED PEST CONTROL

LEGISLATIVE HISTORICAL BACKGROUND

Not long after Congress authorized the establishment of USDA in 1862, the department's commissioner of agriculture recommended establishing a "professorship of entomology," saying "insects are annually destroying vast amounts of the product of our soil and their ravage appears to be increasing." Even though subsequent annual reports of USDA's Division of Entomology contained many references to the damaging losses caused by insect pests of foreign origin, little consideration was given to enacting national legislation to prevent or restrict the introduction of additional plant pests.

In 1881, California became the first state to enact a plant quarantine law. This act enabled California to enforce inspection and other measures to prevent the entry of pests. In 1889, the state of Massachusetts gave its department of agriculture funds to carry out the task of exterminating the gypsy moth. This work was discontinued in 1900, but the appearance of the gypsy moth in adjacent states during the next five years led Congress to appropriate federal funds to control the gypsy moth in 1906. The appropriation act directed USDA to cooperate with state authorities in preventing the further spread of the gypsy and browntail moths. This legislation established the policy of federal-state cooperation in plant pest control programs.

Meanwhile, all but five of the states had followed California's lead in establishing a quarantine law. Six years later, in 1912, the national Plant Quarantine Act [7 U.S.C. 151-167] authorized the creation of a plant inspection system and measures to control and eradicate plant pests. State employees were to perform most of the actual examinations at state expense, however.

In 1918 the Mexico Border Act [7 U.S.C. 145], provided federal funds for surveys to determine the distribution of the pink bollworm in states adjacent to the Mexican border, for the establishment of cotton-free zones in states adjacent to the border, for cooperation with Mexico in exterminating infestations near the border, and for cooperation with Texas or any other state in stamping out infestations. Prior to the discovery of the pink bollworm in Texas in 1917, state authorities had already taken steps to enact legislation authorizing quarantine regulations and the establishment of cotton-free zones. The state of Texas subsequently instituted a pink bollworm quarantine in January 1918, and in February of that year a proclamation of the governor prohibited the growing of cotton in designated districts for a period of three years or as long as the pink bollworm remained a menace. This attempt at eradication failed owing to a lack of grower support and cooperation.

Congress recognized the need for national authority to prevent the introduction of foreign pests and to control any pests that become established when they enacted the Plant Quarantine Act of 1912, as amended (7 U.S.C. 147a); Public Resolution No. 20, 1937 (U.S.C. 148-148e); and the Cooperation with States Act, 1962 (U.S.C. 450). This legislation authorized the Department of Agriculture to:

- restrict and control the entry and interstate movements of plants and plant products to prevent the entry and interstate spread of plant pests;
- cooperate with the states, farmers, farmers' associations, and Mexico to control or eradicate pests that pose a significant economic hazard; and
- cooperate with state agencies in the administration and enforcement of federal laws and regulations related to the control or eradication of plants pests.

Since the passage of the Plant Quarantine Act of 1912, USDA has developed four strategies for dealing with foreign or, where the strategies are applicable, domestic plant pests:

- exclusion: prevention of entry by plant quarantine and inspection;
- eradication: early detection of infestations and the use of eradication techniques that are biologically, environmentally, economically, and socially appropriate;
- retardation: the use of domestic quarantines to prevent artificial spread of the pest and use of population suppression to retard natural spread;
- mitigation: learning to live with the pest through changes in plant cultivation practices and pest control techniques.

In 1926, however, the U.S. Supreme Court ruled that state quarantines were illegal and unwarranted, and invalidated more than 200 such quarantines. Later that same year Congress amended the Plant Quarantine Act of 1912 to grant to states the right to take interstate quarantine action against any plant pest not covered by a federal quarantine, to authorize the Secretary of Agriculture to cooperate with any state or territory in the enforcement of such quarantines, and to authorize any state to exercise its police powers with respect to any articles shipped in violation of a federal plant quarantine. In 1937 Congress authorized an appropriation of $2 million for the general control of incipient and emergency outbreaks of insect pests and plant diseases. Prior to 1937, Congressionally appropriated funds were for specifically named plant pest and disease control programs.

In 1962 Congress enacted the Cooperation with States Act [7 U.S.C. 450], directing the Secretary of Agriculture to cooperate with state agencies in the administration and enforcement of federal laws and regulations related to the marketing of agricultural products and to the control or eradication of plant and animal diseases and pests. While many other federal statutes authorize or direct federal/state cooperation, most of them impose qualifying restrictions on cooperative activities. Under the 1962 Act the Secretary was authorized to enter into cooperative arrangements to the extent he deemed appropriate in the public interest.

States within geographical regions have also organized among themselves to control the spread of plant diseases and insect pests. In 1919 the plant regulatory officials of the 11 western states, the territory of Hawaii, Mexico's District of Lower California, and Canada's Province of British Columbia formed the Western Plant Quarantine Board "to secure a greater mutual understanding, closer cooperation and uniformity of action for the efficient protection of our plant industries against plant diseases and insect pests" (Hagan 1919). Central and Eastern Plant Boards were formed in 1925, while the Southern Plant Board was formed in 1926. These four regional boards then united to form the National Plant Board. While the National Plant Board has no statutory authority, it has considerable influence on policy decisions concerning both domestic and foreign quarantines.

In 1931 the regional plant boards and the National Plant Board adopted the Principles of Plant Quarantines, which, with slight revision in 1936, have provided a sound basis for the initiation of quarantine action. A supplemental document called Definitions and Guidelines was adopted in 1969 (Spears 1974). In 1973, the Plant Protection and Quarantine Division of the USDA Animal and Plant Health Inspection Service (APHIS), in cooperation with the plant boards approved Guidelines for Initiating and Discontinuing State/Federal Plant Protection Programs (USDA:APHIS:PPQ, March 12, 1973). These documents have helped to mold federal publicly supported pest control programs. USDA's procedures for such programs are set forth in Criteria for Participation in Cooperative Plant Protection Programs (USDA:APHIS:PPQ:Draft Oct 1976).

Most federal appropriations of funds for specific insect pest control programs have stated the program objective to be eradication of the pest, even when technology and resources available for the program have offered little chance of eradication. Many cooperative federal-state pest control programs have been efforts to retard the spread of pests, or combinations of suppression measures to prevent artificial spread of the pest with eradication measures applied to isolated infestations.

The Animal and Plant Health Inspection Service (APHIS) of USDA lists 37 plant pests that have been successfully eradicated through state and/or federal action from a limited geographic area in the continental United States (Table 3.1). In general most of the pests on the list are those with limited capability of migration. They had not yet spread to the full potential of their ecological range across the United States and the infestation that was successfully eradicated was of limited geographical distribution.

COTTON INSECT PESTS

The policy of the federal government and of the interested state governments has been to cooperate with cotton growers themselves in aggressive efforts to curb the substantial damage to cotton crops caused by the boll weevil and other cotton insect pests. As Chapter 2 notes, the last two decades have been marked by a host of scientific developments in efforts to deal with cotton insect pests--the continued introduction of new insecticides to replace those rendered less effective by the development of resistance in the insects, efforts to breed new strains of cotton that will have more natural resistance to insect attack, the discovery of the boll weevil pheromone called grandlure and its use in traps for monitoring boll weevil movements, the development of methods for the mass rearing of boll weevils in laboratories, attempts to use mass sterilization of male boll weevils to reduce weevil populations, and, last but not least, discovery of the value of using insecticides against boll weevils at the end of the cotton season to kill diapausing weevils that would otherwise survive the winter and begin to breed anew the following year.

Most of these developments have had their origin, in the last analysis, in the desires of cotton growers themselves to minimize the economic damage they suffer from cotton insect pests every year. In 1969 the National Cotton Council of America, the largest organization of cotton growers, formally asked USDA to conduct an experiment in the heart of the Cotton Belt to determine if it was technically feasible to eliminate the boll weevil, using the newest techniques then available. Such a trial was conducted in an area of south Mississippi between 1971 and 1973. During the trial, known as the Pilot Boll Weevil Eradication Experiment (PBWEE), boll weevil populations were suppressed to very low levels. In August 1973 the technical guidance committee of the National Cotton Council reviewed the data from the PBWEE experiment and concluded that it was technically and operationally feasible to "eliminate as an economic pest" the boll weevil in the United States by using techniques that were also ecologically acceptable.

A new federal law was enacted that same month authorizing and directing the Secretary of Agriculture "to carry out programs to

TABLE 3.1 Successful Plant Pest Eradication Programs from Conterminous United States, APHIS

Pest and (Host) Year and Location	Primary Method Used for Eradication
INSECT PESTS	
Melanaspis aliena (Newstead)–alien scale (orchids)	
1958-71–Florida	Phosphatic sprays and infested host destruction.
Nygmia phaeorrhoea (Donovan)–browntail moth	
1911-48–Vermont	Manual destruction of webs and lead arsenate sprays to foliage.
1911-69–New Hampshire	DDT and carbaryl foliar sprays. Manual destruction of webs.
Aleurocanthus woglumi (Ashby)–citrus blackfly (citrus, mango)	
1934-38–Florida[a]	Destruction and oil sprays of infested host trees. Rotenone and oil sprays.
1956–Texas[b]	
Parlatoria blanchardi (Targioni-Tozzetti)–date palm scale or parlatoria date scale (palms)	
1913-36–California, Arizona, Texas	Summer oil sprays.
Eriophyes litchii (Keifer)–erinose mite (lychee)	
1956-58–Florida	Dicofol sprays and sanitation.
Rhizotrogus majalis (Razoumowsky)–European chafer (roots of turf, trees, and shrubs)	
1954-65–West Virginia	Dieldrin surface treatment.
Lymantria dispar (Linnaeus)–gypsy moth (oak and other hardwood foliage)	
1914-17–Ohio	Arsenate of lead.
1954-65–Michigan	DDT foliar sprays.
1966-70–Michigan[c]	Carbaryl foliar sprays.
Nilotaspis halli (Green)–hall scale (stone fruits)	
1941-67–California	HCN fumigation.
Solenopsis invicta (Buren)–red imported fire ant	
Solenopsis richteri (Forel)–black imported fire ant	
1950–Tennessee	Chlordane surface treatment.
1966–Tennessee	Mirex bait.
Popillia japonica (Newman)–Japanese beetle (turf, flowers, grapes, . . . general feeder)	
1957-65–Iowa	Dieldrin surface treatment.
1961-65–California (Sacramento)	Chlordane surface treatment; carbaryl foliar treatment.
1972-76–California (San Diego)	Chlordane surface treatment; carbaryl foliar treatment.
Trogoderma granarium (Everts)–khapra beetle (stored grains)	
1954-66–Texas, Arizona, New Mexico, California	Methyl bromide fumigation.
Ceratitis capitata (Wiedemann)–Mediterranean fruit fly (fruits and vegetables)	
1929-30–Florida	Host fruit destruction and bait sprays.
1956-58–Florida	Malathion bait sprays, trapping and lures.
1963 (two occasions)–Florida	Malathion bait sprays, trapping and lures.
1966–Texas	Malathion bait sprays, trapping and lures.
1975-76–California	Host fruit destruction, traps, ground treatment with insecticides and sterile releases.
1980–California[d]	Traps, ground treatment with insecticides and sterile releases.
Dacus cucurbitae (Coquillett)–melon fly (cucurbits-melons, etc.)	
1957–California	Trapping.

TABLE 3.1 (continued)

Pest and (Host) Year and Location	Primary Method Used for Eradication
Epilachna varivestis (Mulsant)–Mexican bean beetle (beans)	
1950–California	Foliar sprays with Rotenone.
Anastrepha ludens (Loew)–Mexican fruit fly (citrus)	
1954-56–California	Malathion baitsp ray.
Eurytoma sp. or *Eurytoma orchidearum* (Westwood)–orchidfly (fox-tailed orchid)–a chalcid wasp	
1966-68–Florida	Dimethoate, diazinon, and sanitation.
Asterolecanium epidendri (Boisduval)–orchid pit scale (orchids)	
1968-71–Florida	Destruction of infested plants.
Dacus dorsalis (Hendel)–Oriental fruit fly (citrus)	
1960–California	Methyl eugenon trapping.
1966–California	Methyl eugenon trapping.
1969-78–California each year	Methyl eugenon trapping and methyl eugenon/naled bait.
Reintroduced each year from 1970 to 1978 and eradicated each year.	
Pectinophora gossypiella (Saunders)–pink bollworm	
1933-35–Georgia	Nonplanting zone.
Ceroplastes rubens (Maskell)–red wax scale (Chinese evergreen, anthurium, etc.)	
1955-60–Florida	Dimethoate sprays and sanitation.
1961-68–Florida	Dimethoate sprays and sanitation.
Vinsonia stellifera (Westw.)–stellate scale (orchids)	
1955-58–Florida	Parathion and oil sprays and parathion clips.
Cylas formicarius elegantulus (Summers)–sweetpotato weevil (sweetpotato)	
1962–New Jersey	Host destruction, dieldrin surface treatment.
Graphognathus spp.–whitefringed beetles (roots of crops - peanuts and foliage of truck crops)	
1954-60–New Jersey	Dieldrin soil and soil surface treatments.
1965-70–Maryland	Dieldrin surface treatments.
Has been reintroduced 1979.	
PLANT DISEASES	
Xanthomonas citri (Hasse)–citrus canker (citrus)	
1914-43–Florida and Gulf States to Texas	Destruction of infected host.
Puccinia sorghi–common maize rust (corn)	
1969-70–Florida	Destruction of infected host.
Physopella pallescens (Arth. Cumm. and Ram.)–gamagrass rust (*Tripsacum* and *Euchlaena*)	
1970-72–Florida	Destruction of infected host material.
(virus disease)–Hoja Blanca virus	
1957-65–Florida	Malathion sprays, roguing and plowing under.
(Mycoplasm disease)–lethal yellowing of coconuts Cocunut Lethal Yellowing Mycoplasm	
1955-68–Florida, Key West	Resistant Malayan varieties.
Has been reintroduced.	
Peach Mosaic Virus	
1935-70–Utah	Destruction of infected trees.

TABLE 3.1 (continued)

Pest and (Host) Year and Location	Primary Method Used for Eradication
Puccinia pelargonii - zonalis (Doidge)–pelargonium (geranium) rust	
1970-71–Florida	Dithane, zineb sprays, sanitation, and destruction of infected plant.
Uredo becknickiana (P. Henn)–Phajus rust (orchids)	
1954–Florida	Destruction of infected plants.
Synchytrium endobioticum (Schibb. Perc.)–potato wart (potato)	
1918-74–Maryland, West Virginia, Pennsylvania	Host destruction. Soil treatment with copper sulfate or formaldehyde.
Physopella zeae (Mains, Cummings, and Ramacher)–tropical corn rust	
1970–Florida	Destruction of infected plants.
OTHER	
Helix aspersa (Muller)–brown garden snail (plant feeder)	
1963-64–Florida	Mexacarbate and methyl bromide fumigation.
1964-66–Florida	Mexacarbate.
1969-70–Florida	Methaldehyde-calcium arsenate bait applied aerially.
Achatina fulica (Bowdich)–giant African snail (plant feeder)	
1969-75–Florida	Methaldehyde-calcium arsenate bait, carbaryl drenches, handpicking sanitation.
Globodera rostochiensis–golden nematode (potato, tomato)	
1968-70–Delaware	DD soil fumigation.
Theba pisana (Muller)–white garden snail	
1927–California	Methaldehyde bait.
1940–California	Methaldehyde bait.
1956–South Carolina	Methaldehyde bait.
1969–California	Calcium arsenate bait.

[a] Reintroduced, Fort Lauderdale, Florida, 1976.
[b] Reintroduced, Brownsville, Texas, 1971.
[c] Reintroduced, Michigan, 1972.
[d] Reintroduced, San Jose, California, 1980.

SOURCE: M. J. Pender, APHIS, personal communication, 1981.

destroy and eliminate cotton boll weevil in infested areas of the United States . . . if the Secretary determines that methods and systems have been developed to the point the success in eradication of such insect is assured . . ." The new law also required cotton growers to pay up to one-half of the costs of what the law also referred to as an "eradication" program and gave the Secretary the authority to issue "such regulations as he deems necessary to enforce the provisions of this subsection with respect to achieving the compliance of producers and landowners."

This last proviso, in effect, gave the Secretary full authority to carry out the program, including enforcing the program among all cotton growers and allowing federal officials to enter any private property necessary for success of the program. The provision was a departure from historical practice, in which the states had been vested with authority for enforcement and right-of-entry in insect pest control programs, and was a logical extension of the following statement in the National Plant Board's 1972 Principles of Plant Pest Control: "Since the measures required to implement a pest control program usually involved treatment of private and public property for the benefit of wider interest or the public welfare, they could not be undertaken by private individuals or groups, and therefore to resort to procedures under public authority is logical."

The PBWEE experiment and the 1973 legislation, however, did not settle the question of how to deal with the boll weevil. As the National Cotton Council's technical guidance committee had already recognized, some boll weevils had been found in the PBWEE "eradication zone." This technical guidance committee took the view, however, that what PBWEE had demonstrated was eradication followed by reinfestation. Since boll weevils can migrate at least 45 miles (72 km), and since most of the cotton in the eradication zone was within 45 miles of infested cotton, the technical committee took the view that the boll weevils found in the zone were immigrants. In order to describe what had happened, the committee said that the boll weevils in the zone had been "eliminated as an economic pest" rather than "eradicated."

In 1973 a committee of the Entomological Society of America evaluated the PBWEE experiment. That committee expressed reservations about undertaking any massive program of boll weevil eradication until the techniques used in PBWEE were improved and more attention was paid to the problem of preventing a boll weevil immigration from Mexico in the event boll weevils actually were eradicated from the United States. In 1975 the National Academy of Sciences published a report in which a subcommittee on cotton pest control expressed severe doubt as to the feasibility of eradicating the boll weevil in this country (NRC 1975).

Meanwhile, the agricultural appropriation subcommittee of the House Appropriations Committee had begun to express concern about the 1973 law granting new powers to the Secretary of Agriculture. The subcommittee was concerned about whether the powers granted to the Secretary to carry out the law for controlling the boll weevil amounted to control of private land use by the federal government; it was also concerned about insufficient cooperation with USDA's boll weevil control efforts among cotton growers and the states.

Despite the reservations in various quarters about the results of the PBWEE experiment and about the 1973 federal legislation, the National Cotton Council continued to support a plan it had submitted to the Secretary of Agriculture for eradicating the boll weevil.

A number of conditions have been identified as essential to the success of any effort to eradicate the boll weevil (Brazzel 1976, Guice 1976). They are as follows:

- There must be overwhelming support of the program by growers, by private industry, and by federal and state agencies.
- There must be participation by 100 pecent of the growers.
- Either federal or state governments must have the authority to do the following: establish an eradication zone; grant program inspectors the authority to enter any public or private property in the zone; prohibit the non-commercial raising of cotton; regulate the movement of seed cotton and any other material capable of transporting boll weevils; require mandatory reporting of all cotton acreage; and allow the destruction of volunteer cotton.
- Growers must be willing to contribute up to 50 percent of the cost of the program.

As indicated earlier, all of the states have the statutory authority to regulate the interstate and intrastate movement of insect pests and plant diseases, and most of them have the authority to control specified plant pests through quarantine or other methods. A review of Bruer (1976) showed, however, that most of the states lacked authority to compel cooperation with one or more of the conditions noted by Brazzel and Guice. Bruer concluded that if any eradication program was to be successful, "some revision of state statutes seems to be indicated."

Another problem, and one that has aroused substantial debate ever since the National Cotton Council proposed its plan to the Secretary of Agriculture in 1973, is whether or not "eradication" is desirable, even if feasible.

Part of the disagreement over such a plan comes from the difficulty in defining the term "eradication." While eradication clearly means "to eliminate the population of boll weevils," the questions that must be asked are, For how long? and Throughout what geographical area? In the past these questions have been left unanswered in official documents and hence subject to virtually innumerable interpretations. As Table 3.1 shows, success in eradication in the past has only been obtained for a limited time and in limited areas for other insect pests in the United States. If both the timespan and area of eradication are narrowly defined, these eradication efforts can be termed successful. But if broader definitions are used--for example, eradication for a decade throughout the United States--very few of the eradication programs shown in the table have been successful.

Eradication of a specific pest from a specific area is likely to be the most effective and efficient strategy only when an effective and economical eradication technique is available and when the pest in question is not widely distributed. This is often the case if the pest has recently invaded an area and has a limited habitat. Otherwise, it makes sense from an ecological standpoint to approach the task of eradication cautiously.

Because the suggested plan to eradicate the boll weevil tended to polarize proponents and opponents of the plan, USDA decided in 1977 to conduct two kinds of trials. One was the Boll Weevil Eradication (BWE) trial, to be conducted in adjacent areas of North Carolina and Virginia, and designed to wipe out the insect completely. The other was the Optimum Pest Management (OPM) trial in Mississippi, designed to determine whether it was possible to hold boll weevil populations below levels that are economically harmful to cotton growers. The BWE and OPM trials are described in some detail in the next chapter.

4. DESCRIPTION OF THE OPM AND BWE TRIALS AND OPTIONS FOR FUTURE PEST MANAGEMENT

The Optimum Pest Management (OPM) trial and the Boll Weevil Eradication (BWE) trial were both initiated in 1978 to test in a relatively objective manner the scientific and technical advances made in the last two decades in controlling cotton insect pests. Both trials ended in 1980. This chapter describes the major components of the field trials and alternate pest control strategies for use in the Cotton Belt. The reader is referred to the USDA reports listed in Appendix B for the detailed results of the field trials.

THE OPM TRIAL

The object of the OPM trial was to test the feasibility and effectiveness of an areawide cotton insect management program that would keep cotton insects--particularly the boll weevil--below the population levels at which they cause economic loss to cotton growers. The trial was carried out over a three year period on over 30,000 acres of cotton in Panola County in northwestern Mississippi. The major components of the OPM trial were these:

- the use of traps baited with the pheromone grandlure to monitor the size and extent of the boll weevil population;

- urging cotton growers to plant cotton within certain recommended dates;

- providing recommendations to growers on when to apply pinhead square applications of insecticides, as determined by scouting of the cotton fields for boll weevils and other pests by commercial consultants, employees of grower associations, and extension service employees;

- full reimbursement of the costs incurred by growers who carried out the pinhead square applications of insecticides;

- urging cotton growers to follow extension service recommendations for in-season control of the boll weevil and other cotton insect pests;

- urging growers to destroy cotton plant stalks as soon as their cotton was harvested;

- full reimbursement of the costs incurred by growers who made insecticide applications at the end of the season to eliminate boll weevils entering diapause; and

- developing a system to verify both pinhead and diapause applications of insecticides before reimbursing cotton growers.

In order to determine the success of the OPM trial in Panola County, the results of the trial there were compared with the results achieved through current insect control measures on a similar area in Pontotoc County, which lies to the east of Panola and is separated from it by Lafayette County.

The OPM trial was appraised a biological and technical success by the USDA's Overall Evaluation Team (Economics and Statistics Service 1981a). They based their conclusions on two main points.

- Four late season applications of insecticide treatments used in 1978 and 1979 reduced numbers of boll weevils taken in traps during 1979 and 1980 by 78 and 94 percent, respectively, compared with trap catches in a Current Insect Control (CIC) area in Pontotoc County. There was no need for in-season application of insecticides for control of the boll weevil, and the number needed to control bollworms and budworms declined.

- A high percentage of the cotton acreage was included in fall diapause programs to eliminate areas for reinfestation. In 1978, 1979, and 1980, cotton producers participated at the rate of 98.7 percent, 99.6 percent, and 99.7 percent, respectively.

THE BWE TRIAL

The object of the BWE trial was to test the feasibility of eradicating an established boll weevil population from a cotton-growing area in eastern North Carolina and Virginia that has been infested by the boll weevil since 1922. The cotton acreage involved in the trial increased from about 15,500 acres in 1978 to 32,500 acres in 1980. An evaluation zone was established in the test area, extensive monitoring to determine the size and extent of the boll weevil population was carried out with pheromone traps, and a buffer zone surrounded the trial area.

In order to establish the proper state regulatory authority for the trial, and to establish procedures to measure cotton grower support for it, the legislatures of both North Carolina and Virginia enacted legislation entitled the Uniform Boll Weevil Eradication Act. Under authority of this legislation, each state established regulations to define the geographical area of the trial, to monitor and regulate the movement of certain articles in or through the trial area, to establish a system for recording the registered number of acres planted in cotton by cotton growers, and to permit the collection of funds.

Prior to the adoption of the final state regulations and the appropriation of state funds to pay for 25 percent of the cost of the trial, a statewide referendum of cotton growers was conducted to measure grower support for the trial. In December 1976, growers in North Carolina affirmed, through a referendum, their approval for the trial to be conducted and to pay 50 percent of the costs. Approval for the trial in Virginia was obtained through a public hearing.

The major components of the BWE trial carried out by APHIS were:

- the use of pheromone-baited traps located around every cotton field,
- in-season cotton pest control,
- diapause control following termination of cotton crop,
- defoliation or desiccation of all cotton to hasten harvest operations or to reduce the boll weevil food and breeding sites,
- sterile boll weevils distributed over entire cotton crop, and
- four foliar sprays of diflubenzuron in selected areas.

The BWE trial was considered a biological as well as a technical success by USDA's Overall Evaluation Team (Economics and Statistics Service 1981a). They based their conclusions on two main points.

- ". . .no infestations of weevils were detected in the evaluation area between October 1978 and September 1980. . . . Review and analysis of relative data indicated that the boll weevils found in the evaluation area after June 1979 were 'reintroduced' weevils, therefore, 'native' boll weevils were eradicated from the evaluation area."
- "Overall, in the North Carolina BWE trial, the average number of insecticide applications decreased in the evaluation area and in the associated Current Insect Control (CIC) area in North Carolina by 88 percent and 25 percent, respectively, as compared with the 1974-1977 pretrial averages."

ALTERNATE PEST CONTROL STRATEGIES FOR USE IN THE COTTON BELT

One option for dealing with cotton insect pests throughout the Cotton Belt in the future would be simply to continue to use current insect control (CIC). CIC includes all of the various practices discussed in Chapter 2--insecticides, use of short-season varieties, use of cotton plants with natural host plant resistance to various insect pests, trap cropping, and so on--as they are used by individual cotton growers. As time has gone on, however, CIC has tended to merge into so-called Integrated Pest Management, or IPM, programs. IPM programs vary among the states, but their general objective is to recommend and demonstrate to individual growers the economic advantages of scouting their fields for pests and following insect management practices recommended either by state cooperative extension services or grower cooperatives. IPM programs are voluntary efforts, and individual growers are free to deal with their pest problems as they see fit.

It should be noted here that no comprehensive evaluation of the impact of CIC or of IPM programs on the environment has ever been attempted, and it would seem clear that an environmental assessment would be necessary as part of any attempt to assess the feasibility of alternative cotton insect control programs.

In addition to CIC the USDA has listed several modifications of OPM and BWE programs for implementation beltwide. The definitions for these different beltwide boll weevil/insect management programs are given in Appendix A.

OPM Options

One OPM option that might be used in the future throughout the Cotton Belt would be essentially to use the OPM program tested in Mississippi throughout the belt. Such a program, whose principal thrust is to give cotton growers an incentive to comply by reimbursing them fully for the costs they incur in carrying out insecticide applications when recommended, is often referred to as OPM-I, or Optimum Pest Management with Incentives.

Another OPM option is called Modified Optimum Pest Management (MOPM). MOPM would be used in areas where the application of insecticides at the end of the season just prior to boll weevil diapause could not be implemented or appeared not to be needed. MOPM would use, if applicable, all the other practices tested in the Mississippi trial.

Two other variations of OPM are called OPM-PI and OPM-NI. If the OPM-PI (Optimum Pest Management, Phased Incentives) program was chosen, the financial incentives to cotton growers would begin at 100 percent reimbursement of insecticide costs and would be reduced to zero over a period of four years. OPM-NI (Optimum Pest Management, No Incentives) would be just what that implies. Growers would receive no reimbursement for insecticide applications, but all the other elements of the Mississippi trial would be present, if applicable.

A final variation is called OPM-NI-BWE, or Optimum Pest Management with Boll Weevil Eradication. An OPM-NI-BWE program would last for four years, and the chief characteristics would be as follows:

First year: cotton growers would be given information and education on cotton insect pest management and encouraged to follow recommended control practices.

Second year: cotton growers would be responsible for in-season control of all insects, including the boll weevil. USDA's APHIS would be responsible for releasing sterile boll weevils and beginning in early September (depending on the weather and the area), APHIS would carry out between 5 and 10 diapause insecticide applications, using recommended insecticides.

Third year: APHIS would monitor and be responsible for controlling boll weevil infestations, while cotton growers would be urged to follow recommended procedures to control other cotton insect pests.

Fourth year (and subsequent years): MOPM practices would be carried out to control other cotton insect pests in a weevil-free environment; federal and state regulatory agencies would be responsible for routine monitoring of weevil-free areas and control of incipient weevil infestations. The MOPM program would provide growers with information on how to control the cotton pests other than the boll weevil.

The BWE Option

The BWE option would be a beltwide program carried out by agencies of USDA and designed to eradicate the boll weevil from the United States. This eradication effort would begin in the eastern end of the Cotton Belt and proceed west through eight other zones over a period of three years. At the end of that period a buffer zone would be set up between the United States and Mexico to prevent reinfestation from that country. Pheromone traps would be used to detect any reinfestations of the boll weevil that required eradication. The principal activities under the program would be as follows:

First year: all applications of insecticides throughout the growing year would be carried out by APHIS, following state agency recommendations.

Second year: APHIS would be responsible for all insecticide treatments intended to eradicate the boll weevil, and the distribution of sterile male boll weevils over all lands planted in cotton; cotton growers themselves would be responsible for controlling all cotton insect pests other than the boll weevil, as well as for destroying cotton plant stalks after harvesting; growers would be urged to follow recommendations of cooperative extension services on dealing with other cotton insect pests.

Third year: APHIS would be responsible for monitoring and controlling incipient boll weevil infestations; cotton growers would again be urged to carry out measures against other cotton insect pests as recommended by state agricultural extension services.

The use of pheromone traps during the beltwide eradication program would include:

Pre-Implementation Survey. One trap per acre (a minimum of one per field) would be installed from about August to November. These traps would identify the potential severity of the weevil problem and pinpoint trouble spots. Diapause treatments would be initiated if the traps indicated that weevil populations were excessive.

Use of Traps During Implementation.

- Spring trapping. One pheromone trap per acre would be placed at cotton fields of the previous season and would be oriented toward hibernation sites. The traps would be installed about one month before planting until cotton began to flower, a period of about three months during which newly planted fields would be located and mapped. Insecticide applications would be on an "as-needed" basis as shown by trap catches.

- In-season trapping. Following the spring trapping and insecticide applications, if needed, sterile males would be dropped for about 4 weeks at about the 6- to 8-leaf stage of growth. Traps would be reinstalled at the rate of one per acre, but this time they would be installed in-field.

- Fall trap survey. As cotton plants began to mature, pheromone traps would again be installed around field borders. Trap catches would indicate the need for diapause insecticide applications.

Post-Program Monitoring. If the traps indicated that the weevil population in an area had been eliminated, the area would be assigned to the monitoring unit on about July 1. Traps would be installed in the spring for three months around cotton fields of the previous season and in the fall for three months around current cotton fields.

During the monitoring period the trap densities would be:

- First year: one per 10 acres

- Second year: one per 50 acres

- Third year: one per 200 acres

If boll weevils were captured at any time during this period, trap density would be increased to one per acre in a zone of one to two miles around the detection point or area.

5. APPRAISAL OF THE OPM AND BWE TRIALS AND PLANS FOR THEIR BELTWIDE APPLICATION

INTRODUCTION

The OPM and BWE trials were large-scale demonstrations, and several constraints made it impossible to plan them scientifically. In the case of the BWE trial, one constraint was the need for a large buffer zone that sufficiently isolated the trial area from other weevil-infested areas. Otherwise, suppression of the population in the trial area could be obscured by in-migration from a non-trial area. It was this constraint that led to the selection of areas in North Carolina and Virginia for the BWE trial. As a result, the BWE trial was conducted in areas where the boll weevil population was at a very low density. The need for a large-scale buffer zone also resulted in cost constraints that limited eradication to a single trial. This unreplicated trial in an area untypical of the Cotton Belt as a whole prevented any statistical analysis of the BWE trial's beltwide feasibility. The OPM trial was also unreplicated and so limited in size that in-migration of boll weevils from adjacent areas was clearly detected.

There were two criteria used by the USDA for success in the OPM and BWE trials (USDA 1981b):

(1) Demonstrate proof of the biological success, environmental acceptability, and economic feasibility of each method;

(2) Supply a data base for making judgments on the feasibility of beltwide implementation.

A reliable test of the success of the BWE trials depended on the establishment of statistically acceptable confidence intervals for two factors: (a) pheromone trap efficiency, and (b) log rate of population growth for the boll weevil. Since an eradication program, by definition, deals with populations driven to the verge of extinction rather than with populations in normal ranges, the values obtained for both of these factors may have been quite different than they would have been for normal populations. If both of these factors are known, at any rate, the trap density needed to assure detection of any surviving weevils can be calculated.

There were three possible outcomes for the BWE trial:

(1) a measurable number of boll weevils after the trial period ended would mean that eradication had failed;

(2) no detectable weevils in the trial area would mean that eradication was successful at a given detection level;

(3) detection of low numbers of boll weevils could mean either an in-migration of weevils to the test area or low levels of uneradicated weevils in the test area with a low rate of population increase.

The USDA's biological evaluation team report (SEA 1981) did not give this last possibility the same degree of consideration as in-migration.

As for the OPM trial, there were many uncontrolled variables that make it difficult to analyze the trial's success. There were inherent differences in the weather and the fertility of the fields in Panola and Pontotoc counties. There were also differences in the numbers of secondary insect pests (e.g., more tarnished plant bugs in Pontotoc in 1979). Late-season beneficial insects tended to be higher in Pontotoc, and there were differences in the amounts and kinds of insecticides used in the two counties. In-season spraying against Heliothis, for example, was higher in Panola.

As originally envisioned, the BWE trial would have used sterile male boll weevils as the keystone of the eradication process. But the development of methods to produce large numbers of highly competitive, fully sterile boll weevils has proved to be a highly intractable problem. There is no evidence that sterile boll weevils contributed significantly to population suppression in the BWE trial. Furthermore, some USDA scientists have even suggested that insecticides (a density-independent mortality factor) can serve as a substitute for sterile males (a density-dependent mortality factor).

Two years of surveillance without a single find raises the probability of boll weevil eradication in North Carolina's Chowan County, which was part of the BWE trial area (SEA 1981). Two arguments can be made against that probability: (1) non-detection does not necessarily mean extinction, and (2) some earlier claims about the eradication of certain insects have been erroneous, since relict populations were found years later (Michigan Department of Agriculture 1965, NRC 1969, Wallner 1974). Until a considerable period of time has elapsed, therefore, eradication cannot be demonstrated with reasonable certainty. The situation in Chowan County is best described as a two-year non-detectable weevil population at 1 pheromone trap per acre monitoring density. A description of the situation in the other counties of the eradication zone would be one weevil per 10 thousand acres of cotton detectable at 1 pheromone trap per acre monitoring density.

Since North Carolina and Virginia are at the northern limit of the boll weevil's range and weevil populations in the trial zone had been reduced to extremely low levels by two unusually cold winters immediately before the trial, it would be expected that the APHIS program would reduce boll weevil populations more rapidly in North Carolina and Virginia than could be anticipated elsewhere in a belt-wide program. A more vigorous program of population suppression would be needed in other areas of the Cotton Belt where much larger populations of the boll weevil are entrenched in a more favorable climate. A more reasonable assessment of the BWE trial is that an intensive program of three years' duration followed by two years of intensive monitoring would be the minimum needed to reduce the population to a non-detectable level throughout the Cotton Belt.

Beltwide plans must take into account the subtle interactions of multiple factors, and the chances for error in extrapolating from the trial area to beltwide are obvious. In order to decide which program to adopt, the estimate of benefits should significantly exceed any margin of error in making these estimates.

Since the OPM and BWE trials were unreplicated demonstrations, lacked suitable controls, and involved uncontrollable variables, the scientific knowledge necessary to determine their degree of success or failure is limited. Any assessment of their value or extrapolation from them is a matter of individual judgment.

BIOLOGICAL CONSIDERATIONS

The Committee has evaluated the USDA biological evaluation team's report and commends its members for a job well done, given the constraints imposed. The shortcomings of the report result from the design of the trials, which did not provide the necessary data from which to draw conclusions applicable to the entire Cotton Belt. These shortcomings give rise to major areas of concern, which are discussed below.

Homogeneity of Eradication Trial Versus Heterogeneity of Cotton Belt

Cotton is grown over a wide range of soil and climatic conditions, and is attacked by a wide variety of insects. Thus, no one group of pest control practices can be recommended for all cotton-growing areas.

A major purpose of the eradication trial in North Carolina was the need for information to evaluate the biological implications of a boll weevil eradication attempt. We found that the BWE trial had provided insufficient data and information to resolve several significant issues. The trial did not provide information useful for boll weevil eradication throughout the Cotton Belt, nor was it designed to do so. We discuss here the subjects on which little or no information exists and the research that should be undertaken on these subjects.

The eradication trial was conducted in a relatively homogeneous environment, in contrast to the heterogeneous environment of the entire Cotton Belt. This heterogeneity extends to the boll weevil itself. Hence, one important question is, How would the boll weevil respond to a uniform eradication effort, as proposed in the BWE plan? This question leads to more specific concerns:

- The boll weevil population in the BWE trial area was at a record low. Thus, it might normally take a year longer to reduce average boll weevil populations to the level achieved in the trial. At the very least, therefore, the cost estimates for a beltwide BWE program should be increased by the costs of one additional year.

- The effect of climatic conditions on boll weevil populations varies across the belt. Would these differences affect the eradication program?

- Do all weevil populations respond in the same way to pheromone traps? Is the pheromone trap equally efficient in all of the microclimates that would be included in the beltwide eradication program? Experience with other pheromone traps, such as those developed for the European corn borer, has shown that insect populations can vary widely in their response to a given synthetic pheromone.

- Would boll weevil populations respond equally to the same amount of insecticide, or do they possess varying levels of resistance due to differences in previous exposure to insecticides?

Environmental differences across the Cotton Belt may also substantially influence the success of an eradication effort. Although insect complexes vary substantially across the belt, regional differences in rainfall and other climatic factors have been even more important in determining the best methods of managing cotton insects. Would not these same differences influence the effectiveness of a uniformly applied eradication effort? Differences in temperature and humidity may influence the effectiveness of traps and insecticides as well as the behavior and reproductive potential of the weevil. It is already known that differences in the amount of suitable overwintering habitat, soil conditions, and cropping patterns influence insect management practices.

In Texas, for example, diapause control has proved effective in suppressing weevil populations in west Texas, but diapause programs on a lesser scale in south Texas have met with limited success (Rummel and Frisbie 1978). The environmental characteristics of south Texas--mild winters and abundant overwintering habitats--are more favorable for overwintering weevils than the harsher conditions of west Texas. Since the south Texas environment is not unlike that in other southern cotton-producing areas, the effectiveness of diapause insecticide applications as a component of the eradication program seems debatable. The BWE trial did not offer the opportunity to evaluate this potential problem.

Different cotton varieties are planted across the Cotton Belt, but no measure of how these varietal differences might influence the effectiveness of an eradication effort is in hand. Variations in planting and harvesting dates, stalk destruction, and other cultivation practices also might influence the outcome of the eradication program.

Another problem is that there are host plants other than cotton in the United States that can sustain boll weevil populations (SEA 1981). One of these is *Ciefuegosia drummondi*, a wild host found in the Coastal Bend region of Texas, and another is *Hibiscus*. In addition, several malvaceous plants listed as potential hosts occur in southern Florida, although these are presumed to be too far from present cotton-growing areas to present much of a problem. There is also the possibility that cotton plants in urban areas grown as curiosities or ornamentals could harbor low boll weevil populations, as could cotton plants growing along roadways or other sites where seeds were lost from farm equipment. Any alternative host species must be carefully evaluated and, if found, the sources or the weevils eliminated.

Another thing that should be mentioned is that a large array of pest control practices are currently used throughout the belt. If an eradication program replaced these current practices, the response of insect species other than the boll weevil could vary. Some might change from non-pest or occasional pest to key-pest status. Furthermore, these insect species might vary from location to location in their ability to develop resistance to insecticides.

In summary, considerable heterogeneity exists across the Cotton Belt in terms of the cotton insect complex, environmental characteristics, cotton production practices, current insect management practices, and perhaps in boll weevil populations as well. The BWE trial provided no information on how effective its techniques would be in dealing with this heterogeneity.

We have emphasized heterogeneity with respect to an eradication program because differences at near-zero insect population levels are more important than differences at normal or managed population levels such as would occur under OPM. The eradication plan does not take into account the heterogeneity described above, unlike programs now in use. Furthermore, each state in the Cotton Belt has now developed a modification of the basic OPM strategy to fit local conditions (Economics and Statistics Service 1981c). Although none of the states has tested its program on as large a scale as the OPM trial, they do have a plan which attempts to deal with heterogeneity.

Pheromone Traps

As stated earlier in Chapter 2, grandlure is especially useful in boll weevil detection surveys and in predicting the need for insecticide applications. Further research may demonstrate that boll weevils emerging from diapause in the spring may be effectively "trapped-out" with pheromone traps.

Use of Traps in the OPM Trial

Pheromone traps were used in the OPM trial to provide estimates of boll weevil populations. In the spring and in the fall one trap per 15 to 20 acres was installed infield and peripherally throughout all the cotton acreage in Panola County and in the fall in nearby Pontotoc County. Traps were inspected and serviced weekly. The data on the numbers of weevils captured were extrapolated to give estimates of the number of boll weevils per acre. These extrapolations were based upon earlier studies on the effectiveness of the traps. In the OPM trial the traps gave warning of overwintering weevils leaving diapause in numbers sufficient to require insecticide treatment in early season. Estimates of boll weevil population increases during the season were also obtained through the use of traps.

Use of Traps in the BWE Trial

Pheromone traps provided useful information during several phases of the BWE trial, thus making it possible to determine boll weevil population levels to a degree of accuracy never before possible. Furthermore, their ability to capture weevils at extremely low population densities simplified the program, since data were available to assist in making decisions. Post-eradication monitoring would also be simplified by traps, since the need to scout for weevil survivors or immigrants would be reduced and perhaps eliminated except in special situations. Pheromone traps would be used at several stages in the beltwide eradication plan.

Pheromone Traps: Some Unanswered Questions

The NRC Committee recognizes the sophisticated research that has been done on the boll weevil pheromone, including the accomplishment of developing methods for using the pheromone in a practical way. In several respects the pheromone traps are the foundation on which a beltwide BWE program would be based, since the traps would be essential to surveying, predicting, and monitoring the boll weevil population. Some of the following comments are probably minor, but the traps are so important to the program that their failure could result in significant setbacks.

Potential Variations in Weevil Response to Traps. It has been demonstrated with the pine engraver beetle (*Ips pini*) that a significant differential response to pheromones exists over its range of distribution (Lanier et al. 1980). Such a differential response in boll weevils may not exist. Grandlure has been studied widely for its usefulness throughout the infested areas of the Cotton Belt, and there is little to suggest that boll weevil populations are genetically isolated from one another. Nevertheless, even slight variations in the response of boll weevil populations to the pheromone could have a profound impact upon trap density, distribution, and overall program design. This may warrant careful evaluation and additional research.

Insect behaviorists have speculated about variations in the response to pheromone traps of individuals within a single population. If significant variation exists, pheromone traps may exert a selection effect on the boll weevil population for those weevils that are least attracted to the traps. Variations could be a reaction to the fluorescent yellow color of the trap as well as to the pheromone itself. It seems unlikely that such variations would occur rapidly, if at all, but the possibility of unanticipated responses should be carefully evaluated.

Trap Efficiency and Density. The pheromone traps are remarkably efficient, and it has been clearly established that efficiency is inversely related to density. Thus, efficiency is better when populations are low, as would be the case in an eradication campaign. It is predicted that one trap per acre would be almost 100 percent certain to discover the F_2 generation of any infestation left behind in an eradication program or initiated by an immigrant. The NRC Committee is concerned, however, about the proposed trap density, particularly during the monitoring stage, although we realize that research in the field to determine the exact trap density needed is probably impossible. What concerns the Committee is that trap density may be too low in any case. Insect populations frequently do not behave as expected. Because of weather conditions, for example, they may not increase normally. Hot, dry summers and excessively cold winters are inimical to normal population increases. In extreme situations it might take many generations, or even years, for a suppressed population or a reinfestation to reach detectable levels at the planned trap density.

Effects of Weather on Pheromone Trap Efficiency. In the case of some insects, weather factors are considered to affect pheromone trap efficiency (Elkinton and Carde 1980). Variables such as heat or cold, dryness or humidity, wind or no wind, and perhaps other factors may upset expected results, although these may be only temporary interruptions. The effect of weather on boll weevil trap efficiency has not been studied, insofar as the Committee is aware.

Detectable Population Levels. Despite intensive research on boll weevil pheromones and trapping techniques, there is no clear understanding of the minimum population levels that would be detected. Low-level populations, which may exist after the eradication effort has moved through a zone, may not increase equally in all locations. Population increases may be very slow and may not follow the pattern observed during the original weevil invasion. Large amounts of insecticides are used on cotton for pests other than the boll weevil. These insecticides may change the rate of weevil increase. Rapid increase of F_2 and F_3 generations is an essential assumption for early detection and required for a successful eradication program. Low trap density in the monitoring phase might result in large increases and wide dispersal of weevils prior to detection. If the latter occurred, the capture of few or no weevils for several years after eradication might be followed by a rapid increase of the boll weevil population over a widespread region.

Since damage to U.S. cotton by the boll weevil was discovered in Texas in the early 1890s, it is possible that the insect had reached southern Texas counties from Mexico as early as the 1870s and adapted itself to various environmental situations. It might therefore be 15 to 20 years before boll weevils adapt sufficiently to a new environment to be able to reproduce in large numbers. Other insects have been observed to require a similar span of time between first detection and economic damage levels. It has been estimated, for example, that it took 17 years after its introduction for the cereal leaf beetle to reach damaging population density (Haynes and Gage 1981).

Migration and Dispersal of the Boll Weevil

A key element of a successful eradication program would be keeping zones freed of boll weevils isolated from zones still infested. Our ability to do so may be complicated by the fact that there are two distinct ways in which the boll weevil may have invaded North America. One would have been the gradual buildup of an invading population in a new area, followed by further spread. This concept is used to justify eradication on grounds that it can be successfully maintained. An equal probability, however, is that the boll weevil population dispersed uniformly from its original location, with individuals settling into North American cotton as a function of the square of the distance travelled. Boll weevils may therefore be continually dispersing into North America irrespective of the native North American population. If this were the case, eradication would not be possible unless the original source of the weevils was also eliminated. We have no data to support or refute either argument. The information needed to judge between these two possibilities would have to come from population densities below detectable thresholds. However, a mathematical model could be constructed for both possibilities and perhaps tested by standard validation experiments.

Cross (1981) states that weevils make short flights that are not in response to pheromones. These dispersal flights are random and appear to be related only to wind and sun location.

Boll weevil habits change in August, particularly in west Texas, as females search for better oviposition sites or diapause locations. These migrants have been known to travel as far as 80 kilometers. This long-range dispersal occurs when weevils on short flights are borne aloft by thermal wind currents. Such behavior is quite common among other Coleoptera. Raun (Pest Management Consultants, Inc., Lincoln, NE, personal communication, 1981) reports a large flight of corn rootworm beetles at 4000 feet above ground level over western Nebraska at about 5:00 p.m. in late July of 1976.

Flight-mill studies have shown the boll weevil to fly an average distance of 3.56 kilometers. The longest flight in these studies was 17.66 kilometers. If one speculates that weevils carried by prevailing southwesterly breezes also actively transport themselves, an 80-kilometer flight may not be uncommon. Davich et al. (1970) captured weevils 40 to 72 kilometers from cultivated cotton.

Boll weevil migration and dispersal can occur by several means and for various reasons:

- Weevil movement is stimulated by pheromone attraction, by the need for hosts upon which to feed and by the need to find egg-laying and overwintering sites.
- Weevils also make random flights of short duration for no identifiable reason.
- Weevils may be borne aloft and carried for a substantial distance by the wind.
- Catastrophic climatic occurrences (tornadoes, hurricanes) can lift weevils or plant parts with weevils and carry them long distances.
- There is the further possibility of weevil dispersal through automotive, rail, or aircraft transportation, either in bolls as larvae or as adults.

The final report of the BWE trial (APHIS 1981b) indicates the following forms of weevil "reinfestation":

(1) Two adults were trapped in 1979. One was found near a motel, the other near an APHIS field office. Both were found in the fall and are believed to have been transported by vehicles from outside the evaluation zone.

(2) A partly disintegrated adult was found in a trap in May of 1980. This is believed to have been a weevil caught the previous year but not removed from the trap.

(3) Two weevils were trapped in the evaluation zone on August 18, 1980, and another was trapped September 15. All 3 were in traps at a distance from cotton fields.

(4) On September 11, 1980, one adult was trapped in a cotton field. Between September 15 and 24, 1980, 9 boll weevils were detected by visual examination of cotton bolls, or by trapping, at the same site. Three of these 9 were inside unopened bolls, with one of them in the pupa stage.

The BWE trial final report also indicates trap captures with the "migration zone" grid of traps. These captures extended as far as 144 kilometers from infested areas.

Although boll weevil suppression in the eradication zone was outstanding, the capture of occasional weevils in both 1979 and 1980 and the discovery of at least one breeding site in 1980 led the NRC Committee to speculate on these captures. The accuracy of this speculation is largely dependent on how efficient grandlure traps are, an efficiency not known.

If we accept the view that the probability of detecting 1 weevil per acre with 1 trap per acre is 60 percent (Leggett et al. 1981), extrapolation would indicate considerable opportunity for incipient weevils to escape detection by the system used in the BWE trial. It is also possible that the trapped and discovered weevils were natural migrants who were either carried in by winds, flew in on their own power, or were transported by vehicular traffic.

Whichever explanation is accepted, only time will reveal whether the boll weevil has been eradicated from the evaluation zone. These weevil finds, however, raise questions left unanswered by the BWE trial that must be considered in any attempt to extrapolate the results of the trial on a beltwide basis. If these weevil finds indicate migration reinfestation or an incipient infestation that was not eradicated, a considerable problem would be posed. But if these individual weevils are just individual weevils and not indicators of a larger population, the problem is not nearly as great. Nonetheless, individuals and small populations that escaped a beltwide eradication program would have to be discovered immediately. If they went undetected, they could remain undetected for several generations by the proposed trap net.

Various estimates of the reproductive potential of the boll weevil have been given. Most of them are qualified and, depending on environmental conditions, range from below zero to as high as 80x per generation. The most common increase reported per generation seems to be 2x to 8x. With this level of reproduction, and a trapping efficiency of only 60 percent (when traps are used at a level of 1 per acre), the maintenance trap net could easily fail to disclose breeding populations. This would be particularly true during a period when environmental conditions kept reproductive efficiency low for a period of several years.

Quarantine methods are proposed to prevent migration and dispersal. These might be effective for weevils on vehicles but would fail in the case of wind-borne or flying migrants. The movement of the eradication frontier, from east to west, is in the direction most likely to allow leap-frogging of the frontier. The direction of prevailing winds would be from infested areas into eradicated areas. This would also be true at the Mexican border, with migrants riding air currents across the buffer zone.

The NRC Committee believes that the USDA's biological evaluation team should have considered various scenarios before concluding that the BWE trial had accomplished its objectives. If the team considered other scenarios for explaining nondetection of weevils in the eradication zone and discarded them as unlikely, it should have discussed its rationale for doing so.

Role of Sterile Males in Eradication

Conclusions about the efficacy of sterile male boll weevils in suppressing low-level populations to the level of non-detectability rest upon (1) an experiment performed in Louisiana in 1962 in which an induced low population of weevils was reduced to non-detectability by the end of the season (Davich et al. 1965) and (2) theoretical considerations of the oversaturation of low-level populations with sterile weevils based on information from experiments which failed to achieve their objective but provided some information. It is on this basis that estimates have been made as to what the results of carefully controlled field operations might be.

The lack of conclusive data is disturbing, and two basic questions remain to be answered. Can eradication be consistently achieved in different areas by oversaturation with sterile weevils? If so, what level of oversaturation is necessary to achieve it? The answers to both are theoretical and controversial.

The role of sterile males in the proposed BWE program is unclear. The costs for operators and for the dispersal of sterile weevils are included in the estimates, but capital expenditures for the necessary expansion of facilities to produce the sterile males are not. Comments by USDA personnel as to the necessity for a sterile male component in the proposed BWE program were conflicting.

Effect of Boll Weevil Eradication on Biological Control of *Heliothis*

Insecticide Use

A reduction in future insecticide use has been identified as a major justification for a beltwide eradication program (USDA 1981b). If the amount of insecticide used in current insect control is taken to be 100 percent, estimates of insecticide use in an OPM-NI program and an OPM-NI-BWE program are 77 percent and 54 percent, respectively. In the NRC Committee's view these estimates, derived from Delphi process estimates, are questionable. Judging by the past history of efforts to eradicate such insects as the gypsy moth and fire ant, insecticide use increases during the eradication program, and it is impossible to establish the time at which eradication will be accomplished.

It has been repeatedly stated that frequent insecticide applications for boll weevil control have produced "biological deserts" virtually devoid of natural parasites and predators. As a result of being freed of normal environmental hazards, the bollworm and the tobacco budworm have become rampant pests requiring ever more frequent insecticidal treatment. Because of the rapid onset of *Heliothis* resistance to insecticides (see Table 2.1) the situation has worsened and led in some areas to the total elimination of cotton cultivation (Reynolds et al. 1975).

It is by no means certain that the removal of the boll weevil would restore the ecological balance. Thirty years of genetic selection and recombination in *Heliothis* due to intensive insecticide use have produced resistant biotypes of these pests that are considerably different from their progenitors. Beneficial insect populations in cotton fields have been reduced because of heavy insecticide use. Moreover, cotton varieties, cultivation practices, and insecticidal treatments on adjacent crops are entirely different from those of 30 years ago. The use of massive insecticidal applications for cotton pest control is solidly ingrained in cotton growers. It is therefore quite possible that essentially the same amounts of insecticides will continue to be used, regardless of the presence or absence of the boll weevil.

The estimates of insecticide use in OPM-NI and OPM-NI-BWE programs also underestimate the potentialities of CIC as it evolves into integrated pest management in which ecologically based population regulation strategies are guided by skilled entomologists in the private sector operating under principles now under development by inter-university consortia. Such endeavors have already achieved major reductions in insecticide use in such areas as the Coastal Bend in Texas (Phillips et al. 1980). The most conservative estimates of the effectiveness of IPM programs suggest reductions of 50 to 75 percent in current insecticide use. Thus, over time, current insecticide use may decrease materially from the 100 percent level upon which the OPM-NI-BWE program is based and justified (USDA 1981b). Of major concern in this regard is the level of federal and state support for integrated pest management that can be expected if massive USDA expenditures are made for OPM-NI-BWE or OPM programs.

Host Plant Resistance (HPR)

Cotton varieties have a number of morphological and biochemical characteristics that confer measurable resistance to insects, and the beneficial insect complex of parasites and predators tends to moderate pest population levels. Therefore, beneficial arthropods and host plant resistance are complementary elements in crop protection.

Only a few of the known host-plant resistance factors (Table 5.1) have been incorporated into commercial varieties of cotton. Most of these factors also have a negative effect that reduces yield when the genes controlling these factors are transferred into a commercial variety. Pubescent cotton, which has a positive breeding effect, and nectariless cotton, which is neutral, are exceptions to this general rule. Good varieties carrying these traits are already in use.

The effect of the remaining HPR factors is cumulative, in that yield decreases with each additional HPR factor transferred. This limits the number of HPR factors that can be added to a commercial variety. Another problem develops when an added HPR factor causes susceptibility to a different insect species. Heavy pubescence, for example, causes a cotton plant to be resistant to *Lygus*, fleahopper, and leafhopper attack but susceptible to *Heliothis*.

If the boll weevil were eradicated, plant breeding efforts could be targeted against either *Heliothis*, pink bollworm, or *Lygus*. Nectarilessness is available to offer some protection against all three. Other HPR factors could be added on a regional basis, depending on which local pest causes the most severe problem.

TABLE 5.1 Host plant resistance (HPR) factors and their relative effect on cotton yield and susceptibility to key cotton insect pests.

		Effect of HPR Factor on Pest Species			
HPR Factor	Effect on yield	Boll weevil	*Heliothis*	Plant bugs	Pink bollworm
Pubescent	Increase	-	+	-	0
Glabrous	Decrease	0	-	+	-
Nectariless	Neutral	0	-?	-	-
High gossypol	Decrease	0	-	-	0
High tannin	-	0	-	0	0
Red plant (R_1)	Decrease	-	0	0	0
Red stem (R_2)	Decrease	-	0	0	0
Frego bract	Decrease	-	-?	+	0
Okra leaf	Decrease	-	0	0	0
Male sterile	Decrease	-	0	0	0
Oviposition suppression factor	Unknown	-	0	0	0
AET 5 antibiosis	Unknown	0	-	0	-

\- = Less damage than normal

\+ = More damage than normal

0 = No significant effect documented

? = Controversial results

Beneficial Arthropods

Cotton fields contain a surprisingly varied and complex insect pest and entomophagous fauna. Many entomologists are convinced that it would not be possible to produce cotton economically without parasitic and predaceous insects (Reynolds et al. 1975).

Changes in cotton cultivation techniques (e.g., fertilizer and irrigation) and the use of different cotton varieties should be carefully evaluated for more than total yield and quality of fiber and seed before being adopted. Such changes can have profound effects upon beneficial insects as well as insect pest populations. Applications of chemical insecticides, particularly when they are repeated, often reduce the numbers of beneficial insects, largely negating their impact. As a consequence, populations of "primary target" species may resurge rapidly following insecticide applications, and secondary pests also may increase.

Both the BWE and OPM trials demonstrated better management of beneficial arthropods. Careful management and timing of insecticide applications to control boll weevils reduced insecticide loads. As a result, *Heliothis* was better controlled by beneficial arthropods. Much of this success came from the use of insecticides late in the production season to reduce the number of boll weevil adults leaving the fields to enter diapause. These applications are made after *Heliothis* is no longer a potential problem.

While there are unknowns in the interrelationships among pesticide applications, beneficial arthropods, and *Heliothis* species, it is certain that the eradication of the boll weevil would sharply reduce *Heliothis* damage in some areas. An OPM program would also reduce *Heliothis* damage, though perhaps not as effectively. Successful integrated pest management (IPM) programs also have demonstrated the ability to reduce *Heliothis* damage.

Biological Consequences of Failure

If a boll weevil eradication program was instituted and later abandoned short of eradication, what would be the biological consequences? It can be assumed that the OPM programs that preceded the eradication program would have resulted in very low densities. Hence, damage to the cotton crop from weevils would not be of immediate concern, and it would take several years for the boll weevil to return to preprogram density levels. In addition, growers who had participated in the OPM program would use their acquired knowledge to control other cotton pests, which would have a significant impact on boll weevil survival. Thus, the boll weevil population would be kept below damaging levels for undetermined but significantly long periods of time. If the eradication program was not completed, a decision to declare it a failure would not be clear cut. No such judgement could be made until a fairly lengthy period of time had passed.

Boll weevil populations in eradication zones 1, 2, and 3 (see Figure 5.1), for example, may never be reduced to levels below detection. If boll weevils were still detected in zone 1 or 2 some 5 or 6

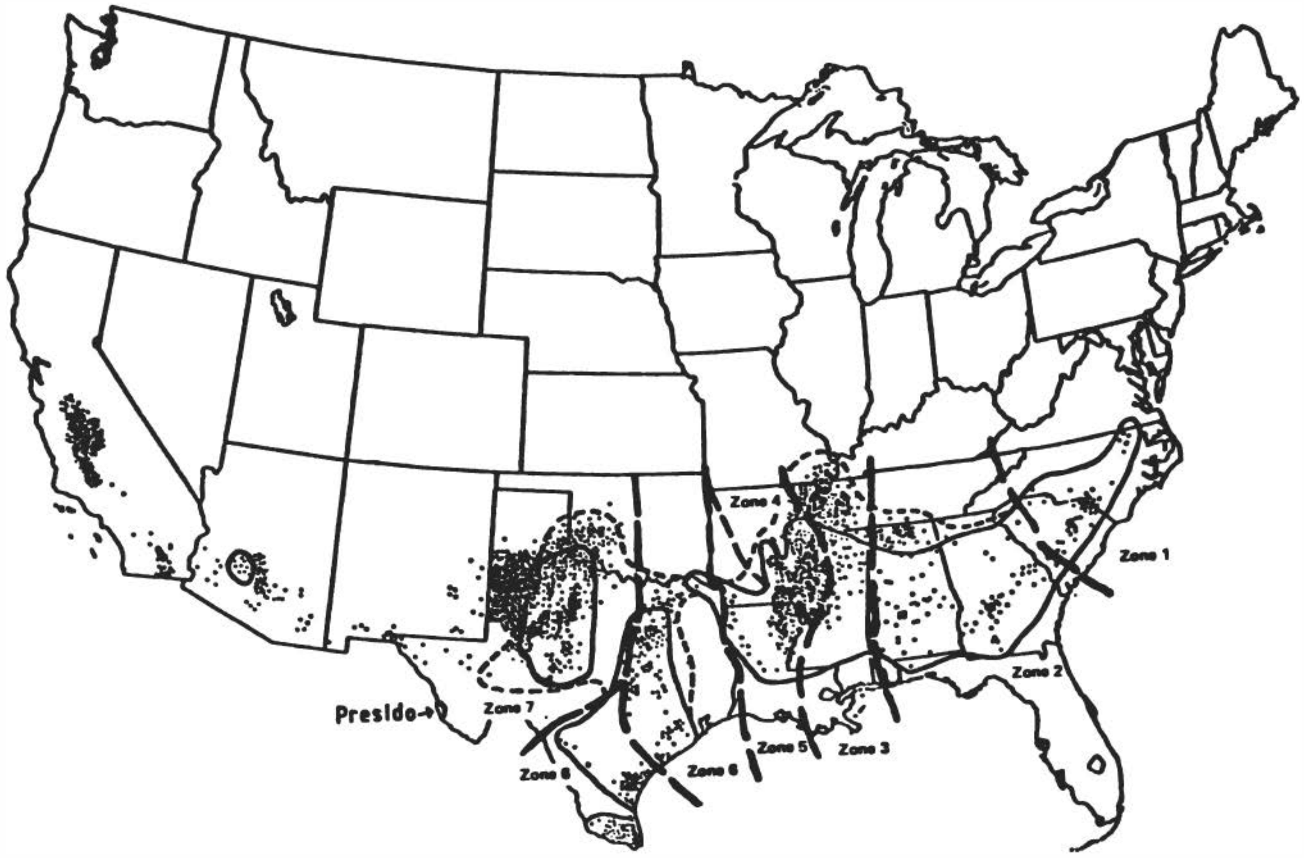

FIGURE 5.1 Cotton distribution in the boll weevil infested areas of the Cotton Belt divided into zones of program operations. Each dot represents 5000 acres of cotton. The area within the dashed line represents areas where the boll weevil has the potential for reaching economic status in occasional years. The area within the solid line is cotton acreage where the boll weevil reaches economic status in most years--stubbed cotton only in Arizona.

SOURCE: After Economics and Statistics Service (1981a) years after the eradication program began, the program would most likely revert to an optimum pest management program. This form of failure would produce the least disruption in the cotton ecosystem and be the least expensive. The amount of insecticides used in retreating areas where boll weevils are found will increase over the original amount planned only slightly and over a relatively short time interval (5 to 6 years).

A second possibility would be a reduction of the boll weevil population to such low levels that detection of small, incipient populations might require 8 or more years. If this occurred, the eradication program would have moved to the final zone before populations reached detectable levels in the first 2 zones. Retreatment of these zones with insecticides could become a significant factor, and there could be major disruptions of IPM programs by greatly decreasing the effectiveness of natural enemies. Subjecting low-level boll weevil populations to insecticides could accelerate the development of natural resistance in the boll weevil. Failure of this type would be the most costly, both economically and environmentally. An evaluation of this type of failure might require more than a decade, and the failure might become a major political issue.

A third form of failure could be eradication of the boll weevil from several zones and survival of a persistent population in others. This could be the result of a lack of cooperation between agencies and cotton growers, or it could have an unforeseen biological basis. In either case, the persistent population would be subject to intense insecticide applications over a limited geographic area. Secondary outbreaks could result, disrupting existing IPM programs. This could result in considerable economic loss to growers in that limited area.

Failure would not be instantly recognized in any of these situations, but the net result would be to greatly increase the use of insecticides, accelerate pest resistance to insecticides throughout the Cotton Belt, reduce the role of natural enemies, and increase the probability of secondary pest outbreaks.

Biological Consequences of Success

Initially, a beltwide boll weevil eradication program would have a large and beneficial effect not only because a key pest of cotton had been eliminated but also because cotton growers would become more knowledgeable about integrated pest management methods. The NRC Committee points out here some of the other possible biological consequences of a successful eradication program.

As a result of boll weevil eradication the management of cotton production would change. Early season insecticide treatments would be greatly reduced, and this would probably have positive effects on populations of beneficial organisms. On the other hand, insect pests that had been held in check by insecticide treatments aimed at boll weevils might increase to the point where early season sprays again were required for their control. This would eliminate some of the economic and environmental benefits that justify an attempt at boll weevil eradication. The research needed to evaluate this problem has not been done, and it would require the absence of insecticides for a period of several years to determine the response of other insect pests and beneficial arthropods.

Since eradication of the boll weevil would reduce the need for insecticide applications, secondary pest outbreaks would be reduced because insecticides would no longer be destroying beneficial arthropods. But there is no information on other key pests that may be kept under control by the insecticides used in current boll weevil control programs across the belt.

Another possible consequence of a successful eradication program would be a change from early maturing varieties of cotton to higher yielding, late-maturing varieties. This would tend to make cotton more susceptible in years favorable to the development of other pests and more vulnerable to reinvasion by the boll weevil.

Probably the most serious biological consequence of successful eradication would be the significant increase in cotton acreage on land ill-suited for sustained cotton production, even though total cotton production would be expected to remain the same. Much of this land was taken out of cotton production as a result of severe boll weevil problems and associated pest control costs. This marginal land would be subjected to increased erosion and soil degradation if replanted in cotton.

It is important to evaluate the biological and environmental consequences of both success and failure. Not all of the effects of failure would be negative, nor would all the effects of success be positive. What seems to be clear is that the BWE trial provided very little information for judging these effects.

ECONOMIC CONSIDERATIONS

The assignment of the USDA's economic evaluation team was to estimate the market consequences of the successful beltwide implementation of each of the proposed boll weevil eradication and control strategies. Cotton yield increases and the cost reductions expected for specific locations were needed to make these estimates. USDA systematically accumulated the opinions of local experts through a Delphi approach, and the opinions of several experts from each area were averaged to identify the probable insecticide-use and lint-yield changes (Economics and Statistics Service 1981d).

The USDA economic evaluation team is to be commended for its creative efforts to obtain beltwide cotton production data, project the future, and develop market benefits and redistribution effects of successful implementation. But, the USDA team was less thorough and creative in developing data on the public cost and probability of success of each program. Based on the collection and averaging of divergent opinions of practitioners, the costs were less than the benefits. The future, however, is unknown and experts do not agree about either the cost or the benefit of public management or eradication of the boll weevil. The market benefits estimated by the USDA team assume successful implementation, but the estimated public costs do not guarantee beltwide success in either management or eradication.

Several experts contributing to the Delphi survey indicated concern about a possible bias toward the success and feasibility of public programs. For example, extension service personnel believe that additional extension service educational activities and technical assistance would result in improved cotton insect management and higher yields (Economics and Statistics Service 1981b).

The USDA report admits that there is a degree of uncertainty in the Delphi estimates of control costs and yields, but no uncertainty is expressed about the cost estimates of beltwide OPM or BWE programs (Economics and Statistics Service 1981b). The considered opinion of the NRC Committee is that there is considerable uncertainty in both the benefit and cost estimates, and that this uncertainty is sufficiently high to preclude their being used as a basis for deciding between programs. The Committee believes that producers in some regions might benefit considerably in economic terms from public boll weevil management or eradication but that the nation's total agricultural production would not change very much.

Consumer Benefits

The USDA economic evaluation report concludes that a successful eradication or control program would lower the cost of producing a pound of cotton in some areas and thus encourage more cotton to be produced. The result of this increased efficiency and production of cotton would be to reduce the price of cotton and other agricultural products to consumers in the U.S. and abroad. This conclusion is not surprising, since consumers generally have benefited from past improvements in agricultural productivity.

In dollar terms, the USDA report (Economics and Statistics Service 1981b) presents consumer benefits for five different types of program (OPM-NI, OPM-PI, OPM-I, CIC-BWE, and OPM-NI-BWE) over the long term--these are the total present dollar values of all future years' benefits. A discount rate of 7.125 percent was used. About 40 percent of these estimated consumer benefits are from a reduction in the price of cotton of between 2.2 and 3.6 percent (or 1.7 to 2.7 cents per pound), and the remaining 60 percent are from the expected reduction in the consumer costs of the cotton seeds and crops that comprise the U.S. feed-grain complex--namely, soybeans, corn, cotton seeds, soybean meal, and so on. The total consumer benefits are estimated to range from $4.17 billion for the CIC-BWE program to $6.46 billion for an OPM-NI-BWE program (see Table 5.2).

The net benefits of each of the five programs are the above benefits to consumers minus the cost of the program and minus a loss in net income to cotton and other agricultural producers. The net market benefits range from $2.44 to $3.89 billion (see Table 5.2).

The estimated program costs to be paid by the government are small relative to the net market benefits. The USDA report states that consumers could afford to compensate agricultural producers for

TABLE 5.2 Present Values of Benefits and Costs for Alternative Boll Weevil Management Programs [a]

Group or Item	Changes in Present Values [b]				
	OPM-NI	OPM-PI	OPM-I	CIC-BWE	OPM-NI-BWE
	Billion Dollars				
Consumer benefits [c]	4.58	4.50	5.16	4.17	6.46
Net income to cotton producers	-.85	-.84	-.60	-.42	-.96
Net income to other producers [d]	-1.10	-1.09	-1.04	-.84	-1.37
Program costs paid by the government [e]	.06	.12	.44	.16	.24
Net market benefits [f]	2.57	2.45	3.07	2.75	3.89
B/C ratio [g]	44:1	21:1	8:1	18:1	17:1

[a] Net benefits and B/C ratios are based on unrounded data. Represents changes in present values of benefits and costs as compared with a baseline representing current insect control.

[b] Future benefits and costs in 1979 dollars, discounted at a 7.125 percent rate in perpetuity.

[c] Consumers include all market participants beyond the farm gate, including processors, mills and final consumers.

[d] Includes producers of soybeans, corn for grains, grain sorghum and small grains.

[e] Producers were assumed to pay 50 percent of eradication program costs, exclusive of capital costs and follow-up monitoring. Producer shares of program costs are reflected in returns to cotton production.

[f] Net market benefits equal the sum of above consumer and producer benefits less program costs paid by the government. Generally considered best criterion if there are no budget constraints.

[g] B/C ratios are calculated as the sum of consumer and producer benefits divided by public program costs. Generally considered best criterion if there are budget constraints.

SOURCE: Economics and Statistics Service (1981a) any losses they suffered in net income as well as pay the full public costs of the program and still come out ahead.

The NRC Committee, however, believes that the probability that consumers would benefit to such a degree from a boll weevil control or eradication program, which would cost so little, is extremely small.

According to the NRC Committee's estimates, the reduction in insect control costs plus the value of the increased cotton yield on historical cotton acreage would result in a productivity gain of only about $125 million per year. Since the United States already produces a cotton crop each year that is worth about $5 billion, such a productivity gain would amount to only a 2.5 percent gain over 10 years, or 0.25 percent a year. An expected productivity gain of this small magnitude could have little effect. U.S. agriculture as a whole produces about $140 billion in agricultural commodities each year. It seems unlikely to the NRC Committee that such a relatively small improvement in cotton productivity would depress the net incomes of other producers by $1 billion as the USDA report predicts (see Table 5.2). For example, USDA estimates that the cottonseed crop also would rise by 2.8 percent; this would mean an increase in the cottonseed crop each year of about 130,000 tons of seeds. Total U.S. production of oil seeds from all types of crops, however, amounts to about 61 million tons a year. Thus, the increase in the cottonseed crop would amount to only 0.2 percent of the annual oil seed crop. The USDA economic evaluation report estimates that such an increase would reduce the value of the cottonseed crop from the present $580 million a year to somewhat less than $500 million. A more realistic view, in the NRC Committee's opinion, is that the price of cotton seeds would decline by a smaller percentage than the percentage of increased production. The result would then be a slight increase in the value of the cottonseed crop.

The USDA economic evaluation report correctly recognizes that any control or eradication program for cotton boll weevil would have positive impacts on net incomes of cotton producers in areas inhabited by the boll weevil but negative effects on the other areas and producers of other commodities. Such redistribution consequences are important to individuals significantly affected. The NRC Committee believes the pattern of the redistribution estimated by the USDA team is correct, but believes that the extent of the redistribution has been overestimated by USDA.

The USDA's economic evaluation does not report the consequences of the sequential reduction in production costs that would occur as the eradication program moved across the boll weevil-infested areas of the Cotton Belt. Producers in the initially eradicated zones would receive the advantages of production cost reductions, yield increases, and reduced risk without the disadvantage of reductions in cotton prices. Conversely, producers in the last zones to be eradicated would suffer the disadvantage of price reductions without the advantages. This has already begun to occur in the eradication trial area of North Carolina, where there has been a 75 percent increase in the acres planted in cotton since 1979.

Economic Consequences of Program Failure

There are several reasons why a beltwide eradication or control program might not be completed after it had been started. These include a lack of the necessary funding from the federal government, state governments, or the growers themselves, a failure to obtain the necessary regulatory laws through legislative action or by means of a grower referendum, or a failure of the program itself to achieve eradication in its early stages. The probability that the program might come to a premature end would be increased to the extent that its economic costs were understated.

A premature end to the program would cause economic harm to all of the producers whose farms had not yet been reached by the program. These producers would have suffered the economic damage of a decline in cotton prices without ever benefitting from the reductions in costs postulated as results of the program.

Evaluation of Program Costs

In 1973 the Stanford Research Institute (1973) conducted a study designed to estimate the costs of beltwide eradication of the boll weevil. That study, which was based on the costs and results of the 1971 to 1973 PBWEE experiment, projected the high cost of a beltwide eradication effort at $2.46 billion and the low cost at $1.11 billion. These projections, corrected to take account of the inflation that has occurred since then, would run from $2.24 to $4.9 billion.

In contrast, the USDA economic evaluation report implies that an initial appropriation of $240 million, invested at an interest rate equal to future inflation rates plus 7.125 percent, would be sufficient to pay all of the government costs of an eradication program (see Table 5.2).

The NRC Committee believes, however, that the probability of successful beltwide eradication from an appropriation of only $240 million would be extremely small, for at least three reasons:

- The initial required capital and facility outlays are not taken into account in the estimate of program costs.
- The estimated cost of future eradication operations appears to be only a fraction of the operating costs actually experienced in the BWE trial in North Carolina.
- The eradication trial in North Carolina--conducted after two severe winters had reduced the boll weevil population--lasted three years but beltwide eradication costs include only two years of program costs.

A larger probability of success would necessarily be associated with a larger appropriation for the beltwide OPM or BWE program. To achieve a very high probability of success with the BWE program--for example, 95 or 99 percent eradication within 10 years for the entire Cotton Belt--it would be necessary to make an appropriation of perhaps as much as $5 and $10 billion, and to give government authorities the power to compel near 100 percent participation by cotton growers. The USDA report should have included cost-benefit ratios for different levels of costs for both OPM and BWE. Higher costs and smaller benefits would be associated with less favorable weather, less cooperation from growers and state governments, and delays or repetition in executing the program. Because the economic evaluation report does not include alternative costs and alternative benefit-cost ratios for each program, an informed and intelligent decision about which program to select, if any, cannot yet be made.

The NRC Committee feels that the cost estimates shown in the USDA economic evaluation report for the three types of OPM programs are underestimated. For example, estimated costs for scouting and aerial application of insecticides are unrealistic in reference to current operational practices.

The NRC Committee therefore urges that an accurate estimate of program costs be developed by an independent agency prior to any USDA request for public funding of a beltwide eradication or management program.

ENVIRONMENTAL CONSIDERATIONS

The USDA environmental evaluation team report (APHIS 1981a) was prepared by members of the Environmental Evaluation Staff of APHIS and a subcontractor, Ketron, Inc., who provided an analysis of the trial results (Miller and Carpenter 1979, Carpenter and Miller 1981a, 1981b). Additional unpublished data were provided by APHIS on insecticide residues in North Carolina and Mississippi during the first two years (1978 and 1979) and later for the third year of the trials. These data consisted of samples of soil, vegetation, water, sediment, insects, mammals, birds, and fish collected under APHIS supervision. Samples were analyzed for 14 insecticides at the USDA Gulfport, Mississippi laboratory (APHIS 1981a).

The contractor used the BOLL-1 Model created by Ketron Inc. (Arlington, VA), the principles of which have been outlined by Carpenter and Miller (1981a) and consists of seven modules, to address different aspects of environmental impact combined and normalized to produce an overall Q index. The seven modules were:

- off-site pesticide drift,
- human ingestion,
- research conflicts,
- fish farms and hatcheries,
- endangered and threatened species,

- wildlife, and
- aquatics.

The combined Q index involved weights for impacts determined by a Delphi survey of scientists (Carpenter and Miller 1981a) and threshold values representing the level of hazard not to be exceeded if the impact is to be judged acceptable.

Monitoring the Environmental Effects of OPM, CIC, and BWE Trials

Prior to the time the trials began, the major value of monitoring their environmental effects appeared to be the generation of information that could be extrapolated to beltwide programs. Secondarily, techniques for assessing environmental effects could be tested in the trials with a view toward evaluating them for a beltwide effort. Sampling, analytical procedure, the applicability of simulation models, and problems with extrapolation might be so evaluated.

A beltwide boll weevil eradication or control program would require a thorough analysis of potential environmental risks. Such an analysis would presumably be similar to an environmental impact statement (EIS)--either as a legislative requirement or at least in the spirit of the National Environmental Policy Act (NEPA) of 1969. Recent guidelines issued by the Council on Environmental Quality for environmental impact statements require that an initial public statement be made defining federal objectives, raising significant environmental issues (both risks and benefits), and examining alternatives. Therefore, any evaluation of a beltwide boll weevil management program should examine all alternatives--including no management, continuation of current practices, implementation of new control strategies, and eradication--in light of the probability of achieving the desired objectives, the economic benefits versus costs, and the environmental risks and impacts.

Generic Environmental Issues

Management Concerns. There were several inconsistencies in the Delphi process from which the insecticide application estimates were derived. The estimates were strongly influenced by persons familiar with CIC practices who had limited knowledge of new management techniques being developed in the trials. Similarly, it is unclear how the detailed management program from the OPM and BWE trials can be extrapolated to take account of the diversity of regional pest and crop relationships throughout the Cotton Belt.

Environmental Constraints on Boll Weevil Management. A number of environmental factors, both controllable and uncontrollable, would influence the effectiveness of the various proposed programs. The presence and density of alternate plant hosts, and the conditions for reintroduction of weevils, would affect not only the efficacy of eradication but also the extent and location of buffer zones. The availability and costs of water for irrigation, fertilizers to augment regional differences in soil fertility, and methods of managing other cotton pests could affect the future distribution of cotton cultivation, with or without boll weevil eradication. These factors should have been considered in any beltwide plan.

Short-Term vs. Long-Term Impacts on Environmental Quality. An intensive beltwide eradication program would involve a trade-off between the ecological risks of short-term increases in insecticide residues and the long-term benefits of an overall reduction in insecticide use once eradication was achieved. The eradication effort might fail to reduce insecticide use in the long run, however, either through failure to eradicate the boll weevil or, if eradication was achieved, through the continued use of insecticides to control other pests.

Catastrophic Effects on Biota. Despite statements to the contrary (Economics and Statistics Service 1981a), it remains to be demonstrated that species capable of withstanding current cotton insect practices would not be seriously affected by an OPM or BWE program. During the initial stages of a BWE program, heavy and repeated applications of general biocides (such as methyl parathion) would be applied to a major part of the agricultural environment. These might cause irrevocable damages to life forms that would not recover at subsequent lower insecticide levels. Examples include honeybees, other pollinators, biological control agents, endangered or threatened species without the resiliency for population recovery, and coastal and estuarine shellfish, whose extremely low tolerance for diflubenzuron could result in substantial kills. The occupational exposures of workers and the potential effects of increased insecticide use on the health of human populations in the region also deserve careful scrutiny.

Effects on Land Use. Boll weevil eradication could influence land use, although it is unclear whether the current patterns of cotton acreage would change. It is also unclear where, and if, cotton would be competitive with other agricultural land uses, or if, with increased cotton yields, the acreage planted would be increased or decreased, or if fallow lands and those in plantation sylviculture would be converted to cotton production. Other external factors, such as water availability and energy costs, could conceivably direct future demands on agricultural productivity to areas formerly unimportant agriculturally. The potential environmental effects of intensified southern agriculture in general, and cotton agriculture in particular, should therefore be examined. Issues that need to be addressed include increased soil erosion, the effect of concomitant increases in suspended solids on surface water quality, and degradation of the soil fertility of soils in the South that are still recovering from previous intensive agricultural use.

None of the aforementioned issues have been adequately dealt with in the initial environmental evaluations of beltwide boll weevil management alternatives by the USDA team. Before the adoption of any management strategy, particularly beltwide eradication, these issues should be scientifically examined. Outlined in the following sections are the environmental factors, types of data, and sources of information that should be utilized in such an assessment.

Environmental Toxicology and Health

One of the major externalities resulting from the massive employment of insecticides for cotton insect control is their effect on non-target organisms and on overall environmental quality. Although there are at present at least 36 insecticides registered for cotton insect control, a relatively small number are predominant (see Table 2.2). Before 1946, calcium arsenate comprised more than 90 percent of the total amount of insecticide applied. From 1946-1955, DDT and toxaphene comprised at least 90 percent of the total applied. By 1964 (the time of the first reasonably accurate survey) toxaphene comprised 34 percent, DDT 30 percent, and methyl parathion 11 percent of the total. By 1971, toxaphene was 38 percent; DDT, 18 percent; and methyl parathion, 31 percent. By 1976, toxaphene comprised 44 percent; methyl parathion, 31 percent; and EPN, 10 percent. The mix changed rapidly because of pest resistance, local pest problems, withdrawal of compounds by the manufacturer (e.g., chlordimeform in 1976), and legal restrictions on the use of DDT in 1973, aldrin and dieldrin in 1974, heptachlor and chlordane in 1976, and endrin in 1979 (NRC 1975) (see Table 2.2).

It is estimated that a total of about 2.3×10^9 lbs. of insecticide (>200 lbs. per acre) have been applied to U.S. cotton soil--largely calcium arsenate, 850×10^6 (total >80 lbs. per acre); DDT, 500×10^6 lbs. (>50 lbs. per acre); toxaphene, 600 million lbs. (>60 lbs. per acre); and methyl parathion, 300×10^6 lbs. (>30 lbs. per acre). The overall environmental effects have varied but have included widespread soil contamination with persistent residues of calcium arsenate, DDT, and toxaphene; large kills of fish; widespread mortality and decreased reproduction of terrestrial wildlife; substantial mortality in honeybee populations; decimation of beneficial parasites and predators; and ubiquitous contamination of the bodies of fish, mammals, birds, and human beings.

Unfortunately, systematic data to quantify these effects are scarce, but some idea of the prevalence of insecticide residues in the Cotton Belt can be gained from data provided by the national soil and air monitoring programs of the Environmental Protection Agency shown in Tables 5.3 and 5.4. Heavy use of calcium arsenate in cotton-growing areas has left residues that have persisted for 25 years or more. Compared with the national averages for cropland soils, residues of DDT and its breakdown products (referred to as DDT-Total or DDT-T) and of toxaphene occur at substantially higher levels in the cotton-growing states (Table 5.3).

The air-monitoring data from suburban locations in three cotton-belt cities (Montgomery, AL; Little Rock, AR; and Monroe, LA) show substantially higher airborne residues of DDT-T, toxaphene, methyl parathion, and endrin than are present in cities monitored outside the cotton-growing area (Table 5.4).

TABLE 5.3 Mean values of insecticide residue in ppm in cropland soils, 1969.

Insecticide	States									
	AL	AR	AZ	CA	GA	LA	MS	NC	SC	43-states
Arsenic	6.11	8.98	6.58	5.15	2.61	2.15	5.70	6.18	3.28	6.43
DDT-T	1.13	0.67	0.76	1.47	0.96	0.99	2.06	0.53	1.17	0.31
Dieldrin	0.01	0.02	--	0.02	>0.01	0.02	0.01	0.08	0.04	0.03
Endrin	>0.01	0.01	0.07	0.01	0.02	>0.01	0.01	>0.01	>0.01	>0.01
Toxaphene	0.69	0.27	1.09	0.16	0.60	0.57	0.78	0.28	0.10	0.07

SOURCE: Wiersma et al. (1972)

TABLE 5.4 Average concentrations of insecticide in the air in ng/m^3 in suburban areas in the United States, 1972 and 1977.

Suburban Region	Insecticides					
	p,p'-DDT	DDT-T	Dieldrin	Endrin	Methyl parathion	Toxaphene
Jan. - Dec. 1972						
Montgomery, AL	8.0	13.2	1.2	0.6	4.1	13.1
Little Rock, AR	5.3	9.6	1.5	0.3	6.4	41.0
Monroe, LA	12.5	19.5	1.0	0.3	2.1	120.6
Augusta, ME	3.6	6.5	0.8	ND	3.7	ND
Columbus, OH	3.3	6.3	0.9	ND	1.8	ND
Salt Lake City, UT	2.1	6.1	1.0	ND	ND	ND
Miami, FL	0.7	0.11	0.5	ND	ND	ND
Topeka, KS	3.7	7.1	1.1	ND	2.8	ND
Louisville, KY	7.0	11.6	1.6	ND	0.9	ND
Nov. 1976 - Sept. 1977						
	p,p'-DDT	Chlordane	Diazinon	Malathion	Methyl parathion	Toxaphene
Greenville, MS	1.61	0.68	27.52	15.04	4.99	9.34
Midvale, UT	1.53	ND	0.16	ND	ND	ND
Pasadena, CA	5.48	4.02	0.48	ND	ND	ND
Wheaton, IL	6.70	0.08	ND	1.23	ND	ND

ND = None detected.

SOURCE: Ann E. Carey, EPA Office of Toxic Substances, Washington, DC, personal communication, 1979.

Monitoring of living organisms reflects the generally higher pollution of the Cotton Belt environment by insecticides, although there are few comprehensive surveys. A comparison of residues of persistent insecticides in the wing tissues of woodcock (McLane et al. 1978) showed much higher residues of DDT, dieldrin, and heptachlor epoxide in birds from Louisiana and the "tri-states" (Georgia, North and South Carolina) than from Maine or Michigan (Table 5.5). The national monitoring program for persistent pesticides in human adipose tissues shows that DDT residues among inhabitants of the Cotton Belt are substantially higher than those of other states (Table 5.6).

The effect of specific insecticides upon environmental quality has been severe. Toxaphene, or chlorinated camphene, has had the widest use of all the persistent organochlorine insecticides on the cotton crop. Composed of at least 175 individual chlorinated terpenes, of which 2,25-endo-6-exo-8,9,9,10-octachlorobornane is the most active ingredient, toxaphene is water-soluble to about 0.40 ppm and has an average octanol/water partition of 825 (Sanborn et al. 1976). Toxaphene, on the average, persists in soil for 3 to 10 years and up to 6 years in water; it is bioconcentrated up to 100,000-fold in fish (NRC 1975). As shown in Tables 5.3 and 5.4, toxaphene residues in the Cotton Belt are high and ubiquitous.

Toxaphene is highly toxic on an acute basis. The rat oral LD_{50} is 69 mg per kg; guinea pig, 15; mallard, 71; pheasant, 40; bobwhite, 85; and sharp-tailed grouse, 10-20. Toxaphene is extremely toxic to fish, with LC_{50} values for rainbow trout 0.0028, bluegill 0.0035, and black bullhead 0.005 ppm. For aquatic invertebrates, LC_{50} values range from 0.006-0.180 ppm (Pimentel 1971). Fish in water exposed to toxaphene levels as low as 0.0005 ppm suffer from "broken back" syndrome, a crippling collagen deformity (Mehrle and Mayer 1977). Toxaphene has been demonstrated in several bioassays, including the National Cancer Institute bioassay, to be highly carcinogenic in rats and mice (Reuber 1979).

Methyl parathion, or o,o-dimethyl o-p-nitrophenyl phosphorothionate, is the organophosphorus insecticide most widely used on the cotton crop. Unlike toxaphene, methyl parathion is substantially biodegradable, although soil persistence up to 5 years and water persistence up to 2 years have been recorded (NRC 1975). Methyl parathion has a water solubility of about 20 ppm and an octanol/water partition of about 800. Methyl parathion is not bioconcentrated to any marked degree. It is, however, an extremely toxic insecticide on an acute basis: the oral LD_{50} for rats is 14-24 mg per kg; for mallards, 10.0; and for pheasants, 8.2. The LC_{50} values for fish are 2.75 ppm for rainbow trout and 5.72 ppm for bluegill. For aquatic invertebrates, LC_{50} values range from 0.005 to 0.070 ppm (Pimentel 1971).

The widespread use of methyl parathion is a constant threat to the health of farm workers because of its high toxicity when inhaled or contacted by skin. In cotton-growing areas in Texas, 25 percent of the workers loading spray planes reported acutely toxic effects.

TABLE 5.5 Average insecticide residue levels in woodcock wing muscle tissue (ppm), 1971-1972.

State	DDT	DDE	Dieldrin	Heptachlor epoxide
Tri-state area (GA, NC, and SC)	6.82	26.03	1.64	0.51
LA	2.97	9.80	2.46	0.69
ME	1.19	4.07	0.16	ND
MI	0.92	3.16	0.20	ND

ND = none detected.

SOURCE: McLane et al. (1978)

The extent of methyl parathion poisoning among field workers, flagmen, and residents--in particular, children--is unknown because of inadequate reporting practices. The use in El Salvador in 1972 of 4,800,000 lbs. of methyl parathion and its even more dangerous relative parathion resulted in 2,861 reported cases of poisoning and 30 deaths. About 2,560,000 pounds of active parathion ingredients were applied to U.S. cotton in 1971 (see Table 2.2). The World Health Organization estimates that about 500,000 accidental poisonings and about 20,000 fatalities occur worldwide each year, largely from the use of methyl parathion and parathion (Copplestone 1977).

Other insecticides used to control cotton insect pests are also hazardous to environmental quality and human health. Endrin, or 1,2,3,4,10,10-hexachloro-6,7-epoxy-1,4,4a,5,6,7,8,8a-octahydro-1,4-*endo*,*endo*-5-8,-dimethanonaphthelene, is the most toxic of the widely used organochlorines. The rat oral LD_{50} is 1.5 to 17.8 mg per kg; mallard, 5.6; pheasant, 1.8. Endrin is the most toxic insecticide to fish, with an LC_{50} value for rainbow trout of 0.0018 ppm, and for blue gills, 0.00035 ppm; its LC_{50} values for aquatic invertebrates range from 0.002 to 0.020 ppm (Pimentel 1971). Endrin has an octanol/water partition of 1,600 and a water solubility of 0.06 ppm. It bioconcentrates to at least 3,000-fold. Endrin has a soil half-life estimated at 4 to 8 years. Endrin has been responsible for widespread fish kills and damage to vertebrate and invertebrate

TABLE 5.6 Average insecticide residue levels in ppm in human adipose tissues, 1968.

State	Insecticide			
	DD-T		Dieldrin	
	White	Black	White	Black
AL	5.92	11.36	0.01	0.00
AR	13.23	28.86	0.21	0.10
GA	9.68	11.70	0.18	0.19
LA	8.55	14.75	0.10	0.06
NC	7.73	13.21	0.11	0.11
TE	9.28	14.14	0.17	0.08
22-state average	6.32	12.06	0.12	0.14

SOURCE: U. S. DHEW (1969).

wildlife (Pimentel 1971). Approximately 1,068,000 lbs. (active ingredient) of endrin were applied to U.S. cotton in 1971 (see Table 2.2).

The organophosphorus insecticide EPN, or o-ethyl o-p-nitrophenyl phenylphosphonothioate, is also extremely hazardous. It has a rat oral LD_{50} of 7.7 to 36 mg per kg; mallard, 3.1; pheasant, 53; partridge, 14. Few studies have been made of the environmental effects of EPN, but it is known to be a delayed neurotoxin that can produce irreversible paralysis in chickens at very low levels of acute or chronic ingestion. About 6,140,000 lbs. (active ingredient) of EPN were applied to U.S. cotton in 1976.

Data provided by the USDA environmental evaluation team from Delphi estimates of the insecticides likely to be used and their application rates in a beltwide eradication program, as well as data on the insecticides used in the OPM and BWE trials, indicate that 15 chemical formulations (and diflubenzuron, which is not included in the table) are likely to be employed (Table 5.7). Four insecticides--dimethoate, endrin, fenvalerate, and sulprofos--were used in the OPM trial but not in the BWE trial (Table 5.8). All formulations were used in at least two of the three trial years, except for acephate, azinophosmethyl, and chlorpyrifos in the OPM trial. Of these 16 insecticides, only 7 (chlorpyrifos, diflubenzuron, EPN, fenvalerate, methyl parathion, permethrin, and toxaphene) were monitored by APHIS in the environment surrounding the North Carolina and Mississippi trial areas.

During the three years of monitoring by USDA, only 3 insecticides used in the trials were detected (Carpenter and Miller 1981a). Methyl parathion (mean conc. 0.019-0.061 ppm, max. conc. 0.477-0.830 ppm) was detected in 6 percent of 315 samples of avian tissue, and chlorpyrifos (mean conc. 0.004-0.506 ppm, max. conc. 0.237-0.300 ppm) in 1 percent of the samples. No residues were detected in 60 water samples and 70 sediment samples during the trial years. No fish or aquatic biota were analyzed. It is difficult to understand why there were not more signs of residues, why only a small number of the insecticides were detected, and why parathion and malathion were detected even though they were not reported to have been used in the trials. The absence of positive signs of residues was certainly due, in part, to the fact that not all 16 insecticides were analyzed for. The environmental sampling design and analytical techniques used in the monitoring were not explained. At best, however, the data are entirely inadequate for extrapolation to a beltwide level.

The known toxicities of various insecticides to non-target biota are shown in Tables 5.9, 5.10, and 5.11. The few data reported from the monitoring program for birds and mammals are well below LD_{50} values. Aquatic organisms, however, are much more sensitive to nearly all of the insecticides used. The extensive literature on insecticide-related fish kills makes it very hard to understand why aquatic biota were not monitored.

The measurement of insecticide residues in soils should have been initiated before any additional insecticides were applied and on a continuing basis afterwards. This would have provided a pretrial background measurement of insecticide residues in agricultural soils and measurements of the rates of accumulation. These accumulation rates, together with information on rates of applications, would have been valuable for making beltwide extrapolations. Moreover, the soil analysis appears to have proceeded independently of information about actual applications of insecticides. For example, an attachment to the USDA environmental evaluation report (Carpenter and Miller 1981a) lists 15 insecticides applied to the trial area in Panola County between 1978 and 1980, however, the analysis of pesticide residues did not include most of those insecticides that were used in the trial area.

Organisms in aquatic ecosystems are notoriously sensitive to insecticide damage. Field measurements in small calibrated drainage systems would have made it possible to estimate the amounts of insecticides reaching aquatic ecosystems and their subsequent dilution, degradation, concentration in sediment and biota, and effects on

TABLE 5.7 Cotton insecticide data for OPM fields in Panola County, Mississippi.

Chemical and application rate (lbs/acre)	Average number of pounds applied per acre in the OPM area		
	1978	1979	1980
Acephate 1.30-2.00	-	0.04	-
Azinophosmethyl 0.16-0.25	-	-	0.01
Chloridimeform 0.13-0.25	-	0.05	0.03
Chlorpyrifos 0.33-0.50	-	0.01	-
Dicrotophos 0.10-0.25	0.09	0.35	0.07
Dimethoate 0.10-0.20	0.02	0.35	0.07
Endrin 0.27	-	0.01	<0.0
EPN 0.50-0.75	0.28	0.38	0.22
Fenvalerate 0.05-0.20	0.03	0.12	0.11
Methomyl 0.30-0.45	0.22	0.33	<0.0
Methyl parathion 0.25-1.50	0.28	0.82	2.29
Monocrotophos 0.20-1.00	<0.01	0.01	0.02
Permethrin 0.10-0.20	0.13	0.03	0.03
Toxaphene 1.50-2.00	0.05	0.52	-
Sulprofos 0.50-1.50	0.07	-	0.01

SOURCE: Carpenter and Miller (1981a)

TABLE 5.8 Cotton insecticide data for CIC-MS sample fields in Pontotoc County, Mississippi.

Chemical and application rate (lbs/acre)	Average number of pounds applied per acre in the OPM area		
	1978	1979	1980
Acephate 1.30-2.00	< 0.01	-	< 0.01
Azinophosmethyl 0.16-0.25	0.08	-	0.06
Chloridimeform 0.13-0.25	0.03	-	0.01
Chlorpyrifos 0.33-0.50	0.01	0.14	-
Dicrotophos 0.10-0.25	0.11	0.01	-
EPN 0.50-0.75	0.06	-	0.11
Methomyl 0.30-0.45	-	0.07	0.12
Methyl parathion 0.25-1.50	0.02	0.71	0.69
Monocrotophos 0.20-1.0	0.10	0.01	-
Permethrin 0.10-0.20	0.02	0.01	0.06
Toxaphene 1.50-2.00	0.01	0.72	0.13

SOURCE: Carpenter and Miller (1981a)

TABLE 5.9 Avian toxicity data for selected insecticides.

Pesticide	Organism	LD_{50}[a] (mg/kg)
Carbamate		
Lannate	Mallard duck	15.9
	Quail	15.0
Insect growth regulator		
Diflubenzuron	Mallard duck	>2000
	Quail	>5000
Organochlorine		
Toxaphene	Mallard duck	70.7
	Ring-necked pheasant	40.0
Organophosphate		
Azinophosmethyl	Mallard duck	136
	Ring-necked pheasant	74.9
Chlorpyrifos	Mallard duck	75.6
	Quail	16
Dicrotophos	Mallard duck	4.24
	Ring-necked pheasant	3.21
Dimethoate	Mallard duck	41.7
	Wild bird	50.7
EPN	Mallard duck	3.08
	Ring-necked pheasant	53.4
Malathion	Mallard duck	1485
Methyl parathion	Mallard duck	10.0
	Wild bird	50.7
Monocrotophos	Mallard duck	4.76
	Ring-necked pheasant	2.83
Synthetic pyrethroid		
Permethrin	Mallard duck	>4640
Fenvalerate	Mallard duck	>9932

[a] LD_{50} is defined as the lethal dose to 50 percent of the test population. References for the source of these data are given in Carpenter and Miller (1981a).

SOURCE: After Carpenter and Miller (1981a).

TABLE 5.10 Acute mammalian toxicity data for selected insecticides.

Pesticide	Organism	LD_{50}[a] (mg/kg)
Carbamate		
Lannate	Mule deer	11-22
	Rat	27
Insect growth regulator		
Diflubenzuron	Rat	4640
	Mouse	4640
Organochlorine		
Toxaphene	Mule deer	139-240
	Mouse	112
Organophosphate		
Azinophosmethyl	Mouse	7.15
	Rat	13
Chlorpyrifos	Mouse	152
	Rat	145
Dicrotophos	Mouse	11
	Rat	16
Dimethoate	Mule deer	>200
	Rat	152
EPN	Mouse	42
	Rat	8
Malathion	Rat	1400
	Mouse	886
Methyl parathion	Rat	12-16
	Mouse	18.5
Azodrin	Mule deer	25-50
	Rat	21
Synthetic pyrethroid		
Permethrin	Rat	410
Fenvalerate	Rat	451

[a] LD_{50} is defined as the lethal dose to 50 percent of the test population. References for the source of these data are given in Carpenter and Miller (1981a).

SOURCE: After Carpenter and Miller (1981a).

TABLE 5.11 Aquatic toxicity data for selected insecticides.

Pesticide	Test	Organism	LC_{50}[a] (ppm)
Carbamate			
Lannate	24-h	Channel catfish	0.92
Insect growth regulator			
Diflubenzuron	96-h	Channel catfish	370
Diflubenzuron	96-h	Rainbow trout	240
Organochlorine			
Toxaphene	96-h	Pinfish	0.0005
Toxaphene	96-h	Fathead minnow	0.014
Organophosphate			
Guthion	96-h	Brown trout	0.004
Guthion	96-h	Catfish	3.29
Malathion	96-h	Bluegill	0.103
Malathion	96-h	Catfish	8.97
Methyl parathion	96-h	Bluegill	1.6
Methyl parathion	96-h	Catfish	5.71
Methyl parathion	96-h	Crayfish	0.003
Synthetic pyrethroid			
Permethrin	96-h	Bass	0.0085
Permethrin	96-h	Channel catfish	0.0011
Permethrin	96-h	Crayfish	0.00062
Fenvalerate	24-h	Rainbow trout	0.021

[a] LC_{50} is defined as the concentration of insecticide in the water that is lethal to 50 percent of the test population. References for the source of these data are given in Carpenter and Miller (1981a).

SOURCE: After Carpenter and Miller (1981a).

biota. Aquatic systems linked with the cotton fields should have been the major ecosystems sampled. The aquatic samples collected and analyzed were insufficient in terms of the variety of environmental components sampled and the numbers of replicates taken.

Environmental Quality

The monitoring of terrestrial biota could have included systematic sampling of beneficial insects, pollinators such as honeybees, insectivorous birds, raptors, and small mammals. In this way the concentration of chemicals and their effects on sensitive organisms might have been documented. As it was, only vegetation was routinely sampled.

The BOLL-1 model allows various environmental factors to be included in an overall index, Q, for each insect control alternative. Of the seven modules, the Endangered and Threatened Species Module seems to have been particularly well evaluated (Carpenter and Miller 1981a). The index yielded a significant environmental impact value for the BWE trial in 1979, but subsequently Q was set arbitrarily at zero for 1980. The Offsite Drift Module is well explained, but no actual measurements of drift were made that would have allowed an evaluation of its assumptions. The role of wind in dispersal was not considered, nor was the presence of other crop sprayings. The Human Ingestion Module assumes a rather high drift of sprayed insecticides to non-target agricultural land (25 percent) but assumes that drift would be equally apportioned over non-target areas. This module might have been made insecticide-specific to account for differences in persistence, toxicity, bioaccumulation, and so forth. Different pathways of exposure should have been included (inhalation, water intake, fish and wildlife consumption), as well as the information on the current background level of insecticide intake for humans.

The Wildlife Module used white-tailed deer as an indicator species, and hunter-kill records were used to evaluate changes in the trial areas. This was a dubious procedure to use, considering the size of the OPM area and the short-term nature of the records. Game birds (quail, mourning dove) might be more significant indicators than deer in parts of the trial area. In 1980 the wildlife module was set at zero. The USDA environmental evaluation team judged the methodology to be unsuitable.

The Research Conflicts Module and the Fish Farms and Hatcheries Module both yielded zero results. No research conflicts arose, and no fish hatcheries were located near the trial areas. Obviously, extrapolation to beltwide programs would change the results for these modules. The Aquatics Module appears to have failed because of lack of data. No field data appear to have been collected, nor were there adequate bodies of water for sampling biota near the fields.

The Overall Index Module ultimately depended, therefore, on two indices with non-zero values, namely, Offsite Drift and Human Ingestion. Other modules either did not apply to the trial areas (Research Conflicts, Endangered and Threatened Species, and Fish Farms) or were not adequately measured (Wildlife, Aquatics). Comparisons of overall indices calculated for OPM, BWE, or CIC trials thus were based on minimal considerations, and extrapolation to beltwide programs would not be valid.

The overall indices differed greatly between 1979 and 1980, and the contractor's report (Carpenter and Miller 1981a) and summaries by APHIS (1981a) and the Economics and Statistics Service (1981a) differed in their results. Table 5.12 compares the Q index for these two years for the two trial areas and the current insect control comparison areas (Carpenter and Miller 1981a, Economics and Statistics Service 1981a). The Q index for OPM increased by a factor of five in the second year, while the Q index for BWE shrank by a factor of seven. The index thus classified BWE as the least desirable alternative in 1979 and the most desirable in 1980. The difference between years for OPM may have been due principally to a change in insecticide use in the areas (Carpenter and Miller 1981a), but it is not clear why the CIC index escalated by an order of magnitude. The BWE index for 1979 included significant contributions from the wildlife and endangered species modules. If these are removed, the Q index drops from 86.2 to 39.8, making BWE more environmentally desirable than OPM but less so than CIC. There is no indication of what range of statistical variations the indices include, nor how significant the differences among Q values for different trials might be.

Endangered and Threatened Species

The most significant environmental impact of a beltwide boll weevil management program would be the direct and indirect effects of insecticides on non-target organisms. Aquatic biota are clearly the most sensitive, and natural ecological processes would ultimately move and concentrate insecticide residues in streams, rivers, and estuaries of the Cotton Belt. Endangered species are a special concern; fish, molluscs, reptiles, and amphibians constitute the majority and, with the exception of one snail, all are inhabitants of aquatic ecosystems. The toxicology data summarized in Tables 5.8, 5.9, 5.10 provide no values for molluscs, reptiles, or amphibians. Saltwater crustacea and freshwater crayfish, although not endangered, would also have to be examined closely prior to any beltwide program because of their high sensitivity to diflubenzuron (about 0.003 ppm).

Unresolved Issues

The information provided to the NRC Committee by the USDA environmental evaluation team is almost exclusively data generated during the three-year trials. The NRC Committee believes that a truly comprehensive environmental evaluation would have to rely as well on the substantial body of published scientific data on insecticides. The USDA environmental evaluation team did not adequately review and evaluate the extant data.

TABLE 5.12 Overall Index ("Q" Index) for OPM, BWE, and CIC, 1978-1980, as calculated by the USDA Environmental Evaluation Team. Note how different assumptions in the methodology employed change the final Q value (different estimates for the same years) and how these changes drastically affect the ranking of suitable management alternatives.

Trial	Year				
	1978[a] (rank)	1978[b] (rank)	1979[c] (rank)	1979[b] (rank)	1980[b] (rank)
OPM	68.5 (2)	257 (4)	401 (4)	346 (4)	329 (4)
BWE	86.2 (3)	160 (2)	131 (1)	24 (1)	12 (1)
CIC Mississippi	14.9 (1)	37 (1)	207 (2)	138 (2)	164 (2)
CIC North Carolina	-- --	219 (3)	221 (3)	294 (3)	171 (3)

SOURCE: Numeric values obtained from the following inter-related sources:

a. Miller and Carpenter (1979).

b. Carpenter and Miller (1981a, 1981b), Economics and Statistics Service (1981a).

c. Carpenter and Miller (1980).

A fundamental shortcoming in the team's report (APHIS 1981a) is that the trials were not designed to measure environmental effects and thus obtain the data necessary to predict the environmental effects of beltwide OPM or BWE programs. The primary emphases of the trials were biological effectiveness and economic practicality. This criticism alone does not mean that a beltwide program would have unacceptable environmental risks, but simply that the trials provided inadequate information upon which to base a beltwide environmental assessment. The critical environmental question is whether a beltwide program would cause significant environmental deterioration.

The exposures of human beings, wildlife, and fisheries resources to insecticides cannot be accurately estimated from the information provided by the trials. Models for potential ingestion would have to use data on insecticide degradation, persistence, and toxicity that were specific for each class of insecticides being considered. It is not adequate to consider the ingestion of agricultural products as the only route of exposure--the inhalation of aerosols and suspended soils, the use of surface waters, and the ingestion of dairy products, poultry, domestic and wild animals, and fish would also have to be evaluated.

USDA reviews of the OPM and BWE trials essentially did not reveal any significant environmental impacts (APHIS 1981a); no obvious, short-term, acute effects were observable. But the data are not adequate to demonstrate in unqualified terms a lack of impact or to detect potential long-term and chronic environmental impacts. Because no definitive statements on the degree and kind of environmental effects can be made, no realistic estimates of the environmental risks have been incorporated in the calculations of the economic costs of beltwide eradication.

The sole measure of environmental risk is that calculated by the BOLL-1 simulation model, which provides a relative impact index, Q (Carpenter and Miller 1981a). The precision of this index is questionable, since there are no associated measures of uncertainty. The range of Q values is five to tenfold between 1979 and 1980 for OPM, BWE, and CIC, respectively. These deviations are, in part, due to different insecticide applications in each trial area in different years, but they are also a result of fundamental differences in the contribution of the various indices in different years. The fact that year-to-year variations in Q for the same trial exceeded, in most cases, the differences between the trials makes the usefulness of this approach doubtful.

Conclusions

Beltwide boll weevil/cotton insect management programs would pose a number of potential environmental hazards which were not evaluated in the USDA risk analysis (Economics and Statistics Service 1981a). A number of environmental issues (Table 5.13) should be addressed region by region before any program is adopted. Much of the information necessary to do so (Table 5.14) can be obtained from

TABLE 5.13 Factors which need to be considered in developing a beltwide environmental assessment of boll weevil eradication from cotton production regions of the United States.

- Land area involved
    - Acreage
    - Land-use categories
    - Categorization by drainage basins
    - Endangered and threatened species
    - Soil classifications/erodibility
    - Regional precipitation
    - Water discharge statistics
- Quantities of chemicals utilized
    - Cotton management alternative applications
    - Acreages involved, temporal applications
    - Inventory of pesticides to be used
    - Analysis of chemical persistence on various media
- Environmental fate
    - Suspended solids in rivers
    - Residence time in soils
    - Water/sediment exchange coefficients
    - Food chain concentration factors (aquatic & terrestrial)
    - Erosion potential by soil classification
    - Sedimentation rates in rivers and estuaries
- Ecological toxicology
    - Toxicity thresholds
    - Toxicology to aquatic resources (also estuarine)
    - Toxicology to terrestrial resources
    - Deleterious effects on natural environment
    - Effects on beneficial insect fauna
- Regional ecology
    - Biological control alternatives
    - Genetic engineering of cotton varieties
    - Alternative hosts - boll weevil refugia
    - Presence of regional aquatic and terrestrial economic resources
- Compliance with environmental legislation
    - Clean Air Act
    - Clean Water Act
    - Toxic Substances Control Act

Table 5.14 Example of extant data resources available for a beltwide environmental assessment of boll weevil eradication from cotton production regions of the United States.

- Cotton production (by Water Resource Regions)

  Acres planted
  Acres harvested
  Lbs/acre yield
  County statistics
  - % cropland
  - % cotton
  - % other

  Yield with and without irrigation
  Yield by county

- Land use

  Cotton (lbs/acre per county)
  Land use - rangeland/pasture
  Land use - cropland
  Land use - urban
  Land resource regions
  Land capability classes

- Insecticides in the environment

  Residues in water (EPA)
  Residues in soils/sediments (USDA)
  Residues in food (FDA)
  Monitoring of bioaccumulation in biota
  Monitoring of residues in human adipose tissues

- Climate

  Annual rainfall
  Moisture index
  Evapotranspiration index
  Annual temperature
  Min. annual temperature
  Max. annual temperature

Table 5.14 (Continued)

- Soils
  - Erosion index vs rainfall
  - Erosion index vs % cropland in cotton counties
  - Erosion index vs % county in cotton
  - Types, agricultural suitability classifications
- Water resources
  - Average runoff
  - No. of lakes/state
  - Major rivers/estuaries
  - Principal drainage basins
  - Surface water runoff
  - Season's highest streamflow
  - Season's lowest streamflow
  - Water resource regions
  - Suspended sediments
  - Annual turbidity
  - Water quality
- Unique resources by Water Resource Region
  - Rare and endangered species
  - Wilderness areas
  - Proposed wilderness areas
  - National forests
  - National parks
  - National wildlife refuges
  - National scenic rivers
  - Research national areas
  - Nature conservancy areas

existing sources. The future trends of a CIC program, an OPM-BWE program with continued maintenance and the establishment of a buffer zone, and a publicly managed OPM program are the three alternatives that would require environmental evaluation. As CIC improves, the technological differences between OPM and CIC will disappear with time. Initially, however, an OPM program would have environmental advantages over CIC in some regions of the Cotton Belt. Projections of environmental impact should also consider trends in cotton production in the infested regions if no beltwide plan is implemented. Reduced cotton acreage and improved private cotton insect control practices might reduce the present environmental impacts.

The two major types of environmental effects appear to be (1) those related to changes in insecticide use patterns, and (2) those related to changes in cotton acreage. It should be possible to construct a baseline estimate of the total insecticide load in the Cotton Belt region by region. Projecting this estimate to cover the years 1980-2000 would be more difficult but would seem to be necessary for evaluating the alternative strategies. The estimation process should include insecticide residue concentrations in air, water, sediments, soils, foods, human adipose tissue, and selected biota on a regional basis. These projections should be stochastic to allow for variations in space and time. The environmental effects of implementing a beltwide OPM or BWE program should be evaluated as alternatives to the projected environmental effects of CIC practices.

A BWE program (the OPM-NI-BWE option) would be expected to result in increased chemical concentrations initially but reduced concentrations over time except in the Texas buffer zone, where high rates of insecticide use would continue, and in those parts of the southeast where frequent spraying is required to control Heliothis. USDA has not clearly determined whether biota would be adversely affected during the initial eradication phases, but the shellfish industries would be placed in a particularly sensitive position. Whether they would survive the initial phases of the program and benefit from the reduced phase is a question that has not been answered technically, even though advocates of eradication draw this conclusion without evidence (Economics and Statistics Service 1981a). Similarly, aquatic systems would need to be evaluated in terms of changes in the sediment load of insecticides. Socioeconomic pressures would obviously be important factors in projecting the size of these loads.

Some clear environmental benefits would accrue from generally reduced insecticide use. Beneficial insects and spiders would become more important parts of pest management programs, and aquatic life in streams and rivers (especially in the vicinity of fields heavily sprayed in previous years) should benefit from decreased use. The estuarine systems of the Atlantic and Gulf Coasts might also respond positively to reduced insecticide use. Wildlife in terrestrial systems also should benefit. Two environmental benefits appear likely to accrue to human beings directly. One would be the decreased exposure of insecticide applicators and other field workers, while the other would be a reduced concentration of insecticides in human foodstuffs and tissues. While these are potential benefits, they have yet to be demonstrated as reasonable probabilities.

SOCIOLOGICAL IMPLICATIONS

The probability of successfully carrying out an eradication or OPM program would rest heavily on human behavior. Beltwide implementation of an eradication program would require legislative action at the state level, and the economic and environmental factors that caused North Carolina farmers to accept eradication regulations (by means of a referendum) might not exist in Texas and thus influence the outcome of a referendum there. Without the necessary regulatory authority in each state, eradication would be impossible.

On the other hand, areawide pest management would not require total elimination of the weevil to be successful. The OPM trial in Mississippi demonstrated the value of a pest management program with a publicly funded incentive, and this carrot-and-stick approach might be more successful in obtaining nearly 100 percent participation among growers than an educational approach. But in either case, grower acceptance would be much more likely if the program selected for implementation allowed flexibility and individual choice, which are always more acceptable to the American farmer than governmental decrees.

The data developed in the OPM and BWE trials clearly show that area programs are more successful in maintaining low boll weevil populations than the "each-grower-do-his-own-thing" approach (CIC). Thus, it would seem logical to consider various scenarios that might provide the impetus for grower acceptance of a beltwide OPM or BWE program.

Optimum Pest Management

The approach used in Panola County was a good example of farmer-government cooperation to achieve a goal. The use of a subsidy, maintained for 3 years in the form of compensation for weevil diapause treatments, was extremely successful. It suggests that such a model would be useful elsewhere in the Cotton Belt to obtain areawide participation.

The cessation of the subsidy will mean that a certain percentage of growers will cease making diapause treatments. How large a percentage will do so remains to be seen, but the benefits of the trial should persuade most of the growers, perhaps 75 percent, to continue doing so. If weevil populations begin to resurge, growers who ceased making treatments would logically resume making them for economic reasons.

Pest Management Associations and Cooperatives

Pest management associations and cooperatives, and private pest-management consultants, have successfully organized and handled cooperative cotton insect management programs in Texas, where cotton-growing areas have more environmental diversity than those of any other state in the Cotton Belt. Texas is the largest cotton-producing state in the boll weevil infested area of the Cotton Belt, but there are many areas in the state where the weevil is not a major pest. These areas are the least likely to receive great benefits from weevil eradication. Thus, Texas may be the most difficult state in which to obtain grower approval of a mandatory weevil eradication.

The state Extension Service had a great deal to do with organization of the Texas Pest Management Association, which, along with private consultants, has been very active in bringing about grower acceptance of crop management practices that will provide the best control of cotton pests. All of these practices are economically sound and lead toward reduced insecticide use.

The extension service in other states has also fostered areawide approaches to cotton insect management. Such approaches can be carried out in any area of the Cotton Belt, limited only by the desire and imagination of the local populace.

Current Insect Control (CIC)

Current insect control (CIC) is not without its success stories. Pontotoc County, the comparison area for the OPM trial, has been used as an example of successful CIC, and in some other Mississippi counties, 90 percent of the cotton acreage is under a pest management consultant's care (J. Kimbrough III, Lexington, MS, personal communication, 1980). In areas where private consultants are particularly active, growers utilizing their services have seen the economic and ecologic advantages of coordinated pest management in practice. The adoption of more sophisticated pest management practices because of greater environmental and economic awareness among growers is increasing each year. Current insect control practice is rapidly evolving into integrated pest management (IPM), which lacks only government subsidies for diapause treatments to become optimum pest management (OPM).

APPENDIX A

USDA DEFINITIONS OF ALTERNATIVE BELTWIDE COTTON INSECT MANAGEMENT PROGRAM OPTIONS

Six beltwide boll weevil/cotton insect management programs were defined and approved by SEA-ES and APHIS personnel in consultation with Optimum Pest Management Regional Extension Education Advisory Committee (OPMREEAC), the Overall Evaluation Team, and the Facilitator Group. The program definitions are:

Current Insect Control (CIC) assumes insect control as now practiced by producers ranging from no control to intensive treatment with insecticides. Current insect control implies a continuation of extension education and technical assistance at the present level of funding.

Optimum Pest Management with Continuing Incentives for Boll Weevil Management (OPM-I) would consist of two major insect management options, whichever is most applicable for a particular area. Additional extension personnel and support would be required to implement both options. One option, Optimum Pest Management (OPM) would utilize the boll weevil/cotton insect management practices that were tested in the Mississippi trial with emphasis on diapause and pin-head square treatments, as needed, and full reimbursement for the cost of these treatments. In all areas where the diapause strategy could not be implemented or where it is not needed, an alternate option, Modified Optimum Pest Management (MOPM) would be followed. It would utilize, if applicable, all the practices tested in the Mississippi trial except the organized areawide diapause strategy, but may include voluntary diapause treatments by individual producers.

In areas having potential for moderate-to-heavy infestations of boll weevils, the OPM option would be implemented where effective. Dispause and pinhead square treatments would be specified as recommended technology. The criterion for an effective program is to maintain the midseason population of boll weevils below treatment levels on 90 percent or more of the acreage prior to onset of *Heliothis* pressure. Growers would be reimbursed for boll weevil diapause and pinhead square treatments at such a level and over sufficient treated acreage to achieve an effective program.

As an example, OPM in Mississippi would: (1) use grandlure baited traps as survey tools; (2) urge producers to plant cotton within recommended dates; (3) recommend [treatments] and reimburse producers for pinhead square applications, if needed; (4) scout all cotton by commercial consultants, grower organizations, CES employees, or trained producers; (5) urge producers to follow CES recommendations for in-season control of boll weevils and other cotton insects; (6) reimburse producers for boll weevil diapause treatments, if needed; and (7) urge producers to destroy stalks, if harvested prior to frost. Consultant and grower organizations would be involved, with CES providing information on recommended insect control practices.

However, in areas, if any, where the required acreage for an effective program could not be reached with the OPM option or where boll weevil infestations are historically light and usually do not reach treatment levels, the Modified Optimum Pest Management (MOPM) option would be implemented. This option implies that the diapause and/or pinhead square technology either could not be adopted on a sufficient percentage of the cotton acreage for an effective areawide OPM option or it would not be needed because of the low population levels of boll weevil. The objective of MOPM is to reduce the number of unnecessary in-season treatments for boll weevil and other cotton insects through effective scouting and monitoring. Examples of areas where diapause and/or pinhead square treatments are not commonly needed include north Alabama, some areas in the Mississippi Delta, Upper Concho area of Texas, and north Oklahoma.

To implement both options under the OPM-I program, additional extension personnel and funds would be required to provide technical information and educational guidance in the management of boll weevils and other cotton insects. All available proven technology may be applied in implementing this program. Use of the technology recommended and participation in this program would be voluntary on the part of the grower. From 1 to 3 years may be required to fully implement this program, depending on cotton acreage and availability of staff. The acreage that one entomologist can handle will vary because of the location and intensity of cotton acreage as well as historic patterns of insect management problems.

<u>Optimum Pest Management with Phased Incentive Payments for Boll Weevil Management (OPM-PI)</u> includes the same program components including personnel and funds as OPM-I except that incentive payments for diapause and pinhead square treatments would be phased out over time as follows:

1st year:	Same as OPM-I, 100 percent of needed treatment
2nd year:	75 percent of needed treatment
3rd year:	50 percent of needed treatment
4th year:	No incentive payment

The logic in evaluating this program is that in some areas an incentive may serve to demonstrate the technical and economic feasibility of diapause and pinhead square treatments and that growers may continue the use of these practices. If the required acreage for an effective diapause/pinhead square option could not be maintained after payments are phased out, the MOPM option would be implemented.

Optimum Pest Management with No Incentive Payments for Boll Weevil Management (OPM-NI) is the same as OPM-I with the exception that no reimbursements to producers would be made for diapause or pinhead square treatments. If the required level of acreage could not be reached, the MOPM option would be established and the diapause/pinhead square technology would not be implemented on an areawide basis.

Optimum Pest Management with No Incentive Payments and with Boll Weevil Eradication (OPM-NI-BWE) includes eradication of the boll weevil as a major component. The beltwide eradication component would use the technology proven by the North Carolina trial and ongoing research. However, it does not need to be a replication of the North Carolina trial.

Boll weevil eradication would begin in the Southeast and proceed west through eight separate zones, followed by the maintenance of a buffer zone between the United States and Mexico to inhibit reinfestation. To insure efficient implementation of this program, OPM-NI would be implemented beltwide 1 year prior to the initiation of eradication. MOPM practices for the control of other insects would be in place during and following eradication. The major components of the program to eradicate the boll weevil from a designated zone are:

(1) Prior to eradication, the voluntary program with no incentive payments to producers (OPM-NI) would involve information and education, organization of producers and encouragement of producers to follow recommended insect control practices.

(2) During the first year of eradication, growers would be responsible for in-season control of all insects, including boll weevils. Growers would be urged to follow recommendations for all cotton insects. Beginning in early September (depending on area and weather) APHIS would initiate a boll weevil eradication program with diapause treatments of boll weevils, using guthion, malathion, or other recommended insecticides, as needed. A range of 5-10 treatments is projected to be required on all acreage in infested areas.

(3) During the second year of eradication, APHIS would monitor and control incipient boll weevil infestations by the use of sterile weevils, Dimilin, and organophosphorous insecticides, as needed. Growers would be urged to follow recommended practices for control of other insects.

(4) During subsequent years, growers would continue with MOPM practices for the control of other insects in a weevil-free environment, while regulatory agencies would assume responsibility for routine surveillance of the areas cleared (trapping density of 1 per 200 acres) and the control of incipient boll weevil infestations. Following eradication, the Extension Service would continue to provide information to growers on how best to manage cotton insects in the absence of the boll weevil.

Current Insect Control with Boll Weevil Eradication (CIC-BWE) also would include eradication of the boll weevil as a major supplement to the current cotton insect management program. The beltwide eradication component would use the technology proven by the North Carolina trial and ongoing research. The eradication component remains essentially the same as in OPM-NI-BWE, but there are no provisions for additional staffing or funding of CES programs prior to, during, or following eradication.

APPENDIX B

U.S. DEPARTMENT OF AGRICULTURE REPORTS EVALUATED

Animal and Plant Health Inspection Service 1980. Operational Evaluation Plans of Beltwide Boll Weevil/Cotton Insect Management Programs. Overall Evaluation, Appendix H. APHIS Staff Report, January.

Animal and Plant Health Inspection Service 1981a. Environmental Evaluation of Alternative Beltwide Boll Weevil/Cotton Insect Management Programs. Overall Evaluation, Appendix C. APHIS 81-33, April.

Animal and Plant Health Inspection Service 1981b. Boll Weevil Eradication Trial, Final Report. Overall Evaluation, Appendix F. APHIS Staff Report, April.

Economics and Statistics Service 1981a. Overall Evaluation of Beltwide Boll Weevil/Cotton Insect Management Programs. ESS Staff Report, May.

Economics and Statistics Service 1981b. Economic Evaluation of Alternative Beltwide Boll Weevil/Cotton Insect Management Programs. Overall Evaluation, Appendix B. ESS Staff Report, April.

Economics and Statistics Service 1981c. Program Definitions and Public Costs, Beltwide Boll Weevil/Cotton Insect Management Programs. Overall Evaluation, Appendix D. ESS Staff Report, April.

Economics and Statistics Service 1981d. The Delphi: Insecticide and Lint Yields, Beltwide Boll Weevil/Cotton Insect Management Programs. Overall Evaluation, Appendix E. ESS Staff Report, April.

Mississippi Cooperative Extension Service 1981. Optimum Pest Management Trial, Final Report. Overall Evaluation, Appendix G. Cooperative Extension Service, Mississippi State University Report, April.

Science and Education Administration 1981. Biological Evaluation of Alternative Beltwide Boll Weevil/Cotton Insect Management Programs. Overall Evaluation, Appendix A. SEA Staff Report, April.

U.S. Department of Agriculture 1981. Executive Overview of Alternative Boll Weevil/Cotton Insect Management Programs, May.

APPENDIX C*

ADDITIONAL COMMENTS ON THE USDA ECONOMIC EVALUATION

Arnold Paulsen

This appendix will comment on 1) the goals and approach; 2) the data base; 3) the method or model used to estimate beltwide benefits and costs; 4) a graphical interpretation; 5) the accuracy and the risk of the estimates; and 6) the policy inferences and public choice recommendations that can be based on the estimates of the Economic Evaluation Report (Economics and Statistics Service 1981b).

Goals and Approach

The overall goal of the economic evaluation was to facilitate the choice of a beltwide cotton insect management program and more specifically "to estimate and evaluate the current and future localized and beltwide economic impacts of alternative boll weevil/cotton insect management programs" (see page 2, Economics and Statistics Service 1981b).

The beltwide focus of the economic evaluation was appropriate to "facilitate the [public] choice." This meant the economic analysis could not draw all data from the trial areas. The future focus of economic evaluation was also appropriate but implied that projections or forecasts of the future had to be made and that these would be unverifiable and speculative. The economic analysts recognized and

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*This appendix was prepared by Dr. Arnold A. Paulsen, a member of the NRC Committee, to provide additional evaluations of the USDA Economic team's report beyond those included in Chapter 5. The views expressed in this appendix are those of Dr. Paulsen and are not necessarily those of the National Academy of Sciences or of the National Research Council. This appendix was not subjected to the customary review process of the National Research Council.

reported a great deal of geographical variation in program impact among areas of the boll weevil belt. USDA did not report variation in cost of implementation due to weather, or variation of payoff or benefits due to weather or other factors. Only the normalized estimates are presented.

The USDA Economic Evaluation correctly perceived that the implementation of alternative public cotton insect strategies is similar to the adoption of technological advances. Each of the proposed cotton insect management programs is assumed to be fully adopted and successful, which they may not be. USDA apparently expects the benefit to continue forever which it may not.

A summary of USDA economic feasibility findings is contained in a table reproduced in this report (Table 5.2). In this table the present value of estimated public costs are compared with the present value of estimated future national benefits. These market benefits of full implementation of each alternative are estimated to far exceed the estimated public costs of implementing BWE or OPM. The difficulty is that the probability of the benefits actually being so large as estimated may be small. The probability of the program costs being as small as estimated also appears to be very small. Thus the probability of the B-C ratio being accurate may be exceedingly small.

For the public choice among BWE, OPM, or CIC the question of economic feasibility or rate of return to public expenditure is important. There are, however, several additional considerations in deciding among public eradication, public management, or continuation of current insect policy. First, public resources are limited, and only those projects expected to be feasible may be carried out. Second, non-market costs and returns of BWE and OPM may make the social benefit to cost ratio larger or smaller than the market or economic B-C ratios. For example, no cost or benefit is included for change in human health, aquatic life, or environmental quality in the economic feasibility calculation. Third, income redistributions are estimated by USDA and reported, but of course, not included in economic feasibility. The prospect that economic growth may be stimulated in the boll weevil belt relative to other cotton areas as a consequence of public boll weevil management may make public action more or less desirable. Fourth, other consequences may favor more public participation in cotton insect control such as "the joy of being free from boll weevil," or limit public participation such as the fear of urban taxpayers that public costs may overrun.

The Data Base

The task of the economic evaluation team was to provide estimates of the economic consequences of beltwide implementation of each of the proposed boll weevil eradication and management strategies. Data that could be used to make these estimates were accumulated through a Delphi technique. The USDA Delphi method was well designed to identify probable insecticide-use and lint-yield changes (Economics and Statistics Service 1981d).

The data on future BWE and OPM program actions and costs were generated by an informal "Delphi method" not by hard science measurement. The required future insect management and eradication actions and costs are "speculation" or expert opinion rather than scientific data. The economic report does not describe completely the procedure and qualification of experts used to generate program costs. The experts formulating program and public cost data seem to have been less numerous, less diverse in opinion, and less representative of the full spectrum of expert opinion than the panel of experts involved in generating the data on cotton yield and control cost change. As a result the data on the program cost were obtained by a method less systematically designed and thus more uncertain. The full range and uncertainty of the volume of BWE and OPM activities required to obtain boll weevil eradication or management below the economic threshold remains unreported. The program cost data provided by USDA cannot be used to accept or reject hypotheses about the level of future public costs with known confidence. The USDA team can be criticized for not reporting in more detail the uncertainty and diversity of expert opinion about program cost. The program costs reported by USDA completely ignore the important issues of probability of program success and rate of adoption and opposition.

The Method or Model

No itemization is given by USDA of the sources of consumer benefit (Table 5.2). An approximation can be inferred by multiplying expected price changes by estimated 1980-1981 quantities, see Table C.l. From this approximate itemization it seems that only one third of consumer benefits are directly from additional lint. The equations of the USDA model seem to have transferred most of the consequences of reduced cost and increase yield on cotton into price depressing effects on cotton seeds, vegetable oil, and grains. This is a puzzling distribution since the gain in lint is 2.8 percent and the market for lint--at least domestically--usually is unwilling to absorb more lint even at sharply lower prices. The gain in cotton seeds is also 2.8 percent, but the market for oil seeds is very large and usually willing to absorb more material at a slightly lower price.

The USDA estimates total U.S. cotton lint production would increase 2.8 percent, and the U.S. cotton lint price would be depressed 3.6 percent. These relative price-to-quantity changes indicate a slightly inelastic demand. Since the U.S. cotton market is relatively open, U.S. cotton prices are very similar to world cotton prices. Most additional cotton produced by better control of boll weevil probably would be exported or stored rather than sold on the U.S. market. If nearly all the additional cotton, i.e. 0.3 million bales, were exported, this additional U.S. cotton would raise U.S. exports 5 percent, but would add only about 1.5 percent to world trade or add 0.5 percent to total world production. A price decline for U.S. cotton lint of 3.6 percent when 2.8 percent more is produced would be much too little if only the U.S. market were considered.

Table C.1 Approximate Itemization of the Benefits to Consumers

Commodity	Expected Price Change[a]	Basic Simulation Quantity[b] (x 10^6)		Change in Value of Crop[a] (10^6 dollars)
Cotton	- 2.73 ¢/lb.	11.7[c]	bales	-160
Corn	- 0.8 ¢/bu.	6,100	bu.	- 49
Soybeans	- 2.0 ¢/bu.	1,560	bu.	- 31
Small grain	- 0.3 ¢/bu.	2,600	bu.	- 8
Grain sorghum	+ 1.4 ¢/bu.	780	bu.	+ 10.9
Cotton seeds	-19 $/ton	4.7	tons	- 89
Cotton seed meal	- 8.3 $/ton	1.74	tons	- 14.4
Cotton seed oil	- 1.62 ¢/lb.	1,460	lbs	- 23.7
Soybean meal	- 3.8 $/ton	21.3	tons	- 80.9
Soybean oil	- .02 ¢/lb.	10,120	lbs.	- 2.02
		ANNUAL TOTAL		$ 447
		PRESENT VALUE[d]		$6268

[a] From Column OPM-NI-BWE in Table 6, p. 34 (Economics and Statistics Service 1981b)

[b] 1980-1981 production from an unpublished description of the econometric model by Robert Taylor obtained at the April 1, 1981 meeting of the USDA Economic Evaluation Team in Arlington, VA

[c] From Table 8, p. 39 (Economics and Statistics Service 1981b)

[d] If the annual total of $447 is capitalized at 7.125 percent as a stream of perpetual benefits the present value is obtained.

But when the 2.8 percent more of production is translated to 0.5 percent more cotton produced in the world the 3.6 percent price decline seems reasonable. The increase in U.S. and foreign consumer surplus at $160 million per year from expanded U.S. cotton production as a result of boll weevil eradication seems reasonably accurate.

Generally since 1974, the U.S. opportunity to export has expanded. Thus, the lint price depression estimated by USDA does not imply an absolute reduction in U.S. cotton lint price from 1980 to 1990 if OPM or BWE is implemented. The price change anticipated by USDA is relative to what would be without the improvement in U.S. cotton insect control. If long run world cotton prices rise, the contemplated improvement in U.S. cotton insect control would merely prevent world cotton prices from rising as much as they otherwise would.

The USDA seems to estimate an overly large benefit to consumers and loss to producers from 2.8 percent more cotton seeds and some small percent change in total grain. This would seem to arise from a faulty set of demand equations (or calculations) for cotton seed, vegetable oil, grains, and feeds. These few additional cotton seeds and grains would seem to add only slightly to the very large U.S. and world total supply of oil seeds, vegetable oils, and high protein feeds and grains. The aggregate of U.S. oil seeds is about 61 million tons. Thus, the anticipated 130 thousand tons more of cotton seeds would be only a 0.2 percent increase in oilseed supply. This small change would depress U.S. and world prices of oilseeds, via additional vegetable oil and high protein feeds, but probably by less than 0.5 percent. The cotton seed price reduction estimated by USDA was 15.5 percent. USDA estimates a reduction of about $89 million per year in the value of a crop of cotton seeds to cotton producers. This seems to be an overestimate. It seems to this reviewer more likely that cottonseed price would decline by a smaller percent than the percent by which cottonseed production expanded. The result would be an increase in cottonseed value of about 2 percent under OPM-BWE.

The USDA demand equations estimate a loss in value of cottonseed oil of about $23 million per year or 2 percent. The volume of cottonseed oil is expected to rise 40 million pounds or 2.8 percent, but the price is expected to fall about 4.8 percent. This seems excessive. The vegetable oil market of the world is large--about 56 million metric tons--and rather open and competitive. The additional 40 million pounds or 0.2 million tons more U.S. cottonseed oil is almost negligible. Even the 20 percent smaller U.S. soybean crop in 1980 did not raise the world price of vegetable oil. From better U.S. boll weevil control only about 0.1 percent would be added to the world vegetable oil aggregate. This probably would depress world oilseed prices less than 0.5 percent and not 4.8 percent as USDA estimates. It seems probable that the total value of the oil component of U.S. cotton seeds would actually rise as a result of increased cottonseed production.

The USDA estimates imply that much of the annual consumer benefit will be derived from depressing prices in the large U.S. feed-grain-livestock complex. The likelihood of significant price declines in the large feed-livestock aggregate by so small a technological advance in cotton seems remote to this reviewer. Apparently USDA anticipates some more feed will be produced, but the quantity changes are not reported.

The anticipated gain in efficiency in cotton is only a gain of about 2.5 percent and is applied to only 3 to 4 percent of total U.S. agriculture. The gain emerges only after 10 years of implementation. After full implementation, the Delphi panels anticipated about $50 million savings per year in cotton insect control cost on historical acreages. Additional lint yields would provide the same total lint from fewer acres, thus saving additional production costs of about $75 million per year. USDA expects more acres of land to be used for cotton because more cotton will be produced on lower-yielding, non-irrigated acres in Texas.

The net release of land and other resources from cotton will be small and can have only a small impact on total U.S. agricultural capacity. A productivity gain of $125 million in cotton--a big crop valued at $5 billion--is only 2.5 percent over 10 years or 0.25 percent per year. $125 million in cotton productivity gain is exceedingly small compared to the very large total of $141 billion value of all U.S. agricultural production. It is only 0.09 percent after 10 years or 0.009 percent per year. Productivity gains in U.S. agriculture occur regularly from diverse technological, organizational, and management improvements. Each year these raise the productivity of U.S. agriculture about 1.5 percent or 15 times as much in one year as the impact of improved boll weevil and cotton insect management is expected to raise productivity over 10 years. Probably this relatively small gain in cotton resource productivity would not depress feed livestock prices and the total value of the products by as much as anticipated by USDA. Additional capacity in U.S. agriculture will be needed and can be absorbed without significant disruption of the feed-livestock markets or income loss to U.S. agriculture.

The demand for U.S. agricultural products is expected to grow about 2 percent per year over the next decade or so. The real terms of trade for agricultural products may rise. Any agricultural resource productivity improvement from cotton insect management, if accurate, might not reduce feed livestock prices absolutely but only relative to what they would be without this improvement.

A Graphical Interpretation

The market consequences from improvements in cotton insect management can be explained or interpreted graphically (see Figure C.1). The increased public involvement via OPM-BWE moves the supply curve down and to the right--more cotton will be supplied at the same price because the boll weevil is no longer a key pest. Before public eradication of the boll weevil USDA estimates that at $0.76 per pound 11.5 million bales of cotton lint will be offered (the intersection of the supply curve before eradication, S_B, and the Demand Curve, D, in Figure C.1). After eradication USDA estimates that 2.8 percent

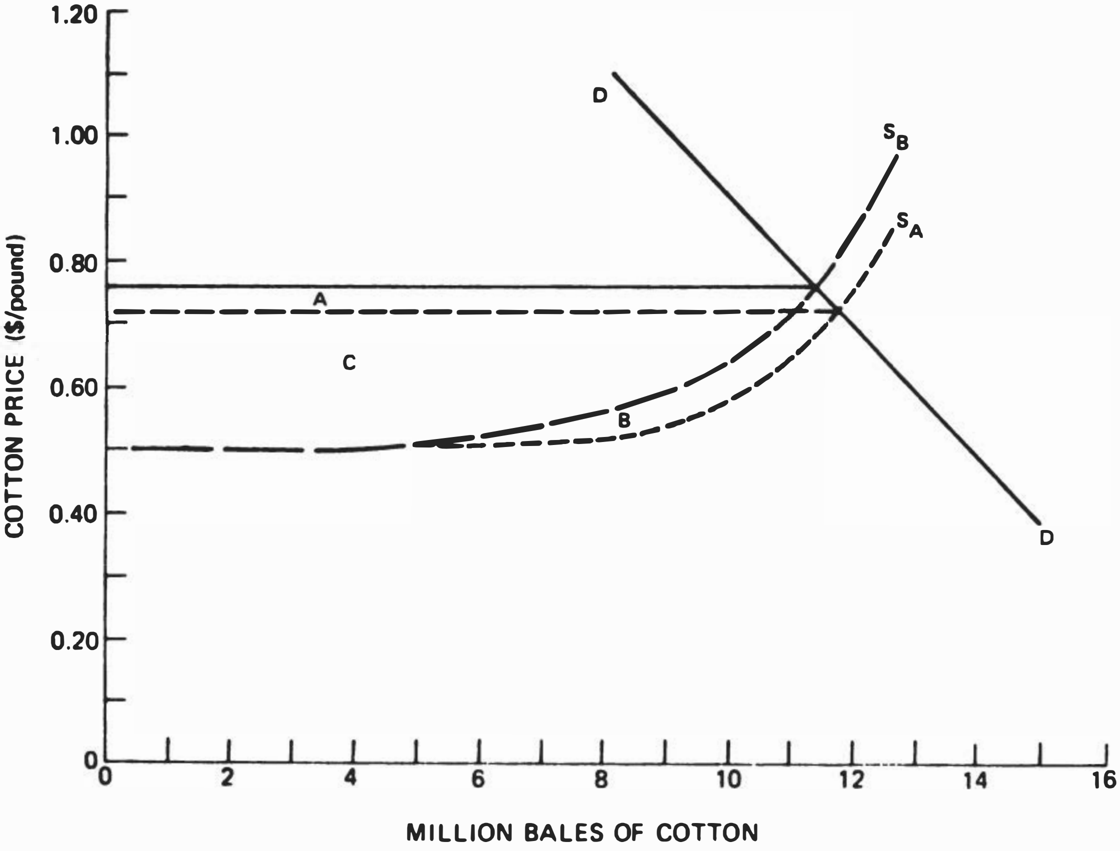

FIGURE C.1 Approximate cotton lint market in the United States before and after boll weevil eradication.

more cotton will be produced or 11.8 million bales will be offered. This larger quantity will be offered willingly by producers at a 3.6 percent lower price of $0.732 per pound (note the intersection of the Supply Curve, S_A, and D, in Figure C.1).

The benefit to the consumer is the change in the area under the demand and above the price line (labeled Area A in Figure C.1). This area is equal to the reduced expenditure by consumers on cotton plus the value of the additional cotton consumed. The value of this area is the consumer market benefit and can be approximated by $0.028 per pound or $161 million per year for 11.5 million bales at 500 pounds per bale. If this benefit continues to accrue to consumers each year forever and the interest rate is 7.125 percent, the stream has a present value of about $2.3 billion.

This benefit to consumers in the form of a drop in the price is offset by a loss of the same size in net income to producers (see Area A in Figure C.1). Producer net income is the area above the supply curve and below the price line. If the price did not fall when production expanded 0.3 million bales, producers would receive $0.76 per pound times 11.8 million bales, or a gross revenue of $4.48 billion. However, at $0.732 they receive $4.32 billion or $160 million less per year. If this loss to producers continued and the interest rate is 7.125 percent, the stream of loss to producers has a present value of $2.3 billion. By expanding production the improvement in cotton insect management redistributes each year via the operation of the market $160 million of income or welfare toward consumers and away from producers. The Area labeled A is a transfer and does not appear and should not appear in USDA calculations of economic feasibility.

The costs of production for some acres are reduced by the improved management of cotton insects. In parts of Texas, lint yields are estimated to be improved 25 to 50 pounds per acre as a result of public involvement in cotton insect management. In parts of Georgia, Alabama, and Texas the cost of insect control is reduced $10 to $40 per acre. The aggregate value of these yield increases and reductions in cost of production over the whole belt can be indicated graphically. Note the area labeled B in Figure C.1. This is the area below the old supply curve S_B and above the new more efficient supply curve S_A. The dollar total value of this area each year can be approximated by multiplying the estimated saving in insect control cost by historical acres ($44 million for OPM-I and $57 million for OPM-NI-BWE) plus the lint increases of 123 million pounds for OPM-I and 168 million pounds for OPM-NI-BWE valued at $.50 per pound (the data to make these calculations are in Tables 3, 4, and 12 in Economics and Statistics Service 1981b). The sum is about $105 to $125 million per year. This is an indication of the productivity gain to the U.S. economy of improved cotton insect management. Area B is the net market benefit of Table 5.2. Area B represents the gain in productivity or the opportunity to get more cotton for the same resources or the same cotton for less resources.

USDA's presentation was not graphical but tabular. Logically the calculus done by USDA can be restated as follows in terms of areas in the graphical presentation of Figure C.l.

Consumer benefit = A

Producer loss = Net before less Net after

$$= (A + C) - (C + B) = A - B$$

Net market benefit = Consumer benefit - producer loss

$$= A - (A - B) = B$$

Thus, graphically the net economic or market gain to the society from public cotton insect control is Area B, namely, the gain in yield and the saving in control cost. Area A is the gain to consumers but is offset by an equal size loss to producers and represents the redistribution effect of this productivity gain. The increase in cotton yield plus savings of insect control resources is the only net economic gain for the entire society and market. The size of A indicates the amount of income redistribution. Area B estimates economic welfare gain to the whole society or economy. USDA's model and tables quantify the concepts graphically presented in Figure C.l.

The Accuracy and Uncertainty of the Estimates

The consumer benefits and producer losses presented by USDA and illustrated graphically as Area A in Figure C.l seem inflated. Specifically the price depression in the animal feed and vegetable oil complex seems excessive. Thus, an overestimate may have been made of the redistribution consequences, namely toward consumers and away from producers.

USDA estimates that if $240 million were appropriated and placed in a fund at an interest rate equal to the future inflation rate plus 7.125 percent that the balance in that fund would pay for all the public costs of efforts needed to successfully eradicate the boll weevil forever. The probability of success from such an appropriation seems to this reviewer extremely small in light of the costs for the North Carolina trial and the Stanford Research Institute estimates.

USDA's program cost estimates shown in Table 5.2 do not address the probability of success. There is uncertainty in weather, peoples' cooperation, and rate of program execution. Through 80 years of eradication history and 70 years of extension history efforts have not always been 100 percent successful.

The uncertainty of the estimated ratios of costs to benefits are the product of the uncertainty of the costs and of the benefits. When both terms of the ratio are uncertain constructing a ratio multiplies the uncertainty. For example, if the benefits have a low probability (e.g., 0.1) of being so high and the costs have a low probability (e.g., 0.1) of being so low the probability of the combination occurring is very low (e.g., 0.01).

The Policy Implications and Public Choice

For policy makers to allocate scarce public resources responsibly it is necessary they know not only the benefit-cost ratio but also the probability of success. Budget makers have to take informed risks, but they need to have analysts provide reasonable estimates of the risks involved with each proposal. USDA was unrealistic in providing only one benefit-cost ratio without associated probability of success. To present only one B-C ratio not clearly at the mode of the distribution and possibly with an extremely low probability of success, seems unbalanced. Several alternative program costs, each with an explicit probability of success, should have been provided. High risk operations like OPM-NI usually look more profitable than low risk operations like OPM-I until the relative risk is considered.

The USDA did not report any critical review of the uncertainties in the OPM or BWE program proposals and program costs. Alternative benefit-cost ratios which had equal or larger probability of occurring should have been presented. The uncertainty of insect eradication costs, timing, and success are well known and widely understood. Because the 1981 USDA evaluation did not present alternative costs and alternative benefit-cost ratios with a probability of success associated with each, an informed and intelligent public choice cannot be made at this time. The situation is too uncertain to make a rational choice among alternative proposals for public cotton insect control.

REFERENCES

Adkisson, P. L. (1971) Objective use of insecticides in agriculture. Pages 43-51, Agricultural Chemicals - Harmony or Discord for Food, People, Environment. Proc. Symp. Univ. Calif. Div. Agric. Sci. Sacramento, California, edited by J. E. Swift. University of California.

Adkisson, P. L. (1973) The principles, strategies and tactics of pest control in cotton. Pages 274-282, Studies in Population Management, edited by P. W. Geier. Mem. Ecol. Soc. Austr., Vol. I.

All, J. N., M. Ali, E. Hornjak, and J. B. Weaver (1977) Joint action of two pyrethroids with methyl parathion, methomyl, and chlorpyrifos on *Heliothis zea* and *Heliothis virescens* in the laboratory and cotton and sweetcorn. J. Econ. Entomol. 70:812-817.

Altieri, M. A., and W. N. Whitcomb (1979) The potential use of weeds in the manipulation of beneficial insects. HortScience 14:12-18.

Animal and Plant Health Inspection Service (1981a) Environmental Evaluation of Alternative Beltwide Boll Weevil/Cotton Insect Management Programs. Overall Evaluation, Appendix C. APHIS 81-33, April.

Animal and Plant Health Inspection Service (1981b) Boll Weevil Eradication Trial, Final Report. Overall Evaluation, Appendix F. APHIS Staff Report, April.

Bailey, J. C., B. W. Hanny, and W. R. Meredith (1978) Comparisons of insect populations on cotton varieties at Stoneville, Mississippi in 1977. Beltwide Cotton Prod. Res. Conf., National Cotton Council, Memphis. p. 83. (Abstr.)

Bergman, D., T. J. Henneberry, and L. A. Bariola (1981) Boll weevil in Arizona stub cotton. Beltwide Cotton Prod. Res. Conf., National Cotton Council, Memphis. (in press) (Abstr.)

Boll Weevil Research Laboratory (1981a) Concerning: South Mississippi, 1980. Attractivenss of females to sterilized and unsterilized males and grandlure. USDA-SEA, Mississippi State, Mississsippi. Unpublished report.

Boll Weevil Research Laboratory (1981b) Concerning: Summary of 1980 results in field competitiveness studies. USDA-SEA, Mississippi State, Mississippi. Unpublished report.

Boll Weevil Research Laboratory (1981c) Concerning: North Carolina aerial release of boll weevils to determine efficacy of pheripheral versus infield drops. USDA-SEA, Mississippi State, Mississippi. Unpublished report.

Brazzel, J. R. (1961) Boll weevil resistance to insecticides in Texas in 1960. Tex. Agric. Exp. Stn. Prog. Rept. 2171.

Brazzel, J. R., H. Chambers, and P. J. Hammen (1961) A laboratory rearing method and dosage - mortality data on the bollworm _Heliothis zea_. J. Econ. Entomol. 54:949.

Brazzel, J. R. (1963) Resistance to DDT in _Heliothis virescens_. J. Econ. Entomol. 56:571-574.

Brazzel, J. R. (1964) DDT resistance in _Heliothis zea_. J. Econ. Entomol. 57:455-457.

Brazzel, J. R. (1976) A Plan for Boll Weevil Elimination in the Cotton Belt. Pages 154-158, Boll Weevil Suppression, Management and Elimination Technology. Proceedings of a Conference, Feb. 13-15, 1974. Memphis, TN, ARS-S-71. April 1976. Washington, DC: U.S. Department of Agriculture.

Bridge, R. R., W. R. Meredith, Jr., and J. F. Chism (1971) Comparative performance of obsolete varieties and current varieties of upland cotton. Crop Sci. 11:29-32.

Brown, W. L. Jr., T. Eisner, and R. H. Whitlake (1970) Allemones and kairomones. Transpecific chemical messengers. Bioscience 20:21-22.

Bruer, H. L. (1976) Regulatory Aspects of Boll Weevil Eradication in the Cotton Belt. Pages 159-160, Boll Weevil Suppression, Management, and Elimination Technology, USDA ARS-S-71.

Bull, D. L., and G. W. Ivie (1978) Fate of diflubenzuron in cotton, soil, and rotating crops. J. Agric. Food Chem. 26:515-520.

Butenandt, A., R. Beckmann, D. Stamm, and E. Hecker (1959) Uber den sexual Lockstaff der Seidenspinnen _Bombyx mori_, Reindarstellung und Konstitution. Z. Naturforsch. B14:283-284.

Call, T. B., and J. B. Weaver (1980) Resistance to _Heliothis_ in an interspecific cotton hybrid. Beltwide Cotton Prod. Res. Conf., National Cotton Council, Memphis.

Carpenter, K. E., and D. H. Miller (1980) Final Report on the Environmental Evaluation of the 1979 Boll Weevil Control Trial Programs. KFR 273-80, 25 July 1980. Ketron, Inc., Arlington, VA. (This appears as attachment C in APHIS 1981a.)

Carpenter, K. E., and D. H. Miller (1981a) Final Report on the Environmental Evaluation of the 1980 Boll Weevil Control Trial Programs. KFR 303-81, 23 January 1981. Ketron, Inc., Arlington, VA. (This appears as attachment D in APHIS 1981a.)

Carpenter, K. E., and D. H. Miller (1981b) Three Year Summary of the Boll Weevil Control Trial Programs. KFR 312-81, 13 February 1981. Ketron, Inc., Arlington, VA. (This appears as Attachment I in APHIS 1981a.)

Clower, D. F. (1980) Changes in *Heliothis* spp. attacking cotton in recent years and how they have affected control. Beltwide Cotton Prod. Res. Conf., National Cotton Council, Memphis.

Coad, B. R., and G. L. McNeil (1924) Dusting cotton from airplanes. USDA Bull. 1204.

Collins, K., R. B. Evans, and R. D. Barry (1979) World Cotton Production and Use Projections for 1985 and 1990. U.S.D.A. Economics, Statistics, and Cooperatives Service; Foreign Agriculture Service.
Foreign Agric. Econ. Report No. 154. Washington, DC: U.S. Department of Agriculture.

Copplestone, J. F. (1977) A global view of pesticide safety. Pages 147-155, Pesticide Management and Insecticide Resistance, edited by D. L. Watson and A. W. A. Brown. New York: Academic Press.

Council on Environmental Quality (CEQ) (1978) Biological Agents for Pest Control: Status and Prospects. Library of Congress No. 77600057. Washington, DC: Office of Environmental Quality.

Cross, W. H. (1973) Biology, control and eradication of the boll weevil. Ann. Rev. Entomol. 18:17-46.

Cross, W. H. (1981) Ecology of cotton insects. *In* Cotton Insect Management with Special Reference to the Boll Weevil, USDA Agricultural Handbook Series. (in press)

Crowder, L. A., M. S. Tollefson, and T. F. Watson (1979) Dosage mortality studies of synthetic pyrethroids and methyl parathion in the tobacco budworm. J. Econ. Entomol. 72:1-3.

Davich, T. B., and D. A. Lindquist (1962) Exploratory studies on gamma radiation for the sterilization of the boll weevil. J. Econ. Entomol. 55:164-167.

Davich, T. B., J. C. Keller, E. B. Mitchell, P. Huddleston, R. Hill, D. A. Lindquist, G. McKibben, and W. H. Cross (1965) Preliminary field experiments with sterile males for evaluation of the boll weevils. J. Econ. Entomol. 58:127-131.

Davich, T. B. (1976) Boll weevil sterility. Pages 53-58, Boll Weevil Suppression, Management, and Elimination Technology. USDA ARS-S-71.

Davich, T. B., D. D. Hardee, and J. Acala M. (1970) Long range dispersal of boll weevils determined with wing traps baited with males. J. Econ. Entomol. 63:1706-1708.

Davis, D. D. (1979) Synthesis of commercial F_1 hybrids in cotton. II. Long strong-fibered *G. hirsutum* L. X *G. barbadense* L. hybrids with superior geonomic properties. Crop Sci. 19:115-116.

Davis, D. D., J. J. Ellington, and J. C. Brown (1973) Mortality factors affecting cotton insects: I. Resistance of smooth and nectariless characters in Acala cottons to *Heliothis zea*, *Pectinophora gossypiella*, and *Trichoplusia ni*. J. Environ. Qual. 2:530-535.

Davis, J. W., J. A. Harding, and D. A. Wolfenbarger (1975) Activity of a synthetic pyrethroid against cotton insects. J. Econ. Entomol. 68:373-374.

DeBord, D. V. (1977) Cotton insect and weed loss analysis. The Cotton Foundation.

Dilday, R. H., and T. N. Shaver (1980) Variability in flower-bud gossypol content and agronomic and fiber properties within the primitive race collection of cotton. Crop Sci. 20:91-95.

Ebeling, W. (1980) The Fruited Plain. The Story of American Agriculture. Berkeley: Univ. Calif. Press.

Economics and Statistics Service (1981a) Overall Evaluation of Beltwide Boll Weevil/Cotton Insect Management Programs. ESS Staff Report, May.

Economics and Statistics Service (1981b) Economic Evaluation of Alternative Beltwide Boll Weevil/Cotton Insect Management Programs. Overall Evaluation, Appendix B. ESS Staff Report, April.

Economics and Statistics Service (1981c) Program Definitions and Public Costs, Beltwide Boll Weevil/Cotton Insect Management Programs. Overall Evaluation, Appendix D. ESS Staff Report, April.

Economics and Statistics Service (1981d) The Delphi: Insecticide and Lint Yields, Beltwide Boll Weevil/Cotton Insect Management Programs. Overall Evaluation, Appendix E. ESS Staff Report, April.

Elkinton, J. S., and R. T. Carde (1980) Distribution, dispersal and apparent survival of male gypsy moths as determined by capture in pheromone-baited traps. Environ. Entomol. 9:729-737.

El-Sebae, A. H. (1977) Incidents of local pesticide hazards and their toxicological interpretation. Pages 137-152, Proceedings UC/AID University of Alexandria Seminar Pesticide Management. Alexandria, Egypt.

EPA (1979) Diflubenzuron Decision Document. Special Pesticide Review Decision, March 26, 1979.

Fisher, W. D., and M. D. Cannon (1981) A production system for short-season cotton production in Arizona. Beltwide Cotton Prod. Res. Conf., National Cotton Council, Memphis. (in press) (Abstr.)

Foster, R. N., R. T. Staten, and E. Miller (1977) Evaluation of traps for pink bollworm. J. Econ. Entomol. 70:289-291.

Gaston, L. K., H. H. Shorey, and S. A. Saario (1967) Insect population control by the use of sex pheromones to inhibit orientation between the sexes. Nature 213:1155.

Georghiou, G. P., and C. E. Taylor (1977) Pesticide resistance as an evolutionary phenomena. Pages 759-785, Proc. 15th International Congress Entomol. Washington, D.C.

Gipson, J. R., and H. E. Joham (1968a) Influence of night temperature on growth and development of cotton (Gossypium hirsutum L.). I. Fruiting and boll development. Agron. J. 60:292-295.

Gipson, J. R., and H. E. Joham (1968b) Influence of night temperature on growth and development of cotton (Gossypium hirsutum L.). II. Fiber properties. Agron. J. 60:296-298.

Gonzalez, D., D. A. Ramsey, T. F. Leigh, B. C. Ekbom, and R. van den Bosch (1977) A comparison of vacuum and whole-plant methods for sampling predaceous arthropods on cotton. Environ. Entomol. 6:750-760.

Griffin, J. G., P. P. Sikorowski, and O. H. Lindig (1981) Mass rearing: boll weevils. Cotton Insect Management with Special Reference to the Boll Weevil, edited by R. L. Ridgway, E. A. Lloyd, and W. H. Cross. (in press)

Guice Jr., O. T. (1976) Regulatory Activities Carried on Under the Pilot Boll Weevil Eradication Experiment, 1971-73. Pages 73-73, Boll Weevil Suppression, Management, and Elimination Technology. USDA ARS-S-71.

Hagan, H. R. (1919) The Formation of the Western Plant Quarantine Board. California Dept. of Agriculture. Mo. Bul. 8 (8):493.

Hajjar, N. P., and J. E. Casida (1978) Insecticidal benzoylphenyl ureas: structure activity relationships as chitin synthesis inhibitors. Science 200:1499-1500.

Hartstack, A. W., J. A. Witz, and R. C. Ridgway (1975) Suggested applications of a dynamic Heliothis model (MOTHZV-1) in pest management decision making. Pages 118-122, Proceedings of 1975 Beltwide Cotton Production Research Conference.

Haynes, D. L., and S. H. Gage (1981) The Cereal Leaf Beetle in North America. Ann. Rev. Entomol. 26:259-287.

Heilman, M. D., M. J. Lukefahr, L. N. Namken, and J. W. Norman (1977) Field evaluation of a short season production system in lower Rio Grande Valley of Texas. Beltwide Cotton Prod. Res. Conf., National Cotton Council, Memphis. pp. 80-83.

Herbicide Handbook of the Weed Science Society of America. (1974) 3rd. ed. Champaign, Illinois: WSSA. 430 pp.

Jenkins, J. N., and W. L. Parrott (1971) Effectiveness of frego bract as a boll weevil resistance character in cotton. Crop Sci. 11:739-743.

Jones, J. E. (1972) Effect of morphological characters of cotton on insects and pathogens. Beltwide Cotton Prod. Res. Conf., National Cotton Council, Memphis. pp. 88-92.

Jones, J. E., D. F. Clower, M. R. Milann, W. D. Caldwell, and D. R. Melville (1976) Resistance in upland cotton to the banded-wing whitefly. Beltwide Cotton Prod. Res. Conf., National Cotton Council, Memphis. pp. 88-98.

Jones, J. E., D. F. Clower, B. R. Williams, J. W. Brand, K. L. Quebedeaux, and M. R. Milam (1977) Isogenic evaluation of different sources of glabrousness for agronomic performance and pest resistance. Beltwide Cotton Prod. Res. Conf., National Cotton Council, Memphis. pp. 110-111.

Jones, J. E., B. R. Williams, J. W. Brand, D. F. Clower, and D. T. Bowman (1978a) Interacting effects of the okra leaf, frego bract, and glabrous traits on pest resistance and agronomic characters. Beltwide Cotton Prod. Res. Conf., National Cotton Council, Memphis. pp. 84-85. (Abstr.)

Jones, J. E., J. B. Weaver, Jr., and M. F. Schuster (1978b) Host plant resistance to the boll weevil. Pages 50-73, The Boll Weevil: Management Strategies, Southern Cooperative Series Bulletin 228.

Karlson, P., and A. Butenandt (1959) Pheromones (ectohormones) in insects. Ann. Rev. Entomol. 4:39-58.

Knipling, E. F. (1960) Use of insects for their own destruction. J. Econ. Entomol. 53:415-420.

Knipling, E. F. (1979) Basic principles of insect population suppression. U.S. Dept. Agr. Handbook No. 512. Washington, DC.

Lanier, G. N., A. Classon, T. Stewart, J. J. Piston, and R. M. Silverstein (1980) *Ips pini*: Basis for interpopulational differences in pheromone biology. J. Chem. Ecol. 6:677-687.

Lee, J. A. (1971) Some problems in breeding smooth leaved cottons. Crop Sci. 11:448-450.

Leggett, J. E., E. P. Lloyd, and J. A. Witz (1981) Efficiency of infield traps in detecting and suppressing low population levels of boll weevils. Environ. Entomol. 10:125-130.

Lloyd, E. P., J. R. McCoy, and J. W. Haynes (1976) Release of Sterile Male Boll Weevils in the Pilot Boll Weevil Eradication Experiment in 1972-73. Pages 95-102, Boll Weevil Suppression, Management, and Elimination Technology. USDA ARS-S-71.

Lukefahr, M. J., (1977) Varietal resistance to cotton insects. Beltwide Cotton Prod. Res. Conf., National Cotton Council, Memphis.

Lukefahr, M. J., and D. F. Martin (1966) Cotton-plant pigments as a source of resistance to the bollworm and tobacco budworm. J. Econ. Entomol. 59:176-179.

Lukefahr, M. J., D. F. Martin, and J. R. Meyer (1965) Plant resistance to five lepidoptera attacking cotton. J. Econ. Entomol. 58:516-518.

Maley, F. W. (1902) Report on the boll worm. College Station, TX: Texas A&M University.

McLane, M. A., E. H. Dustman, E. R. Carl, and D. L. Hughes (1978) Organochlorine insecticides and polychlorinated biphenyl residues 1971-1972. Pesticide Monitoring J. 12:22-25.

Mehrle, P. M., and F. L. Mayer (1977) Bone development and growth of fish as affected by toxaphene. Pages 301-314, Fate of Pollutants in the Air and Water Environments, edited by I. H. Suffett, Pt. 2 New York: John Wiley and Sons.

Meredith, W. R., Jr. (1980) Use of insect resistant germplasm in reducing the cost of production in the 1980s. Beltwide Cotton Prod. Res. Conf., National Cotton Council, Memphis. pp. 307-310.

Meredith, W. R., Jr., and M. F. Schuster (1979) Tolerance of glabrous and pubescent cotton to tarnished plant bug. Crop Sci. 19:484-488.

Metcalf, C. L., W. P. Flint, and R. L. Metcalf (1962) Destructive and Useful Insects, 4th ed. New York: McGraw Hill.

Metcalf, R. L., and J. R. Sanborn (1975) Pesticides and environmental quality in Illinois. Bull. Illinois Natural History Survey 31(9):381-436.

Metcalf, R. L., Po-Yung Lu, and S. Bowlus (1975) Degradation and environmental fate of 1-(2,6-difluorobenzoyl)-3-(4-chlorophenyl) urea. J. Agric. Food Chem. 23:359-364.

Metcalf, R. L. (1980) Changing role of insecticides in crop protection. Ann. Rev. Entomol. 25:219-256.

Meyer, J. R. (1957) Origin and inheritance of D_2 smoothness in upland cotton. J. Hered. 48:249-250.

Meyer, J. R., and V. G. Meyer (1961) Origin and inheritance of nectariless cotton. Crop Sci. 1:167-169.

Michigan Department of Agriculture (1965) Plant Pest Control Programs. Annual Report--1965. Plant Industries Division. Lansing: Michigan Department of Agriculture.

Milam, W. R., J. N. Jenkins, W. L. Parrott, and J. C. McCarty, Jr. (1980) Inheritance of tarnished plant bug resistance and its association with agronomic properties in a cross of Deltapine 7146N by Bulgarian 3279. Beltwide Cotton Prod. Res. Conf., National Cotton Council, Memphis. pp. 89-90. (Abstr.)

Miller, D. H., and K. E. Carpenter (1979) Revised Report on the Environmental Evaluation of the Boll Weevil Control Trial Programs. KFR 229-79, 7 December 1979. Ketron, Inc., Arlington, VA. (This appears as attachment B in APHIS 1981a.)

Mitchell, E. B., and D. D. Hardee (1974) In-field traps: a new concept in survey and suppression of low population of bollweevils. J. Econ. Entomol. 67:506-508.

Mitchell, E. B., M. Jacobsen, and A. H. Baumhover (1975) *Heliothis* spp. Disruption of pheromonal communication with (Z)-9-tetradecen-1-a format. Environ. Entomol. 4:577-579.

Mitchell, E. B., M. E. Merkl, J. E. Wright, T. B. Davich, and R. F. Heiser (1980) Sterility of boll weevils in the field following treatment with diflubenzuron and gamma irradiation. J. Econ. Entomol. 73:824-826.

Murray, J. C., L. M. Verhalen, and D. E. Bryan (1965) Observations on the feeding preference of the striped blister beetle *Epicauta vitatta* (Fabricus) to glanded and glandless cottons. Crop Sci. 5:189.

Namken, L. N., M. D. Heilman, J. N. Jenkins, and P. A. Miller (1981) Host plant resistance and modified cotton culture. *In* Cotton Insect Management with Special Reference to the Boll Weevil. USDA Agricultural Handbook Series (in press).

National Academy of Sciences, Committee on Scholarly Communication with the People's Republic of China, Rept. No. 2 (1977) Insect control in the People's Republic of China. Washington, DC.

National Research Council (1969) Principles of Plant and Animal Pest Control. Volume 3. Insect-Pest Management and Control. Washington, DC: National Academy of Sciences.

National Research Council (1975) Pest Control: An Assessment of Present and Alternative Technologies. Volume 3: Cotton Pest Control. Washington, DC: National Academy of Sciences.

Newsom, L. D., and J. R. Brazzel (1968) Pests and their control. Pages 367-405, Advances in Production and Utilization of Quality Cotton: Principles and Practices, edited by F. C. Elliott, M. Hoover, and W. K. Porter, Jr. Ames: Iowa State University Press.

Odum, E. P. (1971) Fundamentals of Ecology. Third Edition, Philadelphia: W. B. Saunders Co.

Olivier, J. E., A. B. Demilo, R. T. Brown, and D. G. McHuffey (1977) AI-63223: a highly effective boll weevil sterilant. J. Econ. Entomol. 70:286-288.

Parencia, C. R., Jr. (1978) One hundred twenty years of research in cotton insects in the United States. USDA Handbook No. 515. Agricultural Research Service. Washington, DC: U.S. Department of Agriculture.

Parrott, W. L., J. N. Jenkins, and J. C. McCarty, Jr. (1981) Performance of the high gossypol strain test under artificial infestation of tobacco budworm. Beltwide Cotton Prod. Res. Conf., National Cotton Council, Memphis. (in press) (Abstr.)

Parrott, W. L., J. N. Jenkins, and D. B. Smith (1973) Frego bract cotton and normal bract cotton: How morphology affects control of boll weevils by insecticides. J. Econ. Entomol. 66:222-225.

Parvin, D. W., Jr., F. A. Harris, and M. L. Foster (1977) Cotton insect control in Mississippi. Beltwide Cotton Prod. Res. Conf., National Cotton Council, Memphis. pp. 212-214.

Phillips, J. R., A. P. Gutierrez, and P. L. Adkisson (1980) General accomplishments toward better insect control in cotton. Pages 124-150, New Technology of Pest Control, edited by C B. Huffaker. New York: John Wiley and Sons.

Pimentel, D. (1971) Ecological Effects of Pesticides on Non-Target Species. Executive Office of the President, Office of Science and Technology. Washington, D.C.

Pimentel, D. (1973) Extent of pesticide use, food supply, and pollution. J. N.Y. Entomol. Soc. LXXXI 13-33.

Post, G. B. (1924) Boll weevil control by airplane. Ga. State College Agric. Bull. 301, Athens, Ga.

Proverbs, M. D. (1969) Induced sterilization and control of insects. Ann. Rev. Entomol. 17:81-102.

Proverbs, M. D. (1970) Procedures and experiments in population suppression on the Codling moth, Lasecyresia pomonella (L.) in British Columbia orchards by release of radiation-sterilized moths. Manitoba Entomol. 4:46-52.

Reuber, M. D. (1979) Carcinogenicity of toxaphene: a review. J. Toxicol. Environ. Health 5:729-748.

Reynolds, H. T., P. L. Adkisson, and R. F. Smith (1975) Cotton insect pest management. Pages 379-443, Introduction to Insect Pest Management, edited by R. L. Metcalf and W. H. Luckmann. New York: John Wiley and Sons.

Robinson, S. H., D. A. Wolfenbarger, and R. H. Dilday (1980) Antixenosis of smooth leaf cotton to the ovipositional response of tobacco budworm. Crop Sci. 20:646-649.

Roussel, J. S., and D. F. Clower (1955) Resistance to the chlorinated hydrocarbon insecticides in the boll weevil (Anthonomus grandis Boh.) La. Agric. Exp. Stn. Cir. 41.

Rummel, D. R., and R. E. Frisbie (1978) Suppression of potentially overwintering boll weevils as a pest management practice. Pages 39-49, The Boll Weevil: Management Strategies. Southern Cooperative Series Bulletin 228.

Rummel, D. R., J. R. White, S. C. Carroll, and G. R. Pruitt (1980) Pheromone trapping index system for predicting need for overwintering boll weevil control. J. Econ. Entomol. (in press)

Sanborn, J. R., R. L. Metcalf, W. N. Bruce, and Po-Yung Lu (1976) The fate of chlordane and toxaphene in a terrestrial aquatic model ecosystem. Environ. Entomol. 5:533-538.

Sappenfield, W. P., and R. H. Dilday (1980) Breeding high terpenoid cottons: The 1978 regional tests. Beltwide Cotton Prod. Res. Conf., National Cotton Council, Memphis. pp. 92-93.

Sappenfield, W. P., L. G. Stokes, and K. Harrendorf (1974) Selecting cotton plants with high square gossypol. Beltwide Cotton Prod. Res. Conf., National Cotton Council, Memphis. pp. 87-92.

Schuster, M. F., and F. G. Maxwell (1974) The impact of nectariless cotton on plant bugs, bollworms, and beneficial insects. Beltwide Cotton Prod. Res. Conf., National Cotton Council, Memphis. pp. 86-87.

Science and Education Administration (1981) Biological Evaluation of Alternative Beltwide Boll Weevil/Cotton Insect Management Programs. Overall Evaluation, Appendix A. SEA Staff Report, April.

Serebrovsky, A. S. (1940) Possible new methods for controlling insect pest populations. Zool. Zh. 19:618-630.

Shepard, H. A. (1951) The Chemistry and Action of Pesticides. New York: McGraw Hill.

Shorey, H. H., R. S. Kaae, and L. K. Gaston (1974) Sex pheromones of Lepidoptera. Development of a method for pheromonal control of Pectinophora gossypiella in cotton. J. Econ. Entomol. 67:347-350.

Singh, I. D., and J. B. Weaver (1972) Studies on the heritability of gossypol in leaves and flower buds of Gossypium. Crop Sci. 12:294-297.

Smith, R. F., and H. T. Reynolds (1972) Effects of manipulation of cotton agroecosystem on insect pest populations. Pages 373-406, The Careless Technology - Ecology and International Development, edited by M. T. Farvar and J. P. Milton. Garden City, NY: Natural History Press.

Spears, J. F. (1974) A Review of Federal Domestic Plant Quarantines. USDA-APHIS-PPQ, Hyattsville, MD. Jan 1974.

Stanford Research Institute (1973) Refined Cost Estimates for a Beltwide Eradication of Boll Weevil. P. Stent and A. Korsack, Stanford Research Institute, Project 2372. Unpublished report to Cotton, Incorporated.

Thomas, F. L., W. L. Owen, J. C. Gaines, and F. Sherman III (1929) Bollweevil control by airplane dusting. Tex. Agric. Exp. Stn. Bull. 394.

Todd, R. L. (ed.) (1981) Nutrient Cycling in Agricultural Ecosystems. (In press)

Toscano, N. C., A. J. Mueller, V. Sevacherian, R. K. Sharma, T. Nilus, and H. T. Reynolds (1974) Insecticide applications based on Hexalure trap catches versus automatic schedule treatments for pink bollworm. J. Econ. Entomol. 67:522-524.

Townsend, C. H. T. (1895) Report on the Mexican cotton boll weevil in Texas (Anthonomus grandis Boh.). Insect Life 7:295-309.

Tumlinson, J., R. C. Gueldner, D. D. Hardee, A. C. Thompson, P. A. Hedin, and J. P. Minyard (1971) Identification and synthesis of the four compounds comprising the bollweevil sex attractant. J. Org. Chem. 36:2616-2621.

USDA (1965) Quantities of pesticides used by farmers in 1964. Agric. Econ. Rept. No. 131.

USDA (1970) Quantities of pesticides used by farmers in 1966. Agric. Econ. Rept. No. 179.

USDA (1974) Quantities of pesticides used by farmers in 1971. Agric. Econ. Rept. No. 252.

USDA (1978) Farmers' Use of Pesticides in 1976. USDA Agric. Econ. Rept. No. 418.

USDA (1979) Cotton-insect research and control. 32nd Annu. Conf. Rept. Phoenix, AZ. Jan. 8-9.

USDA (1981a) Agricultural Statistics 1980. Washington, DC: U.S. Government Printing Office.

USDA (1981b) Executive Overview of Alternative Boll Weevil/Cotton Insect Management Programs, May.

U.S. DHEW (1969) Report on the Secretary's Commission on Pesticides and Their Relationship to Environmental Health. Washington, DC: Department of Health, Education, and Welfare.

Van den Bosch, R., and K. A. Hagen (1966) Predaceous and parasitic arthropods in California cotton fields. Calif. Agric. Exp. Stn. Bull. 820.

Van den Bosch, R. (1978) The Pesticide Conspiracy. Garden City, NY: Doubleday.

Verloop, A., and C. D. Ferrell (1977) Benzoylphenyl urea - a new group of larvicides interfering with chitin synthesis. Pages 237-270, Pesticide Chemistry in the 20th Century. Am. Chem. Soc. Symp. Ser. No. 37. Washington, DC: Am. Chem. Soc.

Walker, J. K., Jr., and G. A. Niles (1971) Population dynamics of the boll weevil and modified cotton types. Texas Agric. Exp. Stn. Bull. 1109.

Walker, J. K., Jr., R. E. Frisbie, and G. A. Niles (1978) A changing perspective: Heliothis in short-season cottons in Texas. Entomol. Soc. Amer. Bull. 24:385-391.

Wallner, W. E. (1974) Gypsy Moth. Forest Pest Leaflet No. 3. Cooperative Extension Bulletin E-78. E. Lansing: Michigan State University.

Wellinga, K., R. Mulder, and J. J. Van Daalen (1973) Synthesis and laboratory evaluation of 1-(2,6-disubstituted benzoyl)-3-phenyl ureas, a new class of insecticides. II. Influence of acyl moiety on insecticidal activity. J. Agric. Food Chem. 21:993-998.

Whitcomb, W. H., and K. Bell (1964) Predaceous insects, spiders, and mites of Arkansas cotton fields. Arkansas Agr. Exp. Stn. Bull. 690.

Whitten, M. J., and G. G. Foster (1975) Genetic methods of pest control. Annu. Rev. Entomol. 201:461-476.

Wiersma, G. B., H. Tai, and P. F. Sand (1972) Pesticide residue levels in soils, FY 1969. Pesticide Monitoring J. 6:194-228.

Wilson, F. D., and J. A. Lee (1976) Interrelationships among gland density, gossypol content, and lint and seed characters in cotton. Crop Sci. 16:860-861.

Wolfenbarger, D. A., M. J. Lukefahr, and H. M. Graham (1973) LD_{50} values of methyl parathion and endrin to the tobacco budworm collected in the Americas and hypothesis on the spread of resistance in these lepidoptera to these insecticides. J. Econ. Entomol. 66:212-216.

Wolfenbarger, D. A., J. A. Harding, and J. W. Davis (1977) Isomers of (3-phenoxyphenyl)-methyl (+)_cis_-_trans_-3-(2,2-dichloroethyl)-2, 2-dimethylcyclopropanecarboxylate against boll weevils and tobacco budworm. J. Econ. Entomol. 70:226-228.

Wright, J. E., and E. Villavaso (1981) Boll Weevil Sterility. _In_ Cotton Insect Management with Special Reference to the Boll Weevil. USDA Handbook Series (in press).