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Utilization of System Analysis for the Development and Implementation of Improved Decision Criteria for Cotton Crop Management

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למדיע החקלאות
בית דגן

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TABLE OF CONTENTS

	Page
1. Abstract	1
2. Overview	
A. Crop response to damage to buds and bolls.	3
B. Insect Studies	6
C. Models	9
D. Developing new management strategies	11
3. Evaluation of research achievement with respect to proposal.	17
4. Description and results of cooperation.	21
5. Benefit to agriculture.	24
6. Appendices:	
A. Studies on Damage Stress Interactions in Cotton.	
B. Cotton Crop Response to Bud and Boll Removal.	
C. <u>Heliothis Armigera</u> Larvae on Cotton : Damage, Development Times and Survival.	
D. Prodenia (Spodoptera Littoralis). (Preliminary field studies).	
E. The Effect of <u>Bemisia tabaci</u> on Cotton Development and Yield.	
F. Biological Studies.	
G. Modelling.	
H. An Algorithm for the Short-Term Prediction of Insect Populations.	
I. An Evaluation of Ethrel Spraying for Compensation Induction in Cotton.	
J. An Algorithm for On-Line Approximate Optimization of <u>Heliothis Armigera</u> Control in Cotton.	
K. The Scheduling of Cotton Harvesting Operations at the Farm Level.	

הסכם המכר
למדעי החקלאות
בית דגן

A B S T R A C T

A three tier approach to improving cotton pest management strategies was adopted. The first level aims at providing basic information and numerical data concerning crop and pest dynamics, the second at incorporating that information into crop and pest models, and the third involves developing and testing new management strategies, based on the results at the preceding levels. Progress was made at all levels, though due to unavoidable time lags only part of the results at each level could be incorporated into the next level in the course of the project.

At the first level, the interaction of early and late pest damage, and of pest damage with water stress, were studied. These combinations often occur in practice, and must be understood if an overall cotton management strategy is to be developed. Water stress and late boll damage alone gave lower yields than when combined with early bud damage. Thus intentional bud damage may be a management option of interest. In the insect studies, measurements were made of the rates of damage, development times and mortalities of Heliothis armigera, of the dispersal patterns and mortalities of Spodoptera littoralis, and of the effects of fertilization and irrigation on Heliothis sp and Anthonomus grandis survivals and feeding. Techniques for studying Bemisia tabaci were developed.

At the modelling level, an improved version of the Israeli cotton model was developed, which describes in more detail the variation in crop development pattern with time. The Texas cotton model was extended to include vegetative growth and soil moisture, and was found to give good agreement with field data. An empirical insect model, whose paramaters are evaluated from field data, was developed for H.armigera.

At the management level, two new management strategies were field tested. The first was the use of ethrel as a commercially feasible way to increase early season bud damage. This study showed that ethrel, unlike hand removal of buds, does not seem suited to reducing the subsequent effect of water stress and late season boll damage. Also, a previously developed model-based Heliothis control algorithm was tested, and was found to reduce the number of spray applications with no observable yield loss. Two other algorithms were developed during this project, but have not yet been tested. An improved Heliothis decision algorithm, using an explicit optimization technique, was defined. Secondly, a whole farm harvest scheduling algorithm was developed. This is of importance because insect damage delays yield, and this in turn has repercussions on the harvesting schedule.

O V E R V I E W

As the title suggests, this project involved studies in a number of different domains related to the cotton crop-insect pest ecosystem. It is not possible, nor desireable, to present the details of these heterogeneous studies in the body of a single paper. Each study therefore has been prepared as a separate report, and these reports are presented here as a series of appendices. The following is an overview of the project which discusses briefly each of the studies, and explains their relation to the overall goal of furnishing improved pest management strategies to cotton growers.

A. CROP RESPONSE TO DAMAGE TO BUDS AND BOLLS

The first aim of this project was to attain a better understanding of the response of a cotton crop to insect damage. Previous work by the Israeli research team concerned the effect of removal of fruiting bodies on cotton growth and development, as a function of the size of fruiting bodies removed, and the timing of removal. These studies followed the response of a crop, given the standard irrigations and protected against subsequent damage, to the removal of buds or bolls over a limited time. They indicated the complex nature of crop reaction to damage, and elucidated a number of the mechanisms by which the crop compensates for damage.

The current project extended those studies, concentrating on the interaction of damage to fruiting bodies with water stress (appendix A), and the interaction of early and late damage (appendix B). Such combinations are common in practice, and it is necessary to understand their effects in order to arrive at an overall strategy of crop management which includes irrigation and control of pests throughout the season.

These studies showed that there is indeed a very strong interaction between damage and water stress, and between early and late damage. In particular, it was found that removal of medium size floral buds combined with severe water stress consistently gave significantly higher yields than the same water stress treatments in the absence of damage. An essential element in explaining these somewhat counter-intuitive results is the effect of early fruiting form removal on the ratio of reproductive (sink) to vegetative (source) plant parts. During the stress period, there is less severe shedding of fruiting forms in previously damaged plants and, once water stress is relieved, the lower ratio of reproductive to vegetative biomass in the damage treatments results in renewed vegetative growth and a younger, more active leaf canopy. These factors enabled flowering to continue in the damaged treatments during the cutoff phase of the corresponding stress-only controls. The extended flowering period compensated partially for the removal of flower buds. In addition, the change in development pattern induced by early bud damage enabled the plant to set approximately 90% of flowers as opposed to about 65% in the undamaged treatments. The overall result was a higher yield in the damage + water stress plots than in the plots with water stress only.

These results emphasize the limitations in managing a cotton crop according to predefined schemas which do not take into account the state of the crop. Such schemas are normally developed for well protected crops, and so would not permit the level of water stress reached here, which reduced the yield of the undamaged crop. In fact, however, this water stress could be accepted for a damaged crop. That is, different management practices are indicated for the undamaged and damaged crops. It should be noted that this goal cannot be achieved by improving measurement techniques of water stress, a topic which has received considerable attention. Here

leaf water potential, which integrates plant, soil and climatic factors, was measured. The treatments were stressed to the same levels of leaf water potential, and nevertheless reacted differently.

The results of the combined early and late damage treatments showed that while late boll damage alone significantly reduced yield, the same pattern of boll damage combined with early bud damage did not significantly reduce yield below the control. By retarding reproductive development, the early bud removal permitted the crop to exploit compensation mechanisms following boll removal that it could not otherwise. These studies again indicate the possible advantage of early season bud damage. More generally, they show that the response of a crop to damage is complex, but that if understood this response can perhaps be manipulated for the benefit of the grower.

In addition to aiding in understanding the growth pattern of a cotton crop, these experiments provide an extensive and detailed data base for use in simulation modelling work.

B. INSECT STUDIES

The second series of studies was undertaken to provide a better understanding of the dynamics of a certain number of insect pests of cotton in Israel and the United States, and of the damage they cause. To this end studies of Heliothis armigera (appendix C), Spodoptera littoralis (appendix D), and Bemisia tabaci (appendix E) were undertaken in Israel, and Heliothis spp. and Anthonomus grandis (appendix F) survival and damage were studied in Texas. Each of these studies had a different focus, depending on the specific characteristics of the insect pest.

The H.armigera study concentrated on the damage caused by larvae of different sizes, and in particular on the distribution of damage among fruiting bodies of different sizes. (The importance of the distribution of damage in determining plant response was shown by the simulated damage field experiments, as well as by the modelling work, of this project. This is but one example of the interaction between the various aspects of the project). This study was judged sufficiently complete so as not to merit further work in the future.

In addition, the development times of H.armigera larvae in the field were determined, and compared to published values from laboratory studies. (The values obtained are similar).

Finally, survival rates for the specific circumstances of one experiment were determined. These values contain large uncertainties, and of course, they cannot be assumed to be valid in general. Nevertheless, they are of considerable interest, since they provide the only data of this sort available.

Based on the survival values and the damage results, it is possible to calculate the savings in damage anticipated from insecticide use, per larva present of each size class. It is found that damage is reduced less per large larva than per medium larva. The reason is that in the absence of insecticide the expected time that the large larva will continue doing damage is limited, due to natural mortality and the relatively short time remaining before pupation. Therefore the savings anticipated from insecticide use is limited. It is this expected reduction in damage that is of interest in deciding whether or not to spray. The current standard strategy for H.armigera control, on the other hand, weights each larval class roughly in proportion to the rate of consumption by larvae in the class, which leads to large larvae being by far the most heavily weighted. This is one example, among others, of the shortcomings in the standard strategy.

S.littoralis attacks cotton leaves and reproductive bodies somewhat later in the season than H.armigera . Unlike the latter, S.littoralis females lay eggs in clusters of up to several hundred eggs. Damage therefore is far from randomly distributed, and this obviously affects the crop response. The field studies during this project focused on mapping the distribution of larvae from individual egg masses though time, and on estimating the survival and damage rates of the various larval size classes. This however is only the start in the development of a model-based control strategy for this pest. The effect of leaf damage on yield, and the effect of clumped damage, have not yet been thoroughly investigated.

B.tabaci , a sucking insect, has only recently become a major pest of cotton in Israel. The experiments conducted were intended to study the effect of this pest on cotton crop growth, development and yield quality, because little is known in these areas. The experimental design involved infecting plants in a growth chamber with large insect populations. However, all the technical difficulties were only overcome in the last year of the project, and therefore only very preliminary results are available. These are nonetheless of interest, since they indicate that even a relatively early infestation (toward the end of flowering) can affect lint quality, which is contrary to previous opinion. Considerable further investigation of the effects of this pest, as a function of population level, timing, and crop status, is warranted. Such studies should go more smoothly, now that the initial technical problems have been overcome.

The Texas insect studies concentrated on the effect of host plant nutrition (nitrogen and water) on Heliothis survival and development, and on levels of damage by Heliothis and by boll weevil. Here again a number of technical difficulties had first to be overcome, so that results are available from only a portion of the project period. It was found that in the field, H.virescens survival increased as the level of N fertilization increased, though not in non-irrigated fields. Boll weevil damage levels were also influenced by N fertilization.

C. MODELS

A central part of this project consisted of using the data generated in the course of the project, in conjunction with information from the literature, to develop cotton crop and insect models that could be used as the basis for suggested improved cotton crop management in the future. Two complementary approaches to crop modelling were followed in Israel and in Texas.

In Israel, the work on cotton concentrated on adding more detail within the framework of a model which treats only reproductive growth and development (appendix J). This work is based on the additional experimental data obtained during this project (see appendix B), which makes it possible to describe more fully crop response to damage. Environmental factors enter the model only through the parameter values. That is, the model is suited to studying how differences in crop state (caused for example by different levels of insect damage) would affect subsequent crop behavior, in a particular environment. The advantage of the model is then its detailed treatment of the effects of damage, based on a great deal of field data, and its disadvantage is its limitation to particular circumstances.

The Texas effort concentrated on expanding a cotton fruiting model to include vegetative growth and soil moisture (appendix G).

The Israeli model has proved an important tool in the research effort. The fact for example that early bud damage may prevent late boll damage from reducing yield was first suggested by the results of the model. The experiment that confirmed this behavior was initiated on the basis of those results. The model also permits very reasonable recommendations for Heliothis control (see below). For future work combining irrigation and pest control management, however, it is clear that extensions such as those made to the Texas model are necessary. Unfortunately, it was not possible in the time frame of this project to incorporate those or similar extensions into the Israeli model.

The basic approach in the Israeli pest modelling work has been to postulate a relatively simple pest population dynamics model, and then to evaluate the parameters from field counts. This is an alternative to the more common approach of describing the pest dynamics in detail, without using feedback from field measurements. This latter approach was not adopted because of the complexity of the pest dynamics, which depend in turn on the dynamics of several predators and parasites. A model based on feedback, if it is meant to be applied by farmers, imposes certain requirements concerning data organization. These requirements are met in Israel by a software package that was begun during the precursor to this project, and has been continuously extended since.

A detailed study was made of the case where the postulated insect model describes a population with age structure, and with mortalities that are constant over time but are different for different age or size classes (appendix H). It was shown firstly how the parameters could be evaluated from field counts of the number of insects in each class, and secondly how the model could be used for short term predictions of insect levels. (Short term here means predictions that do not involve predicting recruitment, but rather only mortality). Applied to simulated populations the predictions were quite accurate. For H.armigera field data the predictions were considerably less so, apparently as a result of the large standard errors in the field counts.

This technique was then extended to include predictions of recruitment for use in the H.armigera control recommendation algorithm (appendix J). The predictions here are over a relatively long period, and it is hardly surprising that they contain large deviations from the observations. However, for Heliothis control it is not the details of the future population levels which are of importance, but rather the pattern of future damage, and this pattern is predicted reasonably well in most of the cases tested.

The algorithm gave close agreement with the data, concerning future damage, for three fields, but tended to seriously overestimate damage in the remaining field. (The accuracy of the predictions varies of course with the time during the season when the predictions are made.)

D. DEVELOPING NEW MANAGEMENT STRATEGIES

Two promising new strategies were field tested as part of this project. The first involves using early bud shedding to reduce the deleterious effects of water stress, and the second involves a model based Heliothis control strategy, developed by the Israeli research team prior to the start of this project. In the course of this project an improved version of this Heliothis control strategy was developed. In addition, an algorithm to aid in planning harvesting operations was developed. These latter two developments, however, have not yet been field tested.

The first strategy tested was based on the results discussed earlier, which indicate that early season bud removal can reduce or eliminate the yield loss associated with severe water stress or late season boll damage. This is of particular importance because it often occurs in the field that, as a result of a particular combination of sowing schedule and constraints imposed by the irrigation system of a farm, the grower knows that certain fields will be subjected to severe mid-season water stress. Such stress alone would often result in yield loss. If, however, early bud damage were to be inflicted in those fields, it might be possible to obtain full yield compensation.

A series of experiments was conducted to investigate the possible exploitation of this aspect of crop behavior. A commercially practical method of provoking bud shed is by application of the shed inducing chemical ethrel (2-chloroethylphosphonic acid) (appendix I).

In the first two years of the project a number of different dosages of ethrel were applied, at various dates. The response to the higher rates, in terms of flowering, resembled the response to hand removal of buds - an early reduction in flowering followed by increased flowering, with total cumulative flowering exceeding that of the control plots. However, unlike hand removal, ethrel tended to reduce the final number of open bolls. This was a direct result of the fact that ethrel tended to decrease percentage boll set. Hand removal of buds, on the other hand, generally increases percentage boll set.

In the third year of the experiment ethrel and hand removal of buds were compared directly. The treatments consisted of a control, a water stress treatment, water stress combined with ethrel or with hand removal of buds, a late boll removal treatment, and late boll removal combined with ethrel or with hand removal of buds.

Water stress alone, or late boll removal alone, reduced yield relative to the control plots. The addition of early bud removal by hand did not eliminate this yield loss here, although it had in previous similar experiments. Apparently bud removal was carried out too late in this case, so that the resulting increase in bud production occurred too late to contribute to yield. This emphasizes the sensitivity of crop response to the exact nature of the damage.

Ethrel in the third year experiment did not affect the crop in the same way as hand removal of buds. The decrease in flowering was much less with ethrel, which overall had relatively little effect on the crop growth pattern. In particular, ethrel did not reduce the yield loss associated with water stress or with late boll damage.

These results indicate that ethrel may not be a suitable management tool, even when early bud removal is desirable. Firstly, it is difficult to obtain the exact degree of debudding desired with ethrel. This is illustrated by the third year results, where the attempts to obtain the same effects with ethrel and with hand removal of buds were not successful. A major reason is that the effect of ethrel depends not only on the dose, but also on the state of the plant. In addition, even where ethrel affects flowering in a manner similar to hand removal of buds, it seems to have a negative effect on boll set. The reason is not clear. One possibility is that ethrel, unlike hand removal of buds, affects vegetative growth as well.

The remaining management strategies to be discussed involve numerical algorithms. These algorithms are already, or are meant to be, incorporated into the cotton software package mentioned previously. This package handles data input and storage, thus making available the data required for the algorithms. The data handling routines are currently used by most of the collective farms in the coastal plains region of Israel.

The Heliothis control algorithm developed in the precursor project and field tested during this project, denoted Program 204, is based on an insect model with standard mortality values and with an immigration rate scaled according to field counts. The algorithm calculates total damage to fruiting forms that would be

caused by this population with and without insecticide application at the decision time. Spraying is recommended if total damage exceeds 60 fruiting forms, and if the difference in total damage between the sprayed and non-sprayed simulations is greater than 10 fruiting forms. Thus the effect of total damage is taken into account, albeit in an empirical fashion, as is the expected reduction in damage due to insecticide use.

Program 204 was compared to the standard control strategy in the field on a number of occasions. The most detailed monitoring was carried out at Kibbutz Maayan Zvi in 1980 (appendix J), though similar overall results were obtained from the other test fields. At Maayan Zvi, the field was divided into 4 sections. In two sections, Heliothis control followed the standard recommendations and the field was sprayed on three occasions: June 10, June 22 and July 7. In the remaining two sections, Heliothis control was determined by Program 204 and the field was not sprayed at all. Results of yield and its components in the sprayed (S) and relatively unsprayed (U) sections of the field at the last harvest date (Oct. 22) were as follows:

=====									
:	:	Seed cotton	:	Total number	:	Mean boll	:	Percentage	:
:	:	(kg/ha)	:	open bolls	:	weight (g)	:	lint (%)	:

:	S :	5420	:	82	:	6.6	:	39.0	:
:	:		:		:		:		:
:	U :	5120	:	78	:	6.6	:	38.5	:
:	:	N.S.	:	N.S.	:	N.S.	:	N.S.	:
=====									

Thus no measurable yield loss resulted from reducing the number of sprays, though yield accumulation in the unsprayed sections was significantly delayed. A delay was also apparent from detailed measurements through the season.

Despite the encouraging results obtained with Program 204, certain major improvements seemed desirable. Firstly, an improved program should use a cotton model to determine the effect of damage, rather than relying on a fixed threshold for cumulative damage. Secondly, an improved program should recommend spraying, when necessary, near the peak of the Heliothis infestation. Program 204 has a tendency to place control actions rather late in the season, when it is clear that the threshold for cumulative damage will be exceeded.

A decision program which incorporates these improvements was developed during this project (appendix J). This program is based on the improved cotton model and on the insect model described above. A dynamic programming approach is first used, in conjunction with the insect model, to find those dates of insecticide which minimize total damage for a given number of insecticide applications. The cotton model is then used to determine the optimum strategy (that which minimizes insecticide cost plus yield loss due to damage) from among this minimum total damage set. This is not a true full optimization, since the true optimum may not be in the set originally determined. However, it is reasonable to suppose that the minimum total damage set contains strategies not too far from the true optimum, and the control recommendations (based on historic data) given by this algorithm seem very reasonable. The computing time for the algorithm is acceptable (about 20-30 sec. of CPU per recommendation on a VAX 750) and it has already been implemented on the regional computer of the coastal plains region. The importance of this study, in addition to the improved Heliothis control it promises, is that it shows that optimization techniques can be employed even for the very complex situations involved here. These techniques must be extended in the future to other aspects of cotton crop management.

The final management algorithm developed involves scheduling harvest operations (appendix K). This problem is closely related to pest management, because the effect of loss of reproductive bodies is often a delay in yield rather than a yield decrease. This delay represents a cost to the grower if the consequence is a continuation of harvesting operations into a period of increasing rainfall probability. This problem has to be approached on a whole-farm basis whereby a delay in a particular field is evaluated in terms of the impact on the harvesting schedule of the farm as a whole.

Options available to the grower if insecticide is used less intensively, and harvesting is therefore delayed, are:

- a. to continue harvesting later in the year and accept the risk of rain damage,
- b. to double harvest the late maturing fields and thereby minimize the risks, and
- c. to hire extra harvesting capacity.

The algorithm compares the costs for strategies involving each of these options. In view of the size of this problem, a series of programs was developed for the optimal scheduling of harvesting operations. Accurate parameterization of the programs involved analyses of historical rainfall data, field experiments on early defoliation and double harvesting, and extensive field sampling to quantify the effect of rainfall on harvesting wastage and lint quality. The field work associated with the development of this package will continue for a number of seasons and parameter estimates will be steadily refined. The harvesting scheduling package will be made available to growers after the first field checks in the 1984 season for standard scheduling purposes, and will be coupled with the Heliothis control package once field evaluation of these programs is completed.

EVALUATION OF RESEARCH ACHIEVEMENT WITH RESPECT TO PROPOSAL

The project was funded for the study of insect pest management. The section of the original proposal devoted to irrigation strategy was not accepted, and therefore that aspect is not considered in comparing the results of the project with the proposal.

The first specific objective listed in the proposal was to "obtain a quantitative understanding of the relationship between cotton crop development pattern and final yield". The basic technique employed was detailed plant sampling throughout the season, for a wide variety of different treatments and therefore different growth trajectories. Emphasis was placed on how bud and boll damage, such as insect pests cause, affect growth pattern and yield. In particular, the interactions between bud damage and water stress, and between bud and boll damage, were studied. The results provide detailed quantitative information for a number of specific situations, but also have led to a better overall understanding of how the crop growth trajectory is altered by water stress and damage, and the concomitant implications for yield. No experiments were conducted to study directly the effect of altering vegetative biomass, and this is a topic that should be investigated in the future.

The second specific objective was to "develop mathematical models of a cotton crop which can be used to predict how the crop will respond to water stress, nitrogen stress or insect damage". The Israeli cotton model treats only insect damage explicitly;

environmental effects enter only through the parameter values, and therefore are identical in all model runs. However, the model was extended to describe the time variation in the standard environment in more detail. One of the simulation runs with the model predicted that bud plus boll damage should have a higher yield than boll damage alone, and this rather counter-intuitive prediction was subsequently tested in an experiment, and shown to be correct. This was the most exacting test of the model, and showed that it can be a valuable tool in predicting crop response to damage to reproductive bodies.

The Texas model, which previously had treated only reproductive growth explicitly, was extended to include vegetative growth and soil moisture. This new version gave good agreement with experimental results.

The third objective of the proposal was to "develop mathematical models of the population dynamics of the major insect pests of cotton in Israel and their closely related species in Texas". The major modelling effort was devoted to developing and testing a simplified population model with feedback from field data. Tests showed that the reliability of the model depends essentially on the accuracy of the field data, and the extent to which insect mortality varies with time. The model was applied to H.armigera . The detailed predictions of future population levels are poor, but cumulative future damage is predicted reasonably well. It is hoped that similar models can be applied to other pests. This was not done during the course of this project, but necessary experimental data was obtained for S.littoralis in Israel. For B.tabaci , new experimental techniques were developed, which should make possible fruitful experimental work in the future. In Texas, information was obtained concerning the effects of irrigation and fertilization on Heliothis survival.

The fourth objective was "to combine the models involving water stress, nitrogen stress, insect damage and insect dynamics so that they can be used to test various alternative management strategies". This goal was achieved by the Texas model. The Israeli cotton model, as already noted, does not explicitly treat water or nitrogen. It has however been interfaced with the Heliothis model, so that the effects of different pest populations can be studied. The interface is in fact quite general, so that any other insect model, or combination of models, can easily be combined with the cotton model. The justification for this objective was that it should "make it possible to choose the best management strategy from among a list of possibilities". In fact, it was possible to exceed that goal in the case of H.armigera . For that pest an optimizing algorithm was developed, which obviates the need to choose manually the possible strategies to be tested.

The fifth and sixth objectives were to "apply the results of the models to commercial field situations" and to "test specific promising management options". One result of this project of practical importance is the finding that early bud damage can reduce the deleterious effects of water stress and late boll damage. An attempt was made therefore to develop a commercially feasible method of causing such bud shedding. Spray applications of ethrel were tested for this purpose. This was indeed found to cause shedding, but did not provide additional compensation for water stress and boll damage. Therefore the practical application of induced bud shedding remains to be achieved.

A computer algorithm for Heliothis control was tested in the field, and gave very promising results, namely an overall reduction in spray applications with no observable loss in yield. An improved version of this algorithm, which replaces the previous empirical decision rule with an optimizing calculation, was developed. It is hoped that this new algorithm will lead to a greater reduction in damage for the same number of spray applications, by timing the spray applications better.

Finally, a harvesting scheduling algorithm was developed. This was an outgrowth of the central concern of this project, which is insect control. Insect damage often delays yield without reducing it. This leads to a delay in harvesting, which increases the risk of rainfall causing yield losses. The delay in harvesting however depends also on the overall harvesting capability of the farm, and on the harvest schedule for all fields. These considerations led to the consideration of harvest scheduling. The algorithm compares various possible harvest strategies, including late harvesting, rental of additional harvesting machinery, and double harvesting of fields.

DESCRIPTION AND RESULTS OF COOPERATION

Cooperation between the U.S. and Israeli scientists included a visit to the U.S. by Dr. D. Wallach in the early stages of the project for discussions concerning the conceptual framework and approach of the project. This trip was not funded by the present grant.

In 1981, Professor G. Curry visited the scientific team in Israel. During this visit, Prof. Curry reviewed the computer-based cotton management system available to growers.

In the summers of 1982 and 1983 Dr. H. Talpaz, who while on other duties at Texas A&M University, reviewed the progress in the project with Prof. Curry and Dr. Cate, and exchanged data for further analysis. Statistical analyses were performed to predict first flowering date. Results and conclusions were then shared by both teams.

A large section of the cotton and Heliothis data base was made available to the U.S. scientists and these data were used extensively in the development and validation of simulation models developed in the U.S. within the framework of this project.

BENEFIT TO AGRICULTURE

The research conducted within the framework of this project commenced shortly after the installation of regional computer facilities in Israel and pioneered the development of agricultural software in this country. Prior to this research, the software available to the farmer was restricted to financial accounting and feasibility studies. The development of biologically orientated programs and simulation models within this project has served as an example for the development of similar systems in other branches of agriculture (for example, potato production). Much of this software has been transferred to various regional computer facilities in Israel.

For the cotton grower, the most direct contribution of this project has been the implementation of a dynamic Heliothis control algorithm. The algorithm was adopted as an alternative strategy by the Council for Insect Control Recommendations in 1983. In its first year of general availability to growers, six collective farms made use of the package in managing a cotton area of 1300 ha. These growers sprayed an average of 0.5 sprays against Heliothis for the entire season whereas other growers in the area, using the old threshold criteria, sprayed an average of 1.5 sprays against Heliothis. Thus, in its first year of implementation, a saving of 1300 ha-spray was achieved, which is equivalent to a cost reduction of \$42000 (based on \$40/ha-spray). If this package were to be adopted widely in the coming seasons and save approximately 1 spray per season over half the cotton acreage in Israel without reducing yield, an annual saving of approximately \$1.2m would be expected, in addition to the ecological benefits of a 100 ton reduction in the quantity of Tionex being released into the environment.

Progress has also been made toward improved strategies for other aspects of cotton crop management. Important basic information on other pest species has been collected, which will lead to improved strategies for their control. Also, an improved understanding of the interactions of pest damage with water stress, and of early with late pest damage, has been achieved. This should eventually lead to overall strategies which cover season long pest control as well as irrigation. Finally, modelling work which can serve as the basic tool for developing new strategies has been carried out.

Perhaps the most important contribution of this project to agriculture is in changing attitudes toward crop management. Whereas previous work concentrated on defining standard management schemes to be applied over large areas, the current project has clearly shown that the response of a cotton crop to various perturbations, such as water stress or late season boll damage, depends on the state of the crop at the time of the perturbation. Management therefore must take the state of the crop into account.

The ultimate goal of deriving a calculated overall management strategy based on the state of the crop lies in the future. However, the principles of field specific management are now being applied by extension workers throughout Israel. Recommendations are based on weekly plant sampling of a number of fields, which can be compared among themselves and with data from past years, and on the principles of cotton growth and development elucidated during the course of the current project and its predecessor.

Specific instances can be cited where this has led to dramatic improvements in fields that had consistently given poor results in the past. For example, one field at Kibbutz Barkai had given low yields for a number of years. An extensive range of soil tests failed to identify any deficiency that might account for the low yields. In the 1983 growing season, the research team of this project included this field in the weekly field monitoring scheme for as long as the work load permitted. By comparing crop development in this field with other fields in the region, a lag in vegetative growth was quickly detected and the extension officer recommended two extra irrigations early in the season. For the first time in many years, the average cotton yield for the area was achieved in this field.

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STUDIES ON DAMAGE
STRESS INTERACTIONS
IN COTTON

APPENDIX A
(a preliminary report)

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B A R D

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ABSTRACT

Cotton variety SJ-2 was sown on April 8, 1983 at Kibbutz Gan Shmuel on high fertility soil. Severe water stress was imposed at various stages of the season. All treatments were carried out with and without hand damage to 120 medium-size floral buds/m-row. Crop response in terms of flowering, boll opening, yield accumulation and vegetative growth was followed in all treatments.

Water stress reduced final yield. Water stress early in the season caused cessation of bud production and shedding of small buds. Mid-season water stress caused shedding of small and large buds. Water stress late in the season caused shedding of small bolls.

The removal of 120 buds/m-row early in the season, caused a reduction in cumulative flowering during the early flowering phase and a late-season continuation of flowering. Total flower production was less in bud removal treatments than in the corresponding stress-only control, though percentage boll set was increased markedly in the bud removal treatments. The increase in boll set compensated for damage caused by bud removal and damage caused by water stress. Final cotton yield in stress plus damage treatments was higher than that of the stress-only treatments.

The damage caused by water stress in terms of final yield is dependent on the state of the plant at the time of the stress. Plants that were stressed at the same calendar date and with the same severity (i.e. the same leaf potential) responded differently according to the reproductive stage of development of the plant at the time of the stress.

MATERIALS AND METHODS

The experiment was conducted at the Gan Shmuel farm, situated in the coastal plains region of Israel (fertile alluvial clay-loam soil). Acala variety SJ-2 was planted on April 8, 1983, in 96.5 cm rows and thinned to 10 plants/m-row shortly after emergence. The plots received the standard commercial fertilization and pest control for the area.

The experiment was arranged in a factorial design, with timing of water stress as one factor and presence or absence of artificial bud damage as the second factor. The experiment was replicated five times; each replicate consisted of 10 rows of 12 m length. The experimental treatments are described in Table 1. In damage treatments, floral buds of 1 cm were removed. Bud removal dates were 20.6, 27.6, 4.7 and 12.7. At each removal date, 3 floral buds were removed from each plant (30 buds/m-row) and hence 120 buds/m-row in total. Irrigation was delivered via a trickle irrigation system with a capacity of 40 m per hour per hectare to simulate sprinkler irrigation.

Flower counts, weekly destructive sampling, weekly open boll harvesting and bulk cotton harvesting were carried out as described in Appendix C. Bulk harvesting was carried out on five dates over the period 2.9.83 to 28.10.83. Soil moisture status was measured in all treatments by the neutron moderation technique. Readings were taken at regular intervals through the season as well as immediately prior to and three days after each irrigation. Leaf water potential was measured by pressure bomb twice weekly immediately prior to each irrigation.

Climatic variables including temperature, humidity, radiation and wind-run were monitored continuously by a meteorological station situated adjacent to the experimental field.

RESULTS

FLOWERING

Water stress treatments reduced bud production, cumulative flowering, total open boll production and final yield. The effect of water stress at different stages of development can be inferred from the cumulative flowering curves (Figure 1). Flower counts continued until August 28 which was 141 days after sowing. In all treatments, including the control, there was no renewed flowering within the period of observation once flowering had ceased.

Early-season water stress (T2), 74-86 days after sowing, caused a reduction in cumulative flowering from about day 106, and a total cessation of flowering from day 120. Thus the flowering response to water stress occurred 32 days after the commencement of the stress period. The development time of a floral bud from its first appearance to flowering is approximately 33 days, of which the first 11 days are the "small bud" phase. Thus, early-season stress caused shedding of small buds and/or cessation of bud production.

Mid-season water stress (T3), 97-107 days after sowing, caused a reduction in cumulative flowering immediately after relief of the stress, and a total cessation of flowering from day 113. Here, the flowering response to water stress occurred 10 days after the commencement of the stress period. It can therefore be inferred that stress at this stage causes shedding of large buds in addition to the shedding of small buds and cessation of bud production.

Late-season stress (T4), 113-126 days after sowing, did not effect the flowering curve. By this stage, flowering has already ceased in the control and thus total flower production is the same in these two treatments.

In previous studies (Kletter and Wallach, 1982) it was found that late-season damage to buds causes a reduction in cumulative flowering without there being a subsequent period of increased flowering over the control. Furthermore, prolonged late-season bud damage (e.g. removal of 200 small squares late in the season) significantly reduced final yield.

Water stress treatments caused a similar response in flowering to that of late-season bud damage. In both instances, fewer flowers are produced towards the end of the flowering period and there is no renewed flowering phase later still. Even in the earliest stress treatment (T2), flowering did not recommence sufficiently early for such flowers to contribute to yield and compensate for damage.

Early damage to 120 buds/m-row consistently caused an early reduction in the rate of flowering relative to the corresponding undamaged treatment. However, flowering continued in the artificial damage treatments during the cutoff period of the undamaged treatments. This would seem to be the result of a significant reduction in the ratio between reproductive (sink) and vegetative (source) plant parts caused by removal of fruiting forms. Once the water stress is relieved, a greater proportion of assimilates is invested in renewed vegetative growth which generates a late-season phase of bud production and hence flowering. Nevertheless, total flower production remained highest in the undamaged treatments (Table 2).

BOLL OPENING

All stress-only treatments (T2, T3, T4, T6) yielded fewer open bolls than the controls (T1, T5). In the late-season stress treatment (T4), the number of open bolls was similar to that of the other stress treatments even though total flower production was similar to that of the control, unlike the other stress treatments. This clearly indicates that late-season water stress caused increased shedding of small bolls.

Percentage boll set was consistently higher in early bud damage treatments than in the corresponding stress-only controls, exceeding 90% in some treatments (Table 2). This mechanism not only compensated for the reduction in flower production resulting from bud removal, but also compensated for the reduction in flowering caused by water stress (Table 2).

YIELD

In all treatments without severe water stress, namely, treatment pairs T1/T7 and T5/T11, seed cotton yield was similar. The plant achieved full yield compensation for the removal of 120 floral buds/m-row, as shown in previous experiments. In the stress treatments, early damage to 120 floral buds/m-row resulted in a significant increase in yield (T2/T8 ; T4/T10 ; T6/T12) and restored the yield level to that of the unstressed, undamaged control.

In previous studies (Wallach and Kletter, 1984), late damage to large bolls significantly reduced yield. Early bud damage in combination with late damage to large bolls did not reduce yield. In this experiment, water stress acted similarly to late-season damage to fruiting forms. Early damage to 120 buds in combination with water stress did not reduce yield.

CONCLUSIONS

It is widely accepted today to irrigate cotton according to standard strategies. The most widespread of these are:

1. fixed intervals between irrigations,
2. on the basis of soil moisture status (measured gravimetrically or by the neutron moderation technique) whereby the grower irrigates when soil moisture content falls below some pre-determined threshold,
3. on the basis of leaf water potential measurements and a threshold deficit value,
4. on the basis of pan evaporation, using some evaporative loss coefficient.

One of the most important conclusions of this study is that the degree of damage caused by severe water stress is highly dependent on the previous history of the crop as integrated by the development stage of the crop at the time of the stress. Thus, water stress at different stages of growth reduced yield in those plants that had a high boll load at the time of the stress. The same stress at the same calendar date did not reduce yield in previously damaged plants that presented a much lower ratio of reproductive to vegetative biomass at the time of the stress (Figure 2). This strongly indicates that in addition to standard techniques for monitoring the water budget in the field, it is necessary to consider the developmental status of the plant in determining an irrigation policy.

REFERENCES

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FIGURE LEGENDS

Figure 1. Cumulative flowering/m-row

---- T1
-X--X- T2
-O--O- T3
-V--V- T4

The arrows bracket the stress period. The numbers under the arrows indicate leaf potential (Bar) at the beginning and end of stress period.

Figure 2. Seed cotton yield

☐ - With damage
☒ - Without damage

Two columns with the same letter are not significantly different at the 0.05 level according to the Duncan Multiple Range Test.

Figure 1

Figure 2

T a b l e 1

Description of treatments

I r r i g a t i o n									
T	R	Stress	I	II	III	IV			
E	timing	date (d.a.s)*	date (d.a.s)	date (d.a.s)	date (d.a.s)	date (d.a.s)			
A		quantity	quantity	quantity	quantity	quantity			
T		(Bar)	(Bar)	(Bar)	(Bar)	(Bar)			
:T1, T7:		21.6 (74)	14.7 (97)	30.7 (113)					
		1100	1200	1300					
		-18.8	-19.1	-14.8					
:T2, T8:	before	3.7 (86)	27.7 (110)	9.8 (123)					
	first	1200	1200	1200					
	irrig.	-20.8	-20.1	-15.6					
:T3, T9:	before	21.6 (74)	24.7 (107)	5.8 (119)					
	second	1100	1300	1200					
	irrig.	-19.1	-25.0	-17.8					
:T4, T10:	before	21.6 (74)	14.7 (97)	12.8 (126)					
	third	1100	1200	1300					
	irrig.	-19.0	-19.1	-21.7					
:T5, T11:		12.6 (65)	30.6 (83)	19.7 (102)	1.8 (115)				
		900	900	900	900				
		-15.2	-19.2	-17.2	-15.9				
:T6, T12:	before	12.6 (65)	17.7 (100)	1.8 (115)					
	second	900	1400	1300					
	irrig.	-15.7	-26.8	-16.8					

* - days after sowing

Treatments T1 - T6 were without damage.

Treatments T7 - T12 were with damage to 120 floral buds/m-row.

T a b l e 2

Total flower production, seed cotton yield and its components

Treatment	Total flowers/ m-row	% of boll set	No.of open bolls/ m-row	Average boll weight	Seed cotton yield/ m-row
T 1	139	66.2 bc	91.6 ab	6.9	629 abc
T 2	119	67.2 bc	79.1 c	7.3	573 c
T 3	129	65.1 bc	83.2 abc	7.1	588 bc
T 4	140	58.0 cd	80.9 bc	7.0	570 c
T 5	141	66.6 bc	93.6 ab	6.8	635 ab
T 6	118	68.6 bc	80.7 bc	7.3	585 bc
T 7	117	75.2 b	88.0 abc	7.1	624 abc
T 8	98	96.9 a	94.9 a	7.0	663 a
T 9	94	94.0 a	88.1 abc	7.2	629 abc
T 10	118	77.6 b	91.3 ab	7.1	643 ab
T 11	114	82.2 b	92.8 ab	7.2	667 a
T 12	86	106.6 a	92.2 ab	7.2	657 a

Numbers within a column followed by the same letter are not significantly different at the 0.05 level according to Duncan's Multiple Range Test.

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COTTON CROP RESPONSE TO
BUD AND BOLL REMOVAL

APPENDIX B

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A B S T R A C T

Short fiber cotton (Gossypium hirsutum L.) was grown on high fertility soils with adequate irrigation. Squares (floral buds) or bolls were removed from the crop and crop flowering, boll opening and seed cotton accumulation were measured.

The two extreme responses to square removal were a relatively large initial decrease in flowering and boll opening, followed by large increases (e.g. large square removal), and a relatively small initial decrease followed by little or no increase in flowering and boll opening (e.g. late small square removal). Overall, no square removal treatment significantly reduced final open boll number or yield.

Small boll removal led to a decrease in open bolls that was substantially less than the number of bolls removed. Increased late season flowering only began some time after boll removal commenced, but was nonetheless sufficient to prevent a yield loss in these treatments as well.

The large boll removal treatments did significantly reduce final yield, because they had a relatively large initial decrease in open boll number, and insufficient late bolls to make up the loss. This was related to the state of the crop at the time of removal. When boll set was delayed by early large square removal, and then large bolls were removed, no yield reduction was observed. The effect of damage here depended on the state of the crop, which then should be taken into account in determining pest control strategy.

I N T R O D U C T I O N

An understanding of the effects of pest damage on cotton (Gossypium hirsutum L.) development and yield is essential for developing pest management strategies.

A number of studies of the effects of damage have been carried out, generally by removing fruiting bodies by hand and following subsequent crop response. Mistic and Covington (1978) studied the effects of different patterns of square (floral bud) removal, with particular emphasis on mimicking boll weevil damage. Kincade et al. (1970) simulated Heliothis damage to cotton. Other studies have investigated the effects of simpler patterns of damage, not meant to imitate a particular pest. Dale (1959) removed all squares from a crop up to 23 and 35 weeks after planting. Passlow and Trudgian (1960) removed all fruiting forms from the crop over various periods. Kletter and Wallach (1982) studied the effects of removing squares and bolls of different sizes over various periods. A number of studies have involved removing flowers. Although certain of these studies were not specifically meant to investigate the effect of damage, they nevertheless provide information on this subject. Horowitz (1962) removed various percentages of flowers, or all flowers over various periods. Ehlig (1969) investigated the effect of removing all flowers, and Ehlig and LeMert (1973) removed all flowers for various periods. Patterson et al. (1978) left different numbers of flowers on the plant over a 90 day period.

A number of different responses to fruiting form removal were reported in these studies. Removal of all squares led to increased vegetative growth and increased production of squares (Dale, 1959). In particular, there was continued rapid formation of squares in the debudded plants after square formation had practically ceased in the control plants. Partial square removal also led to increased numbers of squares (Mistric and Covington, 1968). Similarly, flower removal led to increased plant height (Ehlig, 1969; Patterson et al., 1978) and increased flowering (Ehlig, 1969), particularly after flowering had nearly cut off in the control plots (Ehlig and LeMert, 1973). A late season increase in flowering was also observed following square and boll removal (Kletter and Wallach, 1982). Removal of flowers, squares or bolls also increased percentage boll set (Horowitz, 1962; Mistric and Covington, 1968; Ehlig and LeMert, 1973; Patterson et al., 1978; Kletter and Wallach, 1982), and decreased percentage square shed (Horowitz, 1962). Dale (1959) and Patterson et al. (1978) interpreted their results as being the effect of reduced boll load. Such a reduction would leave more carbohydrates available for vegetative growth and for developing fruiting bodies. Finally, certain square and boll removal treatments have been found to increase average seed cotton per boll (Mistric and Covington, 1968; Kletter and Wallach, 1982).

Only the study of Kletter and Wallach (1982) specifically compared the effects of removing fruiting bodies of different ages, at various times. This sort of comparison is important because different insect pests, or a pest at different stages of development, attack different fruiting bodies at different times, and the plant response is different in each case.

The present study is a continuation of that previous work. As described below, a number of treatments of both practical and theoretical interest not previously studied were included here. As in the previous study, flowering was followed throughout the season and open bolls were harvested weekly from the start of boll opening. Furthermore, in the second year of this study, detailed plant data were taken each week. It is important to follow the crop response throughout the season in order to see how the various reactions to fruiting form removal interact, and finally determine yield. It is important to gather harvest data as a function of time, because the timing of yield is of economic significance.

In the previous study no fruiting body removal treatment significantly reduced final yield. A major goal in the first year of the present study then was to investigate the limits of the ability of a cotton crop to compensate for damage. To this end treatments that seemed likely to decrease yield were included. In particular, whereas in the earlier study only small bolls had been removed, in the present study large boll removal was also carried out. Furthermore, in the previous study only 120 small squares/m-row were removed, while the present study included treatments in which 200 small squares were removed.

Analysis of the first year results, aided by a simulation model (unpublished), suggested that in certain cases combining early square removal with late boll removal would have less effect on yield than boll removal alone. This somewhat surprising conclusion was tested experimentally in the second year of this study. Thus the second year treatments not only provided new patterns of fruiting form removal, including for the first time a pattern

combining different types of damage, but also provided a test of the conclusions based on the earlier results. Furthermore, the effect of combinations of damage is of practical interest, since cotton in Israel is attacked both by early season pests which damage mainly squares (e.g. Heliothis armigera), and by late season pests which damage bolls (e.g. Earias insulana, Pectinophora gossypiella).

In order to predict the quantitative response of a cotton crop to a specific pattern of bud and boll damage, the use of a crop simulation model is probably necessary. It is however important to have a qualitative understanding of the effects of damage as well, and this study can contribute to such an understanding. Furthermore, the results of this study should be valuable for testing crop simulation models, and in particular their predictions of the effects of bud and boll removal. A printout of the complete data from this experiment, including daily climate and all management information, can be obtained from the second author.

M A T E R I A L S A N D M E T H O D S

The 1979 experiment was conducted at the Ein Shemer collective farm in the coastal plains region of Israel, and the 1981 experiment at the Gan Shmuel collective farm in the same region. Both farms have fertile alluvial clay-loam soils. Acala variety SJ-2 was planted on March 26 in 1979, and on April 5, 1981, in 96.5 cm rows. All plots were thinned to 10 plants/m-row shortly after emergence. The plots received standard commercial management practices for the region. In 1979 this included, after a pre-emergence irrigation, irrigations on June 10 (1160 m /ha), July 5 (1200 m /ha), July 20 (500 m /ha) and July 27 (1190 m /ha). Irrigations in 1981 were given on June 21 (1200 m /ha), July 15 (1200 m /ha) and July 29 (1200 m /ha).

The experimental treatments are described in Table 1. The small and large squares removed were approximately in the size ranges <5 mm and >15 mm respectively. The small and large bolls removed were approximately of fresh weight <10 g and >10 g respectively.

The 1979 experiment was arranged in a factorial design. Timing of removal was one factor and type of damage to fruiting bodies was the second factor. The experiment was replicated 4 times. Each replicate consisted of two rows of cotton, one 5 m long used for flower counts, and the other 10 m long used for harvesting open bolls. Untreated border rows separated the treatments.

Newly opened flowers (white blooms) were counted three times a week in each replicate. Flowering between counting days was calculated by linear interpolation. Once boll opening began, open bolls were collected once a week from the 10 m row of each replicate reserved for this purpose.

The 1981 experiment was arranged in a randomized block design, with 5 replicates per treatment. Flowers were counted as in 1979. In addition, 1 m-row was harvested weekly in each replicate of each treatment, and taken to the lab. There numbers and dry weights of fruiting bodies of different sizes were determined, and vegetative growth was measured. (In the period before treatments differed, harvesting was done in only one of the identical treatments). In addition, open bolls were harvested weekly from fixed 10 m sections of row, as in 1979. Only total seed cotton was measured. Numbers of open bolls were calculated, using the values of seed cotton/boll from one meter harvested sections. The final yield results presented in Table 6 are based on the 10 m section results. All other results are from the harvested one meter sections.

In both years, harvesting continued up to what would normally be considered the limiting harvest-date. After this time temperatures fall and the probability of rainfall becomes appreciable.

Daily maximum and minimum temperatures in 1979 were taken from a station of the meteorological service, located adjacent to the experimental field. The 1981 temperatures were measured by a recording thermohydrograph adjacent to the experiment. Day degrees (DD) above a threshold of 12 C were calculated as described in Marani (1979). The values reported represent cumulative degree days from emergence.

R E S U L T S A N D D I S C U S S I O N

EARLY FLOWERING

The 1979 flowering results are reported in Table 2, and the 1981 results are shown in Fig. 1. The control plots in both years have a pattern of flowering that is typical for irrigated cotton in Israel. During the first few weeks, the rate of flowering increases. There is then a period when the rate declines more or less gradually, followed by a fairly sharp cut-off, which occurred around July 22 in 1979, and near August 2 in 1981.

Square removal led initially to a decrease in flowering rate. It seems reasonable to suppose that this was the direct result of the removal of floral buds. To check this, the calculated time of flowering of the last squares removed in each treatment will be calculated. If the supposition is correct, the calculated times should coincide with the times when the maximum reduction in cumulative flowers was observed. The calculation will be done in degree days, since square and boll development times are more nearly constant on this time scale than in terms of calendar days.

Flowering occurs approximately 350 DD after a square is first counted. As defined here, small squares are approximately in the age range 0-70 DD, and large squares are approximately of ages 140-350 DD. Therefore the small squares removed would have flowered up to 350 DD after removal, and the large squares up to 210 DD after removal. Using these values, the calculated times when the last squares removed in each treatment would have flowered are indeed very close to the observed times of maximum reduction in cumulative flowering (Table 3, rows 1 and 2).

In all cases, the maximum reduction in cumulative flowers was less than the number of squares removed (Table 3, rows 3 and 4). That is, the effect of square removal was already reduced, and in some cases very considerably reduced, by the time the last removed squares would have flowered.

The same result was observed by Kletter and Wallach (1982), who suggested that the main reason was that some of the squares removed would have been shed before flowering anyway. This explanation implies that the greater the natural shedding of the square categories affected by removal, that is the greater the number of removed squares that would shed in the absence of removal, the less square removal should reduce flowering. The 1979 results do indeed show this trend.

It has been observed that most square shedding involves small squares, and that the percentage shed increases with time, and approaches 100% late in the season (Horowitz, 1962). Therefore, as a consequence of their greater natural shedding, the removal of small squares should affect flowering less than the removal of large squares which would flower over approximately the same period. The most appropriate comparison in 1979 is between small square removal (T2) and the average of early and late large square removal (T3 and T9). As seen from Table 3 (row 3) the early small square removal treatment has the smaller effect on flowering, as anticipated. Also as anticipated on the basis of natural shedding, early small square removal reduces flowering more than late small square removal (compare T2 and T8, or T4 and T10 in Table 3), and late small square removal (T8 or T10) has relatively little effect on flowering.

The trend among treatments in the maximum reduction in flowers can thus be explained in terms of natural square shedding. However, square removal may also have altered the development pattern of the crop, and this may also have had an effect on the maximum reduction in flowers.

First of all, square removal may not only have replaced square shed to some extent, but may also have reduced shedding of other squares, by reducing competition among squares, and this would have tended to increase flowering. Also, square removal in general leads to a reduction in flowering and boll load, which have been related to increased vegetative growth and associated production of squares (Dale, 1959) and to decreased square shed (Horowitz, 1962; Ehlig and LeMert, 1973; Patterson et al., 1978). This again would have tended to increase flowering. However, there is a delay until this mechanism begins to operate, corresponding to the delay between square removal and decreased flowering or boll load. This may limit its effect up to the time of maximum reduction in cumulative flowers.

LATE FLOWERING

After the maximum reduction in cumulative flowers, most of the debudding treatments and all of the 1979 boll removal treatments had, at least over some period, significantly faster rates of flowering than the controls (Table 2). Square plus boll removal in 1981 (T15) also led to increased late flowering (Fig. 1). Furthermore, Figs. 2 and 3 show that vegetative growth and square numbers were increased by large square removal in 1981 (i.e. were increased in treatment T15 after squares were removed, and before bolls were removed).

These results are consistent with previous studies, cited in the introduction, which also found that removal of fruiting bodies increased vegetative growth, square production and flowering.

The trend in late flowering among the 1979 debudding treatments is that expected if late flowering is increased as a result of decreased boll load. Consider, as before, early small square removal (T2) and the average of early and late large square removal (T3 and T9). Table 3, row 9 shows that small square removal, which caused the smaller reduction in open bolls and therefore presumably in boll load, also had less late flowers. Also, the two debudding treatments which did not lead to significant increases in late flowering rate relative to the control were T8 and T10 (late removal of 120 or 200 small squares), which were also the treatments that caused the smallest maximum reduction in cumulative open bolls.

In each of the 1979 boll removal treatments, there is a delay between the start of boll removal and the time that flowering is first significantly faster than in the control plots (Table 2).

Ehlig (1969) similarly noted a delay of 18 to 40 days, between the start of flower removal and increased flowering rate. A delay is expected if boll removal affects flowering through increased square production or through decreased shedding of small squares. In the first case, the delay corresponds to the time from square production to flowering. In the second case, the (shorter) delay is between the age susceptible to shedding and flowering.

The 1981 boll removal treatment here is somewhat anomalous, as it did not lead to any substantial increase in flowering (Fig. 1). Furthermore, as Fig. 2 shows this treatment did not substantially effect square numbers over the period of measurement. That is, not only was flowering not increased, but there was no indication that flowering would be increased in the future. This may be related to the lateness of this treatment. Bolls were removed later than the last 1979 removal date and at a time when vegetative growth was already very slow (Fig. 3). In this case it seems that vegetative growth and bud production cannot recommence immediately.

EARLY BOLL OPENING

Weekly and total open boll numbers are shown in Table 4 for the 1979 experiment, and in Fig. 1 for the 1981 experiment. For the control and debudded plots, the pattern of open boll accumulation resembles that of flowering, though at a reduced numerical level due to boll shedding.

As for flowering, there is at some time a maximum reduction in cumulative open bolls following square removal. On the average this occurs 561 DD after the maximum reduction in flowering (Table 3, rows 1 and 6). This is a reasonable value for the time from flowering to boll opening, and so it will be assumed that all open bolls produced up to the time of maximum reduction in open bolls, result from flowers that appear up to the time of maximum reduction in flowering. For later times, and for the boll removal treatments, it will be assumed that bolls that open up to any time t result from flowers that appear up to the measurement time closest to $t-561$ DD. The above assumptions make it possible to relate, at least roughly, open bolls and the flowers from which they arise.

The maximum reduction in cumulative open bolls in 1979 was always less than the maximum reduction in flowering following debudding (Table 3, rows 3 and 7), and always less than the number of bolls removed in the boll removal treatments (Table 5, rows 2 and 3). In analogy with the reduction in flowering, one possible reason is that some of the flowers or bolls eliminated would have shed in any case, and so to some extent their removal simply replaces shedding.

Again, the greater the natural shedding of the boll category removed, the less the number of open bolls should be affected. Most boll shedding involves small bolls (Horowitz, 1962; McMichael et al., 1973). Thus a reduction in flowering, or removal of small bolls, should affect open boll numbers less than removal of large bolls, for bolls that would open over approximately the same period.

This is observed in the 1979 results. The large boll removal treatment T6 leads to a decrease of 42 in open bolls compared to a decrease of 18 for small boll removal T5, and a decrease of 21 for early small square removal T2. (See Table 5, row 2 and Table 3, row 7).

In general the percentage shedding of bolls over the main flowering period increases with time (Mistic and Covington, 1968; Ehlig and LeMert, 1973), which implies that late small square removal should reduce open boll numbers less than early removal.

Here on the other hand the two treatments T5 and T11 had nearly the same effect. In fact, however, the results for the controls indicate that the percentage boll shed hardly changed between the two periods of removal. Up to the maximum decrease in open bolls in T5 the control produced 64 open bolls from approximately 133 flowers, while up to the maximum decrease in T11 the control produced 76 open bolls from approximately 141 flowers.

Once again, as for square removal, boll removal or a reduction in flowering may not only have substituted for natural shedding to some extent, but may also have reduced shedding of other bolls.

Previous studies, as noted, have found that flower removal, or square removal, lead to a decrease in percentage boll shed. This might explain the fact that even though there is little natural shedding of large bolls, the reduction in open bolls following large boll removal in 1979 was less than the number of bolls removed.

The 1981 large boll removal treatment, T14, led to a maximum decrease in open bolls nearly equal to the number of bolls removed (Table 5, rows 2 and 3). This is expected since in this case there was only a single removal date, so any effect on younger fruiting bodies, such as decreased shedding of small bolls, would affect open boll numbers after the time of maximum reduction in open bolls.

LATE BOLL OPENING

After the time of maximum reduction in open bolls, all the 1979 square removal treatments added more bolls than the controls, associated with greater late flowering (Table 3, rows 10 and 12). It has already been noted that in general, late flowering was increased more where the initial reduction in open boll number was larger. The increase in late boll opening followed the same trend. As a result, none of the 1979 square removal treatments significantly reduced the final number of open bolls (Table 4).

The boll removal treatments also had an increased number of late open bolls (compare rows 8 and 10 in Table 5). In the small boll removal treatments T5 and T11, with a relatively small maximum decrease in open bolls, the increase in late boll opening was sufficient to make up for the bolls removed. Early large boll removal, with a relatively large maximum reduction in open boll number also had time to make up for the lost bolls, but just barely, since at the next to last harvest date this treatment still had significantly fewer open bolls than the control (values not shown). However, the treatment T12, with both a relatively large maximum decrease in open boll number and the latest removal dates, did cause a significant decrease in final open boll number. The 1981 boll removal treatment T14, with the latest removal date, also significantly decreased the final number of open bolls.

It is worthwhile to consider here in more detail why late boll opening, in the late boll removal treatments T12 and T14, was insufficient to make up for the initial reduction in open boll number.

A number of possible compensation mechanisms for boll removal have already been mentioned. One is decreased shedding of small bolls. But late in the season there are few flowers appearing, and so few small bolls on the plant. Thus the opportunity for reducing boll shedding is slight. Furthermore, Table 5 (rows 9 and 10) shows that essentially all the late flowers in the control contributed to yield already.

Ehlig and LeMert (1973) also found high percentage retention values for the small number of late flowers in their control.

Thus T12 and T14 could not make up for the lost bolls with increased boll set. A second possible compensation mechanism involves reduced square shed. This can lead to an increase in late flowering and boll opening, though boll opening will increase after a longer delay than following decreased boll shed. However, late in the season there are normally few squares on the plant (Fig. 2), so this possibility is also reduced. The only remaining method of compensation is increased square production, with a still longer delay before boll opening is increased. This can explain why in T12 compensation was insufficient, up to the end of harvesting, to make up for the initial reduction in open bolls. Furthermore, it seems from the 1981 results that if removal occurs sufficiently late, even this last response to boll removal may be delayed, or even absent.

The above analysis suggests that late boll removal in 1979 and 1981 reduced final open bolls not only because they were inflicted late in terms of date, but also because they were late in terms of crop growth pattern. This further suggests that the same treatments inflicted on a crop with a different growth pattern need not decrease final open boll number.

In particular it seems that if, in the absence of boll damage, the crop had a high rate of late season flowering, and also a high level of boll shedding, then additional compensation for boll removal could come from reduced boll shed. The indicated crop pattern can in fact be produced by early removal of large squares. As Table 3 (rows 9 and 10) shows, the 1979 early large square removal treatment T3 had many late season flowers, including many which did not produce open bolls. This was the rationale for studying the combination of early large square removal and late large boll removal (T15) in 1981.

The 1981 treatment T15 did indeed behave as anticipated. This treatment had 78 late season flowers, compared to 25 for boll removal only, and these flowers were more than sufficient to make up for both square removal and boll removal (Table 5, rows 9 and 10). The treatment had 66 late open bolls, for a final number of open bolls not significantly different than the control (Table 6).

Although only late season large boll removal in 1979 and boll removal in 1981 significantly reduced the final number of open bolls, almost all treatments led to a delay in boll opening. The only treatments which did not lead to a significant decrease in cumulative open bolls at some time were late removal of 120 and 200 small squares in 1979.

YIELD

The other component of seed cotton yield, besides boll number, is seed cotton per boll. The 1981 control results (Fig. 5) are typical. They show a fairly steady decrease in seed cotton per boll with harvest date except for the last dates, which in any case represent few open bolls. If all treatments had had the same values at each date, then the treatments with a delay in boll opening, and therefore with more of the later, lighter bolls, would have had a lower overall average value of seed cotton per boll. In fact, this was not observed. Rather, the decline in seed cotton per boll generally began at later dates in those treatments with delayed boll opening. As a result, no treatment had a significantly different overall value of seed cotton per boll than the corresponding control (Tables 6 and 7).

Cumulative seed cotton values are presented in Table 7 (1979) and in Table 6 and Fig. 5 (1981). The two treatments which significantly reduced cumulative open bolls, namely late large boll removal in 1979 and boll removal in 1981, also significantly reduced final cumulative seed cotton. In addition, the decrease in final yield following early large boll removal in 1979 was significant, even though the decrease in number of open bolls was not.

CONCLUSIONS

Certain of the 1979 treatments here resembled treatments in the study of Kletter and Wallach (1982). For those treatments, the results in the two cases were also quite similar. Also, in the 1981 square plus boll removal treatment, the effect of large square removal in the period before bolls were removed was comparable to the effect of early large square removal in 1979. It seems reasonable then to suppose that the results here are not exceptional, but rather represent a more or less typical pattern for irrigated cotton in Israel.

None of the square removal treatments here significantly reduced final open boll number or final yield. However, the way in which final yield was attained differed in each case. At one extreme were the large square removal treatments, which affected squares expected to have a low probability of natural shedding. Here debudding led to a relatively large decrease in cumulative flowers and open bolls, but then to rapid late season flowering and boll opening. At the other extreme were the late small square removal treatments. These squares are expected to have a high probability of natural shedding. In this case the initial decrease in flowering and boll opening was slight. Late flowering and boll opening were then hardly increased, but in any case this did not matter, since there was little if any deficit to make up.

The treatments in which 200 small squares were removed, which were chosen to test the limits of compensation of a cotton crop, did not then significantly reduce yield. Obviously there must be some limit to the number of small squares that can be removed without decreased harvested bolls and yield, but that limit was not reached here.

Small boll removal led to a maximum decrease in open bolls that was much less than the number of bolls removed. Late flowering in these treatments was increased, but only following a substantial delay after boll removal began. Nevertheless, late flowering and boll opening was sufficient to prevent a significant decrease in final open boll number or final yield.

The only treatments which did significantly reduce final yield then were the large boll removal treatments T6, T12 and T14. The major contributing factor in each case was the decrease in open boll number. These treatments caused a relatively large maximum decrease in open boll number, and then had insufficient late open bolls to make up the loss. It seems then that one limit to the ability of a cotton crop to compensate for damage occurs when fruiting bodies with a high probability of contributing to yield are removed late in the season. This causes a relatively large decrease in open boll number, and leaves insufficient time to make up for this decrease. As already noted, lateness both in terms of calendar date and in terms of the growth pattern of the crop reduce the possibilities of compensation. Thus the treatment T15, in which large bolls were also removed but in which boll set was delayed due to early removal of large squares, did not significantly reduce yield.

Final harvested seed cotton per boll was not significantly affected by any treatment. However, as already noted, at any particular harvest date seed cotton per boll was affected by fruiting body removal. In the literature, fruiting body removal has been found to significantly alter average boll weight (Mistic and Covington, 1968; Kletter and Wallach, 1982). It would be worthwhile to study the dynamics of boll weight gain more closely, in order to obtain a better understanding of these results.

One important conclusion of this study is that the effect of damage on a cotton crop is very dependent on previous crop history, or equivalently, on the state of the crop at the time of damage. Thus large boll removal in 1981 significantly reduced yield when applied to a previously undisturbed crop, but did not reduce yield when applied to a crop from which large squares had previously been removed. It is important, therefore, to take into account the state of the crop in determining pest management strategy.

Looked at another way, the results of this study show that pest management decisions should depend on expected future damage, and therefore on projected future management strategy. In particular, it was shown that in the absence of late damage, early removal of large squares is disadvantageous, or at best neutral, since though it does not reduce yield it does delay yield. On the other hand, compared to late damage to large bolls alone, the addition of early loss of large squares was beneficial, since it led to a significant yield increase. This emphasizes the importance of considering overall pest management strategy, rather than each decision independently.

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FIGURE CAPTIONS

1. Cumulative flowers and open bolls in 1981

O T13 (CONTROL)
X T14 (BOLL REMOVAL)
Δ T15 (SQUARE AND BOLL REMOVAL)
The arrow indicates the time of boll removal

2. Counted squares/m-row in 1981

O T13 (CONTROL)
X T14 (BOLL REMOVAL)
Δ T15 (SQUARE + BOLL REMOVAL)
The arrows indicate the period of square removal and the date of boll removal

3. Total vegetative dry matter (g)/m-row in 1981

O T13 (CONTROL)
X T14 (BOLL REMOVAL)
Δ T15 (SQUARE + BOLL REMOVAL)
The arrows indicate the period of square removal and the date of boll removal

4. Cumulative seed cotton in 1981

O T13 (CONTROL)
X T14 (BOLL REMOVAL)
Δ T15 (SQUARE + BOLL REMOVAL)

5. Seed cotton (g/boll) in 1981

O T13 (CONTROL)
X T14 (BOLL REMOVAL)
Δ T15 (SQUARE + BOLL REMOVAL)

FIG. 1

FIG. 2

FIG. 3

FIG. 4

- 28 -

SEED COTTON (g)/BOLL

FIG. 5

Treat. number	Fruiting body removed	Total no. removed/ m-row	Removal times					
			D a t e s			D D		
<u>1979 EARLY REMOVAL</u>								
T 1	Control	--	--			--		
T 2	Small squares	120	10/6	17/6	24/6	497	577	665
T 3	Large squares	120	13/6	20/6	27/6	533	616	700
T 4	Small squares	200	10/6	17/6	24/6	497	577	665
			1/7	8/7		745	836	
T 5	Small bolls	60	1/7	8/7	15/7	745	836	915
T 6	Large bolls	60	8/7	15/7	22/7	836	915	1004
<u>1979 LATE REMOVAL</u>								
T 7	Control	--	--			--		
T 8	Small squares	120	20/6	27/6	4/7	616	700	783
T 9	Large squares	120	24/6	1/7	8/7	665	745	836
T10	Small squares	200	20/6	27/6	4/7	616	700	783
			11/7	18/7		866	952	
T11	Small bolls	60	11/7	18/7	25/7	866	952	1039
T12	Large bolls	60	18/7	25/7	1/8	952	1039	1129
<u>1981 TREATMENTS</u>								
T13	Control	--	--			--		
T14	Large bolls	30	10/8			1197		
T15	Large squares	120	12/6	15/6	17/6	478	507	528
			18/6	21/6	23/6	539	570	595
	+		24/6	25/6	28/6	608	620	658
			1/7	2/7	3/7	694	707	720
	Large bolls	30	10/8			1197		

T a b l e 2

1979 FLOWERING

Weekly flowers / m - row*													
Week ending	DD	T 1	T 2	T 3	T 4	T 5	T 6	T 7	T 8	T 9	T 10	T 11	T 12
17/6	577	4a	4ab	2b	5a	7a	5a	5a	5a	5a	4ab	4ab	5a
24/6	665	20a	17a	1b	18a	20a	19a	19a	18a	17a	18a	19a	19a
1/7	745	35a	24c	1e	26bc	34ab	32abc	30abc	30abc	12d	34ab	34ab	33ab
8/7	836	32ab	8c	5c	7c	36a	33ab	36a	33ab	6c	29b	33ab	32ab
15/7	915	24a	6c	13b	7c	25a	25a	26a	21a	4c	15b	26a	25a
22/7	1004	17b	9cd	34a	7cd	14bc	18b	20b	9cd	4d	5d	17b	13bc
29/7	1093	5bc	7b	27a	2bc	3bc	4bc	4bc	1c	4bc	2bc	3bc	3bc
5/8	1173	2d	8bc	25a	2d	3cd	4cd	1d	0d	11b	0d	4cd	2d
12/8	1257	3c	12b	21a	4c	6c	8bc	1c	4c	24a	1c	6c	5c
19/8	1338	1d	6bc	10ab	8b	2cd	6bc	0d	2cd	13a	1d	3cd	2cd
26/8	1423	1e	8bcd	8bcd	12ab	6cde	13ab	1e	4de	16a	2e	9bcd	10bc
31/8	1485	2f	7cd	3ef	12ab	6de	11bc	3ef	5def	10bc	4def	10bcd	15a
TOTAL		147bcd	117ef	151bc	108f	162ab	178a	146bcd	132cde	127def	115ef	167ab	164ab

* Numbers in a given row followed by the same letter are not significantly different at the 0.05 level according to Duncan's Multiple Range Test.

T a b l e 3

Effects of square removal

	T 2	T 3	T 4	T 8	T 9	T 10	T 15
Maximum decrease in cumulative flowers relative to control							
1. TF = Time of maximum decrease, observed (DD)	1004	915	1173	1173	1093	1257	909
2. Time of maximum decrease, calculated (DD)	1015	910	1186	1133	1046	1302	930
3. Decrease at time TF	66	93	68	24	88	34	76
4. Total buds removed	120	120	200	120	120	200	120
5. Cumulative flowers at time TF	68	23	73	117	51	109	16
Maximum decrease in cumulative open bolls relative to control:							
6. TB = Time of maximum decrease, observed (DD)	1614	1542	1614	1752	1614	1843	
7. Decrease at time TB	21	52	20	7	27	10	
8. Cumulative open bolls at time TB	52	12	53	68	42	67	
After maximum decrease in flowers or bolls							
9. Flowers from TF to end of effective flowering (1423 DD)	41	125	23	10	66	2	
10. Open bolls from TB to last harvest	38	78	32	13	49	9	
11. Control flowers from TF to end of effective flowering (1423 DD)	12	29	5	2	4	1	
12. Control open bolls from TB to last harvest	11	19	11	6	11	4	

* Only results for the period before bolls were removed are reported here

T a b l e 4

1979 Open bolls

Week ending		Weekly open bolls / m - row*													
Date	DD	T 1	T 2	T 3	T 4	T 5	T 6	T 7	T 8	T 9	T 10	T 11	T 12		
15/08	1293	6a	4ab	0b	5ab	8a	0b	7a	5ab	5ab	6a	6a	0b		
22/08	1376	17a	13a	1b	14a	12a	1b	15a	16a	13a	12a	14a	2b		
29/08	1460	24a	21a	2d	19a	13b	5cd	20a	21a	9bc	22a	21a	4cd		
5/09	1542	16ab	7c	8c	9c	12bc	16ab	18a	18a	8c	16ab	12bc	8c		
12/09	1614	9bc	7bc	18a	6bc	11b	15a	8bc	6bc	6bc	6bc	4c	7bc		
19/09	1690	4c	8bc	23a	4c	8bc	10b	5bc	2c	6bc	2c	2c	7bc		
25/09	1752	2c	7b	16a	2c	3c	4c	2c	1c	8b	1c	2c	3c		
3/10	1843	1d	12b	12b	7c	5cd	5cd	2d	3cd	23a	1d	4cd	4cd		
10/10	1907	1c	7ab	7ab	8a	2c	4bc	1c	2c	8a	1c	3c	1c		
16/10	1954	1cd	2bcd	1cd	6a	1cd	5ab	0d	3bcd	2bcd	2bcd	3bc	3bcd		
21/10	1999	2e	4de	2e	6bcd	4cde	7bc	3de	5bcde	2e	6bcd	7b	10a		
TOTAL		83ab	91a	90a	85ab	80ab	71ab	81ab	81ab	90a	76ab	78ab	49c		

* Numbers in a given row followed by the same letter are not significantly different at the 0.05 level according to Duncan's Multiple Range Test

T a b l e 5

Effects of boll removal

	T 5	T 6	T11	T12	T14	T15
Maximum decrease in cumulative open bolls relative to control						
1. TB = Time of maximum decrease, observed (DD)	1542	1542	1752	1614	1634	1713
2. Decrease at time TB	18	42	15	47	29	52*
3. Total bolls removed	60	60	60	60	30	30
4. Cumulative open bolls at time TB	46	22	61	21	27	15
Flowers which produce open bolls up to time TB						
5. TF = Measurement time closest to TB - 561 (DD)	1004	1004	1173	1093	1091	1184
6. Cumulative flowers to time TF	136	132	139	130	137	109
After maximum decrease in bolls and corresponding time for flowers						
7. Flowers from TF to end of effective flowering (1423 DD in 1979, 1543 DD in 1981)	20	35	17	20	25	78
8. Open bolls from TB to last harvest	34	49	17	28	37	66
9. Control flowers from TF to end of effective flowering (1423 DD in 1979, 1543 DD in 1981)	12	12	2	4	17	14
10. Control open bolls from TB to last harvest	19	19	5	12	29	18

* result of both square and boll removal

T a b l e 6

1979 Seed Cotton, all harvests

=====						
:	:	Seed cotton/boll	:	Seed cotton/:		
:	Treatment :	(g)	:	(g/m-row) :		

:	T 1	:	6.6 abc	:	544 ab	:
:	:	:	:	:	:	:
:	T 2	:	6.9 ab	:	622 a	:
:	:	:	:	:	:	:
:	T 3	:	6.1 c	:	544 ab	:
:	:	:	:	:	:	:
:	T 4	:	7.1 a	:	608 ab	:
:	:	:	:	:	:	:
:	T 5	:	7.0 ab	:	555 ab	:
:	:	:	:	:	:	:
:	T 6	:	6.6 abc	:	466 c	:
:	:	:	:	:	:	:
:	T 7	:	6.9 ab	:	556 ab	:
:	:	:	:	:	:	:
:	T 8	:	6.9 ab	:	556 ab	:
:	:	:	:	:	:	:
:	T 9	:	6.8 ab	:	614 ab	:
:	:	:	:	:	:	:
:	T10	:	7.0 ab	:	529 b	:
:	:	:	:	:	:	:
:	T11	:	7.1 ab	:	548 ab	:
:	:	:	:	:	:	:
:	T12	:	6.4 bc	:	307 d	:
:	:	:	:	:	:	:
=====						

Values in a column followed by the same letter
are not significantly different at the 0.05
level according to Duncan's Multiple Range Test

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HELIOTHIS ARMIGERA

LARVAE ON COTTON:

DAMAGE,
DEVELOPMENT TIMES
AND SURVIVAL

APPENDIX C

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B A R D

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A B S T R A C T

The damage by Heliothis armigera larvae to cotton fruiting bodies, larval development times, and larval survival rates for two years, were determined in field studies in Israel.

The larval size classes <4 mm, 4-10 mm, 10-15 mm and >15 mm were found to damage respectively .09, .58, .82 and .92 fruiting bodies/day.

Larger larvae damaged larger fruiting bodies, but even for the largest larvae only 11% of damage was to bolls. It should be noted that the period of Heliothis damage in Israel is between the end of May to July.

No significant relation was found between the distribution of damage among different sized fruiting bodies on the crop.

Development times found, in terms of degree days, were similar to those reported in the literature from constant temperature studies, except for the 5th and 6th instar classes, which were found to be shorter here.

Approximate overall larval survival was 14% in 1980 and 6% in 1981, though these values contain very large uncertainties, resulting from the difficulty in following larvae under natural conditions.

Based on the data of this study, the calculated reduction in damage per larva present resulting from insecticide use is similar for small and medium-size larvae (2.7 - 3.4 fruiting bodies/larva) and smaller for large larvae (1.7 fruiting bodies/larva).

I N T R O D U C T I O N

In Israel, Heliothis armigera is the first lepidopterous pest to appear on cotton. Save for locations in which whitefly, Bemesia tabaci Genn., occurs, H.armigera is also the first pest treated with insecticide. This pest normally appears in June, shortly after the first squares (floral buds) appear, and disappears during mid-July.

To determine realistic economic thresholds for H.armigera it is necessary to understand the population dynamics of this pest, and to quantify the damage it does to a cotton crop. Not only the total number of fruiting bodies damaged, but also the distribution of damage among fruiting bodies of different sizes determine the response of a cotton crop to damage (Kletter and Wallach, 1982).

The most detailed study concerning H.armigera damage to cotton is that of Wilson and Waite (1982). They studied the feeding preferences of H.punctigera Wallengren and H.armigera confounded in Australia. They did not measure rates of consumption, but rather assumed that the rates would be similar to those reported by Wilson and Gutierrez (1980) for H.zea.

In the present study, the rate of damage of H.armigera on cotton in Israel was studied, as well as the distribution of damage by fruit size, and its relation to the distribution of fruit sizes on the crop. In addition, durations of larval size classes were determined in the field. H.armigera development rates under constant temperatures have been reported (Pearson, 1958; Twine, 1978) but it is important to verify that the results are applicable to field conditions.

Finally, larval survival rates in the field were determined in two years, though these survivals include large uncertainties, due to the experimental difficulties. These results complement the study of Bar et al. (1979) concerning the causes of H.armigera mortality in Israel.

Combining the results concerning damage with those concerning population dynamics, it is possible to calculate the potential for damage of an arbitrary population of H.armigera, and the expected reduction in damage that could be achieved by using insecticide. Though the results apply strictly only to the conditions of this study, they are nevertheless of interest in that they provide a concrete example of the relation between what the farmer observes, namely the numbers of H.armigera, and the quantities which must determine his decision as to insecticide use, namely the damage to the crop with and without insecticide. In order to evaluate the need for control measures in detail, computer simulation models of the cotton plant-insect pest complex can be used (e.g. Wallach et al., 1980), and the data reported here provide parameters required by such models.

M A T E R I A L S A N D M E T H O D S

The 1980 and 1981 experiments were carried out at Kibbutz Maayan Zvi, in commercial irrigated fields sown to Acala SJ-2. Plot sizes were .3 ha in 1980 and .4 ha in 1981, and these plots received no insecticide against Heliothis before or during the experimental period. The 1980 plot was about 100 meter from the nearest field receiving insecticide, and the 1981 plot was adjacent to a treated field.

At various times the plots were searched for H.armigera eggs and larvae, and those found were followed subsequently until they disappeared or were found dead. If two or more similar sized larvae were found in proximity only one was followed and the others were removed, to avoid confusion. To further facilitate finding a given larva on successive days, groups of plants were isolated within a row. This practice however was discontinued when plants in different rows began to overlap. The plots were usually visited every day but sometimes there was a lapse of a day or (rarely) more between visits.

For each egg or larva followed, the location and larval size were noted at each visit. Larvae were divided into four length categories:

1. < 4 mm
2. 4-10 mm
3. 10-15 mm
4. > 15 mm

which are the categories used in scouting reports for H.armigera in Israel. At each visit a search was made around each larva for fruiting bodies exhibiting signs of feeding by H.amigera .

Those fruiting bodies likely to shed (i.e. with more than superficial damage) were categorized according to size and removed from the plant. The fruiting body size categories distinguished were small squares (<8 mm on a side), medium squares (8-15 mm), large squares (>15 mm), small bolls (<1.5 cm diameter) and large bolls (>1.5 cm). A total of 304 larvae were followed in 1980, between June 17 and July 27, and a total of 277 damaged squares and 18 damaged bolls were found. In 1981 508 larvae were followed, between June 2 and July 22, and 590 damaged squares and 20 damaged bolls were found.

In analysing the data, transitions of larvae from one size class to another were assumed to occur midway between the last observation in the smaller class and the first observation in the larger class. Damage by larvae which changed class between observations was divided equally between the two classes.

In 1980, weekly plant samples (5 2-m long sections of row) were taken from a cotton field 100 meter distant from the experimental plot. This field received the same management as the experimental plot, with the exception that the field was sprayed against Heliothis on June 10 and June 22. The plant samples were taken to the laboratory, where the numbers of fruiting bodies in each size category were counted.

Temperatures in 1980 and 1981 were recorded on a thermohydrograph within 2 km of the experimental plots. Degree days were calculated as in Wallach and Kletter (1981), using a threshold of 14° C (Pearson, 1958). (Twine (1978) however suggests a threshold of 10.6° C for larval development). Temperatures above 26° C were set equal to 26° C, since Pearson (1958) cites 26° C as the optimum temperature for H.armigera larval development.

R E S U L T S A N D D I S C U S S I O N

I Damage

The number of fruiting bodies damaged per H.armigera larva per day according to larval size class is shown in Table 1. The damage is divided by fruiting body size. These data include all larvae followed in the experiments. However, because of mortality, choosing larvae randomly in the field tends to weight younger larvae more than older larvae within a class. Therefore the damage rates were also calculated for only those individuals observed throughout a class (i.e. that were observed in both the preceding and following classes)(Table 1).

The agreement between years, and between all larvae and only those observed throughout a class, is reasonable. The best overall estimates of consumption are taken as the pooled 1980 and 1981 results for all larvae (Table 2).

The results show a trend toward greater total consumption, and consumption of larger fruiting bodies, with greater larval size. The overwhelming majority of total damage observed was to squares rather than bolls (867 buds versus 38 bolls). Of the 38 bolls damaged, 35 were small bolls. The 3 remaining bolls have been included in the small boll category in the results, for simplicity.

The observed trend toward damage to larger fruiting bodies by larger larvae is consistent with Rainey (1948), Ripper and George (1965), and Wilson and Waite (1982). However, these authors indicate considerably more boll damage than found here. Rainey

(1948) reports that 20% of 4th-6th instar larvae were found feeding on bolls 6-19 days old. Wilson and Waite (1982) found 46.3% of 5th-6th instar larvae feeding on bolls. Here the damage to bolls by >15 mm larvae (approximately 5th-6th instar) was found to be only 11% of their total damage. Ripper and George (1965) report that from the end of the 4th instar a larva consumes 2-10 bolls, while here total damage by >15 mm larvae is only about 0.5 bolls (based on a duration of the >15 mm class of 4.8 days (Table 4)).

These discrepancies are perhaps related to differences in the proportions of bolls on the crop, but this cannot be verified, since the proportions of bolls on the crop are not reported in the literature. Another cause of discrepancy is that the proportions of larvae feeding on different sized fruiting bodies is not the same as the proportions of different sized fruiting bodies caused to shed, for two reasons. Firstly, larvae may spend more time feeding on a large fruiting body than on a small one. For Heliothis zea, for example, Wilson and Gutierrez (1980) found that larvae fed much longer on medium and large bolls than on smaller fruiting bodies. Secondly, not all fruiting bodies attacked by H.armigera are caused to shed. However, Wilson and Gutierrez (1980) found for H.zea that it was primarily feeding by small larvae that was too superficial to cause shedding, while essentially all fruiting bodies attacked by large larvae were shed.

II - Relation of feeding to the availability of fruiting bodies

The model for the distribution of feeding among fruiting bodies suggested by Wilson and Gutierrez (1980) is of the general form

$$D(t)_{ij} = a_{ij} + b_{ij} O(t)_j + \epsilon_{ij} \quad (1)$$

$D(t)_{ij}$ is, for larvae of class i , the observed fraction of damage involving fruiting bodies of class j , $O(t)_j$ is the proportion of fruiting bodies of class j on the crop, a_{ij} and b_{ij} are parameters, and ϵ_{ij} is an error term. (Wilson and Gutierrez (1980) relate feeding by larvae of class i to the proportions of fruiting bodies available to those larvae, rather than to the proportions on the crop). The case $a_{ij} = 0$, $b_{ij} = 1$ for all i and j corresponds to random food selection, and the case $b_{ij} = 0$ corresponds to feeding behavior which is independent of the state of the crop. Wilson and Gutierrez (1980) tested whether feeding was independent of availability.

The data from this study were used to test the hypothesis $b_{ij} = 0$. The 1980 plant measurements shown in Table 3 provide four values of $O(t)_j$ for each j . The corresponding $D(t)_{ij}$ values are taken as the observed proportions of damage for the week centered at the plant measurement date. Ignoring those i, j values where the total damage over the four weeks was less than 10 fruiting bodies leaves 8 combinations of i and j . The calculated correlation coefficients for these 8 cases range from .23 to .78 ($df=2$). None of the correlation coefficients (and therefore none of the b_{ij}) are significantly different from zero at the 10% level. For the conditions of this study, then, the hypothesis that feeding behavior is independent of the state of the crop is not rejected.

III Development times

The calculated durations of the <4 mm, 4-10 mm and 10-15 mm larval classes (Table 4) are based on the pooled 1980 and 1981 data for larvae which were observed both in the class preceding and in the class following the class in question, since only for such larvae could the entry and exit times for the class be fixed. The >15 mm class is special, in that the following class is not observed. Rather, all >15 mm larvae not found dead eventually disappeared, without it being known whether they dropped off the plant prior to pupation (i.e. advanced to the next class), died, or simply were lost within the crop. However, the data indicate that mortality of >15 mm larvae is concentrated within the first three days of the class. Thus 35 larvae were found dead to 41 that disappeared up to three days after entry into the class, while only 2 larvae were found dead to 21 that disappeared more than 3 days after entry into the class. It is assumed then that none of the disappearances after 3 days are due to mortality, and that the class duration can be calculated as the average age of disappearance of larvae that disappeared after 3 days. The result of 4.8 days (Table 4) is close to the upper limit of age at disappearance, 5 1/2 days. (Only a single larva was observed for a longer period).

The instar equivalents shown in Table 4 are based on Reed (1965), who presents laboratory data relating instar and length, and on Ripper and George (1965). The literature values for class durations in Table 4 assume a total larval development time of 166°D_{14} (calculated from constant temperature data cited in Pearson (1958)), divided among size classes according to the data in Reed (1965).

The agreement between the literature values and the results here is quite good except for the >15 mm class. The discrepancy for this class, if real, might be due to differences in the definition of the end of the active larval period, which here is taken as the time the larva leaves the plant. (In considering damage to the crop, this is the time limit of interest).

The results here can also be compared with those of Twine (1978) who raised H.armigera larvae at constant temperatures on artificial diet. At 24.6°C, which is close to the average temperature here, he found a larval development time of 16 days, not including the prepupal period. This is quite a bit longer than the 12.5 days found here, and again the main difference is for 5th and 6th instar larvae (7.5 days versus 4.8 here). An additional possible source of discrepancy in this case is diet, which is known to alter the development rate of H.zea (Butler, 1976). However, H.zea development was found to be slower on cotton than on a semi-synthetic diet, while here the field results (the cotton diet) give a faster rate of development.

It should be noted that the coefficients of variation in Table 4 are similar for the class durations expressed in days and in degree days. In this study, that is, the effect of temperature on development rate was similar both within and between years.

IV Survival

Survival through class i (Table 5) is calculated as

$$S_i = (E_i - D_i) / E_i \quad (2)$$

where: E_i = the number of individuals that enter class i,
 D_i = the number of those that die in the class.

Eggs that disappeared are assumed to have hatched, so $E_{<4mm}$ is the number of eggs that disappeared plus the number of eggs subsequently observed as larvae. Larvae that disappeared, on the other hand, are assigned to the last class in which they were observed. That is, they are assumed not to have entered the next class.

There is a large uncertainty in evaluating the D_i , due to the large number of eggs and larvae that disappeared. Table 5 shows minimum, maximum and approximate survival values corresponding respectively to the assumptions that 0%, 100% and 50% of the lost larvae were lost because of mortality.

For the >15 mm class, the mortality assumptions are applied only to larvae that disappeared 3 days or less after entering the class, since mortality is concentrated in this period (see above). All later disappearances are assumed to have hatched, and since no direct evidence of egg mortality was observed, the egg survival consistent with the results in Table 5 is 1.0 for both years.

V Expected damage

The expectation of the damage that will be caused by a larva of a given size during the remainder of its active life depends on the expected time it will spend in its current and in each subsequent size class, and the rate of damage by larvae of each class. The expected damage values in Table 6 are based on the approximate 1980 survivals, with the expected time in each size class calculated as in Wallach (19xx). The approximate 1981 survivals give similar results. The maximum expected damage is from intermediate-sized larvae. The expected damage due to an egg or a <4 mm larva is reduced because of the probability of death before reaching a size which causes substantial damage. The expected damage due to a >15 mm larva is small because of the short time such a larva will remain active. The expected reduction in damage due to insecticide use (Table 6) is calculated assuming that the insecticide is ineffective against eggs, and kills 85% of all larvae. These represent values applicable to Israeli conditions (Sachs, unpublished data). Insecticide is most worthwhile, in terms of damage prevented per larva present, against 4-10 mm larvae. It is nearly as worthwhile against <4 mm and 4-15 mm larvae, but is substantially less worthwhile against >15 mm larvae.

In 1980, the commercial cotton field nearest the experimental plot was sprayed three times against H.armigera (twice during the experimental period and once shortly after the end of the experiment). Using the approximate survival values from the experimental plot for this field, it is possible to evaluate the effect of insecticide in the field, based on the observed field populations of H.armigera before each treatment. The calculations show that the prevented damage was very similar for all three sprays, averaging 17 squares and 2 bolls.

C O N C L U S I O N S

No significant relation was found here between the distribution of damage by H.armigera larvae among different sized fruiting bodies, and the availability of fruiting bodies on the crop. Obviously the two cannot be completely unrelated, e.g. if there are no bolls on the crop, there can be no boll damage. However, the simple assumption of a fixed pattern of damage may be a reasonable approximation to reality, especially over a limited range of growing conditions, as in the coastal region of Israel.

For the conditions of this study, the calculations presented show that the reduction in damage per larva following insecticide use is similar for small and medium sized larvae and quite a bit less for large larvae (Table 6). It is not only the total number of fruiting bodies damaged that determines the response of a cotton crop, but also the timing of the damage (Kletter and Wallach, 1982). To a first approximation, the relative reductions in damage give an idea of the relative importance to attach to each larval class in deciding whether or not to use insecticide. According to Table 6 then, small (<4 mm), medium (4-15 mm) and large (>15 mm) larvae should be weighted approximately in the proportions .8/1/.5 in deciding on control measures. In contrast, the weightings suggested in the Israeli Ministry of Agriculture recommendations are based approximately on the rates of feeding of the different classes, are 0/1/2. These weightings may lead to the situation where insecticide is not used even though a large reduction in damage could be obtained, only to be used later with a smaller reduction in damage. It must be emphasized that the calculations here are based on survivals which contain a very large element of uncertainty. It is important to determine survivals more accurately, and over a range of conditions.

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T a b l e 1
H.armigera damage to cotton fruiting bodies

		Fruiting bodies damaged/larva/day					
Experiment	Larval	size	small	medium	large	small	all fruiting:
	class	squares:	squares:	squares:	squares:	bolts :	bodies :
1980	<4mm	.04	.03	--	--	.07	
all	4-10mm	.34	.12	.01	<.01	.48	
larvae	10-15mm	.46	.19	.05	.02	.72	
	>15mm	.24	.32	.25	.11	.92	
1981	<4mm	.08	.02	--	--	.10	
all	4-10mm	.46	.12	.04	<.01	.63	
larvae	10-15mm	.46	.24	.15	.02	.87	
	>15mm	.30	.19	.33	.10	.93	
1980+1981							
larvae	<4mm					.10	
observed	4-10mm					.49	
throughout	10-15mm					.71	
class							

T a b l e 2
H.armigera damage to cotton fruiting bodies
Best estimates (Pooled 1980 and 1981 results)

		Fruiting bodies damaged/larva/day					
Larval	(% of total damage by this larval class)	Fruiting bodies:					
size		damaged/larva :					
class		small	medium	large	small	total	over entire
		squares:	squares:	squares:	bolts :	fruiting:	class
					bodies :	bodies :	
< 4mm	.06	.02	--	--	.09	.24	
	(72%)	(27%)					
4-10mm	.43	.12	.03	.01	.58	1.74	
	(73%)	(20%)	(6%)	(1%)			
10-15mm	.46	.23	.12	.02	.82	1.64	
	(56%)	(27%)	(15%)	(2%)			
>15mm	.27	.26	.29	.11	.92	4.42	
	(29%)	(28%)	(31%)	(11%)			

T a b l e 3

Fruiting bodies on the cotton crop 1980

D a t e	Numbers of fruiting bodies (number/m-row) (% of total fruiting bodies for given date)					
	Small squares	Medium squares	Large squares	Small bolls	Large bolls	
29/6	118 (53%)	39 (17%)	50 (22%)	15 (7%)	1 (<1%)	
6/7	114 (43%)	51 (19%)	75 (28%)	19 (7%)	6 (2%)	
13/7	93 (33%)	31 (11%)	111 (40%)	32 (11%)	14 (5%)	
20/7	93 (37%)	20 (8%)	72 (29%)	39 (16%)	26 (10%)	

T a b l e 4

Heliothis armigera larval development times

Larval size	Approximate instar equivalent	Sample size	Class duration (coefficient of variation)		
			days	degree days	Literature (degree days)
<4 mm	1+2	16	2.7 (.33)	31 (.35)	35
4-10 mm	3	24	3.0 (.37)	30 (.53)	30
10-15 mm	4	54	2.0 (.45)	20 (.45)	17
>15 mm	5+6	21	4.8 (.17)	50 (.16)	62

T a b l e 5

H.armigera larval survival probabilities
through indicated interval

=====					
:	No. of larvae:	Minimum	:	Maximum	Approximate:
:	Interval	at start of	:	:	:
:	:	interval	:	survival	survival

:	1980	:	:	:	:
:	hatch - 4 mm	:	:	:	:
:	4 - 15 mm	:	:	:	:
:	15 mm-leave plant:	:	:	:	:
:	hatch-leave plant:	:	:	:	:

:	1981	:	:	:	:
:	hatch - 4 mm	:	:	:	:
:	4 - 15 mm	:	:	:	:
:	15 mm-leave plant:	:	:	:	:
:	hatch-leave plant:	:	:	:	:
=====					

* Survival values calculated as products of survivals for individual intervals.

T a b l e 6

Expected damage by H.armigera to cotton and expected
reduction in damage due to insecticide use,
using approximate 1980 survival values

=====					
:	Expected damage	:	Expected reduction in damage:	:	:
:	(fruiting bodies/individual)	:	(fruiting bodies/individual):	:	:
:	Class	-----			
:	Squares	:	Bolls	:	Squares
:	:	:	:	:	Bolls

:	egg	:	:	:	:
:	4mm	:	:	:	:
:	4-10mm	:	:	:	:
:	10-15mm	:	:	:	:
:	>15mm	:	:	:	:
=====

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HADERA Region
Israel Department of Agriculture

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PRODENIA (SPODOPTERA LITTORALIS)
(PRELIMINARY FIELD STUDIES)

APPENDIX D

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B A R D

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INTRODUCTION

Prodenia (*Spodoptera littoralis*) is one of the major cotton pest species in the coastal plains region of Israel. Persistence of this pest in the region is facilitated by the large number of agricultural crop species that provide for over-wintering.

The cotton crop is damaged by *Prodenia* through the eating of leaves and by direct damage to floral buds, flowers and small bolls. If the supply of these preferred plant parts is severely limiting, *Prodenia* has been observed to damage large bolls and even stems.

Eggs are generally laid on the underside of leaves in the uppermost layer of the canopy. A single laying consists of an irregularly shaped egg mass of some 50 to 500 eggs arranged in 2 or 3 layers. At the end of the laying process, the female covers the egg mass with a mesh of brown hairs. Eggs hatch almost simultaneously after 2 to 3 days in summer conditions. Larva feed initially on the oviposition leaf, though they soon spread within the plant and to neighbouring plants. The majority of larvae feed on vegetative plant parts whilst a small proportion feeds on fruiting forms.

In the early stages of development, larvae do not generally leave the plant. Only large larvae of the 4th and 5th instars tend to conceal themselves in the soil during the day and return to the plant to feed at night. Large larvae damage virtually all plants parts and frequently cause serious damage to the apical mainstem of the plant. Pupation occurs in the soil.

In the past, *Prodenia* infested the cotton crop in the coastal plains region from the middle or end of June till harvest; some 80 to 100 days or three to four generations. In recent years, however, the infestation period has almost halved, being concentrated in the latter half of the growing season. Since the pest immigrates into the cotton field from other host species in the region, there is considerable overlap of life cycles. As a result, the farmer witnesses a steady increase in the population through time (in an uncontrolled field) as opposed to the cyclic population dynamics characteristic of many other pest species (e.g. Heliothis).

The gradual contraction of the infestation period of *Prodenia* over recent years may be attributed to four factors:

1. The transition of agriculture in the region towards virtual monoculture of cotton and hence the disappearance of crops that previously provided over-wintering (e.g. sugar-beet, alfalfa, potatoes).
2. The activity of natural enemies - research over recent years has led to a significant reduction in the number of sprays against Heliothis early in the season and this has enabled populations of natural parasitic and predatory species of *Prodenia* to maintain more effective densities. This in turn has resulted in a reduction in the rate of increase in the *Prodenia* population in the early stages of the growing season.
3. The development and widespread use of relatively effective pesticides against *Prodenia* in both cotton fields and other crops that provide over-wintering.

4. The use of chemicals against whitefly (Bemisia tabaci) that are also effective against Prodenia. This is undoubtedly an important factor since whitefly has emerged over recent years as one of the major pest species of cotton in the region.

The build-up of insecticide resistance in Prodenia occurs relatively rapidly. Over the last 30 years, farmers have witnessed the development of resistance to 5 or 6 different insecticides that were initially very effective.

The purpose of the preliminary field studies reported here is to provide basic information concerning the spatial distribution of the pest in the field, survival rates of the various size classes, plant parts damaged by the pest, and the rate of damage according to larval size. The aspect of spatial heterogeneity is of particular importance, since distribution of larvae in the field is extremely clumped and this represents a problem not previously handled in this project.

MATERIALS AND METHODS

Field studies were conducted during the 1982 and 1983 growing seasons. Medium- to large-sized egg masses were located in the field, marked and observed daily until the disappearance of all larvae. For the first day or two after hatching, larval numbers were estimated only. Subsequently, exact counts were made. For each plant infested by larvae from a single egg mass, the following data were recorded daily:

1. Identification of the plant according to a co-ordinate system based on row number and plant number within the row relative to the oviposition plant.
2. The mean size of larva in mm.
3. The number of larvae found on leaves, buds, flowers, small bolls and large bolls.
4. The number of buds, flowers and bolls damaged since the previous visit (damaged fruiting forms were marked).
5. A subjective estimate of leaf damage on a scale of 0 to 4.
6. The number of dead larvae found on the plant. Plants adjacent to the zone of infestation were searched for newly laid egg masses. These egg masses were destroyed to avoid overlapping.

RESULTS

Due to a number of technical problems in data entry for computer analysis, detailed analyses of the data are not yet available. The following results are based on preliminary calculations by hand.

In both years of observations, the rate of decline in larval numbers from individual egg masses was found to be extremely rapid. Within 7 to 10 days, only a few larvae remained from an egg mass of about 300 eggs. Survival of larvae till the final instar stages was almost negligible.

The majority of damage by all larval classes was to leaves. Only 10 to 20% of larvae were found on buds or bolls, though there appeared to be a strong preference for flowers. Damage to fruiting bodies was predominantly by medium- to large-size larvae. Damage to leaf area reached significant levels on the central oviposition plant and plants adjacent within the row.

The spread of larvae from a single egg mass was mainly within the row, though larvae often reached positions two rows to either side of the central plant. There was a clear tendency for the infestation area to spread more rapidly in the direction of the predominant winds.

DISCUSSION

In both years of field studies, the population of Prodenia in the region was relatively low and occurred relatively late in the season. This limited the quantity of data that could be collected from individual fields.

Damage levels in infested fields were also less serious than is normally encountered. It appears that the previous spraying history of a particular field may be important in determining survival rates of Prodenia and in future studies, care will be taken to differentiate between fields that have or have not received insecticide applications prior to the commencement of observations.

The particular chemicals used should also be considered in terms of their effect on Prodenia and natural enemies of Prodenia such as Crysopa carnea , Orius and various parasitic wasp species. Field observations of Prodenia will continue in forthcoming growing seasons.

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THE EFFECT OF BEMISIA TABACI
ON COTTON DEVELOPMENT AND YIELD

APPENDIX E

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A B S T R A C T

A technique was developed for investigating the effect of whitefly (Bemisia tabaci) on the development and yield of the cotton plant in growth chambers.

A number of initial trials were required to overcome various technical problems involved in sustaining a high-density monoculture infestation. In one trial, a high level of infestation was achieved for a period of about two weeks towards the end of flowering. There was no significant effect on seed cotton yield though a trend of reduced boll weight was apparent.

Bemisia infestation caused a significant increase in lint sugar content. Mean percentage sugar content in the control and infested treatments was 0.289 and 0.578, respectively. Since the period of infestation terminated before boll opening, this effect cannot be ascribed to direct contamination by honey-dew. These preliminary results indicate that effective control of Bemisia in the field is important considerably earlier in the season than was previously assumed.

M A T E R I A L S A N D M E T H O D S

The experiments were conducted during the winter months in the greenhouse and growth chambers of the Gan Hashomron Experimental Station. Lighting in the growth chambers was 14 hours at about half natural daylight intensity and 10 hours dark. Temperature was maintained at 28 and 18 degrees C during light and dark hours, respectively. 30 plants were grown in separate 10 liter buckets. An adequate supply of fertilizer and water was provided. Plants were kept free of insect infestation prior to transfer to the growth chambers. Daily flower counts were taken from start of flowering.

After about 4 months growth in the greenhouse, 15 plants were allocated to the control treatment and transferred to a growth chamber. A further 15 plants, similar in size to the control plants, were allocated to the infestation treatment and transferred to a second growth chamber. Infestation was achieved by introducing a small population of Bemisia tabaci, consisting largely of eggs and a few adult larvae, on 6 immature cotton plants. Plants were kept in the growth chambers for about 4 weeks after introduction of the small whitefly population. This allowed for one generation of large larvae at a high infestation level. At the end of this period, plants of both treatments were sprayed against whitefly and returned to the greenhouse till full maturity.

Daily flower counts continued in the growth chambers till the end of flowering. One day before plants were returned to the greenhouse, a count was taken of whitefly infestation. 2 plants from each treatment were taken to the laboratory and the number of insects on every leaf of each plant was counted. For the remaining 13 plants of each treatment, the number of insects at 10 specific leaf positions was counted.

The date of opening of all bolls was recorded. Seed cotton and lint yield was weighed separately for all plants. Quality checking was carried out for each plant separately.

R E S U L T S A N D D I S C U S S I O N

In 1980 and 1981 the experiments had to be abandoned due to technical faults in the growth chambers.

In 1982, a first series of plants was sown on 5 October and plants were transferred to the growth chambers on 15 February, 1983. The whitefly population died out soon after introduction. This was apparently due to the previous use of Cypermethrin in the greenhouse. Presumably, exposure to direct sunlight accelerates breakdown of this chemical. Under greenhouse conditions, the chemical persisted much longer than under field conditions and prevented effective infestation of whitefly some time later when the plants were transferred to the growth chambers.

In the second series (sowing on 7 November, 1982), plants were found to be infested with red spider mites after transfer to the growth chambers. Insecticide could not be used without killing the whitefly so Phytoseiulus persimilies, a natural predator of the mite, was introduced into the growth chambers. Unfortunately, the whitefly population also contained a number of Encarsia formosa wasps which reduced the population and caused early termination of the experiment.

The third series (sowing on 9 December, 1982) was successful. Plants were transferred from the greenhouse to the growth chambers on 14 April, 1983. Counts of whitefly infestation started on 5 May and plants were returned to the greenhouse and sprayed on 10 May. This permitted about 2 weeks of infestation at a very high level. Cumulative flowering for the control and infested plants is shown in Figure 1. Differences in cumulative flowering were not significant at any point.

Whitefly infestation for plants taken to the laboratory for complete counting was as follows:

	<u>Small larvae</u>	<u>Large larvae</u>
Control : 1st plant	61	1
2nd plant	48	7
	--	-
Average	55	4
Infested : 1st plant	2095	863
2nd plant	1811	557
	----	---
Average	1953	710

Larval counts for the 10 leaf positions for plants returned to the greenhouse are shown in Table 1. Yield and its components for the two treatments is shown in Table 2. The short period of high infestation had no significant effect on yield or its components though there is some indication of an effect on boll weight.

Quality checking was carried out about 6 months after termination of the experiment. Bemisia infestation had no effect on Presley, micronaire, fibrograph or uniformity. However, there was a significant increase in lint sugar content (Table 3).

C O N C L U S I O N S

The experimental techniques for the successful control, infestation and monitoring of the whitefly have been established.

A high level of infestation over a relatively short period of time during the late flowering phase is insufficient to cause a significant effect on yield or its components. However, a significant increase in lint sugar content is obtained.

Since the infestation period terminated prior to the commencement of boll opening, these results clearly demonstrate that increased sugar content is not solely a consequence of direct contamination by honey-dew but also derives from physiological effects considerably earlier in plant development. The apparent extent of this effect may suggest the need for more stringent control of Bemisia earlier in the season than is currently practiced. A series of growth chamber experiments is planned which will focus on the effects of timing, level and duration of whitefly infestation.

T a b l e 1

Larval counts of whitefly for 13 plants
at end of infestation period

=====										
:	:	Small larvae		:	Large larvae		:			
:	Leaf position	-----								
:	:	Control	:	Infested	:	Control	:	Infested	:	

:	5th leaf from top	::	0.8 b	:	130.7 a	:	0.4 b	:	52.5 a	:
:	6th leaf from top	::	1.3 b	:	113.1 a	:	0.2 b	:	42.0 a	:
:	7th leaf from top	::	2.8 b	:	134.8 a	:	0.0 b	:	44.7 a	:
:	Branch 6, position 4	::	1.0 b	:	63.5 a	:	0.1 b	:	13.1 a	:
:	Branch 8, position 2	::	0.5 b	:	143.7 a	:	0.0 b	:	38.5 a	:
:	Branch 9, position 2	::	0.2 b	:	50.6 a	:	0.1 b	:	24.6 a	:
:	Branch 12, position 0	::	0.6 b	:	161.5 a	:	0.0 b	:	51.7 a	:
:	Branch 12, position 1	::	0.3 b	:	95.2 a	:	0.0 b	:	38.5 a	:
:	Branch 13, position 0	::	1.5 b	:	163.6 a	:	0.4 b	:	45.8 a	:
:	Branch 13, position 1	::	0.9 b	:	79.5 a	:	0.1 b	:	29.9 a	:

:	mean	::	0.99 b	:	113.6 a	:	0.13 b	:	38.1 a	:
=====										

Numbers within a row followed by the same letter are not significantly different at the 0.05 level according to Duncan's Multiple Range Test.

T a b l e 2

The effect of whitefly infestation on yield
and its components

:	:	Control	:	Infested	:
:	Seed cotton yield (g/plant)	54.3 a	:	52.4 a	:
:	Lint yield (g/plant)	22.9 a	:	22.0 a	:
:	Percentage lint	42.1 a	:	41.8 a	:
:	No. of bolls per plant	10.0 a	:	10.1 a	:
:	Lint yield per boll (g)	2.4 a	:	2.2 a	:
:	Boll weight (g)	5.7 a	:	5.2 a	:

Numbers within a row followed by the same letter are not significantly different at the 0.05 level according to Duncan's Multiple Range Test.

T a b l e 3

The effect of whitefly on lint quality

:	:	Control	:	Infested	:	F value	:
:	Fibrograph 25	114.9	:	112.8	:	N.S.	:
:	Presley	88.3	:	89.1	:	N.S.	:
:	Micromaire	44.5	:	43.2	:	N.S.	:
:	Uniformity	48.9	:	48.1	:	N.S.	:
:	Sugar content (%)	0.289	:	0.578	:	27.21**	:

FIGURE 1.

- 9 -

THE EFFECT OF WHITE FLY INFESTATION
ON CUMULATIVE FLOWERING

THE TEXAS AGRICULTURAL EXPERIMENT STATION

TEXAS A&M UNIVERSITY, COLLEGE STATION, TEXAS

BIOLOGICAL STUDIES

APPENDIX F

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BIOLOGICAL STUDIES

Studies were carried out in 1983 which were designed to provide quantitative and qualitative biological data describing relationships of *Heliothis* development and host plant nutrition in cotton. These studies quantified *Heliothis virescens* larval establishment and survival in relation to nitrogen fertilization and how that relation is affected by irrigation interactions. Also included were investigations of the effects of N and irrigation on natural populations of *Heliothis* spp. and related damage and damage inflicted by boll weevil *Anthonomus grandis* Boheman.

A detailed discussion of these biological studies follows. Included are results from a greenhouse, field nitrogen study, field cage, and an irrigation - nitrogen field study. Data from these studies will provide baseline biological data for future modelling work.

MATERIALS AND METHODS

Greenhouse Experiments

Greenhouse studies conducted in Spring 1983 were designed to develop various techniques for field experiments which followed in the summer. Several experiments were designed to test various artificial infestation techniques and to determine the appropriate life stage of *Heliothis* to be used. In the final analysis use of neonate larvae rather than eggs for field studies was deemed more suitable. The time required in securing eggs on plants was considered excessive as was the additional variability associated with eggs (i.e. infertility, greater potential for damage etc.). Insects used in the preliminary greenhouse studies were *Heliothis zea* (Boddie) which were reared at Texas A & M. Because of recurring disease problems due to a Protozoan infection, the colony was destroyed after greenhouse studies were terminated. Another source provided *Heliothis* larvae for field studies. Limited success was

achieved in the greenhouse studies with regard to insect establishments, however, much was accomplished in terms of perfecting techniques. One greenhouse nitrogen study is briefly described below.

The cotton cultivar, Stoneville 825, was planted in 1/2 gallon plastic pots filled with peat, vermiculite, and sand mixed in equal proportions. There were 2 plants per pot. A slightly modified Hoagland's solution (1/4 strength) was used as nutrient solution. This was delivered in 200 ml H₂O per pot. Nitrogen was provided as Ca(NO₃)₂. The nutrient solution was applied on 3 occasions; when seedlings emerged, 18 days later, and then 18 days later. The total N delivered per pot in 3 applications were 0.14, 0.43, 0.86, and 1.4 g N per plot (hereafter referred to as 1, 3, 6, 10). The study was arranged in a randomized complete block design with 4 replications. Ten plants per nitrogen (N) treatment constituted one replication. Plants within each treatment were selected for uniformity and total number of fruiting forms per plant were recorded. For artificial infestations one neonate (<6 hr) *H. zea* was transferred to the terminal of each plant. Seven days following infestation surviving larvae were collected and taken back to the laboratory where they were weighed. Data were analyzed using an analysis of variance technique.

Field Nitrogen Study

A field study designed to determine the effects of varying levels of nitrogen (N) on establishment of *Heliothis virescens* was performed in the summer of 1983 on research near the campus of Texas A & M University.

Field Properties and Fertilization

The cotton cultivar, Stoneville 825, was planted on April 19 on a Lufkin fine sandy loam soil. Exceptionally dry and cool weather delayed germination and retarded seedling growth in the first 3 weeks following planting. This weather was followed by a particularly heavy rainfall period in which rainfall accumulation was in excess of 18 cm. Because of these poor weather conditions,

application of N was delayed until June 9. At that time N was applied as a sidedress of ammonium nitrate containing 34 percent N using a modified single row hand planter calibrated to deliver desired amounts of fertilizer per unit area. Application was made ca. 10 cm from the plant in a small furrow ca. 4 cm deep which was then covered. The cotton was at ca. 3 true leaf stage.

Fertilizer treatments were different rates of N at 20, 60, 120, and 200 lbs/ac (22.4, 67.2, 134.8, and 224 kg/ha) equivalents replicated 4 times in a randomized complete block design. Individual plots consisted of 4 rows 97 cm apart and 11 m long. No other fertilizer inputs were required according to soil test analyzations by Texas Soil Testing Laboratory procedures. Irrigation was applied as needed throughout the growing season by flooding the furrows using gated pipe.

Three insecticide applications for boll weevil control were made prior to commencement of insect studies in order to assure adequate fruiting densities for *Heliothis* studies. Phosmet (Imidan®) was applied on June 30, July 5, and July 10 at the manufacturer's recommended dosage..

Insect Studies

Natural Populations

Plant growth and development and natural insect population levels were monitored using whole plant sampling procedures. These samples were made in each treatment at weekly intervals beginning 10 weeks after planting, continuing through week 19. Whole plant samples were conducted with five consecutive plants randomly selected within each plot. An attempt was made not to sample any plant more than once during the duration of the study. Whole plant examinations were performed by searching all plant parts beginning with the meristematic terminal areas and working down the plant. All squares (flower buds), blooms (white blooms only) and bolls (including red blooms) were examined for evidence of damage and *Heliothis* spp. larvae. Total numbers of

squares, blooms, bolls, *Heliothis* damaged small squares (<2mm), large squares (>2mm), blooms, small bolls (<7mm), large bolls (>7mm), boll weevil damaged squares, and 1st, 2nd, and large instar *Heliothis* larvae were recorded per plant.

Artificial Infestations

Heliothis establishment and survival was further investigated in artificial infestation studies in the field N study. Weekly shipments of *Heliothis virescens* pupae obtained from the Insect Rearing Facility of the Agricultural Research Service, United States Department of Agriculture at Stoneville, Mississippi allowed continuous supply of eggs.

Ten consecutive plants, randomly selected within each plot were selected, tagged, then subjected to whole plant examination one day prior to artificial infestations. Any *Heliothis* eggs, larvae, or damage was removed; if the terminal was damaged the plant was rejected. Plants and surrounding rows were then sprayed with a low rate of malathion to decrease numbers of natural enemies. At dusk on the following evening, 2 neonate (<6 hours old) larvae were placed on the terminal (top 4 cm of the plant) of each tagged plant using a camel's hair brush. Seven days later, whole plant examinations of tagged plants were performed and larvae collected. Larvae were placed in 7 ml plastic cups, put on ice and transferred back to the lab where they were weighed then stored in the freezer until they could be examined and species identification made. Whole plant examinations were repeated the following day and total fruit and damage recorded.

Two attempts were made at artificial infestation in the field nitrogen (field N) plots, however the first experiment failed. This failure was apparently due to insecticide drift from an adjacent field the morning following infestation. The second attempt, on July 31, was successful in that there was larval survival and recovery. Results were analyzed using an analysis of variance technique.

Plant Analysis

Plant N levels were monitored using petiole analysis of nitrate nitrogen ($\text{NO}_3\text{O-N}$). Petiole samples were taken from each plot at weekly intervals beginning the 11th week following planting and continued until week 17. Each sample contained 12 to 16 petioles of fully expanded leaves of the 4th or 5th vegetative node below the terminal of randomly selected plants within each treatment. Samples were dried at 70 °C overnight and stored until $\text{NO}_3\text{-N}$ determinations could be made.

Determinations for $\text{NO}_3\text{-N}$ were made on petiole samples by extracting with 0.025 M aluminum sulphate, containing 10 ppm $\text{NO}_3\text{-N}$, in a plant material:extractant ratio in the range of 1:100 to 1:800 (w:v) depending upon the concentration. This is a modification of the procedure described by Baker and Smith (1969). Measurements were made with a nitrate electrode and an expanded scale pH meter.

In addition to petiole collection, two weekly samples of 5 leaves were made for analysis of soluble carbohydrates. Samples were taken from the topmost unfurled leaves of the plants and from 4 nodes below the first sample on the same plant. All samples were placed on ice in the field, and transported to the laboratory. Leaf samples were dried in the same manner as the petioles.

These samples were ground in a Wiley mill to pass through a 40-mesh sieve and thoroughly mixed. Soluble carbohydrates were determined using a modification (Tom Cothran, personal communication) of the phenol-sulfuric colorimetric method described by Dubois (1951).

Additional samples were collected for determination of condensed tannin contents of leaves and squares. At least 8 nurse leaves from the 4th or 5th node below the terminal were selected from randomly selected plants in each treatment. One .25-.5 cm square from the 10-12 node below the terminal was collected from at least 8 plants. Samples were placed in small manila envelopes and were quick frozen by submersing them in liquid nitrogen. Samples

were then placed on ice and transported to the laboratory where they were stored in the freezer. Care was taken not to injure the tissue.

Harvested leaves and squares were freeze dried, and ground to pass through a 40 mesh screen. Condensed tannins were extracted with butanol-HCL (95:5,v:v) at 98°C and determined using the method described by Bell and Stipanovic (1972).

Field Exclusion Cage Study

A field cage study was carried out to examine the effects of low and high N levels on *H. virescens* survival without interference of other insects.

Field Properties and Fertilization

Stoneville 825 was planted adjacent to the field N study on May 31. Each plot in the field cage study consisted of two rows 11 m long. On June 10, N as ammonium nitrate was applied as a sidedress at rates of 20 and 200 lb/ac equivalents (22.4 and 224 kg/ha) when the plants were at ca. 2nd true leaf stage. Fertilizer treatments were randomized within each plot with 3 replications. When the cotton was 30 days old, three 11 X 1.8 m exclusion cages (Chicopee brand fabric, style 5003800) were erected over plots so that both rows were contained in a cage. Cages were then treated with 0.25 lb/ac equivalent of azinphosmethyl for boll weevil control. Irrigation was applied as need by flooding furrows.

Insect Studies and Plant Sampling

Heliothis establishment was measured using the technique outlined in the field N study. This experiment was repeated 4 times during the summer on August 1, August 11, August 15, and August 26. For each trial, five plants were selected and tagged in each treatment, except on August 11 when 10 plants per treatment were used. Since the experiments were carried out within exclusion cages, plants were free of natural insect infestation. Plants selected for infestation were at least 1 m from the next tagged plant. Two

neonate *H. virescens* larvae were placed on the terminal of each tagged plant in the very early morning while temperatures were cool. Seven days after infestation, each plant was examined and total squares, blooms, bolls and damage recorded. Plants adjacent to tagged plants were also searched if there was evidence of larval migration. Larvae were handled as described in the field N experiment. During the week of each experiment, plant samples were collected for nitrate petiole testing, carbohydrate and tannin analysis. Sampling procedures were the same as outlined in the field N experiment. Data were analyzed using t-test.

Field Irrigation-Nitrogen Study

A field study to determine the possible effects of interactions of water and nitrogen use in cotton on *Heliothis* establishment was conducted in plots adjacent to the field N and field cage studies in 1983.

Field Properties and Fertilization

Test plots of Stoneville 825 were planted on May 31, an earlier planting had been destroyed by flooding after heavy rains. The experiment was arranged in a split plot design with 2 levels of water input--natural rainfall only and rainfall plus supplemental irrigation to be applied to maintain plots at 50% field capacity. Soil moisture levels were measured with tensiometers to permit proper timing of irrigation. Within the irrigation main plots were N subplots; nitrogen was applied at rates equivalent to 20, 60, and 120 lbs N per acre (22.4, 67.2, and 134.8 kg/ha). Blocks were replicated 3 times.

Because of the soil type (fine sandy loam) frequent irrigations were required to maintain mainplots at or above 50% of field capacity. Since the movement of irrigation water by furrows on coarse textured soil is mainly downward with little lateral penetration, short furrows, small application times and small depths of water applied are required for efficient irrigation. In this study, water was delivered to irrigated main plots through 3/4 inch.

(1.9 cm) garden hose modified to have two female ends. At the top of the plot the hose was connected to a 3/4 inch (1.9 cm) male/male PVC valve. This valve was attached to a threaded PVC elbow connected to a 12.2 m section of 3/4 inch (1.9 cm) schedule 12 PVC pipe capped at the end. The pipe was laid across the top of the plot with a 0.32 cm diameter hole drilled every 91 cm to allow flow into each furrow. The holes were drilled on the opposite of the direction of flow in the furrow to minimize potential erosion problems. Pieces of broken clay pots were placed beneath the holes to further decrease erosion. Row dikes were shoveled in at the base and top of each furrow.

Water flow through the PVC was controlled using the valve at the hose connection. Using this procedure, irrigation could be applied easily and with reasonable precision so as to deliver comparable irrigations to each main plot. There were no insecticidal applications for boll weevil control.

Insect Studies

Natural Populations

Sampling procedures for monitoring plant growth and development and for natural *Heliothis* populations were similar to those described in the field N study. Whole plant examinations commenced 6 weeks following planting and continued through week 16.

Artificial Infestations

Techniques for artificial infestation of test plots were similar to those described in the field N study, except that only 5 plants were selected per treatment. Infestations with 2 neonate *H. virescens* larvae per plant were performed on 3 different dates: August 14, August 15, and August 30. Severe weather conditions precluded additional tests in mid August. All results were subjected to an analysis of variance.

Plant Analysis

Weekly plant samples were collected for nitrate testing, and carbohydrate and condensed tannin analysis beginning week 12 and continued through week 16.

RESULTS

Greenhouse Experiments

Results from the greenhouse experiment are presented in Table A1 in the appendix. There were slightly more larvae recovered per plant in the highest N treatment, but there were no significant differences. Similarly, there were no differences in larval weights. There were significantly more squares and bolls per plant as N concentration increased. The trend was less obvious in total blooms, although highest number of blooms per plant were observed in the high N treatment.

Field Nitrogen Study

Summaries of insect survival and damage to plants, and plant phenology and yield data from the field N study are located in Tables 1-6 in the appendix.

Insect Studies

Artificial Infestations

The mean number of larvae recovered per plant and their average weights, and total squares, blooms, and bolls per plant, and total *Heliothis* damage per plant are presented in Table 1. The number of *H. virescens* larvae recovered following artificial infestation was significantly ($p=0.05$) higher as the level of N fertilization increased. This was interpreted as a significant increase in larval establishment. Seven days following release of 2 neonate larvae per terminal on ten plants, 0.34, 0.39, 0.75, and 0.78 larvae were found per plant in the 20, 60, 120, and 200 lb/ac treatments, respectively. Nitrogen fertilization did not significantly affect the weights of larvae although the weights of larvae recovered in the 120 and 200 lb/ac treatments were slightly

higher than weights of larvae collected in the lower N plots.

Mean numbers of squares, blooms, and bolls also increased significantly as N fertilization increased. Terminal damage per plant was highest in the 60 and 120 lb/ac treatments with damage in the 20 and 200 lb/ac treatments less severe. The number of *Heliothis* damaged small squares and small bolls was higher in the 200 lb/ac plots, but there were no differences in damaged large squares, blooms, and large bolls.

Natural Populations

Generally, there were relatively low numbers of natural *Heliothis* larvae observed in the field N study. The mean number of larvae of each stage (1st and 2nd instar and large larvae) found per plant in weekly samples in field N plots are presented in Table 2. Second instar larvae were first observed in week 12. First instar and large larvae were not observed in plots until week 15 at which time populations began to increase. Peak levels of all stages were observed in weeks 16 and 17. There appeared to be no difference in the numbers of larvae observed in various N treatments. This was true for all stages observed.

Mean numbers of squares, blooms, and bolls observed per week in N treatments are listed in Table 3. The first squares were observed in weeks 8 and 9. Beginning in week 11, a squaring response to N fertilization became evident with greater numbers of squares/plant in the higher N plots. This trend more or less continued throughout the sampling period although in some weeks there appeared to be no difference in total number of squares per plant in all treatments. Generally, the greatest number of squares were found in the 200 lbs/ac treatment; this was particularly true as the season progressed and cotton in low N plots began to "cut-out" (i.e. mature). This was observed in low N plots ca. 3 weeks earlier than in high N plots.

Blooms were first observed in week 12 in the 200 lb/ac treatment. There was no significant response to N treatments early in the blooming period,

however by week 16 and continuing until week 19, there was a trend of increased numbers of blooms in the higher N plots.

A N response was much more evident in boll sampling. This was especially obvious by the 16th week continuing through week 19. Presented in Table 9 is a summary of open bolls per week and final yields in the field N study. Although there was no apparent difference in the numbers of open bolls per plant in the final week of sampling (week 19), there was a significant yield response to N, with highest yields occurring in the high N treatments.

In Table 4, mean *Heliothis* fruit and terminal damage per plant per week is presented. Although there appeared to be no differences in the number of *Heliothis* larvae in treatment plots, there were periods when differences in damage levels occurred. Terminal damage during week 16 was greatest in the 60 and 120 lb/ac plots; in week 17 damage was significantly greater in the highest N plot. Small square damage was similarly greatest in the high N plot during week 16, however, in other weeks there were no differences between treatments. In weeks 16-18, there were high levels of large square damage. In week 17 and 18 there was a significant N response in that higher N fertilized plots were observed to have the greatest amount of large square damage. Damage to white blooms showed a significant N response in week 17 also. Small and large boll damage did not differ with regard to N fertilization, although there were slightly higher levels of damage in the high N plots during several weeks.

In weeks 15-19, highest levels of boll weevil damaged squares were observed in the 200 lb/ac plots. These data are presented in Table 6. There was a significant N response in week 17; during this sampling period boll weevil damage in the 200 lb/ac plots was nearly 3 times greater than that in the 20 lb/ac plots.

Data presented in Table 3 indicate that there were 2 times the number of squares in the high N plot than the lower N treatments, however, damage by *Heliothis* and boll weevil appears to have decreased those numbers such that there

were fewer blooms in this treatment in the next sampling period (Table 3).

Plant Analysis

Analyses of plant nitrate, carbohydrates, and condensed tannins are not yet complete; these should be completed before May 1.

Field Exclusion Cage Study

A summary of results from the the four field cage tests is presented in Table 7. In the tests performed on August 1, August 11, and August 26 significantly more larvae were recovered on the 200 lb/ac N fertilized plants than on the 20 lb/ac plants. This higher rate of recovery was interpreted as differences in larval establishment and recovery. In each of these tests there were more than 2 times greater larvae recovered per plant in the high N treatment than in the low N treatment. There were slightly more larvae recovered in the high N treatment on the August 15 test but there was no significant difference in the levels of larval establishment. When results from all tests were combined, a mean of 0.63 larvae were in the 20 lb/ac treatment, and in the 200 lb/ac treatment there were 1.15 larvae recovered per plant.

There were no significant differences in weights of larvae recovered from the 2 N treatments, although in all tests, weights were slightly higher in the low N treatments than the high N treatments.

There were no significant differences in numbers of squares, bloom, bolls, or nodes/plant in the August 1 test. In the August 15 test there were significantly greater numbers of squares in the high N treatment. There were a greater number of blooms in the 200 lb/ac treatment in the August 11 test. In the August 26 test, greater numbers of bolls were observed in the high N treatment.

The number of damage plant parts were comparable between N treatments for all tests with only a few exceptions. Significantly higher numbers of damaged

small squares were observed in the August 1 test. In the August 11 test, there was significantly greater damage of terminals, small squares, large squares, small bolls, and large bolls. There was a slightly higher number of damaged blooms in the high N treatments on this date, however, those differences were not significant. Higher damage levels in the August 11 test could have been due to the longer period of larval feeding during that particular test; poor weather conditions delayed sampling of plants resulting in 2 additional days for larval feeding.

There were no significant differences in larval damage between N treatments in the August 15. In the August 26 test, small square damage was significantly higher in the high N treatment.

Field Irrigation-Nitrogen Study

Summaries of results and observations in the irrigation - nitrogen (I - N) study are presented in Tables 8-33.

Artificial Infestations

Irrigation - nitrogen plots were artificially infested with *H. virescens* on three different dates. In Table 8, combined results from those 3 tests are presented. Tables 9, 10, and 11 present data from the August 14, August 15, and August 30 tests, respectively.

Examination of the data presented in Table 8 indicates that there was no significant effect of N in the non-irrigated treatments on the level of larval establishment per plant. There was, however, a significant interaction between irrigation and nitrogen such that highest levels of larval recovery occurred in the irrigated high N fertilized treatment. This effect is not as pronounced when each test is considered individually although it is quite apparent in the August 30 test. Tables 12 and 13 present the same data in a slightly different manner. In Table 12 all irrigation effects are combined so as to reveal possible effects due to N fertilization alone. Table 13 re-orders

the data with N effects combined and allows examination of effects due to irrigation alone.

According to the results presented in Table 12 N alone did not significantly affect the level of larval establishment in any of the three tests even though total larvae recovered in the high N treatments were somewhat higher than the low N plots in 2 of the 3 tests. Results from Table 13 indicate that irrigation did significantly affect larval establishment in the August 30 test. At that time significantly more larvae were recovered in irrigated plots than in non-irrigated plots. There were, however, no differences in larval survival due to irrigation effects in the other tests.

There was no significant N, irrigation, or I - N effect on the weights of recovered larvae.

The mean number of squares per plant appears to have been most influenced by N fertilization rather than irrigation. This is most evident when one considers the data presented in Table 12. In all tests performed, higher square density was observed in the highest N treatments. This effect was significant in the August 14 and August 15 tests and also when test results are combined. An increase in number of squares per plant as N increased was the most notable N effect on fruiting forms. There were no differences in total blooms, and total bolls per plant were different in only the August 14 test. In that instance a lower than expected number of bolls were observed in the 60 lb/ac treatment.

Examination of data contained in Table 13 indicates that there was no significant irrigation effect on production of fruiting forms within the three tests.

Heliothis terminal damage was significantly affected by I X N interaction in August 30 test (Table 11). There was also a significant N response when means from all tests were pooled with irrigation effects combined. Irrigation effects alone had no significant effect on the level of terminal damage (Table

13).

Small square damage was significantly affected by an I X N interaction in the August 30 test (Table 11). In the August 15 test, higher small square damage was observed as N increased when irrigation effects were combined (Table 12).

Large square damage was generally higher in high N and irrigated plots. In the August 15 and August 30, and when all means were combined, damage was greater in the higher N treatments (Table 12). There was a significant N response in the August 30 test and with the combined means. In all cases there was greater large square damage in irrigated plots (Table 13); significantly greater damage levels were observed in the August 14 and August 30 tests.

There were no differences in white bloom damage in any treatments although there were slightly higher damage levels observed in irrigated plots when compared to non-irrigated plots (Table 13).

There was a significant I X N interaction in small boll damage levels in the August 14 test and in combined means for all dates (Tables 8-9). These were the only significant differences in small boll damage among treatments.

Large boll damage was not affected by N fertilization in any tests. Irrigation did, however, apparently result in less boll damage (Table 13). In the August 15 and August 30 tests, non-irrigated plots had significantly higher levels of large boll damage than did irrigated plots. There was no difference in boll damage in the August 14 test.

Natural Populations

Low populations of *Heliothis* larvae were observed in I - N plots throughout the sampling period. In Tables 14-18, data are presented which indicate that in most cases, there was no apparent increase in survival of first or second instar larvae or large larvae that could be attributed to either N or irrigation effects. There were no instances where survival of large larvae appeared to be affected by any treatments (Tables 14, 17, 18). Similar

observations were recorded for occurrence of first instar larvae (Tables 16, 17, 18).

Survival of second instar larvae was significantly affected by N-in week 16 (Table 17). In that week, second instar larvae were observed only in the 120 lb/ac treatments of irrigated and non-irrigated treatments. During weeks 11 and 15, significantly more second instar larvae were observed in non-irrigated plots than in irrigated plots (Table 18).

Mean numbers of squares, blooms, and bolls observed per week in each treatment, with N treatments combined, and with irrigation treatments combined, are listed in Tables 19-23. The first squares were recorded in week 6. During that time, there were significantly more squares observed in the irrigated plots than in non-irrigated (Table 23). This trend continued through week 11. and indicates an irrigation effect on the degree of crop earliness. There was no apparent N response until weeks 12 and 13 when the numbers of squares increased significantly as the level of N rose (Table 22). This response continued through week 19. There were significant I X N interaction effects on squaring in weeks 8, 13, 15, and 16. Indications of this interaction can be observed in Table 19.

The first blooms were recorded in week 9. No statistical or logical trends are readily apparent when bloom data are inspected (Tables 20, 22, 23).

Bolls were first observed in irrigated plots with the high N treatment (Tables 21,22,23). In the second week after bolls were observed, there was a significant difference in the number of bolls in irrigated and non-irrigated plots (Table 23). This was the only occurrence of such distinct differences, however. There was, in the last week of sampling, significantly more bolls in the highest N plots. During week 14, the high N irrigated plots (Table 21) were observed to have the fewest bolls; this trend was not observed at any other time.

Heliothis plant damage observed during the I - N study is summarized in

Tables 24-31. In only one week during the entire study was there any significant difference in plant damage recorded for any treatment. In week 13, significantly higher levels of large square damage occurred in the 20 lbs/ac non-irrigated treatment and in the 120 lbs/ac irrigation treatment (Table 26). Other treatments had few or no damaged large squares. In all other treatments, there were no differences in damage response to N or irrigation.

Boll weevil damaged squares were first observed in week 8 in irrigated high N plots (Table 32). Presented in Table 33 are summaries of mean boll weevil damage when N and irrigation means are combined. Irrigation had no effect upon the number of boll weevil damaged squares. There was, however, significantly more damage related to N during several weeks. Significant differences were first apparent in week 12. From that time on greater damage was associated with higher N fertilization; damage was significantly greater in week 15. A significant I X N interaction was recorded in week 13. During that period greatest damage occurred irrigated treatments with high N fertilization.

DISCUSSION

In the field N study, significantly greater *H. virescens* establishment was observed as the level of N fertilization increased. Although there have been previous reports of increased *Heliothis* populations and damage (Adkisson 1958 and Hayward 1972) following excessive N fertilization, these studies did not quantify establishment using equal sized cohorts.

In field cage and field I - N studies, similar increases in larval establishment were observed in high N treatments when compared in the treatments receiving less fertilizer. Larval recovery in each of the cage studies was much higher than in artificial infestation studies in the other field experiments. One of the possible explanations for this increased recovery (i.e. survival) is the exclusion of natural enemies from the release sites. Since natural enemies were not sampled in any of the field studies it

is not possible to estimate their interference with establishment studies. Although attempts to decrease natural enemy populations were made in the field N and field I - N study (malathion applications 24 hr. prior to infestations), the likelihood of natural enemy interference cannot be negated. Generally, natural enemy populations did not appear to be sufficiently high as to interfere with experiments, however.

Increases in N fertilization did not result in increased larval establishment in non-irrigated treatments in the I - N study. These results could have been due to decreased uptake of N, decreased utilization of N during water stressed conditions, or to other physiological events associated with these conditions such as reductions in feeding sites.

Boll weevil damage levels were not affected by irrigation treatments in the I - N field study. This was interesting in that higher square density resulted from irrigation treatments. This in turn increased the number of potential boll weevil feeding sites. Boll weevil damage levels were more influenced by N fertilization. This was apparent in both the N and I - N studies. Reports of relations between boll weevil damage and N fertilization have indicated similar, yet inconsistent results, (Beckman 1970).

Variations in alleochemic synthesis due to variations in N and water availability to plants could account for many of the observations made in these studies and in others reporting similar occurrences. Changes in concentrations of substances such as phenolic acids, could result in varying degrees of resistance of plants to insects and disease. Yang and Davis (1976) reported decreased gossypyl content in plants under high rainfall conditions. Possibly contradictory to this situation, Guinn and Eidenbock (1982) reported decreased concentrations of catechin and condensed tannins in water stressed plants as compared to non-stressed plants. Variations in phenolic acids such as those mentioned above have been reported associated with N availability to the plant. McClure (1979). reported that high levels of N generally inhibit

phenolic biosynthesis in all plants. Phenolic acid production (and their derivatives) is based upon the availability of phenylalanine and tyrosine. These are aromatic amino acids which may be use for the production of proteins when high levels of soluble N are available. A high N concentration available in the nutrient media of a plant may lead to competition between nitrogen and phenolic metabolism. The resulting decrease in phenolic biosynthesis could lead to a decrease in the level of resistance of the plant to pests.

Carbohydrate levels in plant tissues are also affected by water stress and nitrogen levels. Increases in carbohydrate levels under water stressed conditions is well documented. Increases are also associated with decay of N levels of plants. Completion of plant analyses should provide data sufficient to assist in further investigation of the results observed in the field studies presented in this report.

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APPENDIX

Table A1. Number and average weight of *H. virescens* larvae recovered seven days following artificial infestation in green house cotton grown using 4 levels of nitrogen fertilization. Also shown are total squares, blooms and bolls.

Nitrogen (lbs/ac)	<u>1</u>	<u>3</u>	<u>6</u>	<u>10</u>
Mean # of larvae recovered per plant ¹	0.05 a	0.08 a	0.08 a	0.18 a
Larval Weights (mg)	136.0 a	68.07 a	95.9 a	66.2 a
Total Fruit (mean per plant)				
Squares	1.68 c	2.00 bc	2.10 ab	2.43 a
Blooms	0.20 ab	0.10 b	0.13 b	0.33 a
Bolls	0.65 b	1.13 a	1.32 a	1.07 ab

^{1/} Means followed by the same letter within the same row are not significantly different ($p=0.05$) according to LSD.

Table 1. Number and average weight of *H. virescens* larvae recovered seven days following artificial infestation in cotton grown using 4 levels of nitrogen fertilization. Also shown are total squares, blooms bolls and total plant damage. Artificial infestation with two *H. virescens* larvae per plant was made on July 31.

Nitrogen (lbs/ac)	20	50	120	200
Mean # of larvae recovered per plant ¹	0.34 b	0.39 b	0.75 a	0.78 a
Larval Weights (mg)	13.84 a	14.38 a	34.34 a	22.58 a
Total Fruit (mean per plant)				
Squares	12.51 b	10.48 b	11.79 b	17.02 a
Blooms	1.42 bc	1.00 c	2.30 a	1.95 ab
Bolls	11.13 bc	9.12 c	16.00 a	13.32 ab
Damage (mean per plant)				
Terminal				
Small Squares (<2mm)	0.44 c	0.63 ab	0.68 a	0.48 bc
Large Squares (>2mm)	0.26 b	0.58 b	0.15 b	1.40 a
Blooms	1.23 a	1.73 a	1.47 a	1.85 a
Small Bolls (<7mm)	0.05 b	0.05 a	0.13 a	0.18 a
Large Bolls (>7mm)	0.26 b	0.24 b	0.20 b	0.40 a
	0.42 a	0.34 a	0.52 a	0.55 a

^{1/} Means followed by the same letter within the same row are not significantly different (p=0.05) according to LSD.

Table 2. Mean number of *Heliothis* spp. larvae found per plant per week on cotton grown using four levels of nitrogen fertilization. Data were obtained from whole plant examinations of five consecutive plants, randomly selected each week within each of the treatment plots which were replicated four times.

Nitrogen Week ²	<u>Large Larvae¹</u>				<u>Second Instar</u>				<u>First Instar</u>			
	<u>20</u>	<u>50</u>	<u>120</u>	<u>200</u>	<u>20</u>	<u>50</u>	<u>120</u>	<u>200</u>	<u>20</u>	<u>50</u>	<u>120</u>	<u>200</u>
12					0.02 a	0.05 a	0.05 a	0.05 a				
13					0.10 a	0.00 a	0.00 a	0.00 a				
14					0.00 a	0.00 a	0.00 a	0.00 a				
15	0.05 a	0.05 a	0.15 a	0.25 a	0.00 a	0.50 a	0.20 a	0.10 a	0.15 a	0.05 a	0.10 a	0.40 a
16	1.05 a	0.97 a	1.10 a	0.93 a	0.26 a	0.39 a	0.15 a	0.53 a	0.18 a	0.17 a	0.08 a	0.17 a
17	0.10 a	0.50 a	0.20 a	0.25 a	0.20 a	0.20 a	0.40 a	0.25 a	0.45 a	0.05 a	0.25 a	0.35 a
18	0.00 a	0.05 a	0.05 a	0.15 a	0.00 a	0.05 a	0.00 a	0.10 a	0.05 a	0.05 a	0.05 a	0.05 a
19	0.00 a	0.00 a	0.00 a	0.05 a	0.00 a	0.00 a	0.00 a	0.00 a	0.10 a	0.05 a	0.05 a	0.00 a

¹/Third instar or older larvae are considered large.

²/ Means followed by the same letter within the same row are not significantly different (p=0.05) according to LSD.

Table 3. Mean number of squares, blooms, bolls found per plant per week on cotton grown using four levels of nitrogen fertilization. Data were obtained from whole plant examinations of five consecutive plants, randomly selected each week within each of the treatment plots which were replicated four times.

Nitrogen Week ¹	<u>Total Squares</u>				<u>Total Blooms</u>				<u>Total Bolls</u>			
	<u>20</u>	<u>60</u>	<u>120</u>	<u>200</u>	<u>20</u>	<u>60</u>	<u>120</u>	<u>200</u>	<u>20</u>	<u>60</u>	<u>120</u>	<u>200</u>
10	1.18 a	1.65 a	1.20 a	1.82 a	0.00 a	0.00 a	0.00 a	0.20 a	0.10 a	0.10 a	0.05 a	0.10 a
11	3.95 b	5.40 ab	4.55 b	7.40 a	0.15 a	0.15 a	0.35 a	0.05 a	0.40 b	0.35 b	1.35 a	0.10 b
12	9.25 a	12.55 a	12.80 a	14.65 a	0.75 a	0.55 a	1.15 a	1.10 a	0.80 b	2.10 a	3.85 a	1.75 b
13	15.65 a	14.65 a	15.55 a	11.95 a	0.95 a	0.70 a	1.10 a	0.50 a	6.70 a	6.40 a	8.20 a	6.45 a
14	21.20 c	22.15 bc	29.25 a	28.70 ab	1.42 bc	1.00 c	2.30 a	1.95 ab	11.13 bc	9.12 c	16.00 a	13.32 ab
15	19.15 a	19.60 a	25.35 a	24.95 a	0.50 b	1.20 a	0.60 b	1.45 a	8.50 a	12.40 a	10.60 a	12.90 a
16	12.51 b	10.48 b	11.79 b	17.02 a	0.30 ab	0.05 b	0.95 a	0.10 b	7.90 b	8.00 b	10.90 ab	13.30 a
17	15.50 b	13.80 b	13.15 b	30.30 a	0.10 a	0.45 a	0.05 a	0.35 a	9.30 ab	4.65 c	5.90 bc	10.80 a
18	6.30 a	7.26 a	5.70 a	12.15 a								
19	6.45 b	7.70 ab	5.10 b	10.70 a								

1/ Means followed by the same letter within the same row are not significantly different (p=0.05) according to LSD.

Table 4. Mean number of *Heliothis* damaged squares, blooms, and bolls recorded per plant in cotton grown using four levels of nitrogen fertilization. Data were obtained from whole plant examinations of five consecutive plants randomly selected each week from within each of the treatment plots which were replicated four times.

Damage	<u>Terminal</u>				<u>Small Squares (<2mm)</u>				<u>Large Squares (>2mm)</u>			
	<u>20</u>	<u>60</u>	<u>120</u>	<u>200</u>	<u>20</u>	<u>60</u>	<u>120</u>	<u>200</u>	<u>20</u>	<u>60</u>	<u>120</u>	<u>200</u>
Nitrogen												
Week ¹												
12	0.05 a	0.15 a	0.05 a	0.15 a	0.25 a	0.20 a	0.30 a	0.60 a	0.00 a	0.05 a	0.00 a	0.00 a
13	0.44 c	0.63 ab	0.68 a	0.48 bc	0.26 b	0.58 b	0.15 b	1.40 a	0.10 a	0.00 a	0.00 a	0.00 a
14	0.15 b	0.20 b	0.15 b	0.45 a	1.80 a	0.20 a	0.65 a	0.95 a	0.00 a	0.00 a	0.00 a	0.00 a
15	0.00 a	0.00 a	0.00 a	0.05 a	0.00 a	0.00 a	0.05 a	0.15 a	0.50 a	0.30 a	0.55 a	0.08 a
16	0.00 a	0.00 a	0.00 a	0.00 a	0.00 a	0.15 a	0.10 a	0.05 a	1.23 a	1.73 a	1.47 a	1.85 a
17									0.95 b	0.95 b	1.20 b	2.75 a
18									0.05 b	0.05 b	0.15 b	0.45 a
19									0.10 a	0.10 a	0.00 a	0.15 a
Damage	<u>Blooms</u>				<u>Small Bolls (<7mm)</u>				<u>Large Bolls (>7mm)</u>			
	<u>20</u>	<u>60</u>	<u>120</u>	<u>200</u>	<u>20</u>	<u>60</u>	<u>120</u>	<u>200</u>	<u>20</u>	<u>60</u>	<u>120</u>	<u>200</u>
Nitrogen												
Week ¹												
15	0.00 a	0.05 a	0.00 a	0.05 a	0.00 a	0.05 a	0.10 a	0.00 a	0.00 a	0.00 a	0.05 a	0.10 a
16	0.05 a	0.05 a	0.13 a	0.18 a	0.26 a	0.24 a	0.20 a	0.40 a	0.42 a	0.34 a	0.52 a	0.55 a
17	0.00 a	0.05 b	0.05 b	0.25 a	0.25 a	0.16 a	0.10 a	0.40 a	0.35 a	0.60 a	0.85 a	0.90 a
18	0.00 a	0.00 a	0.00 a	0.00 a	0.00 a	0.05 a	0.00 a	0.00 a	0.25 a	0.21 a	0.40 a	0.60 a
19	0.00 a	0.00 a	0.00 a	0.00 a	0.00 a	0.00 a	0.00 a	0.05 a	0.10 a	0.00 a	0.00 a	0.05 a

^{1/} Means followed by the same letter within the same row are not significantly different (p=0.05) according to LSD.

Table 5. Mean number of open bolls recorded per plant from cotton grown using four levels of nitrogen fertilization. Data were obtained from whole plant from whole plant examinations of five consecutive plants, randomly selected each week from within each treatment block with four replications. Also included are yields from the various nitrogen treatments; plots were hand picked and per acre estimates were made based on four 44 m samples.

Nitrogen (lbs/ac)		<u>20</u>	<u>60</u>	<u>120</u>	<u>200</u>
Week ¹					
17		0.00 a	0.05 a	0.00 a	0.05 a
18		1.00 a	0.74 a	0.65 a	0.70 a
19		4.70 a	4.05 a	5.25 a	5.12 a
Yield (lbs/ ac)		121.3 b	157.0 b	233.8 a	218.3 ab

^{1/} Means followed by the same letter within the same row are not significantly different (p=0.05) according to LSD.

Table 6. Mean number of boll weevil damaged squares recorded per plant from cotton grown using four levels of nitrogen fertilization. Data were obtained from whole plant examinations of five consecutive plants, randomly selected each week within each treatment block with four replications.

Nitrogen (lbs/ac)	Week ¹			
	20	50	120	200
14	0.00 a	0.00 a	0.05 a	0.00 a
15	0.80 a	0.07 a	0.05 a	0.55 a
16	4.65 a	3.76 a	4.55 a	6.60 a
17	2.00 b	3.85 ab	3.85 ab	5.95 a
18	2.25 a	3.62 a	2.15 a	4.20 a
19	3.30 a	4.15 a	2.85 a	6.20 a

^{1/} Means followed by the same letter within the same row are not significantly different ($p=0.05$) according to LSD.

Table 7. Summary of results of field cage study performed on four different dates in cotton grown using two levels of nitrogen fertilization. Included are number and average weights of larvae recovered seven days following artificial infestation with neonate *H. virescens*, total numbers of squares, blooms and total plant damage per plant.

Date	<u>August 1</u>		<u>August 11</u>		<u>August 15</u>		<u>August 26</u>		<u>Combined</u>	
	<u>20</u>	<u>200</u>	<u>20</u>	<u>200</u>	<u>20</u>	<u>200</u>	<u>20</u>	<u>200</u>	<u>20</u>	<u>200</u>
Nitrogen (lbs/ac)										
<i>H. virescens</i>										
Larvae Recovered ¹	0.53	1.00 *	0.60	1.30 *	1.06	1.26	0.33	0.87 *	0.63	1.15 *
Larval Weight	25.62	12.82	185.87	163.64	67.04	50.12	38.9	33.26	109.75	95.87
Total Fruit										
Squares	34.33	33.20	17.43	19.63	12.40	16.27 *	15.27	17.53	19.37	21.25
Blooms	0.93	1.67	1.46	2.23 *	1.00	0.87	0.27	0.73	1.03	1.55 *
Bolls	5.60	7.53	5.11	8.60	4.87	5.00	8.60	12.27 *	5.93	8.40 *
Nodes	18.90	19.00	18.00	18.90	18.00	17.70	21.50	20.90	18.80	19.25
Insect Damage ²										
Terminal	0.73	0.73	1.00	0.87 *	0.93	0.86	0.33	0.73	0.80	0.81
Small Squares	0.46	1.67 *	1.20	2.57 *	1.27	1.27	0.20	0.73 *	0.86	1.76 *
Large Squares	0.47	1.20	0.77	1.33	1.33	1.27	0.67	1.40	0.80	1.31 *
Blooms	0.00	0.00	0.13	0.46 *	0.00	0.00	0.00	0.13	0.05	0.11 *
Small Bolls	0.00	0.07	0.10	0.47 *	0.06	0.33	0.00	0.00	0.05	0.27 *
Large Bolls	0.00	0.00	0.00	0.10 *	0.07	0.00	0.00	0.00	0.01	0.04

* significantly different at P=0.05 level according to t test.

1/ Mean number of *H. virescens* recovered 7 days following artificial infestation of 2 neonate larvae per terminal. Larvae from August 11 were allowed to feed 9 days.

2/ Mean number of *Heliothis* damaged small squares (<2mm), large squares (>2mm), small bolls (<7mm), and large bolls (>7mm) and terminal damage per plant.

Table 8. Number and average weight of *H. virescens* larvae recovered seven days following artificial infestation of cotton grown using three levels of nitrogen fertilization with two irrigation treatments. Also shown are total squares, blooms, bolls and total plant damage. Infestations with two *H. virescens* per plant were made on three dates. Presented here are the combined results from those tests.

Irrigation Treatment	Non Irrigated			Irrigated		
	20	50	120	20	50	120
Nitrogen (lbs/ac)						
Mean # of larvae recovered per plant ¹	0.53 a	0.49 a	0.42 a	0.42 b	0.51 b	0.80 a
Larval Weights (mg)	35.94 a	53.54 a	52.94 a	41.31 a	32.47 a	40.56 a
Total Fruit (mean per plant)						
Squares	6.44 b	6.20 b	9.56 a	6.53 b	9.18 ab	11.04 a
Blooms	0.58 a	0.29 a	0.31 a	0.36 a	0.42 a	0.67 a
Bolls	4.56 a	5.09 a	5.09 a	5.02 a	4.47 a	5.89 a
Damaged Plant Parts (mean per plant)						
Terminal	0.51 a	0.38 a	0.51 a	0.42 b	0.56 b	0.75 a
Small Squares (<2mm)	0.53 a	0.44 a	0.53 a	0.46 a	0.76 a	0.82 a
Large Squares (>2mm)	0.53 a	0.33 a	0.40 a	0.40 b	1.24 a	1.09 a
Blooms	0.11 b	0.04 b	0.00 a	0.16 a	0.09 a	0.04 a
Small Bolls (<7mm)	0.11 a	0.13 a	0.07 a	0.06 b	0.04 b	0.26 a
Large Bolls (>7mm)	0.22 a	0.27 a	0.29 a	0.15 a	0.11 a	0.15 a

^{1/} Means followed by the same letter within the same row are not significantly different (p=0.05) according to LSD.

Table 9. Number and average weight of *H. virescens* larvae recovered seven days following artificial infestation of cotton grown using three levels of nitrogen fertilization with two irrigation treatments. Also shown are total squares, blooms, bolls and total plant damage. Infestations with two *H. virescens* per plant were made on three dates. Presented here are the results from the August 14 test.

Irrigation Treatment	Non Irrigated			Irrigated		
	20	50	120	20	50	120
Nitrogen (lbs/ac)						
Mean # of larvae recovered per plant ¹	0.60 a	0.73 a	0.40 a	0.67 a	0.47 a	0.67 a
Larval Weights (mg)	46.56 a	49.73 a	100.20 a	42.30 a	35.99 a	66.45 a
Total Fruit (mean per plant)						
Squares	7.20 b	6.20 b	14.73 a	10.67 a	10.10 a	11.20 a
Blooms	0.53 a	0.53 a	0.47 a	0.40 a	0.40 a	0.67 a
Bolls	5.73 a	3.20 b	6.40 a	4.93 a	4.33 a	6.60 a
Damaged Plant Parts (mean per plant)						
Terminal	0.86 a	0.80 a	0.73 a	1.00 a	0.86 a	1.00 a
Small Squares (<2mm)	1.27 a	0.87 a	0.67 a	1.20 a	1.33 a	1.07 a
Large Squares (>2mm)	0.67 a	0.80 a	0.40 a	0.73 a	1.20 a	1.27 a
Blooms	0.13 a	0.07 a	0.00 a	0.13 a	0.13 a	0.13 a
Small Bolls (<7mm)	0.20 a	0.20 a	0.07 a	0.00 b	0.07 b	0.40 a
Large Bolls (>7mm)	0.40 a	0.67 a	0.33 a	0.27 a	0.20 a	0.40 a

^{1/} Means followed by the same letter within the same row are not significantly different (p=0.05) according to LSD.

Table 10. Number and average weight of *H. virescens* larvae recovered seven days following artificial infestation of cotton grown using three levels of nitrogen fertilization with two irrigation treatments. Also shown are total squares, blooms, bolls and total plant damage. Infestations with two *H. virescens* per plant were made on three dates. Presented here are the results from the August 15 test.

Irrigation Treatment	Non Irrigated			Irrigated		
	20	60	120	20	60	120
Nitrogen (lbs/ac)						
Mean # of larvae recovered per plant ¹	0.67 a	0.40 a	0.53 a	0.20 a	0.46 a	0.80 a
Larval Weights (mg)	37.63 a	53.85 a	40.45 a	47.30 a	68.20 a	28.4 a
Total Fruit (mean per plant)						
Squares	8.67 a	8.67 a	10.53 a	4.87 b	11.13 a	15.00 a
Blooms	1.00 a	0.27 a	0.27 a	0.33 a	0.67 a	1.33 a
Bolls	4.27 a	7.87 a	4.93 a	4.33 a	4.26 a	6.33 a
Damaged Plant Parts (mean per plant)						
Terminal	0.40 a	0.00 b	0.33 a	0.20 a	0.40 a	0.40 a
Small Squares (<2mm)	0.00 b	0.13 b	0.60 a	0.13 a	0.53 a	0.60 a
Large Squares (>2mm)	0.53 a	0.13 a	0.40 a	0.20 b	1.27 a	1.06 a
Blooms	0.13 a	0.07 a	0.00 a	0.00 a	0.13 a	0.33 a
Small Bolls (<7mm)	0.00 a	0.13 a	0.13 a	0.13 a	0.07 a	0.20 a
Large Bolls (>7mm)	0.07 a	0.27 a	0.13 a	0.17 a	0.00 a	0.00 a

^{1/} Means followed by the same letter within the same row are not significantly different (p=0.05) according to LSD.

Table 11. Number and average weight of *H. virescens* larvae recovered seven days following artificial infestation of cotton grown using three levels of nitrogen fertilization with two irrigation treatments. Also shown are total squares, blooms, bolls and total plant damage. Infestations with two *H. virescens* per plant were made on three dates. Presented here are the results from the August 30 test.

Irrigation Treatment	Non Irrigated			Irrigated		
	20	60	120	20	60	120
Nitrogen (lbs/ac)						
Mean # of larvae recovered per plant ¹	0.33 a	0.33 a	0.33 a	0.40 b	0.60 ab	0.93 a
Larval Weights (mg)	17.08 a	57.7 a	22.33 a	34.67 a	16.47 a	33.69 a
Total Fruit (mean per plant)						
Squares	3.47 a	3.73 a	3.40 a	4.07 a	6.33 a	6.93 a
Blooms	0.20 a	0.06 a	0.20 a	0.33 a	0.20 a	0.00 a
Bolls	3.67 a	4.20 a	3.93 a	5.80 a	4.80 a	4.73 a
Damaged Plant Parts (mean per plant)						
Terminal	0.26 a	0.33 a	0.47 a	0.06 c	0.40 b	0.80 a
Small Squares (<2mm)	0.33 a	0.33 a	0.33 a	0.07 c	0.40 b	0.80 a
Large Squares (>2mm)	0.40 a	0.07 a	0.40 a	0.47 a	1.27 a	0.93 a
Blooms	0.07 a	0.00 a	0.00 a	0.00 a	0.00 a	0.00 a
Small Bolls (<7mm)	0.13 a	0.07 a	0.00 a	0.07 a	0.00 a	0.20 a
Large Bolls (>7mm)	0.20 a	0.47 a	0.40 a	0.13 a	0.13 a	0.07 a

1/ Means followed by the same letter within the same row are not significantly different (p=0.05) according to LSD.

Table 12. Number and average weight of *H. virescens* larvae recovered seven days following artificial infestation of cotton grown using three levels of nitrogen fertilization with two irrigation treatments. Also shown are total squares, blooms, bolls and total plant damage. Infestations with two *H. virescens* per plant were made on three dates. Presented here are means separated by nitrogen fertilization with irrigation effects combined.

	August 14			August 15		
	20	60	120	20	60	120
Nitrogen (lbs/ac)						
Mean # of larvae recovered per plant ¹	0.60 a	0.73 a	0.53 a	0.43 a	0.43 a	0.67 a
Larval Weights (mg)	44.17 a	42.33 a	83.33 a	40.50 a	57.44 a	35.29 a
Total Fruit (mean per plant)						
Squares	8.93 b	8.13 b	12.97 a	6.77 b	9.90 a	12.77 a
Blooms	0.47 a	0.47 a	0.57 a	0.67 a	0.47 a	0.80 a
Bolls	5.33 a	3.77 b	6.50 a	4.30 a	6.07 a	5.63 a
Damaged Plant Parts (mean per plant)						
Terminal	0.93 a	0.83 a	0.87 a	0.37 a	0.30 a	0.20 a
Small Squares (<2mm)	1.23 a	1.10 a	0.87 a	0.07 c	0.33 b	0.60 a
Large Squares (>2mm)	0.70 a	1.00 a	0.83 a	0.37 a	0.70 a	0.73 a
Blooms	0.13 a	0.10 a	0.07 a	0.07 a	0.10 a	0.17 a
Small Bolls (<7mm)	0.10 a	0.13 a	0.23 a	0.07 a	0.10 a	0.17 a
Large Bolls (>7mm)	0.37 a	0.13 a	0.33 a	0.07 a	0.13 a	0.07 a

Table 13. Number and average weight of *H. virescens* larvae recovered seven days following artificial infestation of cotton grown using three levels of nitrogen fertilization with two irrigation treatments. Also shown are total squares, blooms, bolls and total plant damage. Infestations with two *H. virescens* per plant were made on three dates. Presented here are means separated by irrigation with nitrogen effects combined.

Date	August 14		August 15		August 30		Combined	
Irrigation	Irrig	Non Irr	Irrig	Non Irr	Irrig	Non Irr	Irrig	Non Irr
Mean # of larvae recovered per plant ¹	0.60 a	0.58 a	0.49 a	0.53 a	0.64 a	0.33 b	0.58 a	0.48 a
Larval Weights (mg)	65.50 a	47.12 a	43.34 a	41.11 a	32.73 a	29.17 a	38.63 a	47.78 a
Total Fruit (mean per plant)	10.64 a	9.38 a	10.33 a	9.29 a	5.78 a	3.53 a	8.92 a	7.40 a
Squares	0.49 a	0.49 a	0.78 a	0.51 a	0.17 a	0.16 a	0.48 a	0.39 a
Blooms	5.29 a	5.11 a	4.98 a	5.69 a	5.11 a	3.93 a	5.13 a	4.97 a
Damaged Plant Parts (mean per plant)	0.95 a	0.80 a	0.33 a	0.24 a	0.42 a	0.36 a	0.57 a	0.47 a
Terminal	1.20 a	0.93 a	0.42 a	0.24 a	0.42 a	0.33 a	0.68 a	0.50 a
Small Squares (<2mm)	1.07 a	0.62 b	0.84 a	0.35 a	0.89 a	0.29 b	0.93 a	0.42 a
Large Squares (> 2mm)	0.13 a	0.07 a	0.16 a	0.07 a	0.02 a	0.00 a	0.10 a	0.05 a
Small Bolls (<7mm)	0.16 a	0.16 a	0.13 a	0.09 a	0.09 a	0.07 a	0.13 a	0.10 a
Large Bolls (> 7mm)	0.29 a	0.27 a	0.02 b	0.16 a	0.11 b	0.36 a	0.14 a	0.26 b

1/ Means followed by the same letter within the same row are not significantly different (p=0.05) according to LSD.

Table 14. Mean number of large *Heliothis* larvae¹ observed per plant in cotton grown using three levels of nitrogen fertilization with two irrigation treatments. Data were obtained from whole plant examination of five consecutive plants, randomly selected each week within each of the treatment blocks which were replicated three times.

N (lbs/ac)	Week ²	Non Irrigated		Irrigated	
		<u>20</u>	<u>50</u>	<u>20</u>	<u>120</u>
10		0.00 a	0.00 a	0.13 a	0.07 a
11		0.00 a	0.00 a	0.13 a	0.20 a
12		0.06 a	0.13 a	0.40 a	0.13 a
13		0.20 a	0.00 a	0.00 a	0.20 a
14		0.00 a	0.00 a	0.00 a	0.07 a
15		0.07 a	0.13 a	0.07 a	0.07 a
16		0.07 a	0.00 a	0.00 a	0.00 a

1/ Third instar or older larvae are considered large.

2/ Means followed by the same letter within the same row are not significantly different (p=0.05) according to LSD.

Table 15. Mean number of second instar Heliothis larvae observed per plant in cotton grown using three levels of nitrogen fertilization with two irrigation treatments. Data were obtained from whole plant examination of five consecutive plants, randomly selected each week within each of the treatment blocks which were replicated three times.

Irrigation Treatment		<u>Non Irrigated</u>			<u>Irrigated</u>		
N (lbs/ac)	<u>Week</u> ²	<u>20</u>	<u>50</u>	<u>120</u>	<u>20</u>	<u>50</u>	<u>120</u>
10		0.20 a	0.00 a	0.20 a	0.20 a	0.13 a	0.00 a
11		0.46 a	0.20 a	0.13 a	0.07 a	0.07 a	0.00 a
12		0.13 a	0.20 a	0.13 a	0.07 a	0.00 a	0.13 a
13		0.07 a	0.07 a	0.20 a	0.07 a	0.00 a	0.07 a
14		0.00 a	0.00 a	0.07 a	0.00 a	0.20 a	0.07 a
15		0.20 a	0.07 a	0.00 a	0.00 a	0.00 a	0.00 a
16		0.00 b	0.00 b	0.07 a	0.00 b	0.00 b	0.13 a

^{1/} Means followed by the same letter within the same row are not significantly different (p=0.05) according to LSD.

Table 16. Mean number of first instar *Heliothis* larvae observed per plant in cotton grown using three levels of nitrogen fertilization with two irrigation treatments. Data were obtained from whole plant examination of five consecutive plants, randomly selected each week within each of the treatment blocks which were replicated three times.

Irrigation Treatment		<u>Non Irrigated</u>			<u>Irrigated</u>		
N (lbs/ac)	<u>Week</u> ²	<u>20</u>	<u>60</u>	<u>120</u>	<u>20</u>	<u>60</u>	<u>120</u>
10		0.00 a	0.00 a	0.00 a	0.13 a	0.00 a	0.20 a
11		0.33 a	0.00 a	0.07 a	0.00 a	0.27 a	0.07 a
12		0.26 a	0.00 a	0.00 a	0.07 a	0.07 a	0.20 a
13		0.00 a	0.00 a	0.00 a	0.00 a	0.00 a	0.00 a
14		0.13 a	0.07 a	0.07 a	0.00 a	0.00 a	0.07 a
15		0.00 a	0.07 a	0.00 a	0.00 a	0.10 a	0.00 a
16		0.00 a	0.00 a	0.00 a	0.00 a	0.00 a	0.07 a

^{1/}Means followed by the same letter within the same row are not significantly different (p=0.05) according to LSD.

Table 17. Mean number of *Heliothis* larvae^{1/} observed per plant in cotton grown using 3 levels of nitrogen fertilization two irrigation treatments. Data were obtained from whole plant examinations of five consecutive plants, randomly selected each week within each of the treatment blocks which were replicated three times. Presented here are means separated by nitrogen fertilization with irrigation effects combined.

Larvae	<u>Large Larvae¹</u>			<u>Second Instar</u>			<u>First Instar</u>		
	<u>20</u>	<u>60</u>	<u>120</u>	<u>20</u>	<u>60</u>	<u>120</u>	<u>20</u>	<u>60</u>	<u>120</u>
N (lbs/ac)									
Week ²									
10	0.07 a	0.03 a	0.07 a	0.20 a	0.07 a	0.10 a	0.07 a	0.00 a	0.10 a
11	0.07 a	0.03 a	0.17 a	0.27 a	0.13 a	0.07 a	0.17 a	0.13 a	0.07 a
12	0.23 a	0.10 a	0.10 a	0.10 a	0.10 a	0.13 a	0.17 a	0.03 a	0.10 a
13	0.10 a	0.00 a	0.07 a	0.07 a	0.03 a	0.13 a	0.00 a	0.00 a	0.00 a
14	0.00 a	0.03 a	0.10 a	0.00 a	0.10 a	0.07 a	0.07 a	0.03 a	0.07 a
15	0.07 a	0.16 a	0.10 a	0.10 a	0.05 a	0.00 a	0.07 a	0.03 a	0.07 a
16	0.03 a	0.07 a	0.07 a	0.00 b	0.00 b	0.10 a	0.00 a	0.00 a	0.03 a

^{1/} Third instar or older larvae are considered large.

^{2/} Means followed by the same letter within the same row are not significantly different (p=0.05) according to LSD.

Table 18. Mean number of *Heliothis* larvae¹ observed per plant in cotton grown using three levels of nitrogen fertilization with two irrigation treatments. Data were obtained from whole plant examinations of five consecutive plants, randomly selected each week within each of the treatment blocks which were replicated three times. Presented here are means separated by irrigation treatment with nitrogen effects combined.

Larvae	Large Larvae ¹		Second Instar		First Instar	
	Non Irr	Irrig	Non Irr	Irrig	Non Irr	Irrig
Treatment						
Week ²						
10	0.02 a	0.09 a	0.13 a	0.11 a	0.00 a	0.11 a
11	0.04 a	0.13 a	0.27 a	0.04 b	0.13 a	0.11 a
12	0.09 a	0.20 a	0.16 a	0.07 a	0.09 a	0.11 a
13	0.07 a	0.04 a	0.11 a	0.04 a	0.00 a	0.00 a
14	0.04 a	0.04 a	0.02 a	0.09 a	0.09 a	0.02 a
15	0.11 a	0.10 a	0.09 a	0.00 b	0.02 a	0.03 a
16	0.07 a	0.04 a	0.02 a	0.04 a	0.00 a	0.02 a

¹/Third instar or older larvae are considered large.

²/Means followed by the same letter within the same row are not significantly different (p=0.05) according to LSD.

Table 19. Mean number of squares recorded per plant in cotton grown using three levels of nitrogen fertilization with two irrigation treatments. Data were obtained from whole plant examinations of five consecutive plants, randomly selected each week within each of the treatment blocks which were replicated three times.

Irrigation Treatment		<u>Non Irrigated</u>			<u>Irrigated</u>		
N (lbs/ac)	Week ¹	<u>20</u>	<u>50</u>	<u>120</u>	<u>20</u>	<u>50</u>	<u>120</u>
6		1.07 a	0.87 a	0.33 a	1.67 a	1.53 a	2.33 a
7		2.53 a	2.67 a	1.60 a	3.60 a	4.30 a	4.20 a
8		6.80 a	6.05 a	2.67 b	8.30 a	5.20 b	9.47 a
9		12.73 a	11.20 a	8.60 a	17.50 a	15.10 a	15.20 a
10		18.87 a	14.80 a	13.80 a	22.07 a	18.73 a	23.93 a
11		15.73 a	11.47 b	19.47 a	22.20 a	22.13 a	22.20 a
12		9.73 a	8.73 a	13.47 a	11.73 a	10.93 a	16.13 a
13		7.87 a	6.07 a	8.83 a	6.67 b	9.13 ab	11.87 a
14		6.53 a	3.73 a	7.33 a	9.20 a	5.47 a	9.57 a
15		5.43 a	5.50 a	6.53 a	3.37 b	6.06 a	7.33 a
16		3.53 a	5.27 a	5.00 a	1.40 b	3.93 b	10.80 a

^{1/} Means followed by the same letter within the same row are not significantly different (p=0.05) according to LSD.

Table 20. Mean number of blooms recorded per plant in cotton grown using three levels of nitrogen fertilization with two irrigation treatments. Data were obtained from whole plant examinations of five consecutive plants, randomly selected each week within each of the treatment blocks which were replicated three times.

N (lbs/ac)	Irrigation Treatment		
	Non Irrigated		Irrigated
<u>Week</u> ¹	<u>20</u>	<u>60</u>	<u>120</u>
9	0.07 a	0.00 a	0.01 a
10	0.20 a	0.27 a	0.20 a
11	1.20 a	0.53 b	0.80 a
12	0.43 a	0.60 a	0.57 a
13	0.67 a	0.27 ab	0.47 ab
14	0.47 a	0.20 ab	0.00 b
15	0.10 a	0.07 a	0.17 a
16	0.00 a	0.40 a	0.20 a
			0.00 a
			0.13 a
			0.60 a
			0.80 a
			0.40 b
			0.40 a
			0.17 a
			0.07 a
			0.40 a

^{1/} Means followed by the same letter within the same row are not significantly different (p=0.05) according to LSD.

Table 21. Mean number of bolls recorded per plant in cotton grown using three levels of nitrogen fertilization with two irrigation treatments. Data were obtained from whole plant examinations of five consecutive plants, randomly selected each week within each of the treatment blocks which were replicated three times.

Irrigation Treatment	Non Irrigated			Irrigated		
	<u>20</u>	<u>60</u>	<u>120</u>	<u>20</u>	<u>60</u>	<u>120</u>
N (lbs/ac)						
Week ¹						
9						
10	0.53 a	0.93 a	0.67 a	0.00 a	0.00 a	0.20 a
11	3.00 a	0.67 b	3.20 a	2.00 a	2.00 a	1.40 a
12	3.87 a	4.37 a	4.60 a	2.60 a	2.87 a	3.40 a
13	3.93 a	5.90 a	4.10 a	5.13 a	5.20 a	5.50 a
14	4.13 a	6.73 a	5.07 a	4.73 a	5.63 a	5.63 a
15	4.23 a	4.63 a	4.13 a	7.40 a	3.60 b	4.33 b
16	2.87 a	3.07 a	6.13 a	4.57 a	3.88 a	6.00 a
				4.60 a	4.67 a	5.60 a

^{1/} Means followed by the same letter within the same row are not significantly different (p=0.05) according to LSD.

Table 22. Mean number of squares, blooms and bolls per plant in cotton grown using three levels of nitrogen fertilization with two irrigation treatments. Data were obtained from whole plant examinations of five consecutive plants, randomly selected each week within each of the treatment blocks which were replicated three times. Presented here are means separated by nitrogen fertilization with irrigation effects combined.

		<u>Squares</u>			<u>Blooms</u>			<u>Bolls</u>		
N (lbs/ac)		<u>20</u>	<u>60</u>	<u>120</u>	<u>20</u>	<u>60</u>	<u>120</u>	<u>20</u>	<u>60</u>	<u>120</u>
<u>Week¹</u>										
6		1.37 a	1.20 a	1.33 a						
7		3.07 a	3.50 a	2.90 a						
8		7.30 a	5.77 a	6.07 a						
9		14.64 a	13.15 a	11.24 a	0.08 a	0.00 a	0.12 a	0.00 a	0.00 a	0.08 a
10		20.47 a	16.77 a	18.90 a	0.20 a	0.20 a	0.23 a	1.27 a	1.47 a	1.03 a
11		18.97 a	16.80 a	20.83 a	1.00 a	0.57 a	0.80 a	2.80 ab	1.77 b	3.30 a
12		10.73 b	9.83 b	14.80 a	0.50 a	0.70 a	0.73 a	4.50 a	4.78 a	5.05 a
13		7.27 b	8.00 b	10.35 a	0.57 a	0.33 a	0.55 a	4.33 a	5.77 a	4.87 a
14		7.87 a	4.60 b	8.43 a	0.23 ab	0.30 a	0.03 b	5.77 a	5.17 a	4.70 a
15		4.40 b	5.80 ab	6.93 a	0.13 a	0.11 a	0.13 a	4.40 a	4.29 a	5.07 a
16		2.47 b	4.60 b	7.90 a	0.10 a	0.23 a	0.33 a	3.73 b	3.87 b	5.60 a

^{1/} Means followed by the same letter within the same row are not significantly different (p=0.05) according to LSD.

Table 23. Mean number of squares, blooms, and bolls per plant in cotton grown using three levels of nitrogen fertilization with two irrigation treatments. Data were obtained from whole plant examinations of five consecutive plants, randomly selected each week within each of the treatment blocks which were replicated three times. Presented here are means separated by irrigation treatment with nitrogen effects combined.

Treatment	Squares		Blooms		Bolls	
	Non Irr	Irrig	Non Irr	Irrig	Non Irr	Irrig
Week ¹						
6	0.76 b	1.84 a				
7	2.27 b	4.04 a				
8	5.40 b	7.91 a				
9	10.80 b	15.93 a	0.05 a	0.10 a	0.00 a	0.07 a
10	15.80 b	21.58 a	0.20 a	0.22 a	0.71 b	1.80 a
11	15.56 b	22.18 a	0.93 a	0.64 a	2.29 a	2.96 a
12	10.64 a	12.93 a	0.52 a	0.77 a	4.28 a	5.28 a
13	7.86 a	9.22 a	0.37 a	0.60 a	4.64 a	5.33 a
14	5.87 a	8.07 a	0.24 a	0.13 a	5.31 a	5.11 a
15	5.82 a	5.59 a	0.12 a	0.13 a	4.33 a	4.87 a
16	4.60 a	5.38 a	0.22 a	0.22 a	4.78 a	4.02 a

^{1/} Means followed by the same letter within the same row are not significantly different (p=0.05) according to LSD.

Table 24. Mean number of *Heliothis* damaged terminals per plant in cotton grown using three levels of nitrogen fertilization with two irrigation treatments. Data were obtained from whole plant examinations of five consecutive plants, randomly selected each week within each of the treatment blocks which were replicated three times.

Irrigation Treatment		<u>Non Irrigated</u>			<u>Irrigated</u>		
N (lbs/ac)	<u>Week</u> ¹	<u>20</u>	<u>60</u>	<u>120</u>	<u>20</u>	<u>60</u>	<u>120</u>
9		0.00 a	0.00 a	0.07 a	0.00 a	0.00 a	0.00 a
10		0.07 a	0.00 a	0.07 a	0.07 a	0.07 a	0.00 a
11		0.07 a	0.00 a	0.00 a	0.00 a	0.00 a	0.00 a
12		0.07 a	0.13 a	0.13 a	0.07 a	0.20 a	0.20 a
13		0.00 a	0.00 a	0.00 a	0.00 a	0.00 a	0.00 a
14		0.06 a	0.00 a	0.00 a	0.00 a	0.20 a	0.27 a
15		0.13 a	0.00 a	0.07 a	0.00 a	0.20 a	0.13 a
16		0.00 a	0.00 a	0.00 a	0.00 a	0.00 a	0.00 a

^{1/}Means followed by the same letter within the same row are not significantly different (p=0.05) according to LSD.

Table 25. Mean number of Heliothis damaged small squares (<2mm) per plant in cotton grown using three levels of nitrogen fertilization with two irrigation treatments. Data were obtained from whole plant examination of five consecutive plants, randomly selected each week within each of the treatment blocks which were replicated three times.

N (lbs/ac)	Irrigation Treatment	
	Non Irrigated	Irrigated
<u>Week</u> ¹	<u>20</u>	<u>20</u>
10	0.27 a	0.40 a
11	0.33 a	0.13 a
12	0.73 a	0.53 a
13	0.00 a	0.20 a
14	0.13 a	0.27 a
15	0.20 a	0.13 a
16	0.00 a	0.00 a
	<u>60</u>	<u>60</u>
	0.07 a	0.33 a
	0.07 a	0.20 a
	0.33 a	0.00 a
	0.00 a	0.00 a
	0.67 a	0.07 a
	0.13 a	0.27 a
	0.00 a	0.00 a
	<u>120</u>	<u>120</u>
	0.33 a	0.60 a
	0.13 a	0.20 a
	0.20 a	0.90 a
	0.20 a	0.13 a
	0.13 a	0.33 a
	0.20 a	0.27 a
	0.07 a	0.13 a

^{1/} Means followed by the same letter within the same row are not significantly different (p=0.05) according to LSD.

Table 26. Mean number of *Heliothis* damaged large squares (>7mm) per plant in cotton grown using three levels of nitrogen fertilization with two irrigation treatments. Data were obtained from whole plant examinations of five consecutive plants, randomly selected each week within each of the treatment blocks which were replicated three times.

Irrigation Treatment		<u>Non Irrigated</u>			<u>Irrigated</u>		
N (lbs/ac)	<u>Week</u> ¹	<u>20</u>	<u>60</u>	<u>120</u>	<u>20</u>	<u>60</u>	<u>120</u>
10		0.27 a	0.07 a	0.27 a	0.60 a	0.20 a	0.47 a
11		0.53 a	0.40 a	0.40 a	0.80 a	0.33 a	0.27 a
12		0.47 a	0.47 a	0.20 a	0.33 a	0.33 a	1.07 a
13		0.47 a	0.00 b	0.00 b	0.07 b	0.07 b	0.67 a
14		0.13 a	0.00 a	0.20 a	0.27 a	0.67 a	0.20 a
15		0.33 a	0.20 a	0.13 a	0.13 a	0.20 a	0.27 a
16		0.13 a	0.00 a	0.07 a	0.00 a	0.13 a	0.13 a

^{1/} Means followed by the same letter within the same row are not significantly different (p=0.05) according to LSD.

Table 27. Mean number of *Heliothis* damaged blooms per plant in cotton grown using three levels of nitrogen fertilization with two irrigation treatments. Data were obtained from whole plant examinations of five consecutive plants, randomly selected each week within each of the treatment blocks which were replicated three times.

Irrigation Treatment		<u>Non Irrigated</u>			<u>Irrigated</u>		
N (lbs/ac)	<u>Week</u> ¹	<u>20</u>	<u>60</u>	<u>120</u>	<u>20</u>	<u>60</u>	<u>120</u>
10		0.00 a	0.00 a	0.00 a	0.07 a	0.00 a	0.00 a
11		0.13 a	0.07 a	0.13 a	0.06 a	0.00 a	0.20 a
12		0.00 a	0.00 a	0.13 a	0.33 a	0.07 a	0.47 a
13		0.00 a	0.00 a	0.00 a	0.00 a	0.00 a	0.07 a
14		0.00 a	0.07 a	0.00 a	0.00 a	0.07 a	0.00 a
15		0.00 a	0.00 a	0.00 a	0.00 a	0.00 a	0.00 a
16		0.00 a	0.00 a	0.00 a	0.00 a	0.00 a	0.00 a

^{1/} Means followed by the same letter within the same row are not significantly different (p=0.05) according to LSD.

Table 28. Mean number of Heliothis damaged small bolls (<7mm) per plant in cotton grown using three levels of nitrogen fertilization with two irrigation treatments. Data were obtained from whole plant examinations of five consecutive plants, randomly selected each week within each of the treatment blocks which were replicated three times.

Irrigation Treatment		<u>Non Irrigated</u>			<u>Irrigated</u>		
N (lbs/ac)	Week ¹	<u>20</u>	<u>50</u>	<u>120</u>	<u>20</u>	<u>50</u>	<u>120</u>
	10	0.00 a	0.00 a	0.00 a	0.00 a	0.00 a	0.07 a
	11	0.00 a	0.07 a	0.00 a	0.20 a	0.00 a	0.13 a
	12	0.00 a	0.13 a	0.07 a	0.40 a	0.07 a	0.20 a
	13	0.00 a	0.00 a	0.00 a	0.00 a	0.07 a	0.00 a
	14	0.00 a	0.00 a	0.00 a	0.07 a	0.00 a	0.00 a
	15	0.00 a	0.07 a	0.00 a	0.00 a	0.00 a	0.00 a
	16	0.00 a	0.00 a	0.00 a	0.00 a	0.00 a	0.00 a

^{1/} Means followed by the same letter within the same row are not significantly different (p=0.05) according to LSD.

Table 29. Mean number of Heliothis damaged large bolls (>7mm) per plant in cotton grown using three levels of nitrogen fertilization with two irrigation treatments. Data were obtained from whole plant examinations of five consecutive plants, randomly selected each week within each of the treatment blocks which were replicated three times.

Irrigation Treatment	<u>Non Irrigated</u>			<u>Irrigated</u>		
	<u>20</u>	<u>50</u>	<u>120</u>	<u>20</u>	<u>50</u>	<u>120</u>
N (lbs/ac)						
<u>Week</u> ¹						
10	0.00 a	0.00 a	0.00 a	0.00 a	0.00 a	0.00 a
11	0.00 a	0.00 a	0.00 a	0.13 a	0.07 a	0.07 a
12	0.00 a	0.13 a	0.07 a	0.00 a	0.07 a	0.07 a
13	0.07 a	0.07 a	0.07 a	0.20 a	0.00 a	0.07 a
14	0.27 a	0.07 a	0.13 a	0.13 a	0.07 a	0.20 a
15	0.00 a	0.00 a	0.00 a	0.00 a	0.00 a	0.00 a
16	0.00 a	0.00 a	0.07 a	0.00 a	0.00 a	0.00 a

^{1/} Means followed by the same letter within the same row are not significantly different (p=0.05) according to LSD.

Table 30. Mean amount of Heliothis damage per plant in cotton grown using three levels of nitrogen fertilization with two irrigation treatments. Data were obtained from whole plant examinations of five consecutive plants, randomly selected each week within each of the treatment blocks which were replicated three times. Presented here are means separated by nitrogen fertilization with irrigation effects combined.

Damage	N (lbs/ac)	Week ¹	<u>Terminal</u>			<u>Small Squares</u>			<u>Large Squares</u>		
			<u>20</u>	<u>60</u>	<u>120</u>	<u>20</u>	<u>60</u>	<u>120</u>	<u>20</u>	<u>60</u>	<u>120</u>
		9	0.00 a	0.00 a	0.04 a	0.33 a	0.20 a	0.47 a	0.43 a	0.13 a	0.37 a
		10	0.07 a	0.03 a	0.03 a	0.23 a	0.13 a	0.17 a	0.67 a	0.37 a	0.33 a
		11	0.03 a	0.00 a	0.00 a	0.63 a	0.27 a	0.57 a	0.40 a	0.40 a	0.63 a
		12	0.17 a	0.17 a	0.17 a	0.10 a	0.00 a	0.17 a	0.27 a	0.03 a	0.33 a
		13	0.00 a	0.00 a	0.00 a	0.20 a	0.07 a	0.23 a	0.20 a	0.33 a	0.20 a
		14	0.03 a	0.10 a	0.13 a	0.17 a	0.12 a	0.23 a	0.23 a	0.20 a	0.20 a
		15	0.07 a	0.08 a	0.10 a	0.00 a	0.00 a	0.10 a	0.07 a	0.07 a	0.10 a
		16	0.00 a	0.00 a	0.00 a						
Damage	N (lbs/ac)	Week ¹	<u>Blooms</u>			<u>Small Bolls</u>			<u>Large Bolls</u>		
			<u>20</u>	<u>60</u>	<u>120</u>	<u>20</u>	<u>60</u>	<u>120</u>	<u>20</u>	<u>60</u>	<u>120</u>
		10	0.03 a	0.00 a	0.00 a	0.10 a	0.03 a	0.07 a	0.07 a	0.03 a	0.03 a
		11	0.10 a	0.03 a	0.17 a	0.20 a	0.10 a	0.13 a	0.13 a	0.10 a	0.07 a
		12	0.17 a	0.03 a	0.30 a	0.00 a	0.03 a	0.00 a	0.13 a	0.03 a	0.07 a
		13	0.00 a	0.00 a	0.03 a	0.03 a	0.00 a	0.00 a	0.20 a	0.07 a	0.17 a
		14	0.00 a	0.07 a	0.00 a	0.03 a	0.04 a	0.00 a	0.00 a	0.00 a	0.00 a
		15	0.00 a	0.00 a	0.00 a	0.00 a	0.00 a	0.00 a	0.00 a	0.00 a	0.03 a
		16	0.00 a	0.00 a	0.00 a						

^{1/} Means followed by the same letter within the same row are not significantly different (p=0.05) according to LSD.

Table 31. Mean amount of *Heliothis* damage per plant in cotton grown using three levels of nitrogen fertilization with two irrigation treatments. Data were obtained from whole plant examinations of five consecutive plants, randomly selected each week within each of the treatment blocks which were replicated three times. Presented here are means separated by irrigation treatment with nitrogen effects combined.

[illegible]

^{1/} Means followed by the same letter within the same row are not significantly different (p=0.05) according to LSD.

Table 32. Mean number of boll weevil damaged squares recorded per plant in cotton grown using three levels of nitrogen fertilization with two irrigation treatments. Data were obtained from whole plant examinations of five consecutive plants, randomly selected each week within each of the treatment blocks which were replicated three times.

Irrigation Treatment	N (lbs/ac)	Non Irrigated			Irrigated		
		<u>20</u>	<u>50</u>	<u>120</u>	<u>20</u>	<u>50</u>	<u>120</u>
8	Week ¹	0.00 a	0.00 a	0.00 a	0.00 a	0.00 a	0.07 a
9		0.00 a	0.00 a	0.00 a	0.00 a	0.00 a	0.00 a
10		0.00 a	0.13 a	0.00 a	0.20 a	0.20 a	0.27 a
11		2.20 ab	1.20 b	4.33 a	3.33 a	2.67 a	2.80 a
12		2.20 a	2.50 a	4.79 a	3.03 a	3.36 a	3.76 a
13		3.80 a	2.80 a	2.83 a	3.03 b	4.16 a	5.07 a
14		2.27 a	1.53 a	3.27 a	2.93 a	1.47 a	3.33 a
15		2.47 a	2.00 a	2.70 a	0.43 b	2.20 ab	3.53 a
16		2.00 b	3.40 ab	4.00 a	0.73 b	2.07 ab	5.60 a

^{1/} Means followed by the same letter within the same row are not significantly different (p=0.05) according to LSD.

Table 33. Mean number of boll weevil damaged squares recorded per plant in cotton grown using three levels of nitrogen fertilization with two irrigation treatments. Data were obtained from whole plant examinations of five consecutive plants, randomly selected each week within each of the treatment blocks which were replicated three times. Presented here are combined means from nitrogen and irrigation treatments.

Week ¹	Combined Nitrogen			Combined Irrigation	
	<u>20</u>	<u>60</u>	<u>120</u>	<u>Non Irr</u>	<u>Irrig</u>
10	0.10 a	0.17 a	0.13 a	0.04 a	0.22 a
11	3.07 a	1.93 a	3.57 a	2.78 a	2.93 a
12	2.62 b	2.93 b	4.27 a	3.16 a	4.06 a
13	3.45 a	3.42 a	4.25 a	3.36 a	4.06 a
14	1.85 a	2.07 a	2.90 a	2.36 a	2.16 a
15	1.47 b	2.73 b	4.83 a	2.39 a	2.16 a

^{1/} Means followed by the same letter within the same row are not significantly different (p=0.06) according to LSD.

THE TEXAS AGRICULTURAL EXPERIMENT STATION

TEXAS A&M UNIVERSITY, COLLEGE STATION, TEXAS

MODELLING

APPENDIX G

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Modeling

The cotton crop fruiting dynamics model of Curry et al. (1980) was not appropriate for modeling irrigated crops since no water balance or biomass components were in the model. Thus, to model Israeli data and irrigated Texas fields, these components were added to the model. The model then becomes a crop model as opposed to being restricted to a fruiting dynamics model. The crop model was developed utilizing both Texas data (CIPM project of Curry and Cate) and Israeli data (BARD project of Wallach and Kletter) by Robert M. Schoofield as part of his dissertation. A copy of the dissertation accompanies this report.

The specifics of the crop model, with particular emphasis on additional features from the published model of Curry et al. (1980), are summarized in this report. This model tracks very well both the crop data from Israel and the Texas data. No data set had all components measured simultaneously; thus, biomass data from Israel, and soil water and fruiting category data from Texas were amalgamated into a single model. The availability of these detailed data sets each emphasizing specific crop aspects is a particularly fruitful aspect of the joint BARD project.

Model Structure

The basic structure of the crop model as it relates to environment and insect pests is depicted in Figure 1. There are four major subdivisions of the crop model. Insect models are used to estimate the expected population and age structure for each insect pest. These numbers in turn effect the crop model via feeding and oviposition mainly through the fruiting structures. Most of the damaged fruiting forms are abscized by the plant.

The plant model estimates the expected population and age structure of cotton fruiting forms and the expected dry matter of fruiting forms, leaves, stems, and roots. Expected plant canopy height and width are also estimated. The plant model affects the insect model by providing insect food and adult oviposition sites (fruiting forms). It provides crop architecture information necessary for the light penetration model.

The soil water model estimates the status of plant available water in the soil. It determines any water stress that the plant may be experiencing.

The light penetration model estimates light utilization by the plant and shading of the soil surface. It provides information about the microclimates of infested fruiting forms that have been abscised from the plant. It estimates crop canopy closure which affects the photosynthetic potential of the crop. It also provides soil surface shading information necessary to the soil water model.

The specific insect model which was interfaced with the crop model was for the boll weevil. This insect is the key economic pest in Texas cotton in regions where it occurs. Thus, from the Texas point of view this insect was emphasized. Heliothis are also critical economic pests in Texas but the necessary biological information for modeling this species is part of this project and, thus, was not available in the modeling developmental time frame. Since the boll weevil is not an Israeli pest, the insect modeling aspect of the project is not emphasized in this report.

Plant Model

The growth of the cotton plant can be divided into reproductive and vegetative growth. Describing reproductive growth requires a fruiting model that estimates the expected number and size of fruiting forms on the plant. The vegetative growth model describes the expected mass of leaves, stems and

root of the plant and the expected height and width of the plant through time.

Fruiting Forms

Similar to insect cohorts, cotton fruiting forms (buds and bolls) develop at rates that vary with temperature. The developmental times can be thought of as a random variable describing the times from bud initiation to cracking of the carpel wall in the boll under a constant temperature regime. Then the expected developmental rate is defined as the expected value of one divided by these random times. Fruiting form age can be defined by integrating the developmental rate of the temperature regime of the plant canopy microclimate encountered over time. Thus, the biological age describes the path in the plane of time versus fruiting form age that is traveled by a cohort of fruiting forms initiated at the same time.

As a cohort of fruiting forms moves along the characteristic age line it is subject to loss due to fruiting form abscission. The two major causes of abscission are insect damage and nutrient stress within the plant. In the absence of these effects, a certain amount of intrinsic abscission occurs due to nonspecific factors. The effect of these abscission factors on the number density of fruiting forms per plant can be described with the Von Foerster (1959) structure for time and fruiting form age greater than or equal to zero.

In addition to insect damage, the major cause of abscission is attributed to inadequate supply of nutrients to support the growth demands of expanding bolls. The two major nutrients, water and photosynthate, are considered here together as nonspecific "nutrients." Even under irrigation, photosynthate stress can cause up to 50% abscission (Gutierrez et al., 1975). Describing the plant's response to water and photosynthate stress requires a nutrient balance model.

Nutrient Balance Model. The overall structure of the nutrient balance model (Figure 2) is adapted from the carbohydrate pool model of Wang et al. (1977) and Curry et al. (1980). Nutrients available for growth are supplied through photosynthesis and water uptake by roots. They are consumed by various plant parts according to a priority scheme. The three types of demand are (a) growth of set bolls, i.e., bolls that have passed the age of abscission susceptibility; (b) growth of younger fruiting forms that are susceptible to abscission; and (c) initiation of new buds and concurrent vegetative growth.

The dry matter production data of Wang et al. (1977) and Wallach (1978) indicate that vegetative growth continues at a reduced rate even under heavy nutrient demand by fruit. The nutrient model provides for this by shunting a fraction of the nutrients available for growth directly to bud initiation and its associated vegetative growth. If set boll potential growth demand is met, any excess nutrients are available for growth of younger fruiting forms. If this potential growth demand is met, any excess contributes to further bud initiation and vegetative growth.

Biomass. The reproductive dry matter appears to increase in a linear fashion as a function of the fruiting form biological age (Figure 3). Fruiting form mass is calculated by integrating the growth of fruiting forms in each age cohort. For fruit older than some specified age, the actual growth rate depends on the nutrient balance.

The growth of vegetative matter (leaves, stems and roots) is usually concurrent with bud initiation after the first fruiting branch occurs. Leaf, stem and root dry matter accumulation per plant at each time period t is a function of the nutrients available after fruiting forms demands have been met. Plant height increases after the time of first bud is approximately

proportional to the fruit aging rate when nutrient supply is not limiting (Figure 4). Plant width is also approximately proportional to plant height.

Soil Water Balance. The purpose of the soil water component is to estimate the stress (or limitation in growth) imposed on the cotton crop due to inadequate soil water availability. The amount of stress is quantified by a soil water stress scaling factor between 0 and 1. Soil water is added through precipitation and irrigation and lost through surface runoff, crop transpiration and soil surface evaporation. The soil is layed into two zones. For each soil layer, the water balance is kept and stress is related to the current water availability and the maximum layer capacity.

Model Results

The crop model has many parameters or system states that can be compared against measured field data. To illustrate the model results a selected set of comparisons are detailed here. The soil water balance maps well which the entire soil water profile as is illustrated in Figure 5 for a sandy-loam soil under irrigation treatments. Plant fruiting form numbers are compared with 1978 Ein Shemer and Magal (Israeli data) experiments in Figure 6, 7, and 8. The yields are particularly accurate (Figure 8).

For plant vegetative growth, plant height is compared with the 1978 Magal experiment in Figure 9 and the resulting fraction of direct sunlight intercepted by the crop canopy for an experiment by Baker and McKinion (1971) in Figure 10. Predicted and observed reproductive and leaf dry matter data are compared in Figure 11 for the 1978 Magal experiment.

In conclusion, the cotton crop model can respond to water and predicts well both the reproductive and vegetative aspects of the crop. The model also responds well to fruiting form damage due to insects. The resonse to vegetative feeders has not been tested or calibrated at this time.

Figure 1. Basic structure and interactions of the cotton crop model.

Figure 2. Structure of nutrient balance model.

Figure 3. Total reproductive dry matter vs. physiological age of the fruiting form. Note linear trend in dry matter increase. Δa_g is the physiological time interval^g of significant reproductive dry matter increase. Data from Ein Shemer experiment (Wallach, 1978).

Figure 4. Predicted and observed average plant height (cm) vs. physiological time, a_x , after first square. Note linear trend in plant height increase. Data from Ein Shemer experiment (Wallach, 1978).

Figure 5. Predicted and observed available soil water fractions in entire soil profile vs. Julian day for irrigation treatment D (Amemiya et al., 1960). Approximate 95% confidence intervals are shown for observed data.

Figure 6. Predicted and observed square counts per plant vs. Julian day for 1978 Ein Shemer experiment (Wallach, 1978).

Figure 7. Predicted and observed small and large green bolls per plant vs. Julian day for 1978 Magal experiment (Wallach, 1978).

Figure 8. Predicted and observed open bolls per plant vs. Julian day for 1978 Magal experiment (Wallach, 1978).

Figure 9. Predicted and observed plant height (m) vs. Julian day for 1978 Magal experiment (Wallach, 1978).

Figure 10. Predicted and observed fractions of light intercepted by cotton crop canopy vs. Julian day for 40" row width experiment of Baker and McKinion (1971). Approximate 95% confidence intervals are shown for observed data.

Figure 11. Predicted and observed reproductive and leaf dry matter (gm/plant) vs. Julian day for 1978 Magal experiment (Wallach, 1978).

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S I V A N - Association for the advancement of field crops

AN ALGORITHM FOR THE SHORT-TERM
PREDICTION OF INSECT POPULATIONS

APPENDIX H

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B A R D

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A B S T R A C T

An algorithm is presented for predicting how many insects present at a given time will survive to any future time. Such a prediction can be used to evaluate the potential for damage of an observed population.

It is assumed that c -insect classes are distinguished, and that the population is described by c mortalities, and c sampling efficiencies. The algorithm calculates $c-1$ of these parameters from previous insect counts. The remaining parameters must be provided. Any combination of parameters can be chosen as unknowns.

The calculation can be done with as few as two counting dates, and is therefore adapted for real-time use as an aid to pest control decisions.

The predictions of the algorithm were tested against hypothetical series of insect counts, and against field data for Heliothis armigera. The major sources of error were variations in mortality with time and sampling errors.

I N T R O D U C T I O N

The optimization of pest control requires predictions of pest numbers. In order to derive a globally optimum strategy of control, it is necessary to be able to predict pest population numbers at all future times. However, more limited predictions may also be of value. The problem considered here is the prediction of how many of the individuals observed at a given time will still be alive at any future time, in the absence of control measures. The interest of such a prediction is that it is the basis for determining the potential for damage of an observed population. Furthermore this problem is relatively simple compared to the general prediction of pest numbers, since it involves mortalities for only a limited time into the future, and does not require any prediction of recruitment.

The particular situation envisaged is that several size or age classes of a pest are distinguished, and that the number of individuals in each class is counted at more or less regular intervals. This is a fairly common situation in practice. The problem is to predict the future of the individuals observed at the last counting date. The prediction problem consists of two parts. The first is the estimation of the mortalities by class of the population. It will be assumed that mortality is relatively stable over the short-term, so that this first problem in fact consists of evaluating the mortalities from the previous insect counts. The second part of the problem consists of obtaining the actual predictions. Specifically, two quantities are of interest. The first is the number of individuals in each class at any future time. The second is the integral over future time of the number in each class, since damage is often assumed simply proportional to this integral.

A number of calculations of mortality from repeated insect counts have been reviewed by Southwood (1978). Most of these calculations are meant to aid in interpreting historical data, while the goal here is to develop an algorithm appropriate for real-time use as an aid to pest control decisions. Therefore it should be possible to carry out the mortality calculations here at any time, and preferably they should require as little previous data as possible. The methods proposed by Richards et al. (1960), and the method of Kiritani, Nakasuji and Manly (as described by Southwood (1978)) require data covering the entire period when the insect is present, which makes them unacceptable here.

The method proposed by Ruesink (1975) requires that sampling begin when an insect pest first appears, which cannot always be assured in practice. The above methods also make some rather restrictive assumptions concerning the population behavior. In the method of Richards et al. (1960), it is assumed that the same age specific death rate applies to all classes. The method of Manly (1974) makes the same assumption. The method of Ruesink (1975) assumes that the insect classes represent instars, and that mortality occurs only at molting.

The methods of Dempster (1961) and Birley (1977) have data requirements which are more lax. They assume continuous mortality at different rates in each class, and Birley (1977) has specifically considered the use of the survival parameters for determining control measures. Both methods however require that the shape of the recruitment curve be known, whereas in practice this information may be unavailable. Furthermore, none of the above methods seem to have been tested for predictive ability.

A new method of calculating mortalities is presented here. It is assumed that the population is divided into c classes, of known duration, each with a different mortality rate. Furthermore, in order to represent practical situations more closely, it is assumed that the efficiency of sampling is different for each class. There are thus $2c$ unknown parameters, namely the mortalities and sampling efficiencies. Of these, the method presented calculates $c-1$ from the insect counts. The values of the remaining parameters must be obtained from independent information. However, the method is completely flexible as to which parameters are calculated, and for each parameter not calculated, either its value or its ratio to another parameter may be specified. In addition, the results presented below indicate that the predictive ability of the algorithm is not very sensitive to errors in the fixed parameters. No information concerning recruitment in the past is required. The method is also very flexible as to data requirements. It can be used with as few as two counting dates.

Expressions for predicted insect numbers, based on the same assumptions used in calculating the population parameters, are also presented. Since the main concern here is the predictive ability of the algorithm, the predictions are tested with a number of hypothetical populations, as well as with actual field counts of Heliothis armigera, a cotton insect pest.

DESCRIPTION OF THE ALGORITHM

The algorithm is derived from the basic equation which describes the evolution of a population subjected to a continuous mortality:

$$n_i(a,t) = n_i(a - \Delta a, t - \Delta t) \exp(-\mu_i \Delta t) \quad (1)$$

where $n_i(a,t)$ is the population density of age a in class i at time t , and μ_i is the rate of mortality, assumed independent of a and t . The calculations are simplified by assuming that both age and time are measured in day degrees, such that $\Delta a = \Delta t$ for all classes. The total population in class i at time t is:

$$N_i(t) = \int_{\ell_i}^{h_i} n_i(a,t) da \quad (2)$$

where ℓ_i and h_i are respectively the lower and upper age limits of class i . If, on the average, a fraction θ_i of the individuals present in class i is effectively counted in the field, the observable population in class i at time t is:

$$M_i(t) = \theta_i N_i(t) \quad (3)$$

The $2c$ population parameters are μ_i , θ_i , $i=1,\dots,c$. In place of the μ_i it will often be convenient to work with class survivals s_i , defined as the fraction of individuals that survive through class i

$$s_i = \exp(-\mu_i(h_i - \ell_i)) \quad (4)$$

Since only the total population in a class is observed, the distribution of individuals by age within the class is necessarily a matter for supposition. A simple assumption is that the population density by age at time t is of the form

$$n_i(a,t) = b_i(t) \exp(-\mu_i a). \quad (5)$$

Substituting eq. (5) into eq. (2), and using eq. (3), gives an expression for $b_i(t)$ in terms of the observed population $M_i(t)$:

$$b_i(t) = \frac{\mu_i M_i(t)}{\theta_i [\exp(-\mu_i \ell_i) - \exp(-\mu_i h_i)]} \quad (6)$$

Eq. (5) is the basic simplifying assumption of the model. Although only strictly correct in the case of a constant rate of recruitment, the results show that even fairly large deviations from this assumption lead to only relatively small errors in the predictions.

Based on the above equations, it is possible to calculate $A_{ij}(t_1, t_2)$, the number of individuals in class j at time t_2 that were in class i at time t_1 . This calculation is shown in detail in Appendix I. If

$$t_1 > t_2 - \ell_j \quad (7)$$

then the individuals in class j at time t_2 were all present already at time t_1 , and so the total calculated populations in class j at time t_2 , based on the observed populations at time t_1 , is

$$P_j(t_1, t_2) = \sum_i A_{ij}(t_1, t_2) \quad (8)$$

It is by restricting consideration to pairs of counting dates $\{t_1, t_2\}$ sufficiently close in time that condition (7) is satisfied that all explicit dependence on the recruitment curve can be eliminated.

The population parameters are now obtained by requiring that the observed and predicted populations in each class, summed over prediction dates, be equal. Specifically, it is required that

$$\sum P_j(t_1, t_2) = \sum O_j(t_2) \quad j = 2, \dots, c \quad (9)$$

where j is the class index, $O_j(t_2)$ is the observed population in class j at time t_2 , $P_j(t_1, t_2)$ is the predicted population, and the sums are over all pairs of dates $\{t_1, t_2 : t_2 > t_1, t_1 > t_2 - \ell_j\}$. Since the youngest class will always include individuals recruited after t_1 , the first non trivial eq. is for $j=2$. The set of eqs. (9) can be solved iteratively for $c-1$ population parameters, for example using the Newton-Raphson method with analytic derivatives (Dahlquist and Anderson, 1974). (See Appendix I for the derivative expressions).

Eq. (8), together with the expressions for $A_{ij}(t_1, t_2)$ given in Appendix I, apply as well to the prediction of the population in class j at some future time t_2 , based on the populations observed at the last counting time t_1 . As noted earlier, it is also of interest to calculate the integral over time, for each class, of the number of individuals that will result from a given population at time t_1 . This calculation is presented in Appendix II.

The flow chart in Fig. 1 shows the various steps involved in the overall algorithm. The first step is to specify the number of counting dates to be used in calculating the population parameters. Indeed, it may not always be advantageous to use all available data. For example, if there is a strong time trend in the mortalities, it may be better to use only recent data. The order in which values of t_1 , t_2 and j are taken is chosen to minimize the number of calculations. For a given pair of dates (t_1, t_2) , consideration begins with the oldest class $j=c$ at time t_2 , and continues with decreasing j until a class is reached such that condition (7) is no longer satisfied. Since all younger classes will then also include individuals recruited after t_1 , it is possible to go directly to the next larger value of t_2 . If even the oldest class is to be neglected, there is no point in increasing t_2 , and so it is possible to go to the next larger value of t_1 .

TESTS OF THE ALGORITHM

A number of different hypothetical series of insect counts were generated to test the predictive ability of the algorithm. The hypothetical populations were chosen to generally resemble Heliothis armigera. Unless otherwise noted the standard parameter values in Table 1 were used in generating population numbers. The analogy with H.armigera is based on 1 time step = 2°D. A bimodal rate of recruitment was assumed (except in case 1 below), but the population was truncated in time, in order to reduce the number of calculations. This is in any case consistent with the common practice for H.armigera in Israel, that field counts are only begun when significant numbers of medium or large larvae are present. The standard hypothetical population numbers are shown in Fig. 2. The numbers of insects at 15 time step intervals were used to represent field counts. The algorithm was applied at each counting date in turn starting at the second, to predict population numbers at subsequent dates. For each initial date the populations in classes 2, 3 and 4 could be calculated at the following 1, 2 and 3 measurement dates respectively. (Beyond these limits, recruitment after the initial counting date is involved). A total of 56 population numbers could be predicted. Two measures of the accuracy of the algorithm are presented. The first denoted E_1 is the sum of the absolute errors in the predictions, divided by the sum of the true population numbers. The error E_2 is defined as

$$E_2 = \sup_{\substack{\text{(classes,} \\ \text{initial dates)}} \left\{ \frac{\sum_{\text{prediction dates}} |\text{error}|}{\sum_{\text{prediction (true values) dates}}} \right\}$$

That is, E_1 is a measure of the total error, and E_2 is a measure of the maximum error for a single class and a single initial date. In both cases the errors are expressed as a fraction of the observed population.

Unless otherwise noted, the parameters calculated by the algorithm were the mortality rates μ_2 , μ_3 and μ_4 . The correct values of the θ_i , and the correct ratio s_1/s_2 were assumed known. The calculations of the parameters used the data of the most recent four measurement dates, or all preceding data where less than four dates were available. The results are discussed below, and summarized in Table 2.

1. Constant rate of recruitment into population

In this case the assumption embodied in eq. (5) is correct, and the only source of error is the fact that in generating the population discrete time steps were used, while the algorithm is based on a continuous model. The resulting errors in the predictions are very small (Table 2, case 1), and the calculated class survivals ($s_2 = .41$, $s_3 = .56$, $s_4 = .34$) are close to the values used in generating the population. It seems therefore permissible to test the algorithm against population numbers generated using discrete time steps. (This calculation furthermore serves as a check both of the equations in Appendix I and of the programming of the algorithm).

2. Standard population

Errors here will result from the bimodal rate of recruitment, since this will give a different age distribution than that assumed in the algorithm (eq. 5). Despite relatively large deviations from this assumption, the errors in the predictions are quite small (Table 2, case 2). The error E_2 is for the prediction of the numbers in class 4, starting from the second counting date. In part this error results from the fact that only two counting dates are available for calculating the parameters. When the data from two earlier counting dates are included, this error is reduced to 10%. This suggests that there is an advantage to beginning field counts somewhat before the period when control measures may be required, in order to minimize the prediction errors during the critical period.

3. Variable survival

For these generated populations, the class survivals were treated as normal random variables, with means as in Table 1 and standard deviations equal to 20% or 40% of the mean. New class survivals were generated every five time steps or every time step. The errors in the predictions are seen to depend both on the magnitude and on the frequency of the variations in survival (Table 2, cases 3a-3c). It seems reasonable to suppose that in general the assumption of a constant survival will be better if the variation in survival is either very rapid or very slow compared to the time between measurements, than if the variation occurs on a time scale comparable to the time between measurements. The results here, that survivals that change every time step lead to smaller errors than survivals that change every five time steps, is consistent with this supposition.

4. Trend in survival

Survival may follow a long term trend, related to climate or to natural enemy populations. In generating the populations here, it was assumed that over the time span of the data the class survivals decreased by a factor of two, with the standard values of Table 1 attained toward the middle of the time period. As expected, somewhat better predictions are obtained if fewer dates are used for calculating parameters, since longer time intervals now correspond to larger differences in survival (Table 2, cases 4a-4b).

5. Variable development times

The assumption of identical development times for all individuals of a population is not in fact realistic. Here, therefore, it was assumed that the cumulative probability of completing a class increased linearly from 0 to 1 over 12 time periods. (Curry et al. (1978) justified describing the variability in development times by a probability density using a physiological time scale). This variation in development times, although large relative to the standard values of Table 1, had little effect on the generated population numbers or on the errors of the predictions (compare cases 5 and 2 in Table 2).

6. Sampling errors

The population numbers here were each drawn from a normal distribution, with mean equal to the value generated as in case 2 above, and standard deviation equal to 25%, 35% or 45% of the mean.

This case simulates sampling errors of various magnitudes. The predictions were compared to the true (mean) population numbers, except in case 6b. The comparison of cases 6a and 6c of Table 2 indicates the danger of using too few counting dates for the calculation of the parameters when substantial sampling errors are present.

However, there is no advantage in the cases considered to using more than four counting dates (compare cases 6a and 6d in Table 2). It is interesting to note that the predicted values are somewhat closer to the mean values of the generated population than to the values that include sampling error (compare 6a and 6b in Table 2). This suggests that if the algorithm is tested with field data, the errors obtained may overestimate the discrepancies between the predictions and the true population numbers.

7. Combination of deviations from the hypotheses of the algorithm

This simulation included random variations in survival (as in case 3b), a time trend in survival (as in case 4a), a distribution of development times (as in case 5), and sampling errors (as in case 6a). There seems to be some cancellation of errors in E_1 , but E_2 is approximately the sum of the errors for each case.

8. Errors in the fixed parameters

In the first two calculations here, the ratio s_1/s_2 was set equal to 1.5 and 2.5, respectively. (The value used in generating the population numbers was $.8/.4 = 2.0$). These errors had essentially no effect on the accuracy of the predictions (compare cases 8a and 8b with case 2 in Table 2).

In case 8c, the population numbers were generated using $\theta_1 = .6$, $\theta_2 = .4$, while in the parameter calculations the values $\theta_1 = \theta_2 = 1.0$ were used. The situation represented is that only 60% of the youngest class individuals, and 40% of the next class individuals, are counted, and that this selective undercounting is completely ignored in the calculations. The effect on the errors of the predictions is quite small, considering the large discrepancy between the assumptions of the algorithm and those used to generate the population. However, this discrepancy has a dramatic effect on the calculated survival values. For example, the calculated survivals in class 3, which in case 2 range from .5 to .6, now are in the (physically impossible) range 2. - 10.

9. Heliothis armigera

Counts of eggs and three larval size classes (less than 4mm in length, 4-15mm and greater than 15mm) were carried out in a commercial cotton field at Maayan Zvi, in the coastal plain region of Israel. Fig. 3 shows the field data. On the average, the standard errors in the measurements were approximately 40% of the mean values. The field was sprayed against H.armigera on July 28. In order to avoid calculating population numbers across this date, 2000 D were added to all measurement dates after the spray date.

The standard values of the parameters used in the algorithm are presented in Table 1. The threshold for development was taken as 14°C (Pearson, 1958). The duration of egg development was taken from the same source. The durations of the other larval classes, and the standard class survival values, were taken from an experiment carried out in a field adjacent to the field where the Heliothis counts were made, in which individual Heliothis

larvae were followed from day to day. It should be noted however that there are substantial uncertainties in the survival values, due to the fact that many of the larvae disappeared, without it being known whether or not they died.

In a preliminary use of the algorithm, the parameters μ_1 , μ_3 and μ_4 were calculated and the remaining parameters were fixed at their standard values. In view of the large standard errors in the data, eight measurement dates were used, where available, in the parameter calculations. The resulting survival values were widely impossible (s_3 , which logically cannot exceed 1, ranged up to 3840, for example). In analogy with case 8c, this may result from undercounting certain classes. It would not be surprising if this were the case, since the eggs are difficult to find, and small larvae may be hidden in the unfolding leaves. Therefore, it was decided to rerun the algorithm calculating θ_1 , θ_2 and μ_3 . The values of θ_3 , θ_4 and μ_1 , and the ratio s_2/s_3 and s_4/s_3 , were fixed at their standard values. Again eight measurement dates were used, where possible, for the calculations. A total of 139 population numbers were predicted. The calculated parameter values were generally reasonable in this case. μ_3 ranged from .07 to .78, and the θ values from .02 to 1.8, with most of the values toward the middle of these ranges.

The results for the hypothetical population of case 5 indicate that a standard error of 40% of the mean will account for an error E_1 of approximately 55%, when the predictions are compared to measured population numbers. Sampling errors, then, could account for most of the E_1 error obtained here (case 9, Table 2). The very large E_2 error shown in Table 2 represents the prediction of a single class and a single initial date was 252%.

DISCUSSION

The algorithm presented here for predicting insect population numbers is well suited for use as a real-time decision aid for insect control. It is to be incorporated, for example, into a package of programs for cotton crop management (Wallach et al. 1980). The data required are counts of the numbers of individuals in several age or size classes. These data are often gathered in any case, with control decisions based at each time on the latest count. The algorithm here exploits these data more fully, using the time sequence of counts to calculate the population parameters appropriate to the particular field in question. The algorithm can be used with as few as two counting dates, which is important, since often field counts are only begun when the need for control measures is suspected.

The algorithm can also handle in a simple way the case of a field which has recently been treated. It is sufficient to add some fixed number of day degrees, greater than the sum of class durations, to all measurement times after the date of control, in order to insure that the parameter calculations for the period before and after control are separated.

The algorithm is based on a continuous version of the population dynamics equation. This approach is formally satisfying since it relates the observable quantities, the numbers of individuals in each class, to the more basic quantity, the population density by age. This approach furthermore leads to relatively simple expressions for the predictions of insect numbers integrated over time.

The algorithm assumes that the population parameters are constant with time and independent of age within each class, that those population parameters not calculated are known exactly, that the age distribution within each class at each counting date is that which would result from a constant rate of input into the class, and that the insect counts are error-free. Since these conditions will never be met exactly, it is important to assess the gravity of deviations from the hypotheses of the algorithm, and to determine how the effects of deviations can be minimized. The results here suggest that a non-uniform rate of recruitment, or errors in the fixed parameters, are not likely to substantially affect the accuracy of the predictions. However, sampling errors, and variations of survival over time, may lead to very substantial errors in the predictions. In order to minimize the errors introduced by random variations, as much data as possible should be used in calculating the population parameters. On the other hand, the errors introduced by a long-term trend in survival are reduced by using only the most recent data.

Overall, then, the optimal policy will be to use data from some intermediate time span. Predictions made shortly after the start of counting, when little data is yet available, may be less accurate than later predictions.

This suggests that insect counts should be begun some time before the likely period of control measures, so that control decisions will be based on predictions that are as accurate as possible. It should be emphasized that all the results here apply to hypothetical populations which roughly resemble H.armigera, and that the deviations from the hypotheses of the algorithm which were studied were chosen to represent possible situations with regard to this pest.

The predictions of the algorithm for H.armigera are poor. However, the algorithm in this case provides, besides predicted populations, additional information. First, comparison with the results for hypothetical populations suggests that the major source of error is sampling error, and thus indicates that the predictions could be improved by increased sampling. Furthermore, the results in Table 9 can provide at least an estimate of the expected improvement in predictive ability versus decrease in sampling error, which must be the basis for an economic assessment of the utility of increased sampling. In addition, the results of the algorithm indicate that the youngest classes of H.armigera are severely undercounted in the field. Little importance however should be attached to the exact values of the calculated population parameters, since those values seem to be quite sensitive to deviations from the hypotheses of the algorithm.

An alternative approach to the prediction of insect population numbers is through the use of simulation models. In fact, models of Heliothis species have been developed. (Stinner et al. 1974, Harstack et al. 1977). With these models it is possible to explore the effects of various factors on population numbers (Harstack et al. 1975) and to predict long term trends in mortality. However, the accuracy of these models for short-term predictions has not been well documented. They may be particularly poor in cases where certain classes are undercounted in the field. This suggests the possibility of combining an algorithm based on field data, such as that presented here, with a simulation model, with the former providing short-term predictions of population numbers and the latter providing long-term predictions.

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APPENDIX I

The calculation of $A=A_{ij}(t_1, t_2)$, the number of individuals in class j at time t_2 that were in class i at time t_1

Individuals in class j at time t_2 were in the age range

$$R_1 = [\ell_j - \Delta t, h_j - \Delta t] \quad (\text{AI.1})$$

at time t_1 , where $\Delta t = t_2 - t_1$. Let $[x_i > 0, y_i > 0]$ represent that portion of R_1 which corresponds to class i .

Case 1 : $i=j$. The probability of an individual surviving a time Δt is $\exp(-\mu_j \Delta t)$, and so

$$\begin{aligned} A &= \theta_j \int_{x_j}^{y_j} n_j(a, t_1) \exp(-\mu_j \Delta t) da \\ &= \theta_j b_j(t_1) \exp(-\mu_j \Delta t) \left[\exp(-\mu_j x_j) - \exp(-\mu_j y_j) \right] / \mu_j \end{aligned} \quad (\text{AI.2})$$

$$\frac{\partial A}{\partial \mu_j} = A \left\{ \frac{\ell_j \exp(-\mu_j \ell_j) - h_j \exp(-\mu_j h_j)}{\exp(-\mu_j \ell_j) - \exp(-\mu_j h_j)} + \frac{y_j \exp(-\mu_j y_j) - x_j \exp(-\mu_j x_j)}{\exp(-\mu_j x_j) - \exp(-\mu_j y_j)} - \Delta t \right\} \quad (\text{AI.3})$$

$$\frac{\partial A}{\partial \mu_\ell} = 0 \quad \ell \neq j \quad (\text{AI.4})$$

$$\frac{\partial A}{\partial \theta_\ell} = 0 \quad \ell = 1, \dots, c \quad (\text{AI.5})$$

Case 2 : $i=j-1$. During the period from t_1 to t_2 , an individual initially of age a spends a time $h_i - a$ in class i , and then a time $a + \Delta t - \ell_j$ in class j . Therefore

$$\begin{aligned} A &= \theta_j \int_{x_i}^{y_i} n_i(a, t_1) \exp(-\mu_i(h_i - a)) \exp(-\mu_j(a + \Delta t - \ell_j)) da \\ &= \frac{\theta_j b_i(t_1) [\exp(-\mu_j x_i) - \exp(-\mu_j y_i)] [\exp(-\mu_i y_i)] [\exp(-\mu_j(\Delta t - \ell_j))]}{\mu_j} \end{aligned} \quad (\text{AI.6})$$

$$\frac{\partial A}{\partial \mu_i} = A \left\{ \frac{1}{\mu_i} - h_i + \frac{\ell_i \exp(-\mu_i \ell_i) - h_i \exp(-\mu_i h_i)}{\exp(-\mu_i \ell_i) - \exp(-\mu_i h_i)} \right\} \quad (\text{AI.7})$$

$$\frac{\partial A}{\partial \mu_j} = A \left\{ -\frac{1}{\mu_j} + \frac{y_i \exp(-\mu_j y_i) - x_i \exp(-\mu_j x_i)}{\exp(-\mu_j x_i) - \exp(-\mu_j y_i)} + \ell_j - \Delta t \right\}$$

$$\frac{\partial A}{\partial \mu_k} = 0 \quad k \neq i, \quad k \neq j \quad (\text{AI.8})$$

$$\frac{\partial A}{\partial \theta_i} = -\frac{A}{\theta_i} \quad (\text{AI.9})$$

$$\frac{\partial A}{\partial \theta_j} = \frac{A}{\theta_j} \quad (\text{AI.10})$$

$$\frac{\partial A}{\partial \theta_k} = 0 \quad k \neq i, \quad k \neq j \quad (\text{AI.11})$$

Case 3 : $i < j-1$. The times spent in classes i and j are the same as in case 2, but in addition now a time $h_\ell - \ell_\ell$ is spent in each of the classes $\ell = i+1, \dots, j-1$. As a result, the expression (AI.6) for A must now be multiplied by

$$\prod_{\ell=i+1}^{j-1} \exp(-\mu_\ell (h_\ell - \ell_\ell))$$

The equations for the derivatives of A remain valid except eq. (AI.8) which becomes

$$\begin{aligned} \frac{\partial A}{\partial \mu_\ell} &= A(\ell_\ell - h_\ell) & i < \ell < j \\ &= 0 & \ell < i, \ell > j \end{aligned} \quad (\text{AI.12})$$

It should be noted that when a fixed ratio between parameters is assumed, the derivatives with respect to the independent parameter must take this into account. Suppose, for example, that the ratio s_i/s_j is assumed fixed. The parameter μ_j then is to be calculated from the data, and then μ_i is to be calculated from μ_j . In this case :

$$\frac{d}{d\mu_j} = \frac{\partial}{\partial \mu_j} + \left(\frac{h_j - \ell_j}{h_i - \ell_i} \right) \frac{\partial}{\partial \mu_i} \quad (\text{AI.13})$$

APPENDIX II

The calculation of I_j , the integral over time of the number of individuals in class j that will result from a given population at time t_1

The value of I_j is the sum of contributions from individuals that were already in class j at time t_1 , plus from individuals that were in a class $i < j$ at time t_1 . The former contribution, denoted X_j , is obtained by noting that an individual initially of age a in class j will remain in class j for time $h_j - a$, and that the probability of surviving a time t is $\exp(-\mu_j t)$. Then

$$\begin{aligned} X_j &= \int_{\ell_j}^{h_j} n_j(a, t_1) \int_0^{h_j - a} \exp(-\mu_j t) dt da \\ &= \frac{b_j(t_1)}{\mu_j} \left[\frac{\exp(-\mu_j \ell_j) - \exp(-\mu_j h_j)}{\mu_j} - \exp(-\mu_j h_j)(h_j - \ell_j) \right] \end{aligned} \quad (\text{A.II.1})$$

To evaluate the second contribution to insect-time in class j , it is necessary to determine the number of individuals E_i observed in class $i < j$ that survive to the end of that class ;

$$\begin{aligned} E_i &= \int_{\ell_i}^{h_i} n_i(a, t_1) \exp(-\mu_i(h_i - a)) da \\ &= b_i(t_1) \exp(-\mu_i h_i)(h_i - \ell_i) \end{aligned} \quad (\text{A.II.2})$$

The fraction of these individuals that survive to enter class j is

$$\begin{aligned} Y_{ij} &= \prod_{\ell=i+1}^{j-1} s_{\ell} & j &\geq i+2 \\ &= 1 & j &= i+1 \end{aligned} \quad (\text{A.II.3})$$

The contribution of an individual that enters class j to insect time in that class is

$$\begin{aligned} F_j &= \int_0^{h_j - \ell_j} \exp(-\mu_j t) dt \\ &= [1 - \exp(-\mu_j(h_j - \ell_j))] / \mu_j \end{aligned} \quad (\text{A.II.4})$$

The total predicted insect time in any class j is then

$$I_j = X_j + \sum_{i < j} E_i Y_{ij} F_j \quad (\text{A.II.5})$$

T a b l e 1

Standard parameter values of
hypothetical populations

=====					
:	C l a s s	1	2	3	4 :
:	----- :				
:					:
:	Duration (time steps)	15	15	25	25 :
:					:
:	Sampling efficiency				:
:		1.0	1.0	1.0	1.0 :
:	= θ_i				:
:					:
:	Survival through class				:
:		.8	.4	.6	.3 :
:	= S_i				:
:					:
=====					

T a b l e 2

Errors in algorithm predictions

C A S E		E ₁ = overall error	E ₂ = maximum error
1. Constant egg lay		1 %	1 %
2. Standard population		3 %	14 %
3. Variable survival			
a. Std dev = .2 x mean. recalculate every 5 steps		7 %	18 %
b. Std dev = .4 x mean. recalculate every 5 time steps		13 %	28 %
c. Std dev = .4 x mean. recalculate every time step		9 %	23 %
4. Trend in survival			
a. 4 dates used for parameter calculation		13 %	25 %
b. 2 dates used for parameter calculation		10 %	17 %
5. Variable development times		4 %	9 %
6. Sampling error			
a. Std dev = .25 x mean.		27 %	65 %
b. Std dev = .25 x mean. compare predictions with values that include sampling error		36 %	96 %
c. Std dev = .25 x mean. 2 dates used for parameter calculation		47 %	15 %
d. Std dev = .25 x mean. all available dates used for parameter calculation		26 %	65 %
e. Std dev = .35 x mean.		36 %	93 %
f. Std dev = .45 x mean.		46 %	135 %
7. Combination of 3b, 4a, 5 and 6a		35 %	135 %
8. Errors in fixed parameters			
a. $s_1/s_2 = 1.5$ for parameter calculations		3 %	15 %
b. $s_1/s_2 = 2.5$		4 %	14 %
c. $\theta_1 = .6, \theta_2 = .4$ for generating population		11 %	28 %
$\theta_1 = 1.0, \theta_2 = 1.0$ for calculating parameters			
9. <u>Heliothis armigera</u> field counts			
calculate $\theta_1, \theta_2, \mu_3$		86 %	726 %

T a b l e 3

Standard parameter values used

for Heliothis armigera

=====							
:	C l a s s	:	1	2	3	4	:

:		:					:
:	Duration (°D)	:	28	31	51	56	:
:		:					:
:	Probability of observation = θ_i	:	1.0	1.0	1.0	1.0	:
:		:					:
:	Survival through class = S_i	:	.99	.56	.49	.56	:
:		:					:
=====							

FIGURE CAPTIONS

1. Flow chart of the algorithm for predicting insect numbers
2. Population numbers of the standard hypothetical population
3. Field counts of Heliothis armigera . The arrow indicates the date of insecticide application.

Fig. 1

Fig. 2

Fig. 3

Extension Service
HADERA Region
Israel Department of Agriculture

STATE OF ISRAEL
Ministry of agriculture
AGRICULTURAL RESEARCH ORGANIZATION
The volcani center

S I V A N - Association for the advancement of field crops

AN EVALUATION OF ETHREL SPRAYING
FOR COMPENSATION INDUCTION IN COTTON

APPENDIX I

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ABSTRACT

Short fiber cotton (Gossypium hirsutum L.) was grown at 10 plants per m-row in 96cm rows on high fertility soils. Ethrel (2-chloroethylphosphonic acid) was applied in two growing seasons at various application rates and stages of plant development. Subsequent crop response in terms of flowering, boll opening, yield accumulation and vegetative growth was followed. In a third growing season, ethrel application was compared directly with artificial floral bud damage both alone and in combination with late-season large boll removal and mid-season water stress.

Ethrel causes shedding of floral buds over the entire size range present on the plant at the time of spraying. The severity of bud shedding increases with application rate. At a given application rate, the maximum depression in cumulative flowering and rate of late-season continuation of flowering increase with lateness of application. Ethrel spraying causes a reduction in percentage boll set. The effect of ethrel on total flower production and boll set generally cancelled out and total open boll production was not affected. There was a clear trend of reduced mean boll weight and total seed cotton yield with increasing application rate. Yield accumulation was generally delayed by ethrel spraying. Multiple low-dose application of ethrel had less effect on crop development and yield than single-dose applications.

The potential of early-season bud removal to enhance compensation to water stress or boll damage later in the season was clearly illustrated in the 1983 series of treatments. The precise timing of removal and size of bud removed appear to be major determinants of the way in which yield compensation is achieved. A direct comparison of artificial bud damage and ethrel application showed the effect of these treatments on the flowering curve to be quite different. This would seem to be a consequence of the unpredictable pattern of bud shedding caused by ethrel whereby shedding is a function not only of application timing and dose but also of the specific configuration of bud number and age distribution at the time of spraying.

INTRODUCTION

Over recent years, experimentation at the Gan Hashomron experimental station has focused on gaining an understanding of the effects of pest damage and water stress on cotton (Gossypium hirsutum L.) development and yield. By analysing data from these experiments in a quantitative and dynamic approach, integrated irrigation and pest control strategies are being developed. Many studies have served to elucidate the ways in which the plant compensates for stress and damage, and certain results have suggested strategies that may at first appear counter-intuitive. It was found that the plant can achieve full yield compensation for high levels of floral bud damage, and in many instances a significant yield increase was obtained (Kletter and Wallach, 1982). Damage to small bolls did not cause a significant reduction in yield, but large boll damage consistently reduced final yield significantly (Wallach and Kletter, 1984; Kletter and Wallach, 1982). However, combination treatments of early (bud) and late (boll) damage restored yield level to that of the undamaged control (Wallach and Kletter, 1984). Similarly, in a further series of experiments (Kletter, Ungar and Wallach, 1984), early-season bud damage in combination with severe water stress later in the season also eliminated the yield reduction obtained from water stress alone.

These results indicate that it is essential to consider the expected future damage and stress patterns through the season in determining an efficient strategy of pest control. Furthermore, since early-season bud damage (upto 120 buds/m-row) appears to be, at worst, neutral in terms of yield (though not in terms of the timing of yield accumulation), it may prove commercially viable to incur such damage as part of an overall management strategy. This would be of particular relevance, for example, in fields where there is expected to be a prolonged period of water stress for reasons beyond the farmer's control (for example, poor coordination of sowing and irrigation schedules).

The experiments described in the present study were designed to test the use of a chemical shedding agent, ethrel. Ethrel (2-chloroethylphosphonic acid) breaks down in plant tissues to release ethylene and induces identical physiological responses in the plant to those caused by endogenously produced ethylene (Warner and Leopold, 1967; Yang, 1969). These responses are wide-ranging and include: accelerated ripening in many crop species (Ben Yehoshua et al., 1967; Biale et al., 1950; Burg, 1962; Oberbacher, 1968; Pratt and Workman, 1962; Kletter, 1970), epinasty (Warner and Leopold, 1967), dwarfism (Shanks, 1968), chlorophyll degradation (Russo et al., 1968), root initiation (Abeles and Rubinstein, 1964), leaf shedding (Jackson and Osborne, 1970; Rubinstein and Abeles, 1965) and the shedding of buds, flowers and fruits (Collin, 1968; Hartman et al., 1968). In cotton, ethylene synthesis is known to be associated with stress periods and the processes of floral bud shedding (Hall et al., 1957).

The first two years of experimentation studied the effects of ethrel application rate and timing of application on crop development and yield. The third year of experimentation provided direct comparison of simulated bud damage by hand removal and the use of ethrel. This comparison was made alone and in combination with stress and late-season damage treatments.

MATERIALS AND METHODS

The experiments were conducted at the Ein Shemer farm in 1981 and at the Gan Shmuel farm in 1982 and 1983, both collective farms in the coastal plains region of Israel (fertile alluvial clay-loam soils). Acala variety SJ-2 was planted on April 1, 1981, April 5, 1982 and April 8, 1983 in 96.5 cm rows and thinned to 10 plants/m-row shortly after emergence. The plots received the standard commercial fertilization and pest control for the area. Irrigation was given as shown in Table 1. Irrigation scheduling conformed to standard commercial practice for 3 irrigations in 1981 and for 4 irrigations in 1982. In 1983, two contrasting irrigation schedules were used in order to investigate the effect of water stress in combination with ethrel spraying and artificial damage. There is no summer rainfall in this region.

The experiments were arranged in a randomized block design and treatments were replicated five times. The replicates consisted of 10 rows of 12 m length. The experimental treatments are described in Table 2.

Four types of measurement were used over the course of the experiments.

1. Flower counts (FC). Newly opened flowers were counted every other day on a fixed 5 m length in each replicate. Flowering between counting days was calculated by linear interpolation.

2. Destructive sampling (DS). A section of 1 m length from each replicate was brought weekly to the laboratory for detailed measurements. These included the counting of all fruiting forms and all above-ground vegetative components.

3. Weekly harvesting (WH). At the start of the season, 2 fixed sections of 5 m length were marked out in each replicate. A fixed 2 m sub-section (of one 5 m section) was marked and harvested weekly for open bolls. All open bolls were removed by clipping and were counted. The weight of seed cotton, burrs and lint for the entire 2 m section was measured.

4. Bulk harvesting (BH). Bulk harvesting was carried out 3 or 4 times in the season using the 2 fixed sections of 5 m length. The 2 m sub-section used for WH sampling was not included. Each harvest consisted of 2 sets of measurements.

A) The cotton was harvested from 50 open bolls. Consecutive plants in the row were harvested completely until the required number was reached. Seed cotton and lint from these 50 bolls were weighed and the lint was sent for quality checking.

B) The remaining open bolls from the same 8 m of cotton were harvested (but not counted). Total seed cotton was weighed. For each BH sampling, seed cotton yield for the fixed 10 m section was calculated as the seed cotton of the 50 harvested bolls plus seed cotton from the remaining bolls in the 8 m section plus the total weight of seed cotton harvested from the 2 m sub-section at each weekly harvesting since the previous BH sampling date. Open boll weight (seed cotton only) was calculated on the basis of weekly harvesting data since the previous BH sampling date. (Since all open bolls are harvested in WH measurements, there is less sampling bias in calculating mean boll weight.) The total number of open bolls for the 10 m section was calculated as the total seed cotton yield for the 10 m section divided by the mean boll weight.

It should be noted that, due to variability in the field, measurements of yield and its components by the weekly and bulk harvesting methods do not correspond exactly.

Daily maximum and minimum temperatures were measured by thermo-hygrographs placed in standard meteorological shelters adjacent to the Ein Shemer and Gan Shmuel fields.

All tests of statistical significance are according to Duncan's Multiple Range Test at the 0.05 level.

RESULTS AND DISCUSSION

1981 AND 1982 EXPERIMENTS

FLOWERING

Figure 1 shows cumulative flower production for the 1981 and 1982A experiments. Cumulative flowering in the control plots followed a typical pattern, with a period of rapid flowering followed by a fairly sharp cutoff of flowering around 120 days after sowing. For the purposes of this discussion, the flowering curves are divided into 3 phases, as indicated in Figures 1A and 1B.

In the sprayed treatments, there was a period when the rate of flowering was slower than in the control plots (phase I). The decreased rate of flowering was presumably the direct effect of flower bud shedding caused by the ethrel spray. This assumption is supported by field observations during the period after spraying in 1981 which showed a marked increase in shedding in the treatment plots over the control. A correspondence was found between the maximum difference between control and treatment cumulative flowering curves and the difference in the number of shedding scars some time after spraying (Table 3). This too indicates that ethrel causes shedding of floral buds and hence a decreased rate of flowering during phase II.

It is possible to infer from the effect on the cumulative flowering curve the size range of floral buds that are shed as a result of spraying with ethrel. The time from the appearance of a square until it flowers is approximately 33 days; the "small square" phase (<1 cm diameter) lasting about 11 days, and the "large square" phase (1 cm to flowering) lasting about 22 days.

These values are based on measurements made in a number of fields over a period of years. Figure 1A indicates that spraying 67 days after sowing caused a reduction in flowering rate from the time flowering commenced in the control plot (about 20 days after spraying) till approximately 35 days after spraying. Thus the entire size range of floral buds was effected by the spray at these rates of application. The duration of the effect of spraying is similar for both application rates though the severity of shedding is clearly related to the dose.

Figure 1B shows the effect of spraying with ethrel 82 days after sowing, immediately after flowering commenced. At this time there were a substantial number of large buds of the plant. Here too, the reduction in flowering rate extends till about 35 days after spraying, indicating small bud shedding. Large buds are also affected by the spray since the flowering curve is depressed in the sprayed plots from the start. Thus, the entire size range of floral buds was affected by the spray and the severity of shedding was again related to the dose.

The effect of the earliest spray treatment (52 days after sowing) is shown in Figure 1C. The lower application rate had very little effect on the flowering curve, whilst the higher rate caused a maximum reduction of about 14 flowers/m-row. This reduction (at day 97) is not significant, whereas cumulative flowering 84 days after sowing is significantly different from the control and occurs 31 days after spraying, indicating shedding of small buds and perhaps a retardation in bud formation. Here too, the affected buds constitute the entire size range present on the plant at the time of the spray.

In the late application treatments of the 1982A experiment, the effect of the spray is apparent from about 90 days after sowing (Figure 1D). Since spraying occurred at day 64, the effect on flowering commenced 26 days after spraying. This indicates that only small buds up to about 8 days of age were shed despite there being larger buds on the plant at this stage. The higher application rate treatment increased the severity of shedding but not the size range of buds affected.

In previous experiments involving the removal by hand of fruiting forms (Kletter and Wallach, 1982; Wallach and Kletter, 1984) the removal of small squares at increasingly later times was followed by a progressively smaller reduction in flowering. This was largely explained in terms of the fact that as the season progresses an increasing proportion of artificially removed buds would be shed naturally. Results from the present experiment do not conform to this trend.

In the 1981 experiment, treatment HM caused a maximum reduction in cumulative flowering of 68 flowers/m-row whereas treatment HL caused a reduction of 102 flowers/m-row relative to the control. Similarly, in the 1982A experiment, the later treatments caused a larger maximum reduction in flowering than the earlier treatments at the same application rate (see Table 3). These results indicate that the artificial removal of a fixed number of buds at different times is not comparable to the application of a given dose of ethrel at different times.

A number of explanations can be offered to account for this difference. Firstly, artificial bud removal treatments in previous experiments were restricted to specific bud size classes. Damage to large buds caused a relatively large maximum reduction in flowering since the probability of natural shedding is relatively

low. As stated earlier, ethrel generally affects the entire size range of buds present on the plant at the time of spraying. Therefore, early spraying will cause shedding of predominantly small buds whereas late spraying will cause shedding of both small and large buds. Thus late spraying will have a greater effect on the flowering curve. An additional factor may be the quantity of chemical absorbed by the plant. The earlier ethrel is applied in the growing season, the smaller are the cotton plants and the greater the proportion of spray that falls between the rows. If the same dose is applied later in the season, a larger proportion of the spray will reach leaf area and more bud shedding can be expected. A further possibility is that ethrel spraying causes shedding of a certain percentage of buds present on the plant. Since there are more buds on the plant later in the season, the absolute number of buds shed will be greater with later spraying. Finally, it might be suggested that the progressive increase in natural shedding of small buds with time results from greater stress sensitivity or susceptibility to shedding of later formed buds (for example, due to the fact that such buds are situated at the ends of fruiting branches, further away from the main stem). Thus, application of an equal quantity of ethrel later in the season would cause greater shedding of buds.

In all treatments, the period of reduced flowering was followed by a period in which the rate of flowering was at least equal that in the control plots (phase II). Furthermore, treatments that showed a marked early reduction in flowering, continued to flower for a considerable time beyond the cutoff period in the control plots (phase III). An increased rate of flowering can result from increased vegetative growth and bud production, and from a reduction in the natural shedding of buds. It would seem that both mechanisms were operative in the present experiments though it is difficult to quantify their relative contribution to increased flowering. These mechanisms cannot be explained in terms of boll load since boll load in the control was also low during phase II.

Phase III of the flowering curves would seem to be strongly related to the effects of boll load on bud shedding and/or bud formation. The boll load at a given point in time can be estimated from direct counts of large bolls or from a reverse shift of the cumulative open boll curve by about 50 days. This assumes that there is a little or no natural shedding of large bolls and allows approximately 57 days from flowering to boll opening and 6-7 days after flowering till a small boll becomes a significant sink for carbohydrates. The cumulative boll opening curves for the 1981 and 1982A experiments are shown in Figure 2 (based on WH data). In 1981, the flowering cutoff period in the control commences from about day 120. This means there must have been shedding of large buds shortly before this date. Furthermore, since there is no subsequent renewal of flowering, it can be assumed that there was also small bud shedding and cessation of bud production 22 to 33 days earlier, over the period 87 to 98 days after sowing.

The period of rapidly increasing boll load in the control commences about 95 days after sowing and so boll load alone cannot explain the shedding of small buds. However, the second irrigation was given on day 102 and it is known from other investigations that there are interactions between boll load and water stress. In this instance, there was a combined effect of low moisture availability in the soil and a relatively low boll load. Large buds that did not shed at this stage would have been induced to shed prior to the 3rd irrigation at day 121 due to a combination of water stress and high boll load.

In treatment LM, the period of rapidly increasing boll load commences at about day 110. Shedding of small buds at this time would be expected to cause a cutoff in flowering from about 25 days later, which is indeed seen in Figure 1A. The somewhat milder reduction in flowering rate at 125 days would correspond to a less severe shedding response to water stress than in the control. In

treatment HM, the pre-irrigation water stress had virtually no effect on the flowering curve. At the time of the stress there were no fast-growing bolls on the plant. Flowering cutoff in this treatment commences about 137 days after sowing, implying small bud shedding over the period 105-115 days. A heavy boll load accumulates from about day 165 after sowing thus providing an adequate explanation for the greatly extended flowering period and late cutoff of flowering in this treatment.

Flowering curves for the 1982B experiment are shown in Figures 3A and 3B. Curves for the control and LM4 treatments are very similar to those of the control and HM treatments of the 1982A experiment, as would be expected. Cumulative flowering for treatments LM3 and LM4 did not differ significantly for any period. The final flower count of the season was taken 147 days after sowing and the 4th irrigation was given at day 132. Thus water stress in treatment LM3 did not cause additional shedding of those buds within 15 days of flowering. It is possible that there was some effect on smaller buds but observations did not continue sufficiently late in the season to detect such an effect. It should be noted, however, that an increase in small bud shedding at this stage would not directly effect yield since such buds would become open bolls after the latest acceptable harvest date for this region.

Multiple spraying induced a somewhat different response in cumulative flowering from that observed in single dose treatments (Figure 3B). Most notably, multiple spraying eliminated the accelerated flowering effect observed during phase II of flowering of single dose treatments.

BOLL OPENING AND PERCENTAGE BOLL SET

The effect of ethrel spraying on boll opening in the 1981 and 1982A experiments resembled the effect on flowering (Figure 2). There was a period when the number of open bolls fell progressively further below the number in the control plots. The maximum reduction in open bolls occurred approximately 56 days after the maximum reduction in cumulative flowering though the magnitude of this reduction is smaller for open bolls in all treatments (Table 3). This might be due to the natural shedding of small bolls, and/or an increased percentage boll set in the spray treatments.

Percentage boll set can be estimated as the cumulative number of open bolls at a given time, divided by the cumulative number of flowers approximately 56 days earlier. The calculated percentage boll set values up to each of the 4 BH sampling dates for the 1981 and 1982A experiments are shown in Table 4. These figures show that ethrel spraying causes a reduction in percentage boll set. Thus the smaller maximum reduction in cumulative open bolls compared to the maximum reduction in cumulative flowering must be explained in terms of natural shedding of small bolls. The reduction in percentage boll set was significant in 1981 but not so in the 1982A experiment, though a trend is apparent. These results are in sharp contrast to those of artificial bud damage experiments in which a significantly greater percentage boll set was obtained as a result of small and large square removal (Kletter and Wallach, 1982). A possible explanation may be that ethrel causes a retardation in vegetative growth immediately after spraying whilst artificial bud damage affects reproductive growth only.

The effects of increased flower production and reduced percentage boll set cancelled out in most treatments. Only in treatment HM of 1981 was there a significant reduction in total boll production.

Percentage boll set figures for the 1982B experiment are shown in Table 4. Both the single dose treatments significantly reduced overall percentage boll set. Total number of flowers, bolls and percentage boll set did not differ significantly between treatments LM3 and LM4. It appears from Figure 3C, however, that there may have been some effect of 4 irrigations over 3 in the sprayed treatments in terms of added open bolls during the final BH period (days 176-199) though the differences are not statistically significant.

The multiple spray treatments did not cause a reduction in percentage boll set, though at no stage was there evidence of an increase in boll set as found in artificial damage experiments.

YIELD AND ITS COMPONENTS

1981. Results of yield and its components for each of the 4 BH samplings are given in Table 5a. The control treatment gave the highest yield. Yield reduction in the low dose treatments was not significant, though mean boll weight was reduced significantly. The high dose treatments significantly reduced both yield and mean boll weight. Treatment HM also reduced boll number significantly.

1982A. No treatment significantly affected final yield, mean boll weight or total boll production (Table 5b). Nevertheless, the trend in the results seems to indicate that the higher dose had a stronger (negative) effect on yield and its components than the lower dose.

1982B. Treatment LM3 was the only treatment that resulted in a significant reduction in yield (Table 5c). Comparison of treatments LM3 and LM4 indicates that the 4th irrigation significantly increased boll weight during the 4th BH sampling period though total yield or mean boll weight did not differ significantly. Neither the low or high dose multiple spray treatments significantly effected yield or its components though yield accumulation was delayed.

No treatment in 1981 or 1982 showed any consistent effect on percentage lint or lint quality.

1983 EXPERIMENT

FLOWERING

Cumulative flowering curves for the 1983 series of treatments are shown in Figure 4. The B treatment curve is not shown since it is identical to the control; the removal of large bolls occurred too late in the season for the plant to respond with increased flowering before the final measurement date. Similarly, it is reasonable to assume that the flowering curves for treatments S+B and E+B would remain unchanged if the large boll damage had been omitted.

Treatment E+B caused a small reduction in flowering. The maximum difference in cumulative flowering between treatments C and E+B occurs at day 100. This reduction in flower number is significant and occurs 33 days after spraying, indicative of small bud shedding. Increased total flower production does not derive from "phase III" continuation of flowering seen in the previous experiments. Treatment E+B added many more flowers than the control over the period 100 to 120 days after sowing. This corresponds to a large increase in bud number over the 2 weeks prior to this period (Figure 5). The number of fruiting branches was also significantly greater at day 93 in treatment E+B than in the control.

Removal of medium-size buds in treatment S+B reduced flowering rate over the period that removed buds would be expected to flower. The maximal reduction in flowering was about half the number of buds removed. Similar results were obtained by Kletter and Wallach (1982) and Wallach and Kletter (1984) in artificial damage experiments. This form of compensation has been explained largely in terms of the overlap between removed and naturally shedding buds, and the reduced shedding of other buds via reduced competition between them.

Flowering in treatment S+B continued beyond day 120. Presumably, late flowering in this treatment resulted from a reduction in boll load. Total flower production in this treatment (116/m-row) was significantly less than in the control (144/m-row) or large boll removal treatment (143/m-row). This reduction in total flower production was obtained despite significant compensatory effects, which reduced damage of 120 buds m-row to a difference of only 28 flowers/m-row. Failure to achieve full compensation for damage to 120 buds/m-row in terms of total flower production is consistent with results from previous years (Kletter and Wallach, 1982). Full compensation appears to be contingent on the timing of the damage and the size of the removed buds. Where the combination of timing and size reduces the boll load at the beginning of the season to zero, compensation mechanisms become operative at an early stage and there is sufficient time for expression of full compensation. If the specific pattern of damage leaves a number of the early flowers to become early bolls (as in the 1983 experiment), these bolls constitute a negative feedback to the compensatory mechanisms.

Water stress caused a reduction in cumulative flowering from about 110 days after sowing when combined with each of the control, ethrel and bud removal treatments. The period of relative water stress presumably extended from about 85 to 100 days after sowing. If predominantly small buds are shed in response to this stress, the effect on flowering would appear over the period 105 to 135 days after sowing, as observed.

In treatment W there was a fairly abrupt cutoff in flowering at about day 110. By the end of the differential water stress period, there were fewer than half the number of floral buds in treatment W than in the control. This may be due to reduced bud production as well as stress-induced shedding; DS data shows that all aspects of vegetative growth were retarded during the stress period.

Treatment E+W had only a small effect on flowering compared to treatment W, though the trend is similar to that observed in non-stress treatments. The only significant effect of ethrel was to cause a less rapid decline in bud number towards the end of the bud production period (Figure 6). Comparison of treatments E+B and E+W shows that water stress in combination with ethrel spraying caused a large reduction in total flower production of about 50 flowers/m-row.

Water stress caused a significant reduction in cumulative flower production in treatment S+W compared to treatment S+B over the period 115 to 130 days after sowing. There was a second wave of bud production in treatment S+W (Figure 6) and continued bud production in treatment S+B. This is consistent with DS data which shows a renewal of all aspects of vegetative growth towards the end of the season.

The flowering response to multiple ethrel spraying was different in 1983 to that induced by the parallel treatment in 1982 (treatment MLM4). Figure 4C shows that a shortfall in cumulative flowering only occurred during the cutoff phase of the control. The first application of the series appears to have been ineffective, relative to the control.

BOLL OPENING AND PERCENTAGE BOLL SET

Figure 7 shows cumulative open bolls/m-row for the 1983 experiment, based on WH data. Percentage boll set was calculated for each BH sampling date and the results are shown in Table 4. Treatment B had no effect on total flower production and, by the final BH sampling date, produced 30 bolls less than the control, which is the number of bolls removed. Thus, on the basis of BH data, there was no compensation by increased boll set. WH data does indicate a small increase in boll set as a result of large boll removal, with a difference of 18 bolls in total open boll production.

Treatment S+B produced significantly fewer flowers and bolls than the control. The combination of early plus late damage did, however markedly increase percentage boll set. Since there is very little natural shedding of large bolls, removal of large bolls can be taken into account by adding the number removed to the total number of open bolls harvested. This yields a percentage boll set of 84% in treatment S+B.

Treatment E+B yielded a similar number of open bolls to the other boll removal treatments but did so from a significantly greater number of flowers. Percentage boll set is 56% after adding the number of large bolls removed. This reduced boll set was most pronounced during the 3rd BH sampling period.

Water stress treatments showed a higher boll set than the control and this enabled almost equal production of open bolls from significantly fewer flowers. Treatment S+W produced the same number of open bolls as treatment W though by a markedly different pathway of yield accumulation (Figure 7B). Treatment E+W had virtually no effect on yield accumulation compared to treatment W.

Multiple ethrel spraying had little or no effect on open boll production or boll set (Figure 7C).

It can be seen from the number of green bolls remaining at final harvest (Table 6) that boll removal treatments would not have achieved full compensation in boll number if harvesting had continued into November. Even though the total number of bolls harvested was not significantly reduced in the water stress treatments, an extended harvesting period would have enabled these treatments to reach the same number of open bolls as the control.

YIELD AND ITS COMPONENTS

Results of yield and its components for each of the 4 BH samplings are given in Table 5d. All large boll removal treatments significantly reduced seed cotton and lint yield via a reduction in total boll number. Water stress treatments and multiple ethrel spraying had no significant effect on yield or boll number and no treatment significantly affected mean boll weight. Treatment S+B showed a consistent trend of increased boll weight over the bulk harvesting period. This may have been facilitated by renewed vegetative growth and the presence of relatively young leaf area which was induced by bud removal.

Ethrel spraying did not substitute for bud removal in terms of inducing compensation for boll removal. There was a small increase in boll weight over the harvesting period compared to treatments C and B, but the tendency for ethrel to cause a reduction in percentage boll set (see Table 4) cancelled out the small compensation in boll weight.

In treatment W, the potential for compensation via increased boll weight was restricted since relief of water stress was not followed by a renewal of vegetative growth. This would seem to be associated with the fact that the stress period did not increase small boll shedding over the control and thus the accumulation of boll load in treatments C and W was similar. Here too, the addition of bud damage enhanced the compensation potential of the plant. The retardation of vegetative growth as a result of water stress was observed in both treatments W and S+W. However, treatment S+W renewed vegetative growth once this stress was relieved, presumably in response to the relatively low boll load during this period caused by the artificial bud damage. This renewed vegetative growth gave rise to a second wave of bud production (Figure 6) but these buds were formed too late to affect total flower production. However, the presence of a relatively young canopy did facilitate a much greater degree of compensation by increased boll weight and boll set than was possible in treatment W.

CONCLUSIONS

The 1981-1983 experiments show that ethrel is an effective agent in inducing shedding of floral buds. The severity of shedding is dependent on the timing and rate of application. Ethrel generally causes shedding over the entire size range of buds present on the plant at the time of spraying.

Artificial damage by hand, as carried out in this series of experiments, comprised removal of a specified number of floral buds of a specific and uniform size at a defined point in time. The induction of bud shedding by the use of ethrel cannot mimic this form of damage. Firstly, ethrel induces shedding over the entire size range of buds present on the plant and not of a particular size alone. Secondly, there is no control over the number of buds caused to shed since the severity of shedding is not only a function of dose and timing but also of the particular number-size configuration present on the plant at the time of spraying.

In the 1983 experiment, a direct comparison was made between the effect of mechanical bud damage and shedding induced by ethrel. It is difficult to compare these treatments since the severity of damage and the size distribution of damaged buds differed.

In the hand damage experiments, the response of the crop was dependent on the severity of damage, the size of buds removed, and the timing of the damage. The earlier buds are removed or the larger the size class of removed buds, the more pronounced are the effects in the early stages of development. However, as a result of the operation of more compensation mechanisms from an earlier stage of development, more complete damage compensation is obtained. Only late damage to a large number of floral buds or damage to large bolls caused a reduction in yield.

The importance of the exact timing and size range of bud removal was clearly demonstrated in experiments combining early bud damage and late damage to large bolls. Whilst early damage to large buds enables compensation for late-season boll damage (Wallach and Kletter, 1984), when the bud damage is incurred slightly later and to smaller buds, there is insufficient time for the expression of full compensation for late-season damage to large bolls (1983 experiment).

As noted earlier, there is no control over the size or number of buds shed when using ethrel as a shedding agent. Consequently, it is difficult to ascertain whether the same compensation mechanisms are elicited in such a case as when the damage is by hand removal of buds. The fact is that in the 1981 experiment, the plant responded to heavy bud shedding caused by a high dose of ethrel early in the season with an increase in total flower production over the control. This in turn resulted in a reduced percentage boll set and fewer bolls than the control. This was not compensated for by an increase in boll weight.

This series of experiments highlights the relationship between the compensation potential of the plant to damage to fruiting forms and the status of the plant at the time of the damage. Similarly, these results demonstrate the importance of future expected stress and damage patterns to the appropriate crop management tactic earlier in the season.

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T a b l e 1

Irrigation quantity and scheduling

=====				
: Year :	Date :	Days after sowing :	Quantity (m3/ha) :	:

: 1981 :	3 April :	pre-emergence :	500 :	:
:	16 June :	76 :	1200 :	:
:	12 July :	102 :	1300 :	:
:	31 July :	121 :	1300 :	:
:	:	:	:	:
: 1982 :	6 April :	pre-emergence :	400 :	:
:	18 June :	74 :	1200 :	:
:	11 July :	97 :	1200 :	:
:	26 July :	112 :	1200 :	:
:	15 August* :	132 :	800 :	:
:	:	:	:	:
: 1983 :	9 April :	pre-emergence :	400 :	:
:	:	:	:	:
:	5 irrigation treatments :	:	:	:
:	12 June :	65 :	900 :	:
:	30 June :	83 :	900 :	:
:	19 July :	102 :	900 :	:
:	1 August :	115 :	900 :	:
:	10 August :	124 :	800 :	:
:	:	:	:	:
:	4 irrigation treatments :	:	:	:
:	12 June :	65 :	900 :	:
:	17 July :	100 :	1400 :	:
:	1 August :	115 :	1100 :	:
:	10 August :	124 :	1000 :	:
=====				

* omitted for treatment LM3 of 1982-B experiment.

T a b l e 2

Description of treatments

Exp.	Treatment		Ethrel application: rate(kg/ha):	Spraying date	Spraying, days from sowing	Buds/m-row at time,of spraying
1981	Control	(C)	--	--	--	--
	Low-middle	(LM)	1.5	7 June	67	120
	High-middle	(HM)	3.0	7 June	67	120
	Low-late	(LL)	1.0	22 June	82	280
	High-late	(HL)	2.0	22 June	82	280
1982-A	Control	(C)	--	--	--	--
	Low-early	(LE)	0.75	27 May	52	60
	High-early	(HE)	1.50	27 May	52	60
	Low-middle	(LM)	0.75	8 June	64	120
	High-middle	(HM)	1.50	8 June	64	120
1982-B	Control	(C)	--	--	--	--
	Low-middle-3 irrigations	(LM3)	1.50	8 June	64	120
	Low-middle-4 irrigations	(LM4)	1.50	8 June	64	120
	Multiple-low-middle, 4 irrigations	(MLM4)	5*0.25	8,22 June, 6,20 July, 3 August	64,78, 92,106, 120	--
	Multiple-high-middle 4 irrigations	(MHM4)	5*0.50	8,22 June, 6,20 July, 3 August	64,78, 92,106, 120	--
1983 *	Control	(C)	--	--	--	--
	30 large boll damage	(B)	--	--	--	--
	120 medium size buds + 30 large boll damage	(S+B)	--	--	--	--
	Ethrel+30 large boll dam.	(E+B)	1.50	14 June	67	120
	Water stress	(W)	--	--	--	--
	120 medium size buds + water stress	(S+W)	--	--	--	--
	Ethrel + water stress	(E+W)	1.50	14 June	67	120
	Multiple ethrel spraying	(M)	5*0.25	14,28 June, 12,26 July, 9 August	67,81 95,109, 123	--

Note: The terms high and low refer to application rates within an experiment only.

* - Bud removal dates in 1983 experiment: June 20 (day 73), June 27 (day 80),
July 4 (day 87); 40 buds removed at each date.

Boll removal dates: August 15+16 (day 129, 130).

Table 3

The maximum difference in cumulative flowering,
the difference in the number of shedding scars and the
maximum difference in cumulative boll opening between control and sprayed plots

Experiment	Treatment	: Max. diff.:		: Diff. in :		: Max. diff.:	
		: in cumul. :	Days	: # of :	Days	: in cumul. :	Days
		: flowering :	after	: shedding :	after	: open boll :	after
		: curve :	sowing	: scars :	sowing	: curve :	sowing
		: fl/m-row :		: scars/m-row :		: bolls/m-row :	
		: (a) :		: (b) :		: (c) :	
: 1981	1.5 kg/ha ethrel/120 buds m-row (LM)	: 44 :	102	: 69 :	95	: 31 :	158
:	3.0 kg/ha ethrel/120 buds m-row (HM)	: 68 :	102	: 83 :	95	: 56 :	158
:	1.0 kg/ha ethrel/280 buds m-row (LL)	: 36 :	109	: 43 :	95	: 29 :	165
:	2.0 kg/ha ethrel/280 buds m-row (HL)	: 102 :	116	: 165 :	95	: 61 :	165
:							
: 1982-A	0.75 kg/ha ethrel/ 60 buds m-row (LE)	: 3 :	97	: 3 :	62	: — :	—
:	1.5 kg/ha ethrel/ 60 buds m-row (HE)	: 14 :	97	: 8 :	62	: — :	—
:	0.75 kg/ha ethrel/120 buds m-row (LM)	: 17 :	104	: 2 :	69	: 13 :	160
:				: 14 :	90		
:	1.5 kg/ha ethrel/120 buds m-row (HM)	: 29 :	97	: 25 :	69	: 23 :	160
:				: 22 :	90		

a - based on FC measurements.

b - based on DS measurements. Values taken for the earliest measurement after spraying.

c - based on WH measurements.

Table 4

Total flower production and calculated percentage boll set
up to each boll harvesting sampling date.

: Expt.	: Treat.:	: Up to 2.9.81 (154 d)	: Up to 17.9.81 (169 d)	: Up to 11.10.81 (193 d)	: Up to 28.10.81 (210 d)
		: flowers*+ : % set	: flowers : % set	: flowers : % set	: flowers : % set
: 1981	C	: 50 a : 74	: 121 a : 62	: 152 c : 58	: 153 d : 59 a
	LM	: 19 c : 68	: 96 b : 58	: 168 b : 51	: 175 bc : 51 b
	HM	: 1 d : 30	: 73 c : 42	: 187 a : 39	: 199 a : 39 c
	LL	: 33 b : 64	: 86 b : 64	: 157 bc : 57	: 168 c : 56 ab
	HL	: 11 c : 36	: 27 d : 59	: 166 b : 45	: 192 ab : 44 c
		: Up to 2.9.82 (150 d)	: Up to 13.9.82 (161 d)	: Up to 28.9.82 (176 d)	: Up to 21.10.82 (199 d)
		: flowers : % set	: flowers : % set	: flower : % set	: flowers : % set
: 1982-A	C	: 66 a : 45	: 115 a : 59	: 161 a : 55	: 173 a : 55 a
	LE	: 63 a : 43	: 116 a : 56	: 163 a : 55	: 177 a : 54 a
	HE	: 52 a : 44	: 108 a : 59	: 164 a : 53	: 177 a : 53 a
	LM	: 56 a : 32	: 99 ab : 51	: 157 a : 49	: 184 a : 50 a
	HM	: 45 b : 96	: 87 b : 48	: 163 a : 45	: 200 a : 47 a
: 1982-B	C	: 48 a : 65	: 125 a : 50	: 165 a : 49	: 176 b : 50 a
	LM3	: 32 b : 66	: 92 b : 51	: 165 a : 43	: 203 a : 39 b
	LM4	: 33 b : 61	: 87 b : 53	: 163 a : 44	: 201 a : 42 b
	MLM4	: 39 b : 54	: 98 b : 53	: 154 a : 47	: 182 b : 51 a
	MHM4	: 39 b : 51	: 90 b : 51	: 143 a : 45	: 182 b : 48 a
		: Up to 12.7.83 (151 d)	: Up to 19.9.83 (164 d)	: Up to 4.10.83 (179 d)	: Up to 26.8.83 (196 d)
		: flowers : % set	: flowers : % set	: flowers : % set	: flowers : % set
: 1983	C	: 37 ab : 73	: 112 a : 60	: 137 b : 64	: 144 b : 66 a
	B**	: 38 ab : (45)	: 112 a : (43)	: 139 b : (44)	: 143 b : (46 b)
	S+B**	: 25 b : (32)	: 45 b : (36)	: 92 d : (51)	: 116 c : (60 a)
	E+B**	: 28 ab : (43)	: 105 a : (38)	: 162 a : (36)	: 171 a : (38 b)
	W	: 41 a : 83	: 107 a : 64	: 114 c : 68	: 116 c : 72 a
	S+W	: 15 c : 100	: 37 b : 68	: 74 e : 73	: 108 c : 76 a
	E+W	: 35 ab : 83	: 102 a : 62	: 118 c : 67	: 119 c : 71 a
	M	: 37 ab : 81	: 109 a : 62	: 127 bc : 65	: 129 bc : 68 a

* - 56 days previously

** - Boll set figures do not take into account removal of 30 large bolls.

+ - Numbers within a column for a given experiment followed by the same letter are not significantly different at the 0.05 level according to Duncan's Multiple Range Test.

Table 5a

Cotton yield (kg/ha) and its components (1981 experiment)*

T R E A	Until 2.9.81			3 - 17.9.81			18.9 - 11.10.81			12 - 28.10.81		
	Seed	Boll	# of	Seed	Boll	# of	Seed	Boll	# of	Seed	Boll	# of
	cotton	weight	bolls	cotton	weight	bolls	cotton	weight	bolls	cotton	weight	bolls
C	2830 a	7.7 a	37 a	2690 b	7.1 ab	38 ab	720 d	5.5 a	13 d	90 b	4.8 a	2 b
LM	950 c	7.4 a	13 c	3190 a	7.4 ab	43 a	1610 c	5.4 a	30 c	140 b	4.8 a	3 b
HM	20 d	7.2 a	.3 d	2330 b	7.8 a	30 b	2490 b	6.0 a	41 b	120 b	2.2 a	5 b
LL	1490 b	7.1 a	21 b	2270 b	6.7 b	34 b	2080 bc	6.0 a	34 c	160 b	3.6 a	5 b
HL	300 d	7.5 a	4 d	870 c	7.0 b	13 c	3530 a	6.1 a	58 a	410 a	3.7 a	11 a
T R E A T M E N T												
				Up to 17.9.81 (169 d)			Up to 11.10.81 (193 d)			Up to 28.10.81 (210 d)		
Control	(C) : 5520 a			7.5 ab	74 a		6240 a	7.1 a	87 a	6330 a	7.0 a	90 a
1.5 kg/ha ethrel at 120 buds	(LM) : 4140 b			7.4 ab	56 b		5750 a	6.7 ab	86 a	5890 a	6.6 b	89 a
3.0 kg/ha ethrel at 120 buds	(HM) : 2360 c			7.8 a	31 c		4840 b	6.7 ab	72 b	4960 b	6.4 bc	78 b
1.0 kg/ha ethrel at 280 buds	(LL) : 3760 b			6.8 b	55 b		5840 a	6.6 b	89 a	6000 a	6.4 bc	94 a
2.0 kg/ha ethrel at 280 buds	(HL) : 1170 d			7.1 ab	16 d		4700 b	6.4 b	74 b	5110 b	6.0 c	85 a

Table 5b

Cotton yield (kg/ha) and its components
(1982-A experiment)*

T R E A	Until 2.9.82			3.9 - 13.9.82			14.9 - 28.9.82			29.9 - 21.10.82		
	Seed	Boll	# of	Seed	Boll	# of	Seed	Boll	# of	Seed	Boll	# of
	cotton	weight	bolls	cotton	weight	bolls	cotton	weight	bolls	cotton	weight	bolls
C	2370 a	8.0 a	30 a	2820 a	7.5 a	38 a	1160 b	5.6 ab	21 b	430 b	5.7 a	8 c
LE	2120 ab	8.0 a	27 a	2960 a	7.7 a	39 a	1210 b	5.2 b	23 b	380 b	5.7 a	7 c
HE	1810 ab	7.7 b	23 a	2900 a	7.2 a	40 a	1160 b	4.9 b	23 b	380 b	5.5 a	7 c
LM	1460 bc	7.9 a	18 ab	2490 b	7.8 a	32 b	1600 b	6.0 ab	27 b	910 a	5.9 a	15 b
HM	990 c	7.6 b	13 b	2270 c	7.8 a	29 b	2070 a	6.5 a	32 a	960 a	4.9 a	19 a
T R E A T M E N T												
				Up to 13.9.82 (161 d)			Up to 28.9.82 (176 d)			Up tp 21.10.82 (199 d)		
Control	(C) : 5190 a			7.6 a	68 a		6350 a	7.2 a	88 a	6780 a	7.1 a	96 a
.75 kg/ha ethrel at 60 buds	(LE) : 5070 a			7.8 a	65 a		6280 ab	7.1 a	89 a	6660 a	7.0 a	95 a
1.5 kg/ha ethrel at 60 buds	(HE) : 4710 a			7.4 a	64 a		5870 ab	6.7 b	87 a	6250 a	6.7 a	94 a
.75 kg/ha ethrel at 120 buds	(LM) : 3950 b			7.9 a	50 b		5560 ab	7.2 a	77 ab	6460 a	7.0 a	92 a
1.5 kg/ha ethrel at 120 buds	(HM) : 3260 c			7.8 a	42 c		5320 b	7.2 a	74 b	6280 a	6.7 a	93 a

* Numbers within a column followed by the same letter are not significantly different at the 0.05 level according to Duncan's Multiple Range Test.

T a b l e 5c

Cotton yield (kg/ha) and its components
(1982-B experiment)

	: Until 2.9.82			:	3 - 13.9.82			:	14 - 28.9.82			:	29.9 - 21.10.82			:
R	:															
E	: Seed	Boll	# of	:	Seed	Boll	# of	:	Seed	Boll	# of	:	Seed	Boll	# of	:
A	: cotton	weight	bolts	:	cotton	weight	bolts	:	cotton	weight	bolts	:	cotton	weight	bolts	:
C	: 2570 a	8.2 a	31 a	:	2290 a	7.5 a	31 a	:	1200 b	6.2 b	19 bc	:	390 b	6.0 a	7 b	:
LM3	: 1700 b	8.2 a	21 b	:	2010 b	7.8 a	26 a	:	1610 ab	6.7 ab	24 ab	:	420 b	5.5 b	8 b	:
LM4	: 1650 b	8.4 a	20 b	:	2000 b	7.8 a	26 a	:	1810 a	6.8 ab	27 a	:	750 b	6.2 a	12 b	:
MLM4	: 1770 b	8.3 a	21 b	:	2410 a	7.8 a	31 a	:	1430 b	6.9 ab	21 bc	:	1240 a	6.4 a	19 a	:
MM4	: 1590 b	8.1 a	20 b	:	1980 b	7.5 a	26 a	:	1280 b	7.1 a	18 c	:	1470 a	6.4 a	23 a	:
T R E A T M E N T				:	Up to 13.9.82 (161 d)			:	Up to 28.9.82 (176 d)			:	Up to 21.10.82 (199 d)			:
- 4 irrigations				:	4860 a	7.9 a	62 a	:	6060 a	7.5 a	81 a	:	6450 ab	7.4 a	88 ab	:
.5 kg/ha ethrel at 120 buds. 3 irr.				:	3710 b	8.0 a	47 b	:	5320 b	7.6 a	71 b	:	5730 b	7.4 a	78 b	:
.5 kg/ha ethrel at 120 buds. 4 irr.				:	3640 b	8.0 a	46 b	:	5450 b	7.6 a	72 ab	:	6200 ab	7.4 a	84 ab	:
* .25 kg/ha ethrel. 4 irrigations				:	4180 b	8.0 a	52 b	:	5620 ab	7.7 a	73 ab	:	6860 a	7.4 a	92 a	:
* .50 kg/ha ethrel. 4 irrigations				:	3570 b	7.8 a	46 b	:	4850 c	7.6 a	64 b	:	6320 ab	7.3 a	87 ab	:

Table 5d

Cotton yield (kg/ha) and its components
(1983 experiment)

T R E A T M E N T	Until 6.9.83			7 - 19.9.83			20.9 - 4.10.83			5 - 21.10.83		
	Seed cotton	Boll weight	# of bolls	Seed cotton	Boll weight	# of bolls	Seed cotton	Boll weight	# of bolls	Seed cotton	Boll weight	# of bolls
C	2120 a	7.9 bc	27 a	2800 a	7.0 b	41 a	1090 b	5.6 b	21 b	220 b	4.3 b	7 b
B	1330 b	7.9 bc	17 b	2190 bc	6.8 b	32 bc	780 b	6.1 b	13 b	220 b	5.0 ab	4 b
S+B	650 c	8.6 a	8 c	620 d	7.2 b	8 d	2250 a	7.4 a	31 a	1420 a	6.6 a	21 a
E+B	990 bc	7.9 bc	12 bc	1920 c	7.1 b	27 c	1210 b	6.7 ab	18 b	420 b	5.7 ab	8 b
W	2620 a	7.8 bc	34 a	2490 ab	7.3 b	34 abc	620 b	5.5 b	11 b	200 b	4.5 ab	5 b
S+W	1180 bc	8.1 b	15 b	870 d	8.3 a	10 d	2240 a	7.7 a	29 a	1650 a	6.0 ab	27 a
E+W	2210 a	7.5 c	29 a	2480 ab	7.3 b	34 abc	870 b	5.3 b	17 b	200 b	4.1 b	5 b
M	2340 a	7.7 c	30 a	2730 b	7.1 b	38 ab	940 b	6.0 b	16 b	190 b	4.8 ab	4 b
T R E A T M E N T : Up to 19.9.83 (164 d) : Up to 4.10.83 (179 d) : Up to 21.10.83 (196 d) :												
Control	4920 a	7.3 c	67 a	6010 a	6.9 b	88 a	6230 a	6.7 a	96 a			
Removal of 30 large bolls	3520 b	7.3 c	48 b	4300 b	7.0 b	61 b	4520 b	6.9 a	66 b			
Removal of 120 buds + 30 large bolls	1270 d	8.0 ab	16 e	3530 b	7.6 ab	47 c	4950 b	7.3 a	68 b			
Ethrel + removal of 30 large bolls	2910 b	7.4 bc	40 c	4120 b	7.1 b	58 bc	4530 b	7.0 a	65 b			
Water stress	5110 a	7.5 bc	68 a	5730 a	7.3 b	78 a	5930 a	7.1 a	83 a			
Removal of 120 buds + water stress	2050 c	8.3 a	25 d	4290 b	8.0 a	54 bc	5940 a	7.3 a	81 a			
Ethrel + water stress	4690 a	7.4 bc	63 a	5560 a	7.0 b	79 a	5760 a	6.8 a	85 a			
Repeated Ethrel sprays	5070 a	7.5 bc	68 a	6010 a	7.2 b	83 a	6200 a	7.1 a	87 a			

T a b l e 6

The number of large green bolls remaining at final harvest
(21.10.83) of the 1983 experiment.

T R E A T M E N T		: Green bolls/m-row :	
:	:	:	:
: Control	(C) :	3.4 c	:
: Removal of 30 large bolls	(B) :	7.7 bc	:
: Removal of 120 squares + 30 large bolls	(S+B) :	8.0 bc	:
: Ethrel + removal of 30 large bolls	(E+B) :	5.8 bc	:
: Water stress	(W) :	13.3 a	:
: Removal of 120 squares + water stress	(S+W) :	15.4 a	:
: Ethrel + water stress	(E+W) :	9.5 b	:
: Repeated ethrel sprays	(M) :	7.4 bc	:
:	:	:	:

Numbers followed by the same letter are not significantly different
at the 0.05 level according to Duncan's Multiple Range Test.

FIGURE LEGENDS

Figure 1. The effect of ethrel spraying on cumulative flowering.

(a) 1981, treatments C, LM and HM

(b) 1981, treatments C, LL and HL

(c) 1982A, treatments C, LE and HE

(d) 1982A, treatments C, LM and HM

I indicates irrigation date.

Figure 2. The effect of ethrel spraying on cumulative open bolls.

(a) 1981, treatments C, LM and HM

(b) 1981, treatments C, LL and HL

(c) 1982A, treatments C, LE and HE

(d) 1982A, treatments C, LM and HM

Open boll numbers based on WH data.

Figure 3. The effect of ethrel spraying on cumulative flower and open boll production in experiment 1982B.

(a) Cumulative flowering, treatments C, LM3 and LM4

(b) Cumulative flowering, treatments C, MLM4 and MHM4

(c) Cumulative open bolls, treatments C, LM3 and LM4

(d) Cumulative open bolls, treatments C, MLM4 and MHM4

I indicates irrigation date.

Open boll numbers based on BH data.

Figure 4. The effect of damage and stress treatments on cumulative flowering in 1983.

(a) Treatments C, S+B and E+B

(b) Treatments C, W, S+W and E+W

(c) Treatments C, and M

I indicates irrigation date.

S indicates bud removal date.

B indicates boll removal date.

Figure 5. The effect of ethrel spraying and bud removal on large bud (>.5 cm) production in 1983.

Treatments C, S+B and E+B

E indicates ethrel spraying date.

S indicates bud removal date.

B indicates boll removal date.

I indicates irrigation date.

Figure 6. The effect of ethrel spraying and bud removal in combination with water stress on large bud (>.5 cm) production in 1983.

Treatments W, S+W and E+W

E indicates ethrel spraying date.

S indicates bud removal date.

I indicates irrigation date.

Figure 7. The effect of damage and stress treatments on cumulative open bolls in 1983.

(a) Treatments C, B, S+B and E+B

(b) Treatments C, W, S+W and E+W

(c) Treatments C, and M

Figure 1

Figure 2

Figure 3

Figure 4

Figure 5

Figure 6

Figure 7

Extension Service
HADERA Region
Israel Department of Agriculture

STATE OF ISRAEL
Ministry of agriculture
AGRICULTURAL RESEARCH ORGANIZATION
The volcani center

S I V A N - Association for the advancement of field crops

AN ALGORITHM FOR ON-LINE
APPROXIMATE OPTIMIZATION
OF HELIOTHIS ARMIGERA CONTROL IN COTTON

APPENDIX J

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ABSTRACT

An algorithm for the approximate optimization of Heliothis armigera control in cotton is presented. The algorithm is meant to be called after each date on which H.armigera is counted, in each field. The algorithm then recommends whether or not to spray at that time. It is based on a detailed cotton model and an insect model with fixed mortalities and recruitment, but whose parameters are reevaluated, based on all the available insect data, each time the algorithm is invoked. The optimization is carried out in two steps. First a series of candidate spray strategies are generated, using just the insect model, with a dynamic programming technique. Then just two of those strategies are compared using the cotton model. Applied to historical data from 6 cotton fields in Israel, the algorithm recommends reasonable strategies with less sprays than the Ministry of Agriculture recommendations.

INTRODUCTION

Heliothis armigera is the first lepidopterous pest to appear on the cotton crop in Israel. It is most prevalent from June to mid or late July, and during this period destroy mostly flower buds and also some bolls. Control is currently based on a threshold strategy suggested by the Ministry of Agriculture. Counts of the insect are carried out about twice a week in every field, and if the population of medium and large larvae exceeds the fixed threshold, the grower is supposed to spray. This leads, currently, to an average of about 1.5 sprays per field against Heliothis.

It has been suggested that these recommendations are not fully consistent with the known behavior of the plant and insect. In particular, it has been suggested that the decision whether or not to spray should depend on total damage over the season, and not on the population at a single time (Wallach, 1980). That study also indicated that the current weighting of medium versus large larvae is not reasonable.

It seems then advantageous to replace the current empirical control strategy by a strategy based explicitly on current understanding of the cotton crop, the insect and their interactions, as embodied in computer simulation models. A number of cotton crop models have been developed that can be coupled with insect models (McKinion et al., 1974; Wang et al., 1977; Curry et al. 1980; Wallach, 1980). These models have been used to examine the effects of various pest populations and of particular control strategies. The pests studied include Lygus hesperus (Gutierrez et al. 1977), Heliothis zea H. virescens and Anthonomus grandis (Brown et al. 1979), Anthonomus grandis alone (Curry et al. 1980) and H. armigera (Wallach, 1980).

Much less has been done on deriving optimal pest control strategies. Shoemaker (1981) has reviewed many of the applications of optimization techniques to pest control. While these techniques can be used even for complex assumptions concerning the insect dynamics, they generally require that the effect of the insect on the economic crop yield be quite simple. For cotton, however, this is certainly not the case. The cotton crop can compensate to a large extent for insect damage, so that yield loss is far from proportional to damage, and furthermore the effect of damage varies with the timing of the removal of fruiting bodies, and with the sizes of fruiting bodies removed (Kletter and Wallach, 1982). As a result, in order to optimize pest control in cotton, both the crop and insect dynamics must be taken into account. This was done by Talpaz et al. (1978) in their study of boll weevil control. They calculated the optimal insecticide doses for each of 25 different four day periods using a gradient-based method.

The optimization technique of Talpaz et al. is quite general, but requires repeated evaluations of the overall cotton-boll weevil simulation model. Many of the cotton growers in Israel are linked to central computing facilities, but it is not realistic to envision very frequent runs of a cotton model on these computers. Even the relatively simple model of Wallach (1980) requires about 1 minute of CPU time on a PDP 11/70, which is the computer most widely available to the growers. Several tens of runs for each cotton field of each grower then would be unacceptable.

The purpose of this paper is to suggest an algorithm for recommending H.armigera control decisions in cotton that uses an approximate optimization procedure and requires only 2 evaluations of the cotton model. The algorithm is designed for real time use. In particular, it is envisioned that the algorithm will be invoked after each new insect count becomes available, in each field. The algorithm then recommends whether or not to spray at that time. (The spray dosage is assumed fixed).

The cotton model used (section 3) is similar to that described in Wallach (1980). The insect model (section 4) is an extension of the model presented in Wallach (1984). It assumes fixed mortalities and recruitment, but the parameters are reevaluated each time the algorithm is invoked, based on all the available insect data for the field in question.

The optimization (section 5) is carried out in two stages. At first, a set of candidate insect control strategies is determined, which minimize total insect damage for different numbers of spray applications. The generation of these strategies involves only the insect model, and can be efficiently carried out using the dynamic programming technique described by Birley (1979). It is argued that it is sufficient to compare just two of these strategies, using the cotton model, in order to decide whether or not a spray application is justified.

In the sixth section of this paper, the algorithm is applied to historical data from six cotton fields in Israel, and control recommendations are generated for each date on which insects were counted. This indicates the expected behavior of the algorithm for real, and therefore "noisy" data.

FIELD DATA

The field counts of H.armigera from 6 commercial fields in the coastal plains region of Israel are shown in Table 1. The four insect classes distinguished are eggs (class 1) and larvae of length <4 mm (class 2), 4-15 mm (class 3) and >15 mm (class 4).

Each count is the average for 2 to 25 2-meter sections of row, in which each plant was examined. The random selection of sections to be examined was carried out anew at each date. The standard errors in the measurements are generally on the order of 40% of the mean values. It is possible that eggs and <4 mm larvae were undercounted relative to the larger larvae, because the eggs are difficult to see and small larvae may be hidden in the unfolding leaves and small buds. Previous calculations based on the data from one of these fields (Wallach, 1984) suggest that such undercounting does in fact occur.

The two Maayan Zvi fields in 1979 and again in 1980 represent a single field divided into two plots, which received different insecticide treatments. In each case the plot denoted MINAG was treated whenever the population exceeded the Ministry of Agriculture recommended threshold, while one or more of these applications was skipped in the plot denoted UNSPRAY. Yields were measured by weekly hand harvesting of all open bolls in five fixed 2-meter lengths of row in each plot. The results are presented in Table 2.

The degree days shown in Tables 1 and 2 were calculated from daily minimum and maximum temperatures recorded within 3 km of each field. The method of calculation is explained in Marani (1979). The degree days for cotton development, denoted $^{\circ}D_{cot}$, and for Heliothis development, denoted $^{\circ}D_{Hel}$, assume respectively thresholds of development of 12°C and 14°C (Pearson, 1958). The time origin for $^{\circ}D_{cot}$ is crop emergence, and for $^{\circ}D_{Hel}$ is arbitrary.

COTTON MODEL

The cotton crop in the model is described by total plant weight, by the number of fruiting bodies of each age, and by the weight of fruiting bodies of each age. The equations of the model describe the time rates of change of these state variables, that is the rate of total plant weight gain, the rates of bud production and bud and boll shedding, and the rate of fruiting body weight gain. These rates depend on the state of the plant. In particular, the basic feature of the model is the negative feedback of bolls present on the crop on bud production and bud and boll retention.

Environmental effects are included in the model only implicitly, through the parameter values. The model then is adapted to describing how differences in crop state (caused for example by different levels of insect damage) would affect subsequent crop behavior, in a particular environment. This environmental limitation is less restrictive than it might at first seem, since summer weather in Israel is fairly similar from year to year, and since a large part of the cotton crop is managed (and in particular is irrigated) according to a standard pattern.

The model used here is similar to that described in Wallach (1980). The basic difference is that the current model considers in considerably more detail the variation in crop growth pattern over the course of the growing season. In practice, this means that where a single parameter was used before to describe the average crop growth response, there are now several parameters, one for each time period. The additional detail is mainly based on a series of 9 different bud and boll removal treatments carried out in 1978 (Kletter and Wallach, 1982) and on a series of 10 different damage treatments carried out in 1979 (Kletter and Wallach, in preparation). Since the justification of the form of the model was largely presented in Wallach (1980), it will not be repeated here. Rather, just a brief description of the model is presented below.

Whereas a partial analytic solution was found for the previous model, the current model's more complicated equations could only be solved by numerical integration on a computer. To reduce computing time, a time step of $70^{\circ}\text{D}_{\text{cot}}$ (roughly one week) is used in obtaining the solution. The model parameters therefore are defined for each $70^{\circ}\text{D}_{\text{cot}}$ period. (The parameter values are presented in Table 3). The fruiting bodies are also aggregated into age classes that span $70^{\circ}\text{D}_{\text{cot}}$. Thus class 1 contains fruiting bodies aged 0 to $70^{\circ}\text{D}_{\text{cot}}$ at the end of each time step, etc.

Bud production is assumed to begin at $210^{\circ}\text{D}_{\text{cot}}$, and so the numerical solution is begun at this time. (Time step 1 then covers the period $210\text{--}280^{\circ}\text{D}_{\text{cot}}$, etc.). Buds are assumed to flower at the end of the 5th age class. Boll opening on the other hand does not occur at a fixed age, but rather at an age which decreases as the season progresses. At the end of each time period S , a maximum age class M for growing bolls is calculated;

$$M = \text{largest integer in } (18.1 - .2*S) \quad (1)$$

Any growing bolls in higher classes enter the mature boll category (these bolls do not gain weight), and one time period later are added to the open (harvestable) bolls. Boll load is defined as the number of bolls in age classes 7 through the last class of growing bolls, and is denoted NLOAD .

The rate of increase of total above-ground dry matter in time step S is denoted RDM ($\text{g/m-row}/70^{\circ}\text{D}_{\text{cot}}$). Up to a cut off time t_f it is equal to a fixed standard rate ;

$$\text{RDM}_S = \text{PDM}_S \quad S * 70 + 210 \leq t_f \quad (2)$$

After t_f , RDM equals the minimum rate of reproductive weight gain. For the time step during which t_f occurs, RDM equals a fraction of the fixed standard rate, as explained below.

The cutoff time depends on plant development. It occurs when

$$\text{VEG}(t_f) = 24.4 * t_f - 1670 \quad (3)$$

where $\text{VEG}(t)$ is above-ground dry matter at time t , and is calculated as the difference between total above-ground dry matter and reproductive dry matter. t_f is estimated at the start of each time step, based on the rate of increase in VEG during the previous time step. If t_f is estimated to occur during the coming time step, after a fraction f of the step has elapsed, then dry matter production, bud production, and the numbers of buds and bolls not shed are calculated according to the equations applicable to the period before t_f , and then are multiplied by f . This is equivalent to assuming that not only plant growth, but also bud production and bud and boll retention, have a cutoff during this period. For this particular time step then, crop behavior is not considered uniform over the entire $70^\circ\text{D}_{\text{cot}}$ period. If this is not done a small difference in damage may, if it displaces t_f from one time step to another, cause a relatively large difference in yield.

If reproductive development is retarded, for example due to insect damage, vegetative growth increases. This delays the cutoff time in total plant growth, according to eq. (3), thus allowing the crop to compensate for the damage.

Bud production during time step S , DB_S (buds/m-row/ $70^\circ\text{D}_{\text{cot}}$), is negatively related to boll load up to time t_f ;

$$DB_S = PBA_S - PBB_S * NLOAD_S \quad S * 70 + 210 \leq t_f \quad (4)$$

where PBA and PBB are parameters. The rate of production is not allowed to be less than 71 during this period. As already noted, DB is a fraction f of the value calculated from eq. (4) for the time step which includes t_f , and is zero thereafter.

Buds are first susceptible to shedding when in age class 1, and then again in age class 3. A constant 27% of the buds in age class 1 are marked for shedding in all time steps up to the last before t_f . In the step containing t_f , the number not marked is $f * .67 * \text{number present}$, and thereafter all are marked.

A constant 7% of the buds in age class 3 are marked for shedding through time step 7 (i.e. over the period when NLOAD is zero). Thereafter the number not marked, N3, is a decreasing function of boll load ;

$$N3_S = PA3_S - PB3_S * NLOAD_S \quad S * 70 + 210 = t_f \quad (5)$$

where PA3 and PB3 are parameters.

N3 is not allowed to exceed 93% of the buds present. During the time step containing t_f , the value calculated according to eq. (5) is multiplied by f , and in subsequent time steps all buds are marked.

The assumption that bud shedding concerns two age classes is only an approximation, since susceptibility to shedding is probably not limited to just those specific ages. Nevertheless, it is mathematically convenient, and describes the experimental results quite well. The fraction of small buds shed is based on data from the field surrounding the 1979 experiment mentioned above. There both small and large buds were counted, and it was found that the respective initial rates of increase per °D_{cot} were in the proportion 1:.67, which implies that 23% of the small buds do not reach large bud size. The number of class 3 buds not marked for shedding during time step S equals the number of flowers that appear during step S + 2, according to the model. Thus the parameters in eq. (5) could be determined from flower counts in the 1979 experiment. In particular, the various treatments led to different boll loads, which made it possible to estimate the effect of boll load on large bud retention.

Small bolls (i.e. fruiting bodies in age class 6) can also be marked for shedding. Marking begins during time step 7, and the number not marked decreases as boll load increases :

$$N6_S = PA6_S - PB6_S * NLOAD_S \quad \begin{matrix} S \geq 7 \\ S * 70 + 210 \leq t_f \end{matrix} \quad (6)$$

For the time step containing t_f , N6 is calculated as in eq. (6) and then multiplied by f. For later times, N6 is set to zero. The number of small bolls not marked for shedding equals the number of open bolls later in the season, according to the model. Thus the parameters PA6 and PB6 could be evaluated from the open boll counts in the 1979 experiment.

Marked buds and bolls are shed in the period following marking, but not before 7, 8 and 8 for buds in class 1, buds in class 3 and bolls in class 7 respectively.

The rate of weight gain of fruiting bodies in age class a during time step S , denoted $RW_{a,S}$ (g/fruiting body/70 °D_{cot}), is fixed for the first 6 age classes :

$$\begin{aligned} RW_{a,S} &= 0.076 & a &= 1, \dots, 4 \\ RW_{a,S} &= .13 & a &= 5, 6 \end{aligned} \quad (7)$$

For older growing bolls

$$RW_{a,S} = (RDM_S - RWI_S) / NLOAD \quad a \geq 7 \quad (8)$$

where RWI_S is the total weight gain by fruiting bodies in classes 1-6 during period S . The rate for older bolls is not allowed to exceed 1.2, or go below 0.57 g/70 °D_{cot}. The seed cotton per open boll, SC, is calculated from dry matter, DM, according to

$$SC = -.93 + .878 * DM \text{ (g/boll)} \quad (9)$$

The above equations describe crop growth and development in the absence of damage. The effect of insect damage to fruiting bodies is simply to reduce the number of buds or bolls in the appropriate age class. If insect damage involves several age classes, the model as programmed distributes the damage in proportion to the number of fruiting bodies in each class. For the age classes susceptible to shedding, insect damage first simply reduces the number of fruiting bodies marked. Only if damage exceeds the number to be marked, is the number not marked reduced. Fruiting bodies once marked are assumed not to be attacked by insects.

The two treatments in the 1979 experiment that most resemble H.armigera damage are the early removal of 120 small buds and 120 large buds. The model and the experimental results for flowering and for the accumulation of harvestable seed cotton in these treatments are shown in figs. 1 and 2. This is not a test of the predictive ability of the model, but does indicate that the model describes the experimental results quite accurately.

A number of the ways in which a cotton crop compensates for damage are illustrated by these results. First of all, the removal of 120 small buds led to a maximum decrease in cumulative flowering of only 66. It seems that decreased natural bud shedding partially compensated for small bud removal. This compensation mechanism was however less effective following removal of large buds, which had mostly passed the age for shedding. Secondly, the maximum decrease in open bolls (not shown) was less than the maximum decrease in cumulative flowering, apparently because decreased shedding of small bolls partially compensated for the loss of flowers. Thirdly, the damaged plots continued to flower and accumulate open bolls until later in the season than the control plots. All of these compensation mechanisms are described by the cotton model.

As a result of the various methods of compensation, neither damage treatment significantly reduced final cotton yield. The treatments did however delay yield. The cotton crop is normally harvested at 95% boll opening, which occurred here for the control plots at 1680 °D_{cot}. At this time the damaged plots had substantially lower yields. Harvesting would have had to be delayed in these plots in order to attain yields comparable to the control yield.

HELIOTHIS ARMIGERA MODEL

The model adopted for H.armigera is similar to that described in Wallach (1984). It describes a population with age structure, subjected to a natural mortality which varies between classes but is constant over time and for all ages within a class. The basic equation then is

$$n_i(a,t) = n_i(a-\Delta a, t-\Delta t) \exp(-u_i \Delta t) \quad (10)$$

where $n_i(a,t)$ is the population density of age a in class i at time t , and u_i is the mortality in class i . (It is somewhat more convenient to deal with S_i , the probability that an individual survives through class i :

$$S_i = \exp(-u_i(h_i - l_i)) \quad (11)$$

where l_i and h_i are respectively the lower and upper age limits for class i). Both age and time are measured in $^{\circ}D_{Hel}$, so that $a = a(t + \Delta t) - a(t) = \Delta t$. The initial conditions for $n_i(a,t)$ are

$$n_i(a, t_0) = 0 \quad i = 1, \dots, 4 \quad (12)$$

where t_0 is the time when recruitment (egg lay) begins. The boundary conditions are

$$\begin{aligned} n_i(l_i, t) &= n_{i-1}(h_{i-1}, t) & i &= 2, \dots, 4 \\ n_1(0, t) &= R(t) \end{aligned} \quad (13)$$

$R(t)$, the recruitment curve, is assumed to consist of two Gaussian curves separated in time. Explicitly

$$R(t) = 0 \quad t \leq t_b$$

$$R(t) = A \{ \exp[-(t-t_0)^2/(2\sigma^2)] + (1/b) \exp[-(t-t_0-g)^2/(2\sigma^2)] \} \quad (14)$$

$$t_b < t$$

This is based on the observed general form of the population curves in the region of this study, and presumably corresponds to two generations of moths.

The effect of insecticide is assumed to be an instantaneous mortality of some fraction of the individuals in each class. Here again it is convenient to work with the fraction of individuals in class i that survive an insecticide application, denoted f_i .

The observable quantities are not the population densities, but rather are related to the total population in a class. The true population in class i is :

$$N_i(t) = \int_{\ell_i}^{h_i} n_i(a, t) da \quad (\text{number/m-row}) \quad (15)$$

$N_i(t)$ is then related to $R(t)$ by

$$N_i(t) = \prod_{j=1}^{i-1} S_j \int_{\ell_i}^{h_i} R(t-x) S_i^{(x-\ell_i)/(h_i-\ell_i)} \prod_{k=1}^{n_k} [E(t_k - t + x)] dx \quad (16)$$

where

$$E(t_k - t + x) = 1$$

$$h_l < t_k - t + x, \quad t_k - t + x \leq 0$$

The term in E represents the effect of n_k insecticide applications, applied at times t_k . The age of an individual recruited at $t-x$ at the time of spray k is then $t_k - t + x$, and if the individual is then in class l , the survival from insecticide is f_l . The effect of the spray is zero of course (i.e. survival = 1) if the individual was not present at time t_k .

It is assumed that in field counts only a fraction of the individuals in class i are actually found, and so the counted populations are

$$M_i(t) = \theta_i N_i(t) \quad (17)$$

In all the calculations presented here eq. (16) is evaluated numerically, using an interval of $10^\circ D_{Hel}$.

In order to make the model sensitive to the specific conditions of each field, certain of the model parameters are to be recalculated from all the available insect counts for the field, each time the algorithm is invoked. This is equivalent to assuming that the model parameters are fixed for each field but are imperfectly known, and that improved estimates are obtained as more data become available.

The parameters that are recalculated are t_b = the time at which recruitment begins, A = the multiplicative factor in the recruitment function, $\theta_1 = \theta_2$ = the probabilities (assumed equal) that eggs and small larvae are counted, and t_0 = the time of the first peak of the recruitment curve. Late in the season when the population results mainly from the second recruitment peak the parameter b , which is the ratio of the heights of the first and second recruitment peaks, is also calculated. Specifically, b is calculated when

$$t \geq \bar{t}_0 + g + 60$$

where $\bar{t}_0$ is the initial estimate of t_0 .

The start of recruitment, t_b , is calculated independently of the remaining parameters, based on the earliest times when individuals are observed in classes 3 and 4. Two situations are distinguished. If larvae are already present in class i at the first counting time t_1 , then the estimate of t_b based on that class is

$$\bar{t}_1 = t_1 - h_1 \quad (18)$$

The assumption here is that class i at t_1 contains individuals up to the maximum age, h_1 , but that no individuals have yet passed out of the class. If on the other hand class i individuals first appear at the j th counting date ($j = 1$), it is assumed that only half the age range of the class is present, and so

$$\bar{t}_1 = t_j - (l_1 + h_1)/2 \quad (19)$$

The value used for t_b is then the earlier of the estimated starting dates

$$t_b = \inf [\bar{t}_3, \bar{t}_4] \quad (20)$$

(If no individuals have yet been counted in classes 3 or 4 at the time the algorithm is invoked, the recommendation not to spray is automatically given, and no calculations are carried out).

The parameter t_0 and the parameter b late in the season, are calculated by a non-linear least squares minimization routine. At each iteration, A is chosen so that the calculated and observed populations summed over counting dates, and summed as well over classes 3 and 4, are equal. Then θ_1 , (and therefore θ_2) is chosen so that the calculated and observed populations are equal for classes 1 and 2 summed together and over counting dates.

In order to speed convergence, a good initial estimate of t_0 is important. The estimate used is found by summing the observations in classes 1 and 2, and in classes 3 and 4, at each counting date. Then the values for each pair of adjacent dates are summed. The values thus calculated are then scanned in chronological order for each pair of classes. A value is accepted as representing a maximum if there are no larger values within the subsequent four pairs of dates. The corresponding estimate of t_0 for classes i and j (1 and 2 or 3 and 4) is then

$$\bar{t}_{0ij} = (t_k + t_l) / 2 - (l_i + h_j) / 2 \quad (21)$$

where t_k and t_l are the pair of dates with the maximum value for classes i plus j . The final estimate of t_0 is

$$\bar{t}_0 = (\bar{t}_{012} + \bar{t}_{034}) / 2 \quad (22)$$

If however the maximum for classes 3 and 4 occurs at the last pair of dates, and gives an estimate of $\bar{t}_0$ earlier than $\bar{t}_{012}$, this is taken to indicate that the population in these classes has not yet reached the peak, and

$$\bar{t}_0 = \bar{t}_{012} \quad (23)$$

Other combinations of parameters to be calculated could have been chosen. However, the choice made here insures that the model reproduces the essential aspects of the field counts, while keeping the calculations to a minimum. Given the large amount of scatter in the data, it did not seem worthwhile to try to fit the data more closely by adjusting additional parameters. It is also because of this scatter that it was chosen to combine classes or dates in certain calculations, in an empirical attempt to smooth the data somewhat.

The parameters that are not adjusted to field data are given the standard values shown in Table 4. The class durations, survivals and damage patterns are taken from a detailed study carried out in 1980 at Maayan Zvi, in a field adjacent to the fields included here (Wallach et al., in preparation). The fixed recruitment parameter values a and b are those obtained from fitting the model, with the additional parameters, to all the data from field 6 here. The value of g was taken to equal the approximate time between H.armigera generations.

The Heliothis model serves two essential functions. First of all, it provides an estimate of the current population which is based on smoothing all the available data, rather than on simply the most recent counts. It thus makes decisions less sensitive to jumps in the observed population levels. The current population level determines the amount by which an insecticide application on the current day can reduce future damage. Secondly, the model predicts the future population and therefore future damage. This also affects the decision whether or not to spray, because the response of a cotton crop to damage depends on the overall damage pattern.

Table 5 shows the comparison between early and late calculations of damage using the model, for four of the fields considered here. The late calculations are based on all the insect counts, and therefore can be taken as a reasonable approximation of the true damage. This is all the more true, in that the model in this case is constrained to agree with the data as to the numbers of class 1 plus class 2 insects summed over all dates, and as to the numbers of class 3 plus class 4 insects summed over dates.

The early calculations are predictions based on the first five insect counts. This is approximately when the first decision to spray is often made. Predictions made later would in general be more accurate, but of less interest. The values calculated are for total numbers of fruiting bodies damaged up to various dates.

The agreement between the early and late calculations is good for three of the fields, but for field 6 the early calculation predicts about 3.5 times more total damage than the late calculation. This is mainly a result of the fact that the early calculation puts t_0 later than the late calculation. Overall, the model seems nevertheless to differentiate quite well between low and high damage levels.

The distribution of damage among fruiting bodies of different sizes is also indicated in Table 4. There is very little difference among fields, or between the early and late calculations. Over half the damage is to small buds, and almost 80% is to small and large buds combined.

OPTIMIZATION TECHNIQUE

The objective function to be minimized here is $F(S)$, the total cost associated with control strategy S . Explicitly

$$F(S) = C_s n(S) + C_y [Y_0 - Y(S)] \quad (24)$$

where C_s and C_y are respectively the costs of a single spray application and a unit of yield, $n(S)$ is the number of spray applications in strategy S , Y_0 is the yield in the absence of damage and $Y(S)$ is the yield for strategy S . Thus the first term in (24) is the cost of control measures, and the second the cost associated with yield loss.

It is assumed that the field can be sprayed at the current time (i.e. at the time when the question whether or not to spray is posed), and then at subsequent intervals of $40^\circ D_{Hel}$ (about 4 or 5 calendar days) up to some cutoff date. The set of allowable strategies then consists of all possible combinations of spray and no spray decisions at the decision times. The spray dosage is assumed fixed. For 10 decision times, for example, there are $2^{10} = 1024$ possible strategies.

The choice of a $40^\circ D_{Hel}$ interval between decisions means that the optimal spray date may be missed by up to about 2 days. Since the insect population does not seem to have a very sharp peak, this does not seem a serious problem. The chosen interval also automatically eliminates the possibility of sprays spaced more closely than $40^\circ D_{Hel}$, but it seems unlikely that such strategies are desirable given that, according to the insect model, the Heliothis population is still seriously depressed $40^\circ D_{Hel}$ after a spray.

Given the number of possible strategies considered here (on the order of 1,000,000 early in the season, then less as the season advances), an exhaustive examination of them all using the combined cotton and Heliothis models is not feasible. The technique proposed here is to use the insect model alone to choose a small number of candidate strategies, and then to use the cotton model to choose among those.

The two qualities sought for the candidate strategies are firstly that they contain as close an approximation as possible to the true optimal strategy, and secondly that they can be generated using an efficient algorithm.

The set of candidate strategies proposed is the set of strategies that minimize total damage by H.armigera for a given number of spray applications. Initially, that is, an approximate objective function $\tilde{F}(S)$ is defined as

$$\begin{aligned}\tilde{F}(S) &= C_S n(S) + C_D D(S) \\ &= C_S [n(S) + r * D(S)]\end{aligned}\tag{25}$$

where C_D is the cost of one unit of damage and $D(S)$ is the amount of damage (i.e. the number of damaged fruiting bodies) which results from strategy S . $\tilde{F}(S)$ depends only on the insect population, and so can be minimized using the insect model alone.

For different values of the ratio $r = C_D / C_S$ in eq. (25) optimal strategies are generated with different numbers of spray applications. The candidate strategy with i sprays is denoted $\tilde{S}_i$. As explained below, the two strategies of interest are that with the greatest number of sprays which does not include the date in question, and that with the least number of sprays which does include that date. In order to search efficiently for those strategies, it is helpful to have upper and lower bounds for the r

values that will generate them. Let RMAX and RMIN be respectively the greatest and smallest possible reductions in damage that can result from a spray today. Then $r \leq 1/\text{RMAX}$ must lead to a spray on the current day and $r \geq 1/\text{RMIN}$ cannot lead to a spray. This establishes the limits on r within which the strategies required will be generated. RMAX and RMIN are easily calculated. RMAX is the reduction in damage due to adding a spray at the current time when there are no spray applications in the future, and RMIN is obtained when there are spray applications at every future date.

If cotton yield varied linearly with total damage, $\bar{F}(S)$ would be equivalent to $F(S)$, and the optimal strategy for the appropriate value of r in eq. (25) would be the true optimal strategy (denoted S^*). Going a step further, if cotton yield decreased monotonically as total damage increased, but nonlinearly, then the overall approach here would still provide the true optimal strategy. In this case S^* cannot be determined directly using $\bar{F}(S)$ because the proper value of r for eq. (25) is not known a priori. However, whatever the number of spray applications in S^* , say j , S^* must be the strategy with minimum total damage for that number of sprays, and therefore $S_j = S^*$. S^* will then be selected when the strategies in $\{\bar{S}_j\}$ are compared using the objective function $F(S)$.

The response of cotton yield to damage, however, is more complicated still. It is known to depend not only on total damage, but also on the timing of damage, and on the distribution of damage among fruiting bodies of different sizes (Kletter and Wallach, 1982). In this case the set $\{\bar{S}_j\}$ need not include S^* . For example, among two strategies with the same number of spray applications, that with greater total damage but to smaller fruiting bodies might be superior, but will not be included in $\{\bar{S}_j\}$. It is difficult to estimate how serious a problem this represents (i.e. how different the selected strategy will be from S^*). It should be noted, however, that different strategies are unlikely to lead to extreme differences in damage pattern.

Regardless of the strategy, damage must be concentrated fairly early in the season, when Heliothis is present, and involve mostly buds, which are the preferred food of all larval size classes. The above arguments suggest that the set of candidate strategies $\{\tilde{S}_1\}$ should contain a reasonable approximation to the true optimal strategy S^* . The derivation of the $\{\tilde{S}_1\}$ can be efficiently carried out using the dynamic programming approach suggested by Birley (1979). Birley noted that when the recruitment curve is assumed fixed, as is the case here, the insect population at a given time will vary only as a result of different insecticide application patterns prior to that time. For the specific conditions considered here insecticide affects only larvae, and not eggs. The youngest larvae, aged $30 \text{ } ^\circ\text{D}_{\text{Hel}}$, disappear from the population after at most $130 \text{ } ^\circ\text{D}_{\text{Hel}}$. Thus only insecticide applications during the preceding $130 \text{ } ^\circ\text{D}_{\text{Hel}}$ affect the population at time t . During this period there are 3 decision times (assuming that t is itself a decision time), and $2^3 = 8$ possible combinations of decisions. There are therefore 8 possible population levels at any decision time t , and these are the states for the dynamic programming calculation. The dynamic programming calculation is begun at t_1 , late in the season when the population is sure to be at a low level, where $t_1 = t_0 + 2 * \sigma + h_4$.

For each state at time t_1 , the control decision that minimizes $\bar{F}(S)$ is determined. For any earlier time t_1 and state k , the dynamic programming recursive equation states that the optimal control decision is that which minimizes the sum of the total cost up to the next decision time t_{1-1} , plus the minimal total cost from the resulting state at t_{1-1} to the end of the season. The amount of damage in each time interval is calculated from the insect model.

The calculation thus proceeds backwards in time, until at some time the states depend on decisions earlier than the current time. Those decisions are automatically set to no spray, and the true spray dates (which need not have been at multiples of $40^{\circ}D_{Hel}$ before the current date) are taken into account. When the current date is reached then only a single state is considered, and the optimal strategy for that state is the sought for candidate strategy.

In general the proposed approach requires that once found, all the candidate strategies, up to some reasonable upper limit on the number of spray applications, be examined using the cotton model. However, given certain features which are observed for the particular problem considered here, it can be shown that it is sufficient to consider just two of the candidate strategies. This simplification is of considerable practical interest, since execution of the cotton model is a time consuming portion of the algorithm.

This simplification depends on the fact that the real interest is not in the full optimal strategy, but only in knowing whether or not that strategy includes a spray application on the current date. Future strategy is important in that it alters the effect of a spray at the current time but decisions here are never made in advance. Rather, at each new date the algorithm is rerun to determine the recommended strategy at that time.

The first observed feature of interest here is that cotton yield declines more and more rapidly as total damage increases, i.e.

$$\frac{dY}{dD} < 0 \quad \frac{d^2Y}{dD^2} < 0 \quad (26)$$

This is illustrated in Fig. 3, which depicts calculated cotton yield at $1680^{\circ}D_{cot}$ (when the undamaged crop would normally be harvested according to the model), versus total damage for a range of different insect model parameters and control strategies. The exceptions to (26) in Fig. 3 are minor and rare. The observed general behavior follows straightforwardly from the cotton model. For low levels of damage the crop compensates by reducing natural shedding, and the resulting effect on yield is slight. Eventually however, as damage increases, the crop can no longer fully compensate and yield begins to decrease.

It is also observed that for given insect parameters total damage for strategy $\bar{S}_i$ decreases, but more and more slowly, as i increases. That is

$$\begin{aligned}\Delta D_1 &= D(\bar{S}_{i+1}) - D(\bar{S}_i) < 0 \\ \Delta^2 D_1 &= D(\bar{S}_{i+2}) - 2D(\bar{S}_{i+1}) + D(\bar{S}_i) > 0\end{aligned}\quad (27)$$

Examples of this behavior for 3 different sets of parameters are shown in Fig. 4. This behavior is logical, since the strategies $\bar{S}_i$ with successively larger i are generated by increasing r , which is equivalent to lowering the reduction in damage required before a spray is worthwhile.

The third observed feature of interest is that if $\bar{S}_i$ includes a spray at the current time t_n , then all $\bar{S}_j$ for $j > i$ also include a spray at t_n . This is not the case for decision dates other than t_n . The reason is that the damage reduction due to adding a spray application at t_1 depends on the control decisions at other times in the interval $[t_1 - 130^{\circ}D_{Hel}, t_1 + 130^{\circ}D_{Hel}]$. Spray applications within that interval reduce the effectiveness of a spray at t_1 . Thus $\bar{S}_j$ relative to $\bar{S}_i$ ($j > i$) may add a spray in the interval around t_1 , and as a consequence drop the spray at t_1 . The decision time t_n however has a special status, in that different strategies cannot

have different decisions at earlier times. It is indeed possible to prove, for the particular case of $\bar{S}_1$, that if $\bar{S}_1$ generated for some value r_1 of r , includes a spray at t_n , then so do all $\bar{S}_j$ for $j > 1$. The proof involves showing that no strategy without a spray at t_n can be optimal for $r' > r$, because the same strategy with the first spray date, say t_1 , replaced by t_n would be superior. This follows from the fact that a spray at t_n alone must result in less damage than a spray at t_1 alone, and furthermore the remaining sprays in the proposed strategy will be as effective, or more effective, if the initial spray is removed from t_1 to t_n . However, no general proof that the observed behavior must always occur has been found.

It is now possible to show that it is worthwhile to spray at the current time if and only if

$$Y(\bar{S}_k) - Y(\bar{S}_{k-1}) > C_S / C_Y \quad (28)$$

where $\bar{S}_k$ is the candidate strategy with the smallest number of sprays that includes a spray at the current time. Inequalities (26) and (27) imply that yield increases, but more and more slowly, as the number of sprays i in $\bar{S}_1$ increases. The first term in the objective function $F(S)$ (eq. 24) on the other hand increases linearly with the number of sprays. As a result $F(\bar{S}_1)$ has a unique minimum at some value i^* of i . If inequality (28) holds then $F(\bar{S}_k) < F(\bar{S}_{k-1})$, implying that $k < i^*$. Therefore $\bar{S}_1^*$ includes a spray application at the current time, according to the third observed feature of the results indicated above. If inequality (28) does not hold, then $i^* > k$ and i^* does not contain a spray at the current date. Finally, then, the cotton model need only be run with the two candidate strategies $\bar{S}_k$ and $\bar{S}_{k-1}$.

The above discussion assumes that there is a fixed, predefined harvest date. It is worthwhile to consider how to relax this restriction, since damage to reproductive bodies in cotton is known to delay yield build-up (Kletter and Wallach, 1982). Thus different harvest dates may be appropriate for crops with different levels of damage. Given the costs associated with each harvest date, it is possible to determine the adjusted yield value for each strategy, defined as the maximum over harvest dates of yield value minus harvest costs. (The cost associated with the harvest date increases as harvesting is delayed, essentially because the crop must then be protected for a longer time from late season insect pests, and because the probability that rainfall will cause yield losses increases). If it is now assumed that there is a diminishing return in terms of adjusted yield from adding spray applications, then eq. (28) is still the necessary condition for spraying, if the yield values are replaced by adjusted yield values. It should be noted that in practice it may be quite difficult to evaluate the costs associated with different harvest dates. In particular, these costs may depend on the harvest schedule of the whole farm.

RESULTS

The insect and cotton models described above were used in conjunction with the optimization technique to determine the recommended strategy at each date for the fields 1-6. It must be emphasized that each recommendation, except as noted, is based only on insect counts that would have been available on the day in question.

In generating the candidate strategies $\tilde{S}_i$, an upper limit of .1 was generally set for r in eq. (25). (In a small number of cases, larger values of r were considered). If the candidate strategy for this value of r did not include a spray application at the current date (i.e. if a spray application at the current date reduced total damage by less than $1/r = 10$ fruiting bodies), it was assumed that a spray at the current date was not worthwhile. Indeed, in all those cases where the full algorithm was used, and where $\tilde{S}_k$ was generated using $r \geq .1$, the recommendation was not to spray at the current time.

Yields at $1680^\circ D_{cot}$ are used in eq. (28). The possibility of delaying harvesting is not considered. The ratio C_S/C_y is taken as $1/6$, based on 1983 prices.

That is, the cost of an aerial spray application over a field is approximately equal to the price of an additional 6 g seed cotton/m-row over the field. It may be noted that for the cases considered here this represents roughly 1% of total yield, while the standard error in yield measurements is generally about 5% of the mean. The fact that the yield loss that justifies control cannot be measured is one of the major difficulties in determining an optimal control strategy for H.armigera empirically.

For fields 1 and 2, no candidate strategy generated with $r \leq .1$ included a spray at the current date. In these fields then no insecticide application against H.armigera is recommended. This agrees with the strategy actually followed in these fields. (The spray on May 27 in field 2, while effective against Heliothis, was not directed against this pest).

The results for field 4 are shown in Table 5. The algorithm recommends a control application on June 14 (since $Y(\tilde{S}_k) - Y(\tilde{S}_{k-1}) > 6$ for that date). The field was not sprayed at that time,^k and so the algorithm again recommends a control application on June 17. Thereafter, no control applications are recommended. Roughly, then, there is a period of a few days in mid June during which a spray application is worthwhile. If the field is not sprayed then it is no longer worthwhile to spray at later times.

Field 3 is the field adjacent to field 4, which was sprayed on June 12. The results for this field then indicate what the subsequent recommendations of the algorithm would have been, if the first spray recommendation had been followed (ignoring the 2 day difference between the recommended and actual spray dates). For field 3 after the spray application, no candidate strategy generated with $r \leq .1$ included a spray at the current time.

The recommendations of the algorithm then, if followed, would have led to a single early spray in these fields. This is nearly identical to the Ministry of Agriculture recommendations, which led to a single spray on June 12. (The spray given to fields 3 and 4 on July 7 was not directed primarily against H.armigera).

According to Table 5, the yield increase in field 3 resulting from an early spray should be about 10 g/m-row. This then should be the approximate yield difference between fields 3 and 4. As already mentioned, such a difference will not be significant, given the experimental techniques available. The observed yields in fields 3 and 4 are shown in Table 2a. The yields do not, except at a single early date, differ significantly. This at least does not contradict the results of the calculations. It may however be noted that actual yield build-up in fields 3 and 4 was delayed relative to the model. Those fields would not normally be harvested before $1932^{\circ}\text{D}_{\text{cot}}$, while in the model harvest occurs at $1680^{\circ}\text{D}_{\text{cot}}$.

The results for fields 5 and 6 are shown in Tables 5b-5d. Given the poor agreement between the early and late season insect parameters for field 6, the algorithm was run for both sets of parameters. The recommendations are very similar in both cases. At each date early in the season, the algorithm repeats the recommendation that insecticide should be applied. Beyond approximately mid-June, however, a spray application is no longer worthwhile. Field 5 was sprayed on June 10, more or less in keeping with the recommendations of the algorithm. As Table 5b shows, no subsequent spray applications are recommended. The Ministry of Agriculture recommendations on the other hand led to three spray applications in field 5. (The last spray, on July 29, was not directed primarily against H.armigera).

The observed yield differences between fields 5 and 6 are shown in Table 2b. The differences are the result of three extra sprays in field 5. That field would normally have been harvested around 1916 °D_{cot} (again later than according to the cotton model). At that time there is still a significant difference in yield between the fields, which however is eliminated by the following harvest date. The calculations (Table 5c or 5d) indicate that a single spray applied to field 6 at the most effective time would increase yield by only about 10 g/m-row, which is somewhat less than observed.

CONCLUSIONS

The cotton and insect models adopted here represent great simplifications of the true plant and insect dynamics. The approximations made are, however, quite different in the two cases. The cotton model assumes that in the absence of damage the crop develops according to a fixed pattern. In fact, for the purposes of insect control, it is only really important that the effect of damage be identical between crops, which is a less stringent condition. While even the latter condition is certainly not met in general, it may be a reasonable first approximation for a good part of the Israeli cotton crop. Indeed, the model has been found to perform reasonably well for a variety of damage patterns in a number of different cotton fields in Israel. It should be noted that the optimization technique adopted here could be used for any other cotton model as well.

The insect model accepts that the population dynamics differ between fields, but assumes that within each field the insect parameters are fixed. That is, the model ignores the variability in survival and reproduction caused by changes in weather, population density, food availability or natural enemy populations. While these factors are known to be important (the role of natural enemies of H.armigera, for example, has been investigated by Bar et al., 1979), it seems impossible at the present time to accurately describe all these effects on H.armigera population levels. The simple model used here seems capable of at least approximate predictions of future damage levels, and permits the use of an efficient dynamic programming algorithm for determining control recommendations.

Finally, the optimization technique employed is itself only approximate. It has been argued, however, that it may reasonably be supposed to furnish recommendations similar to those of the true optimal strategy.

The overall algorithm, when applied to historic data, gives pest control recommendations which seem quite reasonable. No spray application is recommended in the fields with the smallest populations. In the 1979 and 1980 fields, a single early season spray application is recommended, at a time which coincides roughly with the highest population levels, and with the first spray recommendation of the Ministry of Agriculture. However, the Ministry of Agriculture recommendations led to 2 additional sprays in 1980, which are not recommended by the present algorithm.

It is probably impossible, given the experimental errors in yield measurements, to determine experimentally whether the present algorithm gives strategies superior to other methods. Certain advantages of the algorithm over empirical strategies are however clear.

Firstly, the algorithm aids in understanding the basis for Heliothis control, since it is based explicitly on descriptions of the plant and insect. Secondly, the algorithm can be progressively improved, since it is based on a series of explicit assumptions, each of which can be tested and improved independently. Finally, changes in the system parameters (especially the cost of insecticide, or the price of cotton) can easily be incorporated in the algorithm.

This algorithm will be incorporated, on an experimental basis at first, into a package of programs for cotton crop management (Wallach et al., 1980) which is widely used on-line by the growers in the coastal plains region of Israel. The package already includes a program for input of insect counts, and so those counts will be available to the algorithm.

Future work will concentrate on incorporating H.armigera control strategy into an overall strategy of cotton crop management, including irrigation and control of other insect pests.

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Date	D	number / m-row
	Hel:	eggs : <4mm : 4-15mm:>15mm :
27/5	297	--insecticide application--:
30/5	318	0.2 : 0.3 : 0.0 : 0.0 :
1/6	336	0.0 : 0.6 : 0.0 : 0.0 :
5/6	361	0.2 : 0.0 : 0.3 : 0.0 :
7/6	372	0.8 : 0.1 : 0.1 : 0.0 :
9/6	382	0.9 : 0.2 : 0.3 : 0.0 :
14/6	412	0.6 : 0.8 : 0.4 : 0.0 :
18/6	440	0.3 : 0.9 : 0.7 : 0.3 :
20/6	457	0.9 : 0.6 : 0.7 : 0.0 :
25/6	504	0.0 : 0.0 : 1.9 : 0.0 :
28/6	521	0.2 : 0.0 : 0.5 : 0.0 :
2/7	554	0.1 : 0.3 : 0.7 : 0.0 :
5/7	579	0.0 : 0.2 : 0.3 : 0.0 :
9/7	617	0.0 : 0.1 : 0.3 : 0.0 :
12/7	637	0.0 : 0.0 : 0.0 : 0.0 :
16/7	678	0.0 : 0.0 : 0.0 : 0.0 :
20/7	719	0.0 : 0.1 : 0.0 : 0.0 :
24/7	762	0.0 : 0.1 : 0.0 : 0.0 :

T a b l e 1

FIELD 3. MAAYAN ZVI MINAG 1979

=====						
:	:	:	number / m-row (1)			
:	Date :	°D	-----			
:	:	Hel:	eggs :	<4mm	:4-15mm:	>15mm:

:	11/6 :	0	: 0.50	: 0.71	: 3.29	: 0.42 :
:	12/6 :	11	--insecticide application--:			
:	14/6 :	30	: 0.14	: 0.14	: 0.75	: 0.11 :
:	15/6 :	40	: 0.17	: 0.00	: 0.33	: 0.00 :
:	17/6 :	58	: 0.00	: 0.17	: 0.54	: 0.04 :
:	18/6 :	68	: 0.75	: 0.00	: 0.75	: 0.75 :
:	21/6 :	98	: 0.00	: 0.00	: 0.57	: 0.36 :
:	22/6 :	108	: 0.00	: 0.00	: 0.18	: 0.18 :
:	25/6 :	140	: 0.02	: 0.00	: 0.00	: 0.00 :
:	28/6 :	171	: 0.20	: 0.02	: 0.00	: 0.00 :
:	3/7 :	219	: 1.47	: 1.53	: 0.94	: 0.03 :
:	6/7 :	253	: 3.11	: 0.11	: 0.11	: 0.11 :
:	7/7 :	266	--insecticide application--:			
:	13/7 :	325	: 0.05	: 0.16	: 0.53	: 0.29 :
:	16/7 :	355	: 0.00	: 0.00	: 0.10	: 0.50 :
:	17/7 :	365	: 0.00	: 0.00	: 0.27	: 0.41 :
:	20/7 :	394	: 0.08	: 0.03	: 0.19	: 0.03 :
:	24/7 :	434	: 0.20	: 0.00	: 0.30	: 0.10 :
:	27/7 :	464	: 0.00	: 0.00	: 1.00	: 0.00 :
:	31/7 :	506	: 0.00	: 0.00	: 0.00	: 0.00 :
:	6/8 :	563	: 3.60	: 0.00	: 0.00	: 0.00 :
:	9/8 :	593	: 1.20	: 0.00	: 0.00	: 0.00 :
:	14/8 :	647	: 1.10	: 0.10	: 0.00	: 0.00 :
:	21/8 :	720	: 0.00	: 0.00	: 0.10	: 0.00 :
:	23/8 :	742	: 0.00	: 0.10	: 0.00	: 0.00 :
:	30/8 :	811	: 0.00	: 0.00	: 0.00	: 0.00 :
=====						

(1) The first date refers to the combined fields 3 and 4.

T a b l e 1

FIELD 4. MAAYAN ZVI UNSPRAY 1979

=====						
:	:	:	number / m-row (1)			
:	Date :	°D	-----			
:	:	Hel	eggs	<4mm	:4-15mm:	>15mm

:	11/6	:	0	:	0.50	:
:	14/6	:	30	:	0.04	:
:	15/6	:	40	:	0.75	:
:	17/6	:	58	:	0.00	:
:	18/6	:	68	:	0.21	:
:	21/6	:	98	:	0.83	:
:	22/6	:	108	:	0.17	:
:	25/6	:	140	:	0.25	:
:	28/6	:	171	:	0.03	:
:	3/7	:	219	:	0.56	:
:	6/7	:	253	:	0.08	:
:	7/7	:	266	:	0.26	:
:	12/7	:	314	:	0.04	:
:	16/7	:	355	:	0.18	:
:	17/7	:	365	:	0.07	:
:	19/7	:	385	:	0.10	:
:	24/7	:	434	:	0.13	:
:	27/7	:	464	:	0.25	:
:	31/7	:	506	:	0.30	:
:	6/8	:	563	:	0.00	:
:	9/8	:	593	:	0.00	:
:	14/8	:	647	:	0.00	:
:	21/8	:	720	:	0.00	:
:	23/8	:	742	:	0.00	:
:	30/8	:	811	:	0.10	:
=====						

(1) The first date refers to the combined fields 3 and 4.

T a b l e 1

FIELD 5. MAAYAN ZVI MINAG 1980

=====						
:	:	:	number / m-row (1)			
:	DATE :	°D	-----			
:	:	Hel:	eggs	<4mm	4-15mm:	>15mm:

:	2/6 :	2 :	4.00 :	0.50 :	0.25 :	0.00 :
:	8/6 :	41 :	7.75 :	2.75 :	2.25 :	0.00 :
:	9/6 :	47 :	3.00 :	1.50 :	5.25 :	0.00 :
:	10/6 :	52 :	--insecticide application--:			
:	12/6 :	69 :	0.25 :	0.25 :	0.50 :	0.00 :
:	15/6 :	97 :	2.25 :	1.75 :	0.25 :	0.00 :
:	17/6 :	118 :	0.75 :	2.50 :	0.25 :	0.25 :
:	20/6 :	149 :	1.33 :	2.17 :	3.33 :	0.00 :
:	22/6 :	167 :	--insecticide application--:			
:	23/6 :	175 :	1.33 :	0.00 :	0.17 :	0.00 :
:	27/6 :	214 :	0.67 :	0.33 :	0.33 :	0.00 :
:	29/6 :	233 :	0.50 :	0.67 :	0.00 :	0.00 :
:	1/7 :	254 :	0.50 :	0.17 :	0.00 :	0.00 :
:	4/7 :	284 :	0.17 :	0.67 :	0.67 :	0.00 :
:	6/7 :	306 :	0.33 :	0.33 :	0.17 :	0.00 :
:	9/7 :	338 :	0.33 :	0.83 :	1.83 :	0.00 :
:	11/7 :	359 :	1.67 :	2.50 :	3.83 :	0.00 :
:	12/7 :	369 :	--insecticide application--:			
:	15/7 :	397 :	1.00 :	0.17 :	0.17 :	0.00 :
:	18/7 :	431 :	2.83 :	0.17 :	0.00 :	0.17 :
:	21/7 :	466 :	0.50 :	0.67 :	0.00 :	0.00 :
:	23/7 :	489 :	1.33 :	0.33 :	0.17 :	0.00 :
:	25/7 :	511 :	0.67 :	0.50 :	0.17 :	0.00 :
:	27/7 :	533 :	0.33 :	0.00 :	0.83 :	0.00 :
:	29/7 :	554 :	--insecticide application--:			
:	1/8 :	588 :	0.17 :	0.17 :	0.17 :	0.00 :
:	4/8 :	620 :	0.17 :	0.83 :	0.00 :	0.33 :
:	8/8 :	660 :	0.17 :	0.00 :	0.00 :	0.17 :
:	11/8 :	692 :	0.00 :	0.00 :	0.00 :	0.00 :
=====						

(1) The first dates refer to the combined fields 5 and 6.

T a b l e 1

FIELD 6. MAAYAN ZVI UNSPRAY 1980

=====						
:	:	:	number / m-row (1)			
:	Date :	°D	-----			
:	:	Hel:	eggs :	<4mm :	4-15mm:	>15mm:

:	2/6 :	2 :	4.00 :	0.50 :	0.25 :	0.00 :
:	8/6 :	41 :	7.75 :	2.75 :	2.25 :	0.00 :
:	9/6 :	47 :	3.00 :	1.50 :	5.25 :	0.00 :
:	11/6 :	59 :	6.75 :	1.50 :	5.13 :	0.75 :
:	12/6 :	69 :	1.83 :	0.83 :	6.17 :	0.50 :
:	15/6 :	97 :	5.75 :	2.75 :	3.63 :	1.25 :
:	17/6 :	118 :	1.25 :	2.00 :	2.88 :	0.88 :
:	20/6 :	149 :	0.88 :	1.88 :	2.13 :	0.88 :
:	23/6 :	175 :	0.10 :	1.00 :	1.40 :	0.60 :
:	25/6 :	194 :	1.42 :	0.17 :	0.92 :	0.58 :
:	27/6 :	214 :	0.67 :	0.17 :	0.92 :	0.33 :
:	29/6 :	233 :	0.83 :	1.00 :	0.50 :	0.25 :
:	1/7 :	254 :	1.08 :	1.83 :	0.33 :	0.00 :
:	4/7 :	284 :	0.25 :	0.83 :	1.50 :	0.00 :
:	6/7 :	306 :	0.50 :	0.40 :	0.92 :	0.00 :
:	9/7 :	338 :	0.42 :	0.50 :	1.42 :	0.17 :
:	11/7 :	359 :	1.00 :	1.17 :	2.33 :	0.17 :
:	13/7 :	379 :	2.25 :	0.92 :	1.75 :	0.25 :
:	15/7 :	397 :	0.50 :	0.33 :	1.33 :	0.33 :
:	18/7 :	431 :	1.75 :	1.42 :	0.58 :	0.33 :
:	21/7 :	466 :	0.75 :	0.33 :	0.75 :	0.08 :
:	23/7 :	489 :	0.40 :	0.75 :	0.33 :	0.08 :
:	25/7 :	511 :	0.50 :	0.50 :	0.67 :	0.08 :
:	27/7 :	533 :	0.08 :	0.67 :	0.50 :	0.83 :
:	29/7 :	554 :	--insecticide application--:			
:	1/8 :	588 :	0.83 :	0.08 :	0.33 :	0.58 :
:	4/8 :	620 :	0.17 :	0.67 :	0.17 :	0.42 :
:	8/8 :	660 :	0.00 :	0.00 :	0.33 :	0.33 :
:	11/8 :	692 :	0.00 :	0.25 :	0.08 :	0.00 :
=====						

(1) The first 3 dates refer to the combined fields 5 and 6.

T a b l e 2

SEED COTTON YIELDS IN SPRAYED AND
UNSPRAYED FIELDS

(a) FIELDS 3 AND 4. MAAYAN ZVI 1979 (1)

Date		Cumulative seed cotton:	
		(g/m-row)	
day/month:	^o D	FIELD 3	FIELD 4
:	cot	(MINAG)	(UNSPRAY)
17/08	1344	26 a	15 a
23/08	1428	67 a	31 b
30/08	1526	157 a	88 a
6/09	1610	275 a	208 a
13/09	1694	377 a	340 a
20/09	1778	425 a	409 a
26/09	1848	476 a	474 a
4/10	1932	559 a	548 a

(b) FIELDS 5 AND 6. MAAYAN ZVI 1980 (1)

Date		Cumulative seed cotton:	
		(g/m-row)	
day/month:	^o D	FIELD 5	FIELD 6
:	cot	(MINAG)	(UNSPRAY)
17/08	1376	22 a	1 b
24/08	1472	85 a	30 b
31/08	1569	212 a	122 b
7/09	1665	366 a	242 b
14/09	1753	443 a	359 b
21/09	1836	491 a	430 b
28/09	1916	518 a	460 b
5/10	1994	533 a	484 a
12/10	2069	540 a	505 a
19/10	2136	541 a	511 a
26/10	2196	542 a	512 a

(1) Values followed by the same letter for a given date are not significantly different at the 0.05 level.

Table 3

COTTON CROP MODEL PARAMETERS

=====										
:time: dry : bud production: class 3 shedding: class 6 shedding:										
:step: matter: :										
: s : P D M : P B A : P B B : P A 3 : P B 3 : P A 6 : P B 6 :										

: 1 : 20.00: 41.3 : 0 : -- : -- : -- : -- :										
: 2 : 40.00: 41.3 : 0 : -- : -- : -- : -- :										
: 3 : 50.00: 41.3 : 0 : -- : -- : -- : -- :										
: 4 : 35.00: 41.3 : 0 : -- : -- : -- : -- :										
: 5 : 30.00: 47.6 : 0 : -- : -- : -- : -- :										
: 6 : 80.00: 47.6 : 0 : -- : -- : -- : -- :										
: 7 : 110.00: 47.6 : 0 : -- : -- : -- : -- :										
: 8 : 110.00: 47.6 : .502 : 28 : .412 : 16 : .174 :										
: 9 : 103.75: 98.4 : 1.23 : 29 : .433 : 22 : .239 :										
: 10 : 103.75: 47.6 : .916 : 25 : .431 : 25 : .272 :										
: 11 : 103.75: 47.6 : .794 : 22 : .386 : 19 : .202 :										
: 12 : 103.75: 381.0 : 4.76 : 27 : .375 : 22 : .259 :										
: 13 : 140.35: 381.0 : 4.76 : 39 : .565 : 35 : .438 :										
: 14 : 140.35: 381.0 : 4.76 : 29 : .403 : 47 : .603 :										
: 15 : 140.35: 381.0 : 4.76 : 39 : .527 : 36 : .409 :										
: 16 : 122.00: 381.0 : 4.76 : 32 : .405 : 29 : .279 :										
: 17 : 122.00: 381.0 : 4.76 : 32 : .405 : 12 : .108 :										
: 18 : 122.00: 381.0 : 4.76 : 32 : .405 : 16 : .160 :										
=====										

T a b l e 4

H.ARMIGERA PARAMETERS

	class			
	1	2	3	4
duration ($^{\circ}\text{D}_{\text{He1}}$)	30	30	50	50
fraction surviving through				
class, S_i	.99	.56	.49	.51
fraction surviving				
insecticide, f_i	1.0	.15	.15	.15
probability of				
observation, θ_i	(1)	$=\theta_1$	1.0	1.0
damage				
small buds/larva/ $^{\circ}\text{D}_{\text{He1}}$	---	.006	.044	.026
large buds/larva/ $^{\circ}\text{D}_{\text{He1}}$	---	.002	.016	.025
bolls/larva/ $^{\circ}\text{D}_{\text{He1}}$	---	0	.008	.037
total fruiting bodies/ larva/ $^{\circ}\text{D}_{\text{He1}}$	---	.008	.068	.088

recruitment parameters

A (eggs/ $^{\circ}\text{D}_{\text{He1}}$ /m-row)	(1)
t ($^{\circ}\text{D}_{\text{He1}}$)	(1)
($^{\circ}\text{D}_{\text{He1}}$)	93
b	3.65 (2)
g ($^{\circ}\text{D}_{\text{He1}}$)	420
t ($^{\circ}\text{D}_{\text{He1}}$)	(1)

(1) These parameters are evaluated from the insect counts in each field.

(2) Late in the season (see text) this parameter is also evaluated from insect counts.

T a b l e 5

T a b l e 6

YIELDS FOR STRATEGIES WITH (Y ($\tilde{S}_k$))
AND WITHOUT (Y ($\tilde{S}_{k-1}$)) SPRAY ON CURRENT DATE

a) FIELD 4. MAAYAN ZVI UNSPRAY 1979

[illegible]

b) FIELD 5. MAAYAN ZVI MINAG 1980

: current date		: total damage:		: seed cotton yield at		: (fruiting		: 1680 °D (g/m-row)	
: bodies/m-row:		: cot							
: day/	: °D	:	:	: S~	: S~	: Y(S~)	: Y(S~)	: Y(S~)	: Y(S~) -
: month	: hel	: k	: k	: k-1	: k	: k-1	: k-1	: k	: Y(S~)
:	:	:	:	:	:	:	:	:	: k-1
: 12/6	: 69	: 6	: 44	: 47	: 550	: 549	: 1	:	:
: 15/6	: 97	: 2	: 48	: 54	: 549	: 547	: 2	:	:
: 20/6	: 149	: 1	: 47	: 57	: 548	: 544	: 4	:	:

T a b l e 6

c) FIELD 6. MAAYAN ZVI UNSPRAY 1980

```
(insect parameters based on counts up to current date)
```

[illegible]

d) FIELD 6. MAAYAN ZVI UNSPRAY 1980

(insect parameters based on all counts)

=====									
:	:	:	:	:	:	:	:	:	:
:	current date	:	:	total damage:	:	seed cotton yield at	:	:	:
:	:	:	:	(fruiting	:	1680 °D	:	(g/m-row)	:
:	:	:	:	bodies/m-row:	:	cot	:	:	:

:	:	:	:	:	:	:	:	:	:
:	day/	°D	:	$\tilde{S}$	$\tilde{S}$	$Y(\tilde{S})$	$Y(\tilde{S})$	$Y(\tilde{S}) -$	:
:	month	hel	k	k	k-1	k	k-1	$Y(\tilde{S})_k$	:
:	:	:	:	:	:	:	:	$Y(\tilde{S})_{k-1}$	:

:	8/6	41	2	65	81	542	530	12	:
:	9/6	47	2	70	84	538	529	9	:
:	11/6	59	1	84	104	531	521	10	:
:	12/6	69	1	84	104	530	521	9	:
:	15/6	97	1	85	104	528	521	7	:
:	17/6	118	1	86	104	526	521	5	:
:	20/6	149	1	89	104	524	521	3	:
:	23/6	175	1	93	104	522	521	1	:
:	25/6	194	1	93	104	522	521	1	:

FIGURE CAPTIONS

1. Flowers and seed cotton in 1979 experiment, observed and calculated, for control and early removal of 120 small buds.

control, observed
control, calculated
removal treatment, observed
removal treatment, calculated

40 small buds/m-row were removed at each of the times indicated by an arrow.

2. Flowers and seed cotton in 1979 experiment, observed and calculated, for control and late removal of 120 large buds.

control, observed
control, calculated
removal treatment, observed
removal treatment, calculated

40 large buds/m-row, were removed at each of the times indicated by an arrow.

3. Calculated seed cotton yield at 1680 °D_{cot} versus total fruiting bodies damaged by H.armigera for various insect parameters and control strategies.

4. Total fruiting bodies damaged versus number of sprays in candidate strategy $\tilde{S}$ for three sets of insect parameters.

FIGURE 1

FIGURE 3

FIGURE 4

2
3
4

5
6
7

Extension Service
HADERA Region
Israel Department of Agriculture

STATE OF ISRAEL
Ministry of agriculture
AGRICULTURAL RESEARCH ORGANIZATION
The volcani center

S I V A N - Association for the advancement of field crops

THE SCHEDULING OF COTTON HARVESTING OPERATIONS AT THE FARM LEVEL

APPENDIX K

- (1) ISRAEL, Department of Statistics, ARO, The Volcani Institute
- (2) ISRAEL, Ministry of Agriculture Extension Service

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(B A R D)

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ABSTRACT

An algorithm has been developed that generates feasible whole-farm harvesting schedules, with the associated costs and benefits, for a wide range of basic harvesting options under different weather patterns. These options include the hiring of additional harvesting capacity and early defoliation with double harvesting.

Parameterization of the algorithm required initiation of detailed studies in three areas:

- a) The function of expected rainfall through time.
- b) The effect of rainfall on pre-harvest and harvesting losses, and lint quality.
- c) The effect of defoliation timing and double harvesting on harvesting losses, total yield, and lint quality.

A stochastic model for the generation of rainfall patterns was developed from an analysis of 40 years of rainfall data. On the basis of data from 304 fields, harvesting losses were found to change little through time. Mean harvesting loss was 250 kg seed cotton per hectare. Rainfall of up to 12 mm per day increased harvesting loss negligibly and had no effect on lint quality. Defoliation experiments indicate that defoliation as early as 45% boll opening followed by double harvesting reduces yield over single harvesting (following defoliation at 75% boll opening). Overall quality was reduced by double harvesting; at second harvest percentage lint was reduced to 0.93 of the first harvest value, fibrograph was reduced 4 units, and quality grade reduced 2 grades.

The algorithm has been integrated into the existing computerized cotton management system available to growers in the coastal plains region of Israel. By using it, the cotton grower obtains complete, field by field, harvesting schedules for a range of options (rental of additional equipment or not, double harvesting acceptable or not, etc.), along with an economic analysis of each schedule.

INTRODUCTION

Over recent years, experimentation at the Gan HaShomron Experimental Station has shown that the cotton plant is capable of full yield compensation to quite high levels of direct bud damage by insect pests or bud shedding induced by water stress (Kletter and Wallach, 1982; Wallach and Kletter, 1984). These findings are of great significance to the grower since, in general, the same yield can be obtained with less intensive inputs of insecticides and greater flexibility in irrigation scheduling. However, full yield compensation is invariably accompanied by a significant delay in yield accumulation. In the coastal plains region of Israel, a relatively undamaged crop reaches full maturity (100% boll opening) in the last week of September or first week of October. The problem is that a delay in harvesting brings the grower into a period of rapidly increasing rainfall probability. To date, the grower has been highly apprehensive of the risk of yield and quality reduction that is assumed to result from exposure to rain accompanied by high winds.

In considering a pest control and irrigation strategy for a single field only, three alternatives need to be evaluated:

1. Low-risk timing of harvesting facilitated by standard management practices that avoid a delay in yield accumulation but entail a higher ratio of input cost per unit yield.
2. Delayed harvesting to permit full yield compensation resulting from reduced use of expensive inputs such as insecticide spraying. This entails taking the risk of rainfall damage.

3. Double harvesting to reduce the magnitude of possible rainfall damage. Inputs are reduced and yield accumulation delayed but a large portion of yield is harvested during a period of negligible rainfall probability and only the late-maturing fraction of yield is harvested during the relatively high risk period. This option has the following disadvantages:

- a. extra harvesting costs are incurred,
- b. there may be yield loss from mechanical damage to unopened bolls at the first harvest,
- c. there may be a significant loss of lint quality at the second harvest, and
- d. since complete defoliation is required before harvesting operations can proceed, defoliation must commence at a slightly lower percentage boll opening than normally practiced. This may cause a reduction in yield.

If the problem is extended to a whole-farm context, it is necessary to consider the effect of a delay in a particular field on the harvest scheduling of the farm as a whole. In some instances, a delay in one field may be unimportant if that field would have become harvestable together with a number of other fields. Since the harvesting capacity of the farm is generally a limiting factor, a re-arrangement of the harvesting sequence of these fields may suffice. On the other hand, a delay in a small number of fields may cause a redistribution of harvesting load through time that cannot be met by the machinery and man-power of the farm without continuing harvest into a high-risk period. This creates the additional options of hiring extra harvesting capacity and of advanced defoliation and double harvesting of some fields. Here, the advantage of double harvesting derives not only from reducing the potential magnitude of rain damage but also from the fact that the need to hire extra harvesting capacity is reduced.

Clearly, the number of possible harvesting schedules makes rational decision-making a formidable task. It was therefore decided to develop a computer algorithm that would generate a set of viable scheduling alternatives, together with an economic evaluation of the associated costs and benefits, from which the manager can select. Ultimately, such an algorithm would be linked to existing pest control recommendation programs and provide an evaluation of alternative strategies in terms of their impact on the farm as a whole.

The development of a harvest schedule algorithm requires quantitative information concerning:

1. the expected rainfall as a function of date,
2. the effect of harvest date and rainfall on harvesting loss and quality,
3. the effect of timing of defoliation and double harvesting on cotton yield, quality and harvesting losses.

This report summarizes results obtained thus far in these three areas and presents a brief description of the harvest scheduling algorithm.

Estimating the expectation of rainfall as a function of date

Daily rainfall data for the 40-year period 1940 to 1979 were taken for 3 locations in the coastal plains region of Israel; Givat-Haim, Ein HaHoresh and Gan Shmuel. Rainfall at these locations was measured using small-orifice raingauges. All analyses were carried out for the period September to November and data from the 3 locations were analysed as one data set. Two analyses were carried out, the first to establish the expectation of a rainfall event on a given day and the second, to estimate the quantity of rain that would be obtained at a rain event.

1. The expectation of a rain event

For each date in the period September to November, the number of rain events in the data set was counted and expressed as a fraction of the total possible number of rain events (see Table 1). These figures were converted to a cumulative probability over the period and an exponential function fitted to the data. The differential of this function represents the expectation of a rain event as a function of the number of days from September 1.

2. The expected rainfall at a rain event

Preliminary analysis of the data showed cumulative rainfall to increase exponentially with time, hence the following function was fitted:

$$R = ae^{bt} \quad (1)$$

where: R is cumulative rainfall from September 1 (mm),
a and b are coefficients to be estimated.

Dividing R and a in Equation 1 by the cumulative rainfall at November 30 of each year yields:

$$\rho = \alpha e^{bt} \quad (2)$$

where: ρ is the proportion of total rainfall for the period September to November obtained upto time t ,
 α and b are coefficients.

Differentiating Equation 2 with respect to t provides the proportionate instantaneous contribution of any point in time to total rain:

$$\rho' = b\alpha e^{bt} \quad (3)$$

Finally, the proportionate contribution to total rain of a given day (September 1 $\leq t \leq$ November 30) is given by the integral:

$$R_t = \int_t^{t+1} b\alpha e^{bt} dt \quad (4)$$

It is reasonable to assume that the extent of harvesting loss caused by rainfall is related to the intensity and duration of the rain event. Furthermore, on the basis of field experience of extension personnel in the region, wind intensity during and immediately after a rain event is also an important factor determining the extent of rain damage. Wind and rainfall intensity data is not available over a sufficient period of time to be used as a basis for the present analysis. Instead, the wind factor is ignored at this stage and the rainfall components of intensity and duration are treated together as daily rainfall. Four rainfall intervals are arbitrarily defined:

1. upto 5 mm/day
2. 5 - 15 mm/day
3. 15 - 20 mm/day
4. over 30 mm/day

Parameter estimation of Equation 1 was carried out separately for the 2nd, 3rd and 4th rain intervals and the results are shown in Table 2. An excellent fit was obtained for intervals 2 and 3, though less so for rain interval 4.

Sets of rainfall patterns can be stochastically generated using the above analysis. For a given day, a random number between zero and one is generated from a uniform distribution function. A rain event occurs if this number is greater than the proportionate expectation for rain on that day. The quantity of rainfall for the rain event is then defined by a variant to Equation 4, namely, where all rain intensities are lumped together.

Another way of evaluating the effects of rain is to consider a few typical rain regimes. This is very important since an "expected" rain schedult could distort, rather significantly, the effect of rain due to nonlinearities of the associated response.

To do so the 41 years of rain statistics have been categorized into 10 different typical patterns arbitrarily chosen. These patterns are listed in Table 3.

Each year was classified into one of these categories. The user of the harvesting algorithm (see below) may select any category by taking a particular year. Weighting of each solution may be done using the percent of occurrence.

The effect of harvest date and rainfall on harvesting loss

MATERIALS AND METHODS

Five sections of 1 m length were selected at random immediately after harvest in a large number of commercial fields. These sections were 96.5 cm wide, extending between the exact middle of two adjacent rows of plants. All cotton on the ground in this area and all cotton remaining on one of the bounding 1 m rows of plants was collected. To avoid problems of mud contamination and moisture content, the number of seeds in the sample was counted as a proxy for yield weight losses, and the cotton discarded.

In a further series of samplings, 20 small-orifice raingauges were distributed through the region. At each rain event, readings were taken at each raingauge and fields were located in the immediate vicinity in which harvesting stopped due to the rain. The position in the field where harvesting was interrupted was marked. 10 samples of harvesting loss were taken from the harvested area according to the method described above, and a further 10 samples were taken from the rained-on section of the field when harvesting was completed. In addition, harvested cotton from the 2 sections of the field was marked and ginned separately for checking of effects on quality.

RESULTS

The function of harvesting loss through time

1982. 181 fields were sampled. Figure 1 shows the mean harvesting wastage for all fields harvested on a given date, expressed as number of seeds per m-row. Mean loss was 148 seeds/m-row with a coefficient of variation of 44%. Linear regression of loss against time yielded:

$$W = \begin{matrix} 205.8 \\ (21.9) \end{matrix} - \begin{matrix} 1.42 \\ (0.53) \end{matrix} t; \quad r^2 = 0.039$$

where W = harvesting loss in seeds/m-row,

t = time in number of days from September 1.

Figure 1 indicates an increase in loss with time towards the end of the measurement period. This effect was found to be significant in a second-order polynomial regression analysis which yielded:

$$W = \begin{matrix} 438.7 \\ (78.9) \end{matrix} - \begin{matrix} 13.6 \\ (4.0) \end{matrix} t + \begin{matrix} 0.15 \\ (0.049) \end{matrix} t^2; \quad r^2 = 0.087$$

1983. 123 fields were sampled. Figure 2 shows the mean harvesting loss through time. Mean wastage was 149 seeds/m-row with a coefficient of variation of 46%. The following regression analyses were obtained:

$$W = \begin{matrix} 273.7 \\ (33.6) \end{matrix} - \begin{matrix} 2.82 \\ (0.75) \end{matrix} t; \quad r^2 = 0.106$$

$$W = \begin{matrix} 463.1 \\ (215.8) \end{matrix} - \begin{matrix} 11.5 \\ (9.83) \end{matrix} t + \begin{matrix} 0.097 \\ (0.109) \end{matrix} t^2; \quad r^2 = 0.112$$

Data for both years were analyzed together and the following results were obtained:

$$W = 225.0 - 1.82 t; \quad r^2 = 0.058 \\ (18.2) \quad (0.42)$$

$$W = 368.0 - 8.98 t + 0.085 t^2; \quad r^2 = 0.071 \\ (71.7) \quad (3.5) \quad (0.041)$$

Despite the very low correlation coefficients all the above regression analyses are highly significant.

The effect of rainfall on harvesting loss

Harvesting was not interrupted by rain in 1982.

In 1983, harvesting was interrupted by one rainfall event on October 14. Loss sampling was carried out in 13 fields, with local rainfall ranging from 1 to 12 mm. Rainfall intensity was low and wind intensity during and immediately after the rain event was average. Mean harvesting loss before rainfall was 114 seeds/m-row. Rainfall caused a mean increase in harvesting loss of 16 seeds/m-row (C.V. = 141%) and this effect was found to be significant. Figure 3 shows the change in harvesting loss resulting from rainfall as a function of rainfall quantity. No clear trend is apparent.

The effect of rainfall on cotton quality

Rainfall upto 12 mm was found to have no effect on the quality grading of lint cotton, as graded at the Cotton Marketing Board laboratory.

DISCUSSION

The trend of an initial declining phase in the loss function with time can be explained in terms of more complete opening, and hence harvesting, of bolls through time. Later in the season, the trend for harvesting loss to increase can be explained in terms of a certain degree of natural falling of fully open bolls which may be aggravated by mechanical effects of the harvesting machinery passing along the rows.

Based on measurements taken by extension personnel over a number of growing seasons, it was found that harvesting loss cotton containing 100 seeds is equivalent to approximately 170 kg seed cotton yield per hectare.

On the basis of the combined 1982 and 1983 analyses, a 30-day difference in harvesting date would result in a difference of 90 kg seed cotton per hectare according to the linear regression analysis. The minimum of the polynomial expression occurs at October 23 and represents a reduction of 130 kg seed cotton loss per hectare from the predicted value at September 23.

These results indicate that the reduction in harvesting loss through time is too small an effect to merit consideration in deciding whether to delay harvest of a particular field by a few days.

A time effect on harvesting loss has not been incorporated into the harvest scheduling algorithm. This algorithm fits the risk averter decision-makers, since we feel that a few more years of losses due to rain-wind combinations should be studied before more affirmative conclusions are drawn. However, the gambler can use this algorithm by changing the loss parameters.

Quantification of the effect of rainfall on harvesting loss clearly requires many years of data and only provisional estimates can be provided at present.

On the basis of results from 1983, the scheduling algorithm assumes rain of upto 10 mm/day to have no effect on loss. (The mean increase of 16 seeds/m-row represents about 0.5% of yield. Barker (1982) found that rainfall less than 14.5 mm/day had no effect on pre-harvest losses in the hill areas of Mississippi.)

For rain events of more than 10 mm/day, there is assumed to be a yield loss of 6 kg seed cotton per hectare per mm of rain. This value is based on field measurements in October 1977 when a rainfall of about 80 mm resulted in a loss of approximately 500 kg seed cotton per hectare.

Rain damage parameters in the scheduling algorithm will be refined as further data become available.

The effect of defoliation timing and double harvesting
on cotton yield and quality

MATERIALS AND METHODS

Experiments on defoliation timing and double harvesting were carried out in 1981 in commercial fields at 3 collective farms in the region. Acala variety SJ-2 was sown on April 20 at Metzger, April 28 at Lehavot Haviva and April 1 at Nachsholim. The fields received standard commercial fertilization, irrigation and pest control for the area. Treatments consisted of defoliation timing commencing at 45, 60 and 75 per cent boll opening. Defoliation was in three applications with a 6-day interval between applications. Percentage boll opening counts were conducted at approximately 3-day intervals over 5 randomly selected 1 m sections in each replicate. The experiments were arranged in a randomized block design.

Metzger. Treatments were replicated 5 times. Defoliation was by hand-operated sprayer and harvesting of open bolls was by hand. Harvesting was carried out in every treatment 5 days after the final defoliation of each treatment. Thus all treatments were harvested three times. For the purposes of quality checking, cotton harvested upto 17 days after first defoliation was bulked and examined. This represents yield that would be harvested at the first commercial harvest. Cotton harvested beyond this date was bulked and examined separately, representing commercial "2nd harvest" yield (Table 4).

Lehavot Haviva and Nachsholim. Treatments were replicated 4 times at Lehavot Haviva and twice at Nachsholim.

Defoliation was by aerial spraying and harvesting was by machine. 1st harvest was carried out 5 days after final defoliation of each treatment and second harvest was on the same date in all treatments (October 18) at the end of the season.

Counts were taken of the number of unopened green bolls on fixed 10 m sections in each replicate immediately before and after first harvest.

Seed cotton yield for each replicate was weighed separately but bulked before ginning and lint quality checking.

Lint quality checking was according to commercial standards for each treatment separately as samples arrived at the Cotton Marketing Board laboratory. A further quality assessment was made for all treatments on the same day at the end of the season to obtain a more accurate relative grading.

RESULTS AND DISCUSSION

Percentage boll opening curves and timing of defoliation is shown for the three locations in Figures 4-6. Earlier defoliation appears to accelerate boll opening. Advancing defoliation from 75% to 45% boll opening results in a 5- to 10-day advance in reaching 100% boll opening. On the whole, the rate of boll opening ranges between 2 and 3 per cent per day.

Results of yield and quality are given in Tables 4-7. Total hand harvested yield at Metzger was not affected by early defoliation. At Lehavot Haviva, total lint yield was significantly reduced by early defoliation and double harvesting by machine. At Nachsholim, there was no effect of defoliation timing on seed cotton or lint yield. There was a significant effect of defoliation timing on mechanical damage at first harvest at both Lehavot Haviva and Nachsholim (Table 8). Since the number of replicates was low, data for Lehavot Haviva and Nachsholim were analysed together (Table 9). This analysis shows a significant effect of early spraying and double harvesting on seed cotton yield.

It might be expected that defoliation as early as 45% boll opening would effect cotton yield through reduced boll weight resulting from an early reduction in the supply of photosynthates. The fact that only a small effect was obtained can be explained in view of the following:

- 1) Bolls cease to increase weight about 5 days before complete opening.

2) Defoliation causes leaf shedding approximately 5 days after application. Thus, at an average rate of boll opening of 2.5%/day, one can roughly state that defoliation at 45% is equivalent to a reduction in effective photosynthate supply from 70% boll opening.

3) Defoliation is effected in layers; the first application at 45% causes shedding of the uppermost level of the leaf canopy only (though these leaves are the youngest and most active).

4) The photosynthetic efficiency of leaves declines steadily towards the end of the season and a significant portion of boll weight increase derives from carbohydrate mined from leaves and stems. Thus defoliation as early as 45% boll opening is, at worst, reducing photosynthate supply to 30% of total boll number for a short period towards the end of their development.

It should be noted that the cotton field at Nachsholim was a slowly developing crop. This is evident from Figure 5 and from Table 10 which shows that a relatively high percentage of total yield was harvested at second harvest. Such a field is quite uncommon but was chosen for this experiment in order to examine a wide range of conditions. Defoliation at 75% followed by 1st harvest 17 days later still left over 9% of yield in the field. This illustrates the importance of a dynamic approach to defoliation and harvest scheduling that considers the rate at which bolls are expected to open. A computer program for predicting boll opening on the basis of field counts of boll numbers is available to the growers.

There was a consistent effect of double harvesting on micronaire and colour grading. Double harvesting results in a lower colour grade for 2nd harvest cotton presumably because of discoloration from leaf material and dirt. Micronaire is reduced by about 10 points at 2nd harvest.

CONCLUSIONS

Commencement of defoliation as early as 45% boll opening causes a small reduction in total cotton yield. However, additional financial losses are incurred to the grower through mechanical damage to unopened bolls at first harvest and through a reduction in the lint quality of second-harvest cotton.

Until more data becomes available from further experiments, the following parameters are taken in the scheduling algorithm.

Defoliation is not permitted earlier than 50% boll opening.

Double harvesting is carried out for fields defoliated between 50% and 66% boll opening. This upper limit for double harvesting can be computed from knowledge of the expected cotton yield, lint percentage and economic parameters. Such a calculation will be used in the algorithm at a future stage of development.

On the basis of results from the more typical Lehavot Haviva field, the algorithm assumes the allocation of yield between the first and second harvests to be 94% and 6%, respectively. It is estimated that the quantity of cotton left in the field by single harvesting (after defoliation at 75% boll opening) is approximately equal to any yield reduction caused by earlier defoliation and mechanical damage caused by double harvesting. Hence no yield reduction factor is taken for double harvested fields. Percentage lint for second harvest cotton is taken to be 93% of the first harvest value. A reduction of 2 units in fibrograph and 3 units in quality grade is taken for second harvest lint. In the scheduling algorithm, these effects are incorporated directly in the price of lint.

An algorithm for the scheduling of cotton harvesting operations

The algorithm accepts any number of user-determined harvesting scenarios and calculates for each a feasible schedule and its profitability. A harvesting scenario is defined by:

- 1) whether or not double harvesting is allowed,
- 2) whether or not the hiring of extra harvesting capacity is to be considered,
- 3) if the hiring of extra harvesting capacity is permitted, whether one or two machines can be hired at once and over which period hiring may be considered.

The user may choose the default set of scenarios listed in Table 11 which covers the range of practice.

For each scenario the algorithm computes the recommended harvesting date and defoliation dates for every field, the total number of days required to complete harvesting and the period during which extra harvesting capacity should be hired (if such an option is allowed). In addition, the algorithm provides economic summary estimations including the gross and net income, harvesting, transportation, ginning and defoliation costs, and the yield lost through rain damage.

For a given scenario, a feasible schedule (taking into consideration holidays and weekends) is generated for any number of rainfall patterns. These rainfall patterns can be taken from historical data or generated stochastically using the analysis of rainfall data described earlier. Yield losses are deducted from an average seed cotton yield value provided by the extension officer. The program allows for quality effects of rain though no losses are incurred at present due to lack of data. The grower is advised to take into consideration not only the net profit but also the robustness of alternative solutions to different rainfall patterns.

The algorithm ranks all scenarios according to the net income to the whole cotton farm, and prints it out. The grower may select the "best" (highest net income) or any other one based on his risk aversion behavior.

Information regarding the size and location of cotton fields within the farm, sowing date and variety sown are all drawn directly from the existing data base at the computer installation. The percentage boll opening curve for each field can be computed according to a standard set of parameters. Parameter values are based on observations from many fields over a number of seasons. Values are currently:

For sowing on April 1, boll opening commences at August 15 for Acala cotton and at August 23 for Pima cotton. Commencement of boll opening is advanced 1 day for every 4 days advancement in sowing before April 1 and delayed 1 day for every 2 days delay in sowing after April 1 (all varieties).

Daily rate of boll opening is taken to be 3% upto 45% boll opening, 2.3% from 45% to 66% boll opening and 2% from 66% to 100% in Acala cotton and 1.7% from 66% to 100% in Pima cotton.

The program also accepts field counts of percentage boll opening and these figures override predicted default values upto the specified date.

There is also an option of using an existing algorithm for the prediction of boll opening that provides an accurate prediction based on field counts of large bolls (Wallach and Kletter, 1981).

Default values for daily harvesting capacity and all input and output prices are available to the algorithm but the grower can substitute values for most of these.

The grower can specify days (weekends, holidays, etc.) on which no defoliation or harvesting operations are to be scheduled.

Computation of a feasible harvesting schedule is subject to a large number of constraints. The more important of these are:

- 1) For single harvest fields, the earliest feasible harvesting date is defined by 100% boll opening.
- 2) 1st, 2nd and 3rd defoliation sprays are applied 17, 11 and 5 days prior to the recommended harvesting date.
- 3) Defoliation cannot commence before 50% boll opening is reached.
- 4) Double harvesting is not carried out for fields defoliated after 66% boll opening.
- 5) There is a minimum daily acreage below which defoliation spraying cannot be ordered.
- 6) Pima variety is not double harvested.
- 7) Priority of fields with identical boll opening percentages on a given day is according to variety (Pima over SJ-2) and proximity of fields.
- 8) Start of harvesting operations is delayed to eliminate idle days.
- 9) Rainfall causes a delay in harvesting according to the quantity of rain.

It is intended to use the scheduling algorithm to determine the economic feasibility of joint acquisition of additional harvesting equipment by groups of growers.

The program allows for the easy updating of all economic and biological parameters as new information becomes available.

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FIGURE LEGENDS

- Figure 1. No. of seeds in yield loss per square meter as a function of harvesting date, 1982.
- Figure 2. No. of seeds in yield loss per square meter as a function of harvesting date, 1983.
- Figure 3. Seed difference in harvest losses per square meter as a function of daily amount of rain. The graph represents the average loss for each amount of rain.
- Figure 4. % of open bolls as a function of the date at Metzger. The arrows indicate the defoliation dates.
- Figure 5. % of open bolls as a function of the date at Nachsholim. The arrows indicate the defoliation dates.
- Figure 6. % of open bolls as a function of the date at Lehavot Haviva. The arrows indicate the defoliation dates.

Figure 3

Figure 4

Figure 5

Figure 6

Period	Rainfall class	Sample probability
	Mean annual	0.013
	0 < rain <= 5	0.013
16/9 - 30/9	5 < rain <= 15	0.000
	15 < rain <= 30	0.000
	rain > 30	0.000
	Mean annual	0.075
	0 < rain <= 5	0.045
1/10 - 15/10	5 < rain <= 15	0.021
	15 < rain <= 30	0.007
	rain > 30	0.002
	Mean annual	0.125
	0 < rain <= 5	0.065
16/10 - 30/10	5 < rain <= 15	0.037
	15 < rain <= 30	0.014
	rain > 30	0.009

T a b l e 2

Estimation of parameters a and b in equation
1 for various rainfall intervals

Rain interval	Parameter						R^2
	a			b			
	$\hat{a}$	t_a^*	$\hat{b}$	t_b^*			
2	0.552	15.3	0.043	52.9	0.988		
3	0.338	7.3	0.049	30.6	0.968		
4	0.237	1.54	0.057	7.23	0.665		

*t=statistic for the parameters a and b, respectively

T a b l e 3

Categories of rainfall according to patterns and levels

Category: number	Rainfall quantity (mm in Sept.-Oct.)	Pattern description	% of occurrence
1	0 - 6	--	26.8
2	> 6 - 15	dispersed	9.8
3	> 6 - 15	concentrated	17.1
4	>15 - 30	dispersed	14.6
5	>15 - 30	concentrated	2.4
6	>30 - 50	after Oct. 25	2.4
7	>50 - 60	dispersed	12.2
8	>50 - 60	concentrated	4.9
9	approximately 80	dispersed	4.9
10	approximately 80	concentrated	4.9

T a b l e 4

The effect of defoliation timing on cotton yield at Metzger

=====									
:	:	Seed cotton yield (kg/m-row)						:	%
:	Treat.	-----							:
:	:	1.10	6.10	16.10	Harv.I*	Harv.II	Total	lint	:

:	45 %	439	27	21	439	48 a	487	38.7	:
:	60 %	446	31	24	477	24 b	501	38.7	:
:	75 %	411	31	28	470	--	470	38.5	:
:	:	:	:	:	:	:	:	:	:

* - Harvest I is defined as yield up to 17 days after first defoliation, remaining yield is classed as Harvest II. Numbers within a column followed by the same letter are not significantly different according to Duncan's Multiple Range Test.

T a b l e 5

The effect of defoliation timing on lint quality at Metzger

=====										
:	:	Harvested at 1.10				:				
:	Treatment	-----					:			
:	:	Presley	Micronaire	Fibrograph	Uniformity	:				

:	45 %	:	92.6	:	44.2	:	119.4	:	49.2	:
:	:	:	:	:	:	:	:	:	:	:
:	60 %	:	92.8	:	44.6	:	122.0	:	49.8	:
:	:	:	:	:	:	:	:	:	:	:
:	75 %	:	93.6	:	43.8	:	122.4	:	50.4	:

:	Harvested at 6.10 and 16.10									:

:	45 %	:	93.0	:	37.6	:	122.2	:	47.8	:
:	:	:	:	:	:	:	:	:	:	:
:	60 %	:	91.8	:	35.4	:	119.8	:	48.6	:
:	:	:	:	:	:	:	:	:	:	:
:	75 %	:	91.8	:	37.2	:	118.8	:	49.0	:
=====										

Quality characteristics were not found to be significantly different on the 0.05 level according to Duncan's Multiple Range Test.

		Seed cotton (kg/m-row)::		Lint yield (kg/m-row) ::		% Lint			
Treat.		Harv. I:Harv.II: Total ::		Harv. I:Harv.II: Total ::		Harv. I:Harv.II:			
Lehavot Haviva									
45 %	407 b :	27 a :	435 a ::	134 b :	8 a :	142 b ::	32.9 b:		
60 %	418 ab:	26 a :	443 a ::	137 b :	7 a :	144 b ::	32.8 c:	28.0	
75 %	446 a :	17 a :	463 a ::	152 a :	5 a :	156 a ::	34.0 a:		
Nachshol									
45 %	505 a :	79 a :	584 a ::	164 a :	24 a :	188 a ::	32.5 b:		
60 %	523 a :	62 a :	585 a ::	171 a :	19 a :	190 a ::	32.7 a:	30.6	
75 %	542 a :	56 a :	599 a ::	160 a :	17 a :	177 a ::	29.5 c:		

Table 7

Treat.	Presley	Micro- naire	Fibro- graph	Unifor- mity	Quality grading Commer- cial	Relativ- ranking	Colour
<u>Lehavot Haviva</u> - 1st harvest							
45 %	91	40	112	45	5.0	6.2	fair
60 %	91	40	112	45	5.2	5.3	good
75 %	91	40	112	45	4.8	6.5	good
<u> </u> - 2nd harvest							
	89	28	105	42	8.0	9.0	
<u>Nachsholim</u> - 1st harvest							
45 %	92	40	111	46	6.5	6.8	fair
60 %	92	40	110	45	6.4	6.3	
75 %	91	40	111	45	6.2	6.6	
<u> </u> - 2nd harvest							
	92	31	109	44	8.0	9.0	

T a b l e 8

The effect of defoliation timing on mechanical harvesting damage to unopened bolls at Lehavot Haviva and Nachsholim

=====					
		Number of unopened bolls per 10 m-row			:
TREATMENT	:	:-----:-----:-----:-----:-----:			
:	:	Before harvest	:After harvest I:	Difference*	:
:-----:-----:-----:-----:-----:-----:					
: <u>Lehavot Haviva</u> :					
45 %	::	70.4 a	:	53.2 a	:
60 %	::	54.5 a	:	43.6 a	:
75 %	::	39.3 a	:	35.1 a	:
:-----:-----:-----:-----:-----:-----:					
: <u>Nachsholim</u> :					
45 %	::	161.5 a	:	129.5 a	:
60 %	::	126.5 b	:	89.5 b	:
75 %	::	107.0 b	:	93.0 b	:
=====					

* To adapt numbers to Table 8, a weighted average should be used. Numbers within a column for a given location followed by the same letter are not significantly different at the 0.05 level according to Duncan's Multiple Range Test.

T a b l e 9

The effect of defoliation timing on cotton yield and mechanical harvesting damage for combined Lehavot Haviva and Nachsholim data

=====					
: Seed cotton yield (kg/m-row) :					: Mechanical :
: TREATMENT :	:-----:-----:-----:-----:				: damage * :
:	: Harvest I :	: Harvest II :	: Total :		: Bolls/10 m-row :
:-----:-----:-----:-----:-----:-----:					
: 45% :	: 440 b :	: 45 a :	: 484 b :		: 22.2 a :
: 60% :	: 453 ab :	: 38 ab :	: 491 ab :		: 19.6 a :
: 75% :	: 478 a :	: 30 b :	: 508 a :		: 7.5 b :
=====					

* Defined as the difference between the number of bolls before and after harvest I. Numbers within a column followed by the same letter are not significantly different at the 0.05 level according to Duncan's Multiple Range Test.

T a b l e 10

The effect of defoliation timing
on the allocation of cotton yield between harvests

:	T	:	% total seed cotton yield harvested at						:	Total seed cotton			:	
:	R	:	-----						:	harvested as % of			:	
:	E	:	Harvest I			:	Harvest II			:	harv. I at 75% defol.			:
:	A	:	-----						:	-----			:	
:	T	:	L	:	N	:	L+N	:	L	:	N	:	L+N	:
:	45 %	:	93.8	:	86.5	:	90.7	:	6.2	:	13.5	:	9.3	:
:	:	:	:	:	:	:	:	:	:	:	:	:	:	:
:	60 %	:	94.1	:	89.4	:	92.3	:	5.9	:	10.6	:	7.7	:
:	:	:	:	:	:	:	:	:	:	:	:	:	:	:
:	75 %	:	96.3	:	90.6	:	94.1	:	3.7	:	9.4	:	5.9	:
:	:	:	:	:	:	:	:	:	:	:	:	:	:	:
:	:	:	:	:	:	:	:	:	:	:	:	:	:	:

L = Lehavot Haviva

N = Nachsholim

L + N = Combined Lehavot Haviva and Nachsholim

T a b l e 11

The default set of scenarios for cotton harvesting

=====				
Option	No. of	No. of	Minimum of %	
number	hired	harvests	open bolls at	
:	harvestors	:	1st defoliation:	

0	0	1	66	:
1	1	1	66	:
2	2	1	66	:
3	0	2	50	:
4	1	2	50	:
5	2	2	50	:
6	0	2	55	:
7	1	2	55	:
8	2	2	55	:
9	0	2	60	:
10	1	2	60	:
11	2	2	60	:
=====				