Identification of Viable Biological Strategies

for

Pest Management by Simulation Studies

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Abstract

Interdisciplinary research by management scientists and entomologists at the University of Florida has developed a stochastic computer model for studying interactions between an insect population, its host food crop, and other variables. This population growth model, highly adaptable to any insect and any host crop, is technically characterized by discrete arrivals, infinite servers and multi-stage, continuous service-time distribution functions.

Because steady state is seldom achieved in nature, this paper identifies combinations of critical starting conditions (number of insects, disparate start times for insects

and host crops) and critical stages for induced survival rate reductions to minimize crop damage. Sensitivity analyses serve to identify the most promising areas for future entomological research in pest management strategies.

I. Introduction

This research was initiated in the belief that management science could and should contribute to the solution of ecological problems. One of the most serious of these is the ecological consequences of the unrestricted use of pesticides. Pest management addresses the problem by identifying and testing alternate strategies which would minimize the use of pesticides for crop protection while maintaining the crop's economic worth.

The experiments reported here were performed in response to the following general questions.

> If one has a simulation model of the damage caused by a specific pest on a specific valuable food crop, is there a stage in the pest's life cycle where a fixed decrease in pest population is most effective in minimizing crop damage?
>
> Would the implications of the results of the simulations identify useful strategies for minimizing the application of ecologically dangerous pesticidal materials?

II. The Ecosystem Being Simulated

The ecosystem simulated for the experiments of this report is that of a soybean host crop infested by the velvet bean caterpillar (VBC), one of the major pests for soybeans in North Florida. Soybeans were selected as a host crop because of their worldwide economic importance as a high protein food. [1]

The VBC moth overwinters in South Florida and is suspected of invading Florida from the Caribbean area each year. The adult female moth lays its eggs and about two generations of insects develop during the year until death in late fall (or out-migration of the adult moth) reduces the population to essentially zero in North Florida soybean fields.

The eggs, 800 on the average per female, are laid individually by the adult over a period of about eight days. After hatching, the insect passes through six stages of growth (instars) as caterpillars and a pupae stage before emerging as an adult moth to mate, disperse, and lay eggs for the next generation. The length of time the caterpillar remains in an instar (dwell time) is a stochastic variable influenced by the environmental conditions during the stage. Available field experimental data indicate the dwell time probability distribution to be normal for all instars. Each, however, has a different average and standard deviation. The VBC causes damage by defoliation of the soybean plant, the amount varying with the instar.

The soybean plant was considered to have ten stages of development from emergence to unifoliate leaves through maturity. The plant's leaf developm[illegible] between the critical stages in plant maturity, podset to podfill, and the per cent defoliation by the pest during this period was of primary interest in the model since economic crop damage occurs when threshold defoliation levels are exceeded here.

III. The Ecosystem Model

The simulation model of the insect population dynamics, the growth of the soybean crop, and the damage by defoliation caused by the VBC was developed through the interdisciplinary efforts of a management scientist and three entomologists. Initially knowledge about each others' discipline was minimal. General concepts of model structure emerged during repeated conferences which were mutually educational in biology, agronomy, entomology, management science, and modeling techniques. Specific concepts used in the model structure are described below.

Technically, the insect population dynamics is modelled in terms of stochastic variates characterized by discrete arrival times (the adult moth invasion), a discrete starting population (the eggs), infinite servers (the life cycle for each insect) and multi-stage service time (the continuous distributions for dwell time at each instar.)

The crop development portion of the

model is a deterministic function of time using EV [leaf area] since the leaf area per acre is so large (even at the seedling stage, leaf area is approximately 1×10^6 cm^2/acre). Critical points for the functional relation are seedling, midbloom, podset and podfill. All soybean leaf area growth and defoliation by the VBC are expressed in cm^2 per acre. Insect population counts and leaf damage are calculated at weekly intervals after the date of simular planting.

The model is presently one-dimensional in that it does not consider in-migration or out-migration of the VBC after the starting moth invasion. Nor does it consider the spread or diffusion of the insect population within the field from the point of contact of the initial invading moths. Therefore, simulated population counts and leaf defoliation calculations are average values per acre, ignoring localized hot spots which are expected in the real situation.

FORTRAN IV was chosen as the computer language for the simulation in the belief that it would be more flexible in permitting future expansion of the model to include the above considerations. In addition FORTRAN flexibility would be useful when non-ideal environmental effects (temperature, humidity, day length, rainfall, surround, etc.) were included. It is anticipated that SIMSCRIPT would be used at a more refined stage in the model development.

Biological and entomological data needs emerged as the model was developed. These data were collected in a variety of ways. In some cases, e.g., dwell time per instar, literature search combined with recent experimental results provided the answer; in some cases, e.g., average leaf area eaten per instar per caterpillar, private communications with researchers yielded unpublished results; in other cases, e.g., typical moth invasion dates and crop development data, PERT type "min. - expected - max." questions [2] were posed to the entomologists; in a few cases, e.g., survival rate per instar, little hard experimental information was available and reliance was placed upon general knowledge and intuition for reasonable values.

IV. Operation of the Model

Figures 1 and 2 show simplified flow chart descriptions of the operation of the model.

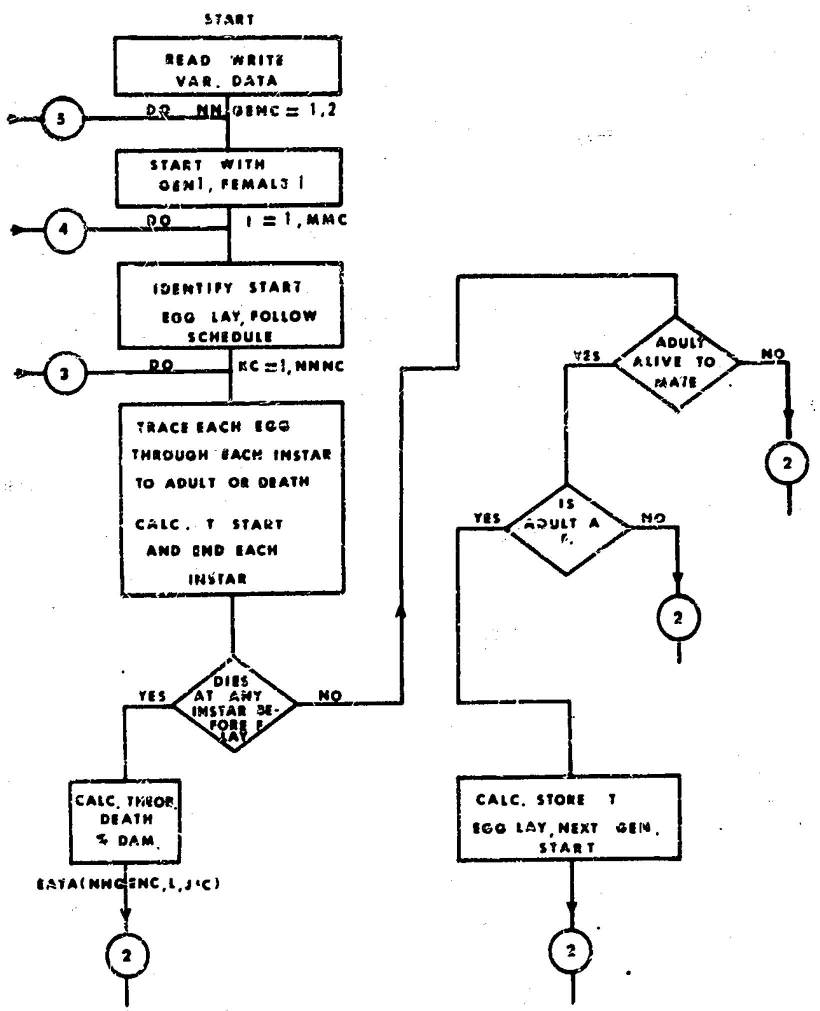

Figure 1

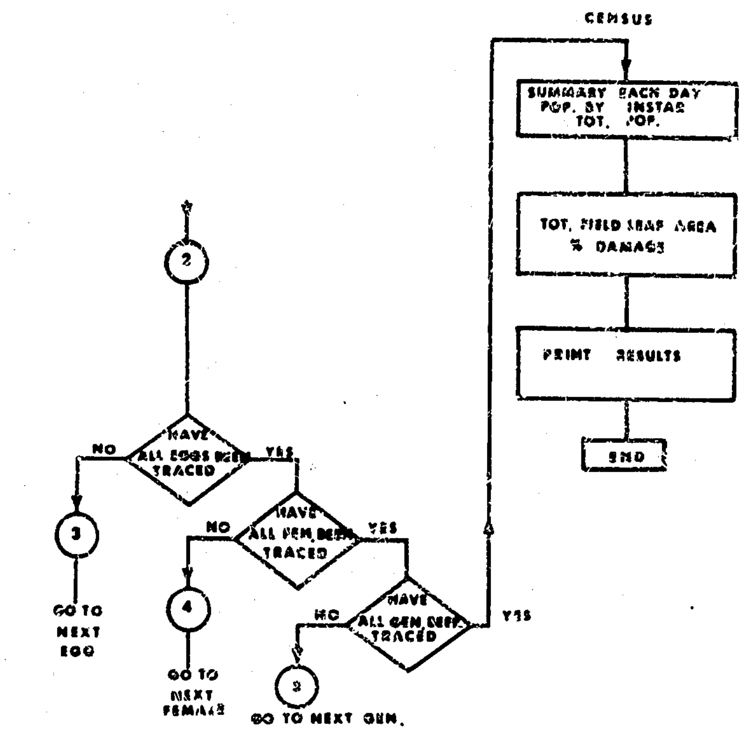

Figure 2

The model traces the development of each egg from each female adult through the instar in which death occurs or until the larva becomes an adult moth. If the adult is a female, the time of egg laying for the next generation of progeny is calculated and recorded. After all eggs from all females of one generation are traced, the program automatically repeats the calculations for the next generation of caterpillars until the required number of generations have been traced.

Monte Carlo techniques are used to calculate survival at each stage of development from egg through adult moth, the time duration a particular individual remains in a particular instar (dwell time), as well as whether the adult is a male or female. Thus 20 different random number series were identified and used for each simulation run. Subsequent simulation runs used different random number seeds, themselves chosen from random number tables for each of the 20 random number series of the run.

After all eggs from all females for all generations have been traced, the program prints out a census calculated at weekly intervals from the starting date for egg laying for the first generation. The census details for each day of count:

1. the population in each instar,
2. the total population including eggs,
3. the total population of larvae only,
4. the cumulated soybean leaf area eaten by all the caterpillars through this day,
5. the crop leaf area available,
6. the per cent of the available leaf area eaten.

Table 1 describes the variables of the model. These are classified according to type (dependent or independent), description, source for numerical values, and if data, the basis for the data.

Figure 3 indicates the assumed dwell-time distributions, the egg laying schedule and the eating habits used in the model for the velvet bean caterpillar. The dwell time distribution for the VBC is based on experimental data as are the data for the eating habits of the caterpiller. [3, 4, 5] Also shown on Figure

Table 1

INDEPENDENT VARIABLES

Variable Description	Used For	Source For Numerical Values	Data Basis
1. Start time, gen. 1	Pests	Data	Watson, 1916; Greene, 1970
2. No. init. females/acre	Pests	Data	Greene, Kerr, Whitcomb, 1971
3. R. N. series	Pests	Data	
4. P(survival) - ea. instar	Pests	Data	P. Lawrence, 1971
5. Avg. dwell time - ea. instar	Pests	Data	
6. σ, dwell time - ea. instar	Pests	Data	Watson, 1916; Greene, 1971
7. P(adult = female)	Pests	Data	
8. Egg laying distribution	Pests	Data	Greene, 1971
9. Leaf area/cat./instar	Pests	Data	Greene, 1971
10. Day of count	Pests	Program	
11. Females forced at gen. end.	Pests	Program	
12. Day of planting	Crop	Data	Greene, 1971
13. Plant growth	Crop	Program	Greene, 1971
14. Leaf area	Crop	Program	Turnipseed, 1972

DEPENDENT VARIABLES

Calculated at Each Day of Count

1. Tot. pop/instar - including eggs
2. Tot. insect population
3. Cumulated defoliation in cm^2
4. Tot. crop leaf area available in cm^2
5. % defoliation

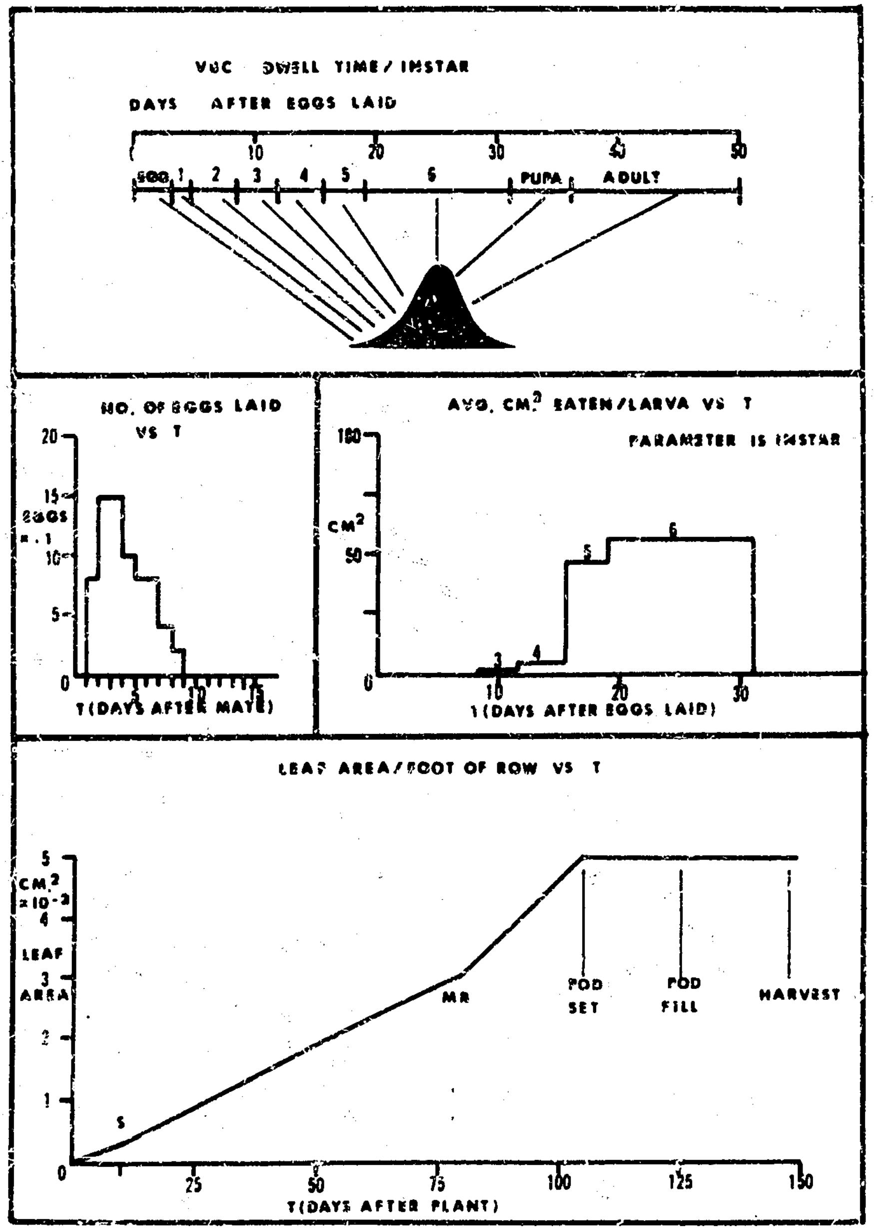

Figure 3

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IN      RATEC      RNC        RHNC    RMEANC      SIGC
 1     0.7000      667         153    0.0000     0.0000
 2     0.7000      233         497    3.0000     0.3000
 3     0.7000      817         779    1.7000     0.1000
 4     0.7000       19         597    3.6000     0.1000
 5     0.7000       31         673    3.5000     0.1000
 6     0.7000      437         739    3.7000     0.2000
 7     0.7000      913         707    3.5000     0.4000
 8     0.7000      609         219   12.0000     2.0000
 9     0.7000      803         369    5.0000     0.3000
10     0.7000      327         197   14.0000     1.0000
11     0.5000      377         763    0.0000     0.0000
  8  18  33  48  58  66  74  78  80

    START GEN 1 IS   199.0000 DAYS AFTER JAN. 1
ORIG. START FEMALES ARE     60
                                    RANDOM SERIES IS.      4.00
                                    DAY OF PLANTING IS. 127

  0.0      0.16      0.64      3.05      8.25      43.30      62.60

HERE1

HERE2

IMMC=      1

HERE1

HERE2
   1     295.1995
   2     296.1492

IMMC=      2

HERE1

HERE2
   1     340.9487

HERE2
   2     339.0483

IMMC=      2

HERE1

HERE2
   1     388.6477

HERE2

IMMC=      1

HERE4
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Figure 4

3 is the assumed development for the soybean crop, in leaf area per foot of row in the field.

Figure 4 is a typical computer print-out showing the data used in the simulation run and the resultant egg laying dates for females from each generation.

Figure 5 is a typical census print-out showing the six census responses enumerated previously.

Preliminary runs with the model confirmed it was following the entomologist's belief that about two generations of the VBC propagated during the time period from the initial moth invasion to the final stage in soybean development where the host crop was sensitive to economic damage caused by defoliation. It was observed that the survival rates at each instar and the differing stochastic dwell-times in each instar combined to produce a mixed response for population as a function of time. That is, the two random variables, the early peak population for each generation and the population in the latter instars including the number of females laying eggs for the next generation, both exhibited large variances from run to run. However, the population counts for time periods when most of the population was in the central instars (roughly instar 3 through instar 5) approached closely EV calculations in these regions. The slope of the population with time in this region was exponential as expected.

This mixed response model therefore does not appear to fit any simple analytical model but does follow the trends predicted by the analytical population models of Watt [6], Pielou [7], Ross [8] and others.

The above details about the population dynamics are apparent in Figure 6 which displays typical population dynamics as predicted by simulation. Slope validation is indicated by the circled points which are calculated EV (overall fraction survival) plotted at weekly intervals, the first plotted point being fraction survival one week after eggs hatch = middle of 3rd instar = $.7^3$ = .343.

Location of the range in time for the second generation population peaks at Figure 6 may be verified by ordinary statistical calculations when it is realized that the start of the second

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POP. IN INSTAR  2 ON DAY 206 IS          300
POP. IN INSTAR  3 ON DAY 206 IS           70
POP. IN INSTAR  4 ON DAY 206 IS           20
POP. IN INSTAR  5 ON DAY 206 IS            0
POP. IN INSTAR  6 ON DAY 206 IS            0
POP. IN INSTAR  7 ON DAY 206 IS            0
POP. IN INSTAR  8 ON DAY 206 IS            0
POP. IN INSTAR  9 ON DAY 206 IS            0
POP. IN INSTAR 10 ON DAY 206 IS            0
TOT POP ON DAY   206 IS          390
        TOT INS ON DAY   206 IS            90
DAMAGE ON DAY 206 IS          10.09 SQ.CM.

TOTAL LEAF AREA ON DAY 206    39900512.00SQ. CM.

CUM. DAMAGE ON DAY 206 IS     0.00 PERCENTAGE OF LEAF AREA
POP. IN INSTAR  2 ON DAY 213 IS            0
POP. IN INSTAR  3 ON DAY 213 IS           20
POP. IN INSTAR  4 ON DAY 213 IS           60
POP. IN INSTAR  5 ON DAY 213 IS           90
POP. IN INSTAR  6 ON DAY 213 IS            0
POP. IN INSTAR  7 ON DAY 213 IS            0
POP. IN INSTAR  8 ON DAY 213 IS            0
POP. IN INSTAR  9 ON DAY 213 IS            0
POP. IN INSTAR 10 ON DAY 213 IS            0
TOT POP ON DAY   213 IS          170
        TOT INS ON DAY   213 IS           170
DAMAGE ON DAY 213 IS          190.81 SQ. CM.

TOTAL LEAF AREA ON DAY 213    46624160.00SQ. CM.

CUM. DAMAGE ON DAY 213        0.03 PERCENTAGE OF LEAF AREA
POP. IN INSTAR  2 ON DAY 220 IS            0
POP. IN INSTAR  3 ON DAY 220 IS            0
POP. IN INSTAR  4 ON DAY 220 IS            0
POP. IN INSTAR  5 ON DAY 220 IS           10
POP. IN INSTAR  6 ON DAY 220 IS           50
POP. IN INSTAR  7 ON DAY 220 IS           60
POP. IN INSTAR  8 ON DAY 220 IS            0
POP. IN INSTAR  9 ON DAY 220 IS            0
POP. IN INSTAR 10 ON DAY 220 IS            0
TOT POP ON DAY   220 IS          120
        TOT INS ON DAY   220 IS           120
DAMAGE ON DAY 220 IS          1619.31 SQ.CM.

TOTAL LEAF AREA ON DAY 220    53347792.00SQ. CM.

CUM. DAMAGE ON DAY 220 IS     0.20 PERCENTAGE OF LEAF AREA
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Figure 5

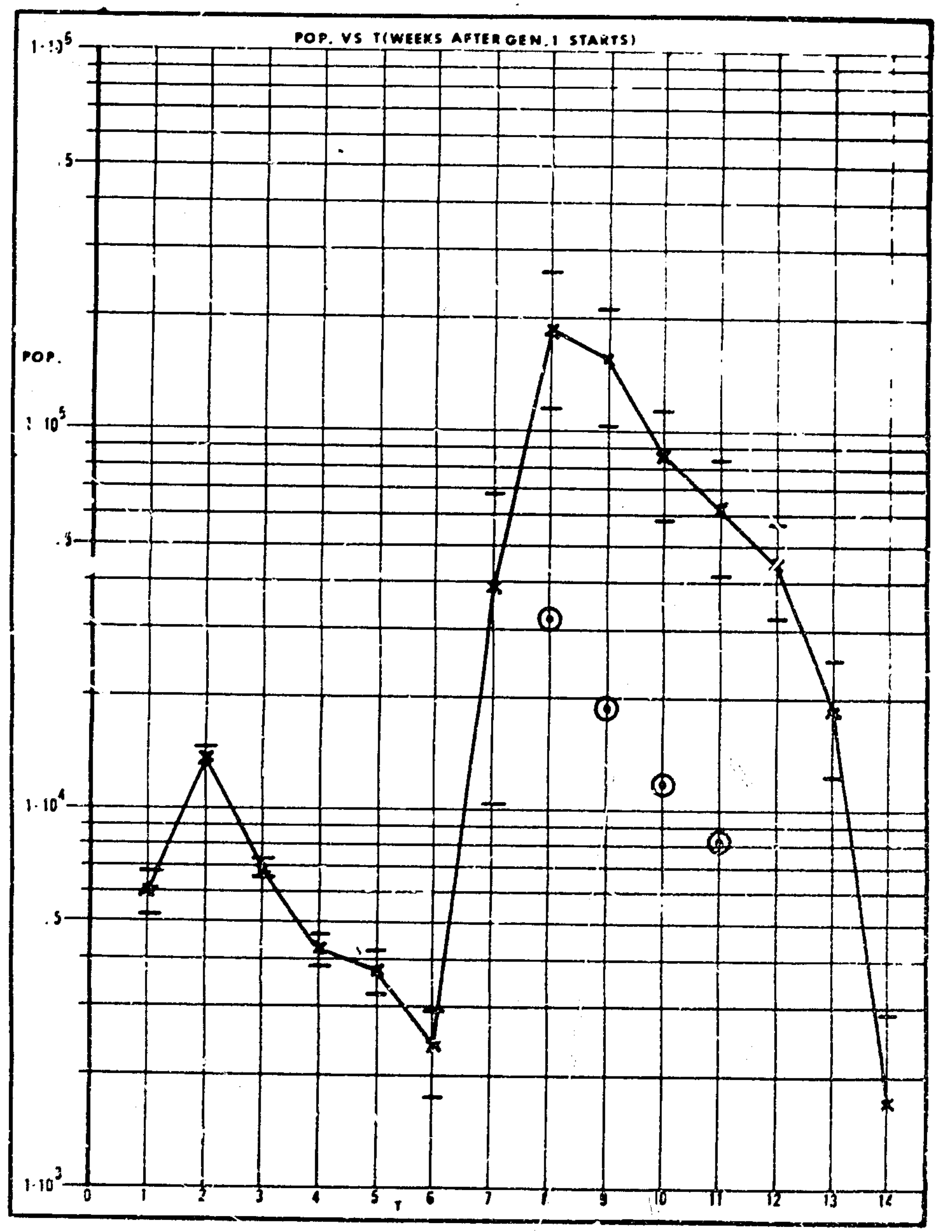


Figure 6

generation is not statistically independent of the first generation. The magnitude of the second generation population peak is a stochastic variate strongly dependent on the number of females that survive the first generation through the egg laying stage. The times at which these lay eggs form the starting conditions for the second generation; the number of survivors determines the second generation population characteristic. Thus the model, as in real life, shows highly volatile, or transient, second generation starting populations; individual second generation population counts can be expected to show significant variance around the average of many simulation encounters.

Validation of results has to date been restricted to the Turing Method both because of the expense involved in time and money and because of the difficulty of obtaining definite experimental data. Population counts in the field are to be taken this summer, 1972. The entomology consultants agree that the results are reasonable and of the correct order of magnitude. One set of population data consisting of three replications in two separate field areas in North Florida was obtained during the 1971 soybean season and conforms to the simulated predicted shape of the average population vs. time. The agreement encourages the belief that the principles used in model construction are valid and that inferences derived from model results merit serious consideration.

V Description of the Experiment

Previous experiments with this model had already determined that the worst possible situation for crop damage occurred for the combination of latest possible planting date for the crop (June 24) and the earliest possible initial invasion date (July 15) for the VBC moth. Note that these two variables are largely uncontrollable and are states of nature, both in the usual sense of these words and in the context of decision making.

Consider the above worst case and rephrase the experimental objective specifically in terms of the following:

$P_j(k)$ = Reduced survival fraction in instar j = $k \cdot Pj$

Pj = Normal survival fraction in instar j

k = Fraction of kill induced by any method

j = Instar

G = Generation in which kill is induced

Then define the experimental objectives as follows.

Find a preferred instar, j, in which a fixed fraction kill, k, will minimize the total per cent of defoliation of the soybean crop by the VBC. Find the implications for pest management strategies when the fixed kill is induced in the first generation only, in the second generation only, or is induced in the preferred instar in both the first and second generations. The fixed conditions for the experiment were:

Worst case states of nature

A massive initial VBC moth invasion (60 females/acre)

Experimental responses were:

Population vs. time

Per cent defoliation vs. time

Census counts every seven days

The experimental design for the simulation model was a complete factorial experiment with three factors, k (fraction kill at two levels), j (instar) at three levels and G (generation in which k is induced) at three levels.

Factor levels were chosen as tabulated below:

k = .25, .5

j = 2nd, 4th, 6th instar

G = generation 1 only, generation 2 only, both generations 1 and 2.

Each response was replicated twice, using ordinary then antithetic variate random number series in order to reduce the variance of the average response. It was believed that this experiment was the minimum size permissible, given the expected appreciable variance in the responses. Responses were compared at podset and podfill, critical points in time in the soybean crop development. These points roughly bracket the time period in which the crop is highly sensitive to defoliation effects. Nine sets of randomly selected random number seeds similar to the set of Figure 4 were used as data in order to generate the ordinary and antithetic random variates for the experiment.

Table 2 shows the averages of the replicate responses (average per cent

Table 2

Per Cent Defoliation at Podset

	k = .25			k = .5		
	j^2	j^4	j^6	j^2	j^4	j^6
G_1	30.8	37.0	34.5	22.2	32.1	21.6
G_2	33.0	30.7	44.4	22.6	25.9	39.5
$G_{1,2}$	23.2	25.7	37.5	12.0	13.7	22.3

Per Cent Defoliation at Podfill

	k = .25			k = .5		
	j^2	j^4	j^6	j^2	j^4	j^6
G_1	39.3	46.7	43.6	27.2	41.2	26.8
G_2	43.4	38.8	53.2	28.3	31.9	45.6
$G_{1,2}$	27.6	31.8	46.1	14.8	17.8	26.1

k = fraction kill

j = instar in which k is induced

G = generation in which k is induced

Table 3

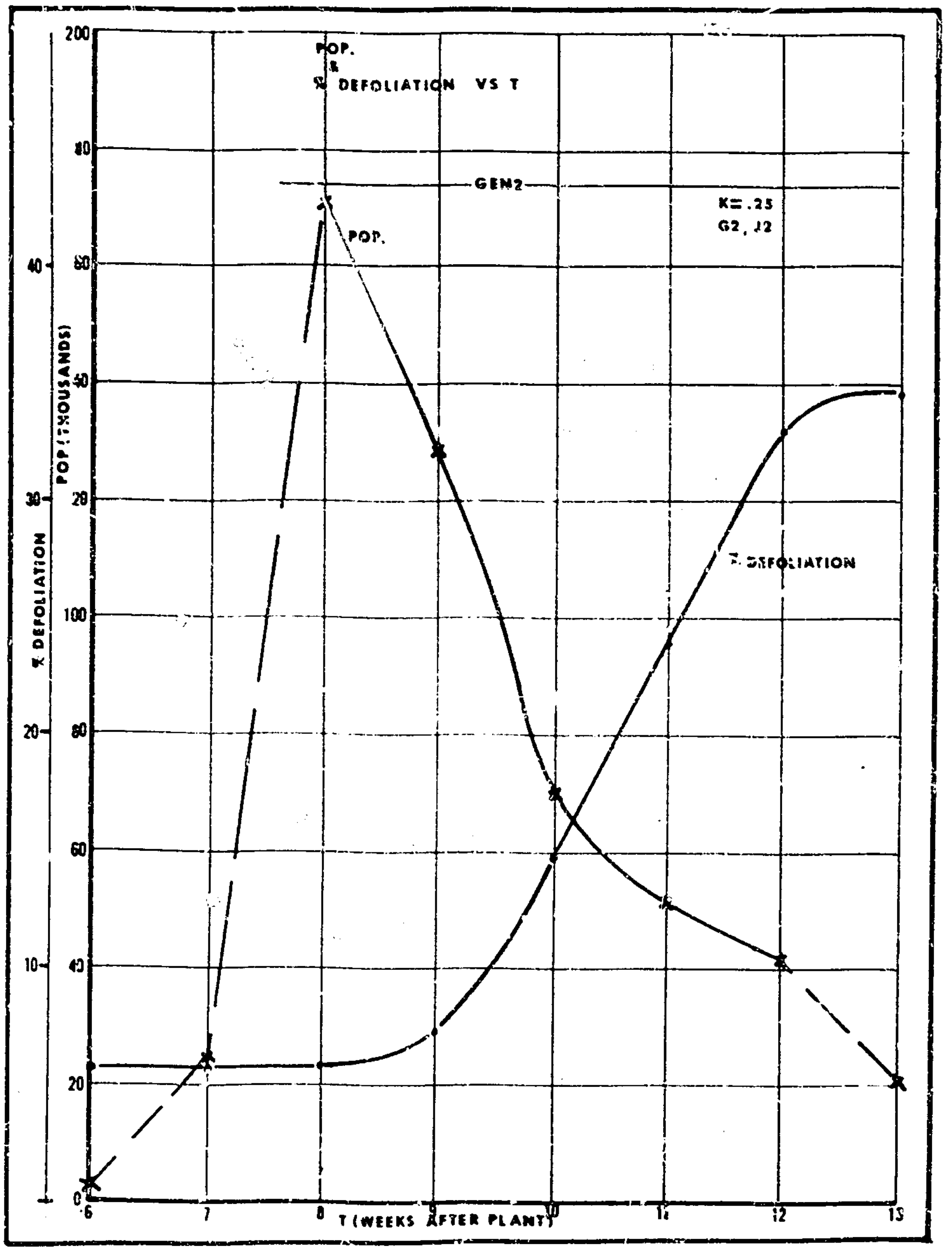
ANOVA - At Potset

Source of Variation	Degrees of Freedom	Sums of Squares	Mean Squares	F	F_{sig}
j	2	532.08	266.04	2.9	$F_{.05}=3.32$
G	2	672.06	336.03	3.7	$F_{.05}=3.32$*
k	1	800.89	800.89	8.72	$F_{.01}=7.56$**
Error	30	2752.5	91.8		

Table 4

ANOVA - At Podfill

Source of Variation	Degrees of Freedom	Sums of Squares	Mean Squares	F	F_{sig}
j	2	617.9	309.0	2.33	$F_{.1}=2.52$
G	2	1098.8	549.4	4.13	$F_{.05}=3.37$*
k	1	1366.5	1366.5	10.3	$F_{.01}=7.72$**
jxG	4	634.3	158.6	1.2	not sig.
Error	26	3455.8	133.		



POP.
&
% DEFOLIATION VS T
GEN2
K= .25
G2, J2
POP.
% DEFOLIATION
% DEFOLIATION
POP (THOUSANDS)
T (WEEKS AFTER PLANT)

Figure 7

defoliation) for each cell of the experimental design at both podset (Oct. 10) and podfill (Oct. 30).

Figure 7 presents superimposed results for the variables, insect population and cumulative damage, (per cent defoliation) vs. time. The time phasing between the two response variables as well as the complex functional relationships that must relate them is clearly indicated.

Figure 6 is provided to indicate the order of magnitude of the population variances generated by the model. The data of Figure 6 were obtained in previous experiments with this model and are the results of six replicate simulations each using a different set of random number series. The 95% confidence limits are indicated by the horizontal lines bracketing the averages for the six runs. It can be noted that the spread of the 95% confidence limits is highly time dependent.

VI. Analysis and Discussion of Results

Analyses of variance for the results of the experiment are shown in Table 3 for podset and Table 4 for podfill. Both sets show consistent results implying that similar relations between k, j, and G exist at these t o points in time. There is no reason to believe the relations change at points in time between these end points.

As expected, fraction kill, k, is a highly significant factor of the experiment. Even with the minimal data of these runs, k was significant at the 1% level. The generation at which kill takes place, G, the next most important factor was significant at the 5% level. The instar at which k occurred, j, was significant at only the 10% level. It is believed that additional replications would show this factor to have a greater effect.

The experimental data were further analyzed at podfill by burying the effects of all levels of the instar and kill factors in order to determine which of the generation factor levels were significantly different. The significance of the difference between generation means was tested by the t test described below.

Mean response

G_1 kill	G_2 kill	$G_{1,2}$ kill
u1	u2	u both
37.48%	40.23%	27.38%

u = average response

n = 12 responses/column

d. of f. = 22 for any 2 column comparisons

$\hat{s}$ = estimated $\sigma_e = \sqrt{133}$ (from ANOVA)

$t = (\bar{y}_c - \bar{y}_j)/\hat{s}\sqrt{2/n}$

$= (\bar{y}_c - \bar{y}_j)/4.71$

where $\bar{y}_c$ = control column mean

$\bar{y}_j$ = test column mean

t_{crit} for $\alpha = .05$, d. of f. = 22: $t_c = 2.074$

Test 1

H_o: u_1 = u both

$t = (27.4 - 37.4)/4.71 = -2.12$

Therefore reject H_o and accept

H_1: $u_1 \neq$ u both at 95% C.L.

Therefore % defoliation for kill at both ($G_{1,2}$) is significantly lower than that for G_1 only.

Test 2

H_o: u_2 = u both

$t = (27.4 - 40.2)/4.71 = -2.72$

Therefore, reject H_o and accept

H_1: $u_2 \neq$ u both at 95% C.L.

Thus per cent defoliation for kill at $G_{1,2}$ is also significantly high- than that for G_2 only.

Test 3

H_o: $u_1 = u_2$

By inspection it can be seen that there is no significant difference between per cent defoliation for G_1 and G_2.

This series of tests appears to indicate that a one time kill is equally effective at either generation one or generation two. As anticipated, a kill applied in both generations results in significantly lower defoliation than a one time kill.

A similar set of tests was made by burying the effects of all levels of the kill and generation factors and comparing mean response for the instars to detect significant instar levels.

Mean response

j = 2	j = 4	j = 6
uj2	uj4	uj6
30.12%	34.71%	40.25%

u = average response

n = 12 responses/column

d. of f. = 22 for any 2 column comparison

t_{crit} for $\alpha = .05$, d. of f. = 22: $t_c = 2.074$

Test 4

H_o: uj4 = uj2

$t = (30.1 - 34.4)/4.71 = -.98$

Therefore accept H_o at 95% C.L.

Therefore there is no significant difference in the effects of instars 2 and 4 upon per cent defoliation.

Test 5

H_o: uj6 = uj2

$t = (30.1 - 40.2)/4.71 = -2.14$

Therefore, reject H_o and accept

H_1: uj6 ≠ uj2 at 95% C.L.

Therefore per cent defoliation caused by a fixed k at instar 6 is significantly higher than that for the same k at instar 2 or 4.

In summary, the two sets of tests reported above indicate:

A. A one time fixed-fraction kill, induced at the same instar in either the first or second generation, is equally effective in controlling per cent defoliation that occurs during the second generation.

B. Early instars (2 through 4) are preferred for application of the induced kill.

C. Kills at both generations, at the same instar, are more effective in minimizing per cent defoliation than one generation kills.

Reference to Figure 6 shows that the second generation population of the VBC is about an order of magnitude larger than that of the first generation. Assume, as a first approximation, that the amount of the factor inducing the kill is proportional to the number of caterpillars to be killed. The fixed fraction kill at the second generation will then require an order of magnitude greater amount of the kill factor, be it insecticide, predator, parasite, etc., than that for the same fraction kill at the first generation. Thus, result A above must be modified to indicate that generation one is preferred in view of the original objective to keep the amount of kill factor at a minimum.

VIII - Conclusions

The above analyses suggest the following biological control strategies should be investigated in the real life situation.

1 - Apply kill factor early in the first generation. This implies a payoff exists for emphasizing early detection of the first generation larvae.

2 - A period of about two weeks is available during each generation's life cycle (Result B above) in which the strategy of 1 above can be used. That is make haste slowly; time is available for careful planning for the most useful strategy.

3 - If the early instars of the first generation are undetected, concentrate on the early instars of the second generation. (The last instars in any generation of the VBC are nearly impossible to kill, per the practicing entomologists). The penalty for having to use this approach is a large increase in the amount of kill factor employed during the favorable two week period.

One has indeed been able to identify viable biological strategies by analysis of the results of a designed experiment for the simulation model. The relative factor effects of instar (j), fixed faction kill (k), and generation (G) at which the kill is induced have been evaluated.

The results of this experiment suggest that future experiments should include fraction kills at the egg stage. Should the egg fraction kill be signicantly effective, experimental efforts on pest controls by specific parasites and predators should be increased. It is anticipated that future research will extend the model design to include environmental effects, pest-predator-parasite-fungi relations, economic damage caused by multiple pests, and consideration of pollution or poisoning effects of alternate management strategies.

IX - Technical Note

Average cost/simulation run = $15. (IBM 360/65).

X - Acknowledgements

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