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SYSTEMS ANALYSIS FOR INTEGRATED MANAGEMENT OF FOUR MAJOR POTATO PESTS

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SYSTEMS ANALYSIS FOR INTEGRATED MANAGEMENT OF FOUR MAJOR POTATO PESTS

By
G.S. Farmer, G.B. White, and D.A. Haith*

INTRODUCTION

Systems analysis is a structured approach to problem solving which involves (Churchman, 1968) the following:

1. definition of a set of objectives and a physical and/or biological system relevant to the problem;

2. development and evaluation of alternatives to accomplish problem objectives; and

3. selection of an alternative which best meets the objectives.

Systems analysis requires a very specific and usually quantitative statement of problem characteristics. Mathematical models of the system are used to develop and evaluate alternatives; identification of the best alternative is facilitated by optimization techniques (Haith, 1982).

The initial step in the systems approach to pest management requires definition of a problem statement and objectives. Mathematical models must then be developed or adapted for various components of the system. Identification of management alternatives is also important in the early stages.

PROBLEM STATEMENT

While formulating a problem statement we carefully considered the number of pests which could feasibly be studied at one time. Although there are many pests which could be included in a systems study on potatoes, we decided on four which are of major concern to New York growers: Colorado potato beetle (CPB), late blight, early blight, and the golden nematode (GN). Crop losses from each of these pests can range up to 100 percent (White and Lazarus, 1986).

In addition to the economic losses caused by these four pests, a second reason for choosing them is the manner in which control measures chosen to manage one impinge upon the success of managing the others. Some fungicides control both late blight and early blight; others are selective. Timing of pesticide applications for late blight need to be planned with the requirements of early blight and CPB control in mind. Fungicide application for the foliage diseases may harm fungi which can be used for biological control of the CPB. Cultivars which are resistant to the golden nematode are generally not resistant to early and late blight. The complexities of these interactions provide the opportunity to demonstrate the value of a systems approach in making management decisions.

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Although there are some pests which may be more significant in some areas of the Northeast than the four which we chose, other factors influenced our decision. For example, the green peach aphid (GPA) is especially important because it not only inflicts damage directly by feeding but also serves as a vector for numerous plant viruses. However, the GPA is of primary concern to the seed potato industry since seed potatoes must be certified free of disease. Furthermore, since the GPA feeds by sucking out juices the damage is of an entirely different nature than the defoliation inflicted by the CPB and to some extent by late and early blight.

The golden nematode (GN) has not been reported in any state except New York, but it was chosen for this study for a number of reasons. Foremost, its presence in New York has resulted in strict restrictions that affect most management alternatives. Moreover, the GN has the potential of inflicting great damage if allowed to spread (Spears, 1968). Thus, effective control of the GN in New York is of utmost importance to the entire potato industry since preventing its spread is beneficial to potato growers in all states.

We, therefore, formulated our problem statement as follows:

Although there are over 40 pests which attack the potato, the Colorado potato beetle, late blight, early blight and golden nematode are among the most serious in New York State. We have identified these four pests as important because control requires large amounts of pesticides, creating an economic burden on the grower and an adverse effect to the environment. For example, groundwater pollution on Long Island by pesticides such as aldicarb, carbofuran and oxamyl has resulted in the loss of their use there, severely limiting growers' ability to manage the CPB and the GN. Furthermore, sole reliance on pesticides for management often leads to pesticide resistant strains. Pest problems and the lack of effective controls have suppressed yields and increased production costs thereby contributing to the decrease in land area used for agriculture in recent years. Pest management is usually implemented on a pest-by-pest basis, ignoring the probability that the methods used to control each pest can have an impact on the means necessary to control the others, exacerbating environmental, economic and pest resistance problems.

OBJECTIVES

Most pest management systems studies have been primarily concerned with maximizing income. In addition to the economic implications of pest management alternatives, it is also important to consider the adverse effects to the environment. Since pesticide residues are becoming an increasingly serious problem in public waters, a strategy which focuses only on economics would be inappropriate if it results in unacceptable levels of pollution.

Furthermore, farmers tend to be conservative in utilizing new policies if they feel that such a policy imposes too great a risk. Thus, it does little good to convince a farmer that he can save $1000 by eliminating some questionable sprays if he feels that such a savings is small compared to the the potential for loss of a significant portion of the crop value. For this reason, one of our objectives considers aversion to risk.

Although the delay of resistance to insecticides is another important concern, we did not specifically include it as an objective. There were two reasons for this: first, resistance is difficult to quantify. Secondly, we feel that the other objectives will place a demand on the reduction of insecticides which will be effective in delaying resistance.

Thus, our objectives were formulated as follows:

The goal of this research is development of management strategies for control of Colorado potato beetle, early blight, late blight and golden nematode which are responsive to the following objectives:

1) Prevent pesticide concentrations in drainage waters from exceeding public health standards (mg/l);
2) Maximize farm income for potato growers ($);
3) Reduce risk (variance) of marketable potato yield loss (kg/ha).

SYSTEM DEFINITION

System definition involves the detailed description of problems to be solved and requires specification of system scale, components and environment. Scale includes time and space dimensions. Does the problem express itself in a minute or a month, or in an infection period of a growing season? Similarly, does the problem express itself on a leaf of a single plant or in a whole geographic region? A system component is a physical or biological entity which is (i) variable, (ii) influences management alternatives, and, (iii) affects objectives. Components depend on problem scale and might include a plant part, a whole plant, or plant populations. Related farming activities such as irrigation, fertilization and planting may be relevant system components. The system environment is the set of factors such as weather, soil type, and economic resources and conditions which influence the system, but are not directly manageable.

It appears that system definition for the potato IPM problem will require a hierarchy of three systems: the potato plant, a field of potatoes, and the potato farm. The first of these will be used to quantify the effects of pest defoliation on the yield of the plant. A potato field appears to be the appropriate vehicle for analyzing pest populations and their impacts, the pesticide content of drainage, and variations in yields and returns (risk). Finally, the total farm must be considered in order to evaluate impacts of pest control programs on farm income.

REVIEW OF MODELS

The following component models will be necessary in order to achieve these objectives: a potato growth model, pest models, pollution models and decision models. Since the potato model is central to the modeling effort, we began our study by evaluating a number of models which simulate potato growth. We reviewed five of those recently developed in order to assess potential for use in a systems analysis of pest management of potatoes. The models and their origin are as follows: Sands et al. (1979), Australia; Ingram and McCloud (1984), Florida; Ng and Loomis (1984), Idaho; Johnson et al. (1986), Minnesota and Fishman et al. (1985), Israel.

Potato Growth Models

The plant growth models reviewed range in complexity from the relatively simple Australia model which can be used on a programmable calculator to the detailed Idaho model which originally required a mainframe computer. Most of the models simulate the dry matter partitioning to four organs: leaves, stems, tubers and roots as well as tuber yield and leaf area index. Since defoliation is an important measure of pest damage, we paid special attention to canopy development. While some of the models included the effect of water stress, others assume optimal water availability. In their initial implementation all assumed an adequate nutrient supply and management of pests so that growth is optimal.

In reviewing the models we considered four general criteria: implementation (inputs, time step, scale, type of computer and outputs), model validation, applicability and limitations. Table 1 presents a summary of each model according to those criteria. In Table 2, we compared the following aspects of the applicability of the models: level of complexity, plant components modeled, whether the model considered moisture stress, and which cultivars were used for testing.

Australia Model

Sands et al. (1979) developed a simple model which describes the development of a potato crop and predicts bulking. The development of the crop is followed from planting to emergence to tuber initiation to the start of tuber growth to the attainment of maximum bulking to the cessation of bulking and attainment of tuber maturity. One of the goals in the development of the model was to compare yields for different cultivars under different management conditions.

Although the model runs on a weekly time step, growth was based on a physiological time which was dependent on maximum and minimum temperatures. The physiological time concept is often used in biological models and is similar to degree days. The physiological time developed for this model is an important contribution to the modeling of potato growth and was later used in the Minnesota model. The timing of a number of crop events based on this physiological time are required to run the model.

Unlike the other models which regulate growth by dry matter partitioning, this model is driven by a tuber bulking rate. The bulking rate and the physiological dates of the various crop events were determined statistically from experimental data. The model can be used on a pocket calculator or a microcomputer.

Validation was somewhat limited since the validation data required some adjustments in the model parameters to account for a different cultivar (Kennebec). A validation of the same cultivar (Sebago) would have been preferable since the model was designed to be nonspecific for site and season.

Since this model does not simulate leaf growth, the model would be less suitable for pest management work than those that do. Furthermore, the model does not consider irradiance, which could limit its applicability in climates such as New York's. However, the model does include a variable for management rating which can indicate the status of pest control along with other management factors.

Florida Model

The potato growth model of Ingram and McCloud (1984) simulates the crop growth and development in one day steps. The model predicts crop yield based on net rate of crop dry matter assimilation (NDMA) and the fraction of NDMA partitioned to tubers integrated from the day of tuber initiation onset to the day of tuber growth cessation.

Table 1: Summary of Potato Model Evaluations

Australia Model

SOURCE: Sands et al. (1979), Regel and Sands (1983), Hackett et al. (1979).
IMPLEMENTATION
<u>Inputs</u>: Daily min and max temps; radiation; soil water potential; timing of crop events (emergence, tuber initiation, maximum bulking, end of bulking); bulking parameter, management rating.
<u>Scale</u>: Tuber development in plant;
<u>Timestep</u>: week;
<u>Outputs</u>: yield (g/plant);
<u>Computer</u>: microcomputer or pocket calculator;
LIMITATIONS: Doesn't model canopy;
APPLICABILITY: Prediction of tuber development for given planting time and weather conditions;
VALIDATION: Verified initially with 3 years of data from 2 Sebago crops and later with a crop of Kennebec. Parameters were derived statistically from collective data for each cultivar.

Florida Model

SOURCE: Ingram and McCloud (1984)
IMPLEMENTATION
<u>Inputs</u>: Daily mean air and soil temps; radiation; seed piece size; growth rates for canopy, root and tuber;
<u>Scale</u>: Development of canopy, tubers and roots of crop;
<u>Timestep</u>: Daily;
<u>Outputs</u>: DW/m^2 of tuber, canopy and roots; time of tuber initiation onset (TIO) and end of tuber growth;
<u>Computer</u>: Not specified;
LIMITATIONS: Doesn't consider effects of water stress;
APPLICABILITY: Predict effect of temp on crop development;
VALIDATION: Validated with two Sebago crops. Parameters derived from greenhouse experiments.

Idaho Model

SOURCE: Ng and Loomis, (1984)
IMPLEMENTATION
<u>Inputs</u>: Ave. daily temp and temp amplitude; dewpoint temp; radiation; windrun; leaf and branch initation rates; growth parameters;
<u>Scale</u>: development of leaves, stems, roots and tubers on organ level for whole plant in plant community;
<u>Timestep</u>: hourly;
<u>Outputs</u>: g dw/m^2 of leaves, stems, roots and tubers; leaf area index;
<u>Computer</u>: Main frame (microcomputer version developed at Cornell);
LIMITATIONS: Requires many physiological parameters which may be difficult to obtain for other cultivars. Doesn't consider water stress. More time consuming to run;
APPLICABILITY: Detailed study of physiological processes as affected by weather and management strategies and could be adapted for defoliation.
VALIDATION: Validated with 2 locations of Russet Burbank. Parameters derived from literature and some experimental data.

Table 1: Summary of Potato Model Evaluations (continued)

Israel Model

SOURCE: Fishman et al. (1984); Fishman et al. (1985)
IMPLEMENTATION
  Inputs: Hourly radiation; daily max and min temp, pan evap; partitioning coefficients, plant density;
  Scale: development of leaves, tubers, stems and roots in plant community;
  Timestep: daily (hourly for some subroutines);
  Outputs: dw of leaves, stems, roots, tubers (kg DM/1000 m^2); Leaf area index;
  Computer: Main frame. (Microcomputer version developed at Cornell);
LIMITATIONS: No apparent limitations;
APPLICABILITY: Predict yield and canopy development under water stress and might be adapted to include defoliation;
VALIDATION: Yes, Desiree'. Parameters derived numerically from data of spring crop and then used again on fall crop for validation.

Minnesota Model

SOURCE: Johnson et al. (1986)
IMPLEMENTATION
  Inputs: Daily min and max temps, radiation, soil water potential. Plant density, fresh to dry weight conversion, dates for emergence, tuber initiation, and leaf senescence. Partitioning parameters;
  Scale: Development of leaves, tubers, stems and roots on whole plant;
  Timestep: daily;
  Outputs: yield (kg/ha); kg DW/plant of leaves, stems, tubers and roots; leaf area index;
  Computer: Cyber 840 (microcomputer version developed at Cornell);
LIMITATIONS: No apparent limitations;
APPLICABILITY: Predicts actual yields along with canopy development and could be used to study effects of defoliation and/or water stress on crop development;
VALIDATION: Verified with 2 years each of Russet burbank and Norland. Parameters derived for each cultivar by trial and error from data of both years.

Table 2: Comparison of Five Potato Growth Models

Model Source	Complexity	Plant Component Modeled	Water Stress Function(?)	Cultivar
Australia (Sands et al., 1979)	1	T	+	SB,K
Florida (Ingram/McCloud, 1984)	2	T,C,R	-	SB
Minnesota (Johnson et al., 1986)	3	T,L,S,R	+	RB,NL
Israel (Fishman et al., 1984)	4	T,L,S,R	+	D
Idaho (Ng/Loomis, 1984)	5	T,L,S,R	-	RB

Key: (1=simple...5=complex)
T=tubers, C=canopy, S=stems, L=leaves, R=roots;
SB=Sebago, RB=Russet Burbank, D=Desiree, NL=Norland, K=Kennebec

By using net assimilation, the model assumes adequate substrates are available for maintenance respiration. Partitioning of available substrates among the sinks was determined from temperature effects on growth rates, ontogeny and organ priority. The model set partitioning boundaries rather than firm partitioning coefficients.

Crop growth and development are computed from the climatic inputs and crop growth rates. The crop growth rates were determined experimentally and the resultant temperature response curves were incorporated into the model. The model assumes optimal soil moisture.

Simulated outputs include tuber initiation onset, tuber growth cessation, and dry weights of seed pieces, roots, canopy, tubers and total plant. The model was validated with field data of the cultivar Sebago. Although this model appears to require less input parameters than some of the others, the response curves for the partitioning would need to be established for different cultivars.

Idaho Model

The POTATO model of Ng and Loomis (1984) contains a high degree of physiological and morphological detail. The model operates on an hourly time step, simulating the growth of leaves, stem, tubers and roots.

The state variables include carbohydrate reserve status of the plant; the water content of the plant; and the number, age, dry weight and physical dimensions of each organ. Physiological inputs which are built into the model are: response functions for the effect of temperature on photosynthesis, effect of reserve water content of plant on leaf growth, effect of assimilated supply on tuber growth, effect of age on fraction capable of growth and the constants for leaf initiation rate, branch initiation rate and specific leaf area. These functions and their parameters were taken from numerous literature sources and from greenhouse and field experiments.

The input data is the basis for the definition of canopy and soil climate. From that, the state variables are updated. First, the transpiration and soil moisture uptake rates are calculated. Gross photosynthesis is calculated next. Rates of change of the state variables associated with each organ and the maintenance and growth rates are then calculated followed by the rate of change in the plant assimilate pool. The state variables are updated again and are advanced through the season in hourly time steps.

The model is structured to include plant community, whole-plant and organ-level variables with interlevel feedback integrating the effects of each level.

The model was calibrated with data from Russet Burbank potatoes and then validated using the same physiological parameters to predict a crop of the same cultivar in a different location. The simulated values satisfactorily agreed with the experimental data.

While the high degree of detail in this model makes it an excellent tool for studying physiological questions, it may be unnecessary for a pest management study. A limitation of the model is the difficulty involved in obtaining all the required parameters which would be necessary for a change of cultivar.

Israel Model

Fishman et al. (1984, 1985) designed a phenomenological model of dry matter partitioning dynamics for potato growth. The plant community level model was designed to predict crop production as affected by meteorological and managerial events.

The model considers only the growth phase when the plant receives all needed substances from the environment while the period of growth that is dependent on the mother tuber is assumed as a given condition.

Daily dry matter produced in the leaves by photosynthesis is distributed among the leaves, stems, tubers and roots and is calculated hourly. Partitioning parameters for each organ along with a coefficient of aging and a proportionality constant were estimated by fitting the numerical solution of a set of differential equations to the field data.

The model was run for the cultivar Desiree and the predicted dry weight for each of the organs was in good agreement with field observations. The model was validated with data from a second season crop of the same cultivar.

Minnesota Model

A simple whole-plant level potato growth model was developed by Johnson et al. (1986). This Minnesota model accumulates and partitions dry matter into four state variables: leaves, stems, roots and tubers. Crop events included as input are given in terms of the physiological age derived from Sands et al. (1979). The model is very sensitive to errors in the times of tuber initiation and 50 percent emergence.

The model was verified with two different cultivars, Norland and Russet Burbank. The partitioning parameters were empirically determined using nonlinear iterative procedures from two years of data for each cultivar. The model predicted yields reasonably well. Each cultivar was simulated for two different years using the same agronomic parameters for that particular cultivar in both years.

The model was also used to estimate yield losses due to varying levels of single event defoliation at various times during the season. Defoliation was varied from 10 to 90 percent and each level was inflicted once in the season at times ranging from time of emergence to the maximum physiological age. The modeled plant was more sensitive to defoliation during midseason. Although there was no validation of the defoliation simulation, the result paralleled those found in a study of Colorado potato beetle defoliation (Hare, 1980). However, this type of single event defoliation is unrealistic since the damage caused by pests is a gradual, continuous process.

Conclusion

Although all of the models adequately described potato growth, two of the models were judged to be the most promising for use in a pest management study, the Minnesota model and the Israel model. The Minnesota model has been tested on two different cultivars, Norland and Russet Burbank. We adapted this model to a microcomputer and tested it on local crops of these same two cultivars along with a crop of Norchip with encouraging results. Dr. Elmer Ewing and associates in the Vegetable Crops Department at Cornell are currently adapting the Israel model to different cultivars and local conditions. Preliminary results of this study have also been encouraging. Progress also continues in that department on the adaptation of the Idaho model to a microcomputer for different cultivars and local conditions. This model will be useful as an analytical tool to investigate questions for which the simpler models are inadequate.

Before any of the models can be used for pest management decisions, however, a validated defoliation subroutine must be incorporated. This may involve extensive work.

The initial attempts of Ewing and associates to incorporate defoliation into the Idaho model found that leaf compensatory growth complicates the problem (personal communication). Elkinton, Ferro and Ng (1985) also adapted the model for defoliation. With their modified model, defoliation which occurred later than 15 days after emergence produced an increase in tuber production. We were not able to duplicate these results and suspect that Elkinton et al. failed to adjust the code correctly. For example, it is easy to overlook the need to reduce the assimilate pool and the water content by the amounts present in the leaf tissue removed during defoliation. Failure to account for the water or the assimilate will lead to overprediction of tuber yields following defoliation. Although some researchers have found that low levels of defoliation can produce a slight increase in yield early in the season, late season defoliation at high levels leads to pronounced yield reductions (Shields and Wyman, 1984).

Although the limited testing of the Minnesota model with defoliation appeared to be successful, it needs further testing with a more realistic type of defoliation. A single event defoliation is unrealistic compared to the gradual continuous defoliation which results in the field from insect consumption.

Defoliation research (Hare, 1980; Wellik et al., 1981; Ferro et al. 1983; Cranshaw, 1980; Shields and Wyman, 1984) has focused on one-time defoliation and therefore could not be used for validation of a model which simulates defoliation similar to the type inflicted by pests. Thus, extensive defoliation experimentation will be required in order to validate a model which incorporates defoliation.

Pest Models

Colorado Potato Beetle

In attempting to evaluate pest models, we were somewhat surprised that there were so few in existence. We found no suitable model for the Colorado potato beetle. The only working model of the CPB reported in the literature is a simple population prediction model by Logan and Casagrande (1980) based on degree days. The model predicts CPB density based on degree days and initial density. The model requires growth rate coefficients which depend on field history, infestation and management practices. A limitation of this model is that it was developed from data from only one variety (Superior) and for one generation (Ferro et al. 1983). Furthermore, we discussed the model with Logan and he advised against using it.

LIFE CYCLE OF CPB - There has been, however, much research on various phases of the insect's life cycle. Harcourt (1971) studied the population dynamics of CPB in Ontario to determine which stage in the life cycle contributes most strongly to the population trends. His analysis showed that the summer adult survival has the greatest influence on populations. Since the pest has no density related mechanism to regulate population for conservation of food, a food resource is usually depleted followed by starvation of the larvae and migration of the adults. He concluded that migration may be regarded as the principal factor for numerical change of population from generation to generation. He developed a logarithmic equation relating the number of spring adults to the number of eggs deposited. This equation, however, was based on observations of one generation/season population and therefore could not be applied to areas such as New York that have multiple generations per season.

Lansky (1984) studied diapause induction, diapause maintenance, end of diapause and the relationship between temperature and the rate of post diapause development for CPB living on Long Island. He found that 147.4 degree days above a threshold of 11.6° C are required for oviposition to begin. Furthermore, the critical photoperiod for diapause was found to be LD 15:9 which occurs in early August on Long Island. Less than fifty percent oviposition occurs following that period. This kind of information could be useful in planning spray schedules.

Lashomb et al. (1984) showed that emergence of CPBs can be predicted by use of accumulated degree days. Emergence was related to degree days by an exponentional equation. Although this equation overestimates emergence up to 15 percent, it fit the data reasonably well for the remainder of emergence. The equation could be used to determine the best time to begin scouting for the insect although these results could only be applied where soil types and weather conditions are similar to those in New Jersey.

CONSUMPTION RATES OF CPB - Although we have not identified an appropriate model for the CPB, we have found extensive literature on the effects of temperature on consumption rates and of defoliation on yield. Grison (1950) observed the effect of temperature on the consumption rate of adult beetles.

He found that consumption increased as temperature increased up to 25°C and then fell at higher temperatures. May (1980) was able to show a logarithmic effect of temperatures between 14 and 25°C on Grison's observed consumption rates.

In Chlodny's 1975 study of the bioenergetics of larval development of the CPB, he measured the consumption patterns of each instar at temperatures ranging from 15 to 30°C. He found that consumption varies with temperature and peaks at around 25°C.

A study by Tamaki and Butt (1978) measured the amount of defoliation afflicted by different life stages of CPB at an average temperature of 24°C (±7).

To correlate leaf feeding to temperature, Ferro et al. (1985) derived a set of least square polynomials based on laboratory studies at temperatures ranging from 12 to 33°C. Equations were developed for the second, third and fourth instars and adult.

Logan et al. (1985) also observed the leaf feeding of the four larval stages. He measured consumption and also calculated leaf shrinkage daily. Leaf shrinkage was correlated to temperature with an exponential relationship.

Results of the different studies are summarized in Table 3 which lists the total leaf consumption during each life stage for comparable temperatures. Figure 1 graphically compares the temperature effect on adult rates.

Table 3: Defoliation Rates of CPB Life Stages at 24 or 25°C

Stage	Average leaf area consumed--cm^2/day			
	Tamaki (24C)	Ferro (25C)	Logan (24C)	Grison (25C)
1st instar	0.65	0.9	0.63	*
2nd instar	1.61	1.8	1.55	*
3rd instar	5.17	8.4	6.14	*
4th instar	19.67	29.5	29.85	*
Adult	6.87	9.65	*	8.00

*None given

EFFECT OF DEFOLIATION ON YIELD - Several recent studies on defoliation have found that yields are most significantly affected during certain growth stages. Cranshaw and Radcliffe (1980) found that plants generally recovered from early season defoliation of up to 33 percent while severe defoliation of 67 percent at this stage resulted in only slight yield reductions. Midseason defoliation produced the greatest yield reductions. They also concluded that the factors which are more apt to increase severity of yield loss due to defoliators are early maturity, injury to top leaves, injury to lower leaves during mid-season and non-uniform plant injury. Defoliation in this study was simulated by cutting the leaves and four cultivars were included in the study.

The study by Hare (1980) was the only defoliation study which observed the defoliation of actual insects. His findings, however, were similar to the simulated tests. He found that yields were mainly affected during the middle 4-6 week period of the season. Yield reduction from defoliation during that period was found to be as high as 64 percent for total defoliation. The critical period during which potatoes are most severely affected by defoliation corresponds with the emergence and oviposition by summer generation adults. Since there does not appear to be a correlation between levels of defoliation and yield during the last month of the season, they questioned the value of insecticide applications at that time.

Defoliation up to 29 percent was found to have little effect on yields by Wellik et al. (1983). In this study defoliation was simulated by using a punch. They found that 58 percent significantly reduced yields. When the effects of 100 percent defoliation were observed over a period of time, it was found that the plants were most sensitive during the 3-5 week period after 50 percent emergence. These studies were conducted on the early maturing variety Superior.

Ferro et al. (1983) developed a data base to determine the economic injury levels and economic threshold levels for CPB on the early season variety 'Superior'. These data could not be used for other varieties, especially late season cultivars which would be subject to an attack by a third generation of insects. However, these results further confirm the relationship between the effect of defoliation of the potato plant and the growth stage. Their results indicated that the potato plant can withstand some defoliation without affecting production and that late season spraying to control CPB is not economically justified.

Shields and Wyman (1984) simulated the effect of defoliation of CPB and cutworm by cutting off the leaves of upper and lower leaves respectively. Superior and Russet Burbank cultivar were defoliated at levels of 10 to 75 percent during four and five different plant growth stages. Defoliation of the upper leaves greater than 10 percent during full bloom was found to significantly reduce yield for both varieties. Defoliation earlier and later in the season had lesser effects. Defoliation thresholds were proposed according to growth stage and are shown in Table 4 for lower leaves.

Figure 1. Adult CPB Consumption Rates

From Tamaki, Grison and Ferro

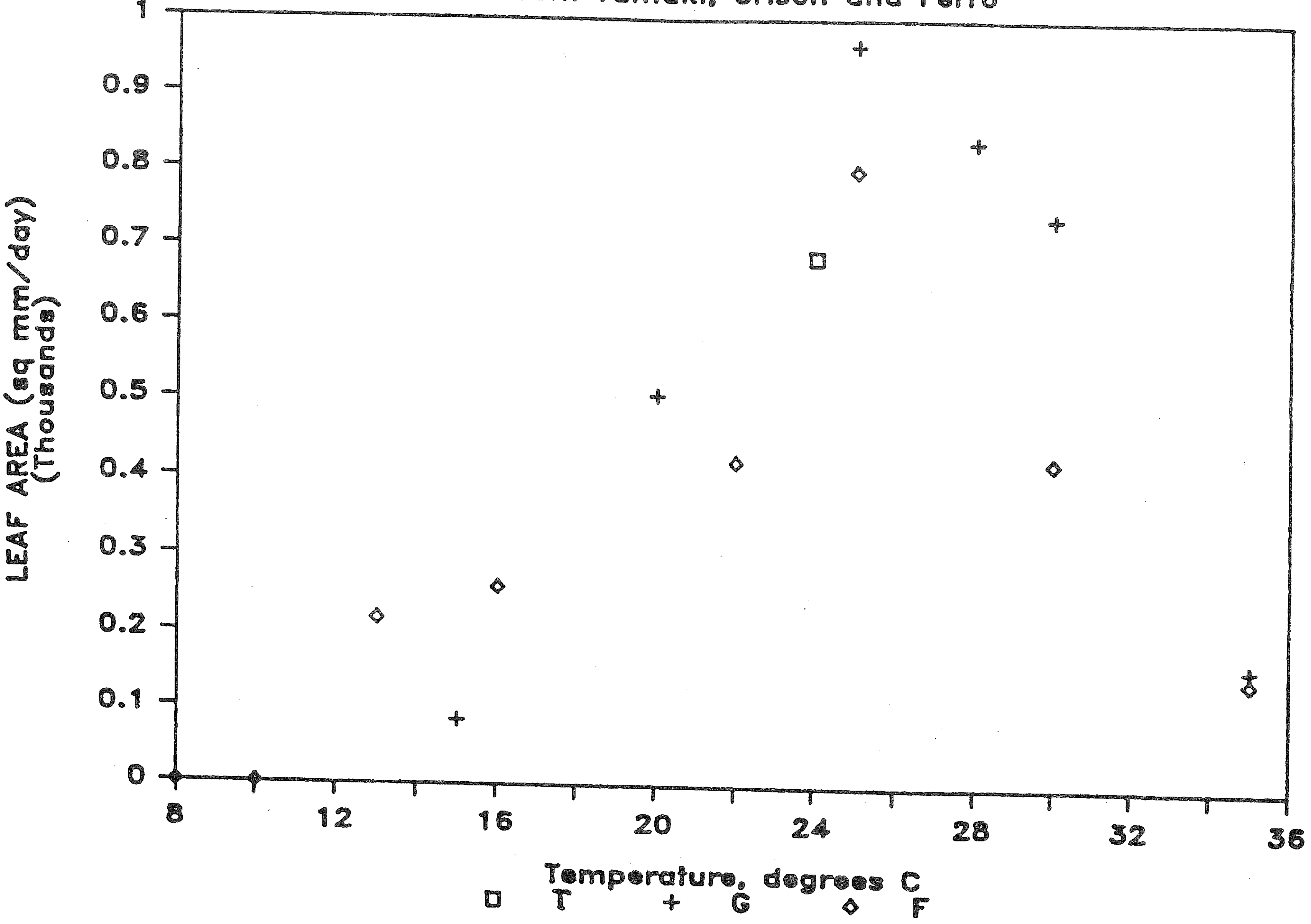

Table 4: Defoliation Thresholds for Various Potato Growth Stages of Two Cultivars*

Plant growth stage	Approximate p-age (p-days**)	Avg. total leaf area (cm^2)	Defoliation threshold percent	Allowable leaf area loss (cm^2)
Superior				
15-20 cm	65	1107 ± 670	75	830
30-40 cm	160	3868 ± 1318	25	967
Full bloom	225	5741 ± 656	10	574
Full grown	350	9719 ± 747	75	7289
Russet Burbank				
15-20 cm	65	744 ± 330	50	372
30-40 cm	160	2025 ± 185	25	506
Full bloom	350	12812 ± 3148	10	1281
Full grown	450	7511 ± 712	25	1877
Maturity	615	6141 ± 288	75	4605

*Adapted from Shields and Wyman (1984)
**p-days based on Sands et al. (1979)

Although there is currently no model of the life cycle of the Colorado potato beetle, most of the necessary components have been studied. The job of putting them together into a suitable simulation model is of utmost importance. In order to realistically incorporate the effects of this pest on potato yield, it will be necessary to have an adequate model of both the plant and the pest.

There is an alternative strategy which can be considered until such models are developed. Since feeding rates have been fairly well established, a plant model could incorporate insect counts and feeding rates into a defoliation subroutine. This approach is similar to that of Gutierrez et al. (1975) which evaluated the effects of defoliators on cotton yield in California without a pest model.

Late Blight

There are three late blight simulators described in the literature. The earliest one, developed by Waggoner (1968), was a crude Fortran simulator which predicted spread of the fungus based on weather conditions and initial infestations. This model was later adapted (Waggoner, 1974) to provide for the characterization of a fungicide as well as for the race and variety of the host. The second version was written in the computer simulation language CSMP. Although the model was tested and shown to mimic the spread of an epidemic, there was no report of validation with actual field data. Furthermore, even though the model was developed over ten years ago, there have been no reported attempts to use it for any real applications for pest management.

Bruhn and Fry (1981) developed a more sophisticated model which simulated the effects of weather variability, host resistance and management activities on the development of late blight. The model was tested with weather data from 1977 and successfully predicted the disease progress curves for four cultivars. Four statistics were used to compare the disease progress curves: apparent infection rate, area under the disease progress curve, the number of days after inoculation until foliage was 50 percent blighted and the final level of disease. The model also predicts yield loss, marketable yield loss and number of sprays.

The model has also been used to test a number of pest management strategies. Fohner et al. (1984) used the model to compare the economics of the Blitecast forecasting system against the traditional grower practice of regular interval spraying for potatoes in New York. This same model was later linked with weather simulation and fungicide deposition models by Fry et al. (1983). The simulation showed that the adjustment of fungicide application frequency to complement host resistance always permitted a reduction in the number of fungicide applications. Spadafora et al. (1984) similarly utilized the model with different fungicides.

The model has been adapted to a microcomputer in the language C. The current version gives three options for scheduling sprays: regular interval, according to Blitecast, and according to Frycast (a modification of Blitecast which incorporates host resistance and fungicide effects).

A late blight model developed by Michaelides (1985) simulates the growth of the fungal spores as affected by weather conditions. Unlike the other two late blight simulators, this model includes the effect of wind speed for spore dispersal. The model predicts the progress of the epidemic in terms of the number of new infections and lesions formed per day as well as totals of both. Although the model has not been field tested, a number of simulations were performed varying environmental inputs such as temperature, wind speed and relative humidity. These tests found the behavior of the model to be realistic. For example, the time predicted for total defoliation under optimal environmental conditions was in line with that reported in the literature.

A comparison of the late blight models using the same criteria on which we evaluated the potato growth models can be found in Table 5. The model of Bruhn and Fry has been well validated and extensively tested. Furthermore, the model was designed for the evaluation of pest management alternatives while the other two seem to be primarily concerned with the biology of epidemics. Therefore, this model is the most suitable late blight simulator.

Table 5: Summary of Late Blight Model Evaluations

Waggoner

SOURCE: Waggoner, 1968,1974.
IMPLEMENTATION
- Inputs: temperature, relative humidity, wet or dry?, initial infection, disease progress rate, fungicide properties.
- Scale: ha.
- Timestep: 3 hr.
- Outputs: lesions/ha;spores/ha;zoospores/ha;incubating infections/ha.
- Computer: mainframe (CSMP).

LIMITATIONS: not field tested;does not simulate production of initial inoculum.
APPLICABILITY: used for comparing epidemics under different environmental conditions.
VALIDATION: never tested with actual field data.

Bruhn and Fry Model

SOURCE: Bruhn and Fry, 1981.
IMPLEMENTATION
- Inputs: Daily ave temperature, hours of RH>90%, rainfall, ave. temp during periods of RH>90.
- Scale: field.
- Timestep: daily.
- Outputs: infection, area under disease curve, # of days until 50% is blighted, final level of disease, yield loss, marketable yield loss.
- Computer: microcomputer.

LIMITATIONS: does not simulate production of initial inoculum.
APPLICABILITY: used for comparing effectiveness of different spray strategies.
VALIDATION: Validated with field data for four cultivars: Monona, Kennebec, Katahdin and Rosa.

Michaelides

SOURCE: Michaelides, 1985.
IMPLEMENTATION
- Inputs: dry and wet bulb temperatures, wind speed, rainfall: recorded every 3 hr.
- Scale: 1 km^2.
- Timestep: 3 hr.
- Outputs: # of new infections and lesions/day; total # of new infections and lesions.
- Computer: not given.

LIMITATIONS: has not been sufficiently validated.
APPLICABILITY: used for comparing effects of environmental conditions on epidemics.

VALIDATION: not tested with field data.

Early Blight

Waggoner and Horsfall (1969) developed an early blight simulator which helped explain the conditions under which early blight can become epidemic. The simulator, EPIDEM, predicts the severity of early blight in terms of the number of lesions per initial lesions. The model requires daily temperature, relative humidity and windspeed as inputs along with an indication of whether the day was sunny or wet. Initial number and size of lesions must also be given. EPIDEM calculates the number of lesions propagated every three hours based on these initial inputs. The model was validated with two years of data of early blight on tomatoes but has not been validated for potatoes. Although the validation showed that the model can predict the relative severity of the disease between years, it did not show that the model can accurately simulate the actual progress of the disease.

Work is currently underway in the Plant Pathology Department at Cornell University by Fry and associates to develop an early blight simulator which considers the effect of weather, host resistance and fungicide application. This model is in the testing stage. Since the model of Waggoner and Horsfall has not been shown to simulate the actual progress of the disease, we will not make a decision on an early blight simulator until the new model has been validated.

Golden Nematode

The Federal Golden Nematode Control Project was instituted in 1946 and provided for systematic sampling of potato fields for the pest. Fields are surveyed and if a field is found to contain the pest, it is placed under regulation. In New York, fields under regulation must follow the guidelines set forth by the New York State Department of Agriculture and Markets. The most recent regulations give the grower the following options (Moyer, 1984b):

1. Grow a crop that is not a host of the golden nematode;
2. Grow a golden nematode resistant potato variety;
3. Any combination of 1 and 2;
4. If a grower is willing to commit 100 percent of his acreage including those not currently under regulation, the following four year rotation can be used:
   Year 1 Resistant variety
   Year 2 Resistant variety
   Year 3 Non host crop
   Year 4 Susceptible variety.

The pest is at a detectable level by soil sampling before there are any plant symptoms and long before there is any damage to the crop (Spears, 1968). Thus, since controls are imposed before the pest is at a serious level, there is less to model the pests development. Fields which are under regulation will have fewer management alternatives than fields which are not.

Although a model of the Golden Nematode is less important because of the controls, a simple model of population could be useful for determining the effectiveness of the regulations. LaMondia and Brodie (1986) studied the effect of initial nematode density on the population dynamics of the golden nematode for both resistant and susceptible cultivars. The initial densities were at lower levels than those which are normally associated with economic loss since it is at the lower levels that controls are imposed. From the populations observed, they developed regression equations which related the final density to the initial density in a logarithmic equation for each type of cultivar.

The population density (Spears, 1968) in these equations is given in eggs/cu cm soil. The Golden Nematode Handbook lists populations at which the nematode is detectable and at damaging levels but these populations are given in the units viable cysts/acre. These units are not compatible and thus can not be compared. However, LaMondia (personal communication) estimates detectable levels to be in the range of 2-20 eggs/cu cm and damaging levels to be 20 eggs/cu cm for Long Island and 100 cysts/cu cm for Upstate New York.

With these figures as guidelines, we used the equations in a simple simulation to test the effect of various rotation schemes on the control of populations. We found that a rotation of two years of a resistant cultivar followed by one year of a susceptible cultivar were sufficient to control detectable populations but a one year rotation is not. A similar simulation for the rotation plan in Option 4 (two years resistant cultivar, one year non-host crop and one year susceptible cultivar) was similarly verified as more than sufficient to control golden nematode populations. In this second simulation, non-host crops were assumed to reduce populations to 40 percent regardless of initial density (LaMondia, personnel communication).

LaMondia (personal communication) is currently attempting to refine these limits. The simulation we attempted will undoubtedly be improved when these densities are adequately defined.

Pollution Models

Water pollution from pesticides can occur in the surface waters from run-off and also in ground water by leaching. A number of mathematical models are available which describe the behavior of pesticides in the agroecosystem. Some models predict percolation of pesticides into the ground water while others predict pesticide in runoff and there are models which predict pesticide losses in both leaching and runoff. A summary of the models reviewed is shown in Table 6.

Table 6: Summary of Pollution Model Evaluations

Haith

SOURCE: Haith, 1980.
IMPLEMENTATION
Inputs: pesticide decay rate and partitioning coefficients and application rate; parameters for USLE and Curve Nos.; rainfall totals and duration; soil density; field area.
Scale: field.
Timestep: daily.
Outputs: dissolved and solid pesticide in runoff (g/ha/day)
Computer: microcomputer.
LIMITATIONS: provides only upper bounds on pesticide loss.
APPLICABILITY: used for water quality and screening for pesticide in runoff.
VALIDATION: validated with 3 years of field data for atrazine.

Enfield et al. (Model 2).

SOURCE: Enfield et al., 1982.
IMPLEMENTATION
Inputs: bulk density and m.c. of soil; sorption coefficients; degradation rate, solubility and application rates of pesticide; monthly precipitation, evapotranspiration, irrigation, runoff; dispersion coefficient.
Scale: field;
Timestep: monthly;
Outputs: concentration of pesticide in soil profile to depths of 300 cm.
Computer: not given
LIMITATIONS: assumes sorption is a linear function
APPLICABILITY: used for determining the potential hazard of nonionic organics in groundwater.
VALIDATION: Validated with field data for aldicarb and DDT.

CTOP

SOURCE: Lindner, 1985.
IMPLEMENTATION
Inputs: meteorological, cropping data; parameters for erosion, runoff and pesticides.
Scale: field.
Timestep: daily.
Outputs: pesticide concentration in soil profile to depths up to 200 cm.
Computer: not given.
LIMITATIONS: substantial input requirements.
APPLICABILITY: used to estimate the pesticide fluxes into ground water.
VALIDATION: validated with 3 yrs of field data for aldicarb.

TABLE 6 (continued): Summary of Pollution Model Evaluations

MOUSE

SOURCE: Steenhuis et al. 1984.

IMPLEMENTATION

Inputs: ave. monthly precipitation and ave. days/mo. with precipication > 0.25 mm. and ave. monthly temperatures for January and July; adsorption parameters for root and lower transmission zones; characteristics of aquifer; chem. degradation and adsorption characteristics; potential evapotranspiration; soil hydrological parameters; application data and incorporation depth.

Scale: field.

Timestep: daily.

Outputs: daily precipitation, ave. air and soil temperatures; amount of infiltraton, percolation, recharge and pesticide to ground water; solute concentration over time and along flow path.

Computer: microcomputer.

LIMITATIONS: restricted to use for training and management decisions.

APPLICABILITY: screening pesticides for ground water pollution under different environmental and management conditions.

VALIDATION: each of four submodels was validated with field data.

CREAMS

SOURCE: Knisel et al., 1981.

IMPLEMENTATION

Inputs: requires over 100 input parameters.

Scale: field.

Timestep: daily.

Outputs: concentration of pesticides, P and N in runoff and leaching.

Computer: mainframe.

LIMITATIONS: extensive input requirements.

APPLICABILITY: determine the effect of management practices on pollution in runoff and ground water.

VALIDATION: validated by Lorber and Mulkey (1985) with 5 yrs. of field data toxaphene and atrazine.

PRZM

SOURCE: Carsel et al. 1984a and 1984b.

IMPLEMENTATION

Inputs: soil properties, partitioning and decay coefficients, Curve numbers, cropping information.

Scale: field.

Timestep: daily.

Outputs: pesticide losses in runoff and pesticide concentration in soil profile.

Computer: minicomputer and microcomputer version by Bretas(1986).

LIMITATIONS: not fully validated.

APPLICABILITY: determine effects of environmental and management conditions on pollution in ground water and runoff.

VALIDATION: partially validated with aldicarb data (hydrology component not validated).

Runoff Models

Haith (1980) developed a model to estimate dissolved and solid phase pesticide losses in runoff. Although many models of this type require calibration, this model does not and the required input parameters are available from secondary sources. Inputs include the decay rate of the pesticide, partitioning coefficient of the pesticide, parameters for the Curve Numbers and Universal Soil Loss Equation, rainfall amounts and duration, the soil density of the top cm, pesticide application rates and field area. The field scale model simulates the amount of pesticide in runoff in both dissolved and solid form in terms of kg pesticide/ha on a daily basis. The model was validated with three years of data from two small Georgia watersheds, predicting measured atrazine levels fairly well with the exception of some single runoff events. Eighty-four percent of the variation in pesticide runoff was explained by the model. The runoff losses predicted by the model were "edge of field" values and thus provide only upper bounds on pesticide input to surface waters. The model runs on a microcomputer and has also been adapted to a programmable calculator, an indication of its relative simplicity.

Leaching Models

Enfield et al. (1982) describes three simple models to predict the transport of organic pollutants through soil to ground water. We will discuss one of these, a model which calculates linear sorption/desorption, degradation and dispersion. The model first calculates the apparent velocity of the pesticide and then evaluates the concentration throughout the soil profile. The model requires bulk density and water content of the soil, sorption coefficients, degradation rates, pesticide application rates, pesticide solubility, monthly precipitation, evapotranspiration, irrigation, runoff and the dispersion coefficient. In order to obtain runoff the model was coupled with the Agricultural Research Model (Donigian et al., 1977). The model was evaluated against two years of field data of aldicarb applied to potato fields on Long Island. The model successfully predicted the location of the peak concentration for both years. Concentration was shown to be extremely sensitive to degradation rates. Therefore, without accurate rates, the model would not be reliable for predicting concentration.

Lindner (1985) developed three separate models to predict the leaching of pesticides. The most promising of these, CTOP, is based on a statistical representation of band movement. CTOP requires a great deal of input data including meteorological, cropping and physical data along with parameters for erosion, runoff and pesticides. The field scale model runs on a daily time step to predict the concentration of pesticide at depths over 200 cm. The model was linked with Haith's runoff model in order to account for total pesticide loss. Field data from a study in which chloride ions, fluormeturon and aldicarb sulphone were applied to a fallow plot at Compton Beauchamp, Oxfordshire on a clay loam soil was used for testing the model. Although the model underestimated peak penetration, the distribution near the surface was accurately predicted. The model was also validated with data from Long Island potato fields which had been treated with aldicarb. There was some difficulty in selecting proper input parameters but after some calibration of input parameters, the model performed well.

Steenhuis et al. (1984) developed a management model which traces the movement and fate of pesticides in the soil. The model, MOUSE (Method Of Underground Solute Evaluation), is classified by the authors as a deterministic functional rate model. MOUSE is composed of four submodels which are interconnected but can also be used alone.

The first submodel is a synthetic climate generator which calculates daily precipitation and air temperature based on average monthly climatic statistics for the area. The data generated from the climate submodel can then be used as input for the next submodel, the vadose water balancer. In all of the submodels (except for the climate generator) the user has the option of supplying the required input data or generating it in the preceding submodel. The vadose water balancer simulates the movement and retention of water in the unsaturated zone and considers snowfall, snowmelt, rainfall, runoff, infiltration, evaporation transpiration, downward movement and changes in snow and liquid water storage. The next submodel, the vadose solute transporter simulates the movement and attentuation of chemicals within the unsaturated zone above the water table. In addition to the data generated by the vadose water balancer, this submodel requires adsorption parameters for the root zone and lower transmission zones as well as pesticide degradation rates. The solute concentration pattern which results from the simulation can be used to drive the last submodel, the aquifer water and solute transporter which simulates the movement of the water as well as the movement and degradation of the solute.

The submodels were each well validated in separate tests against actual data. For example, the solute transporter was tested against experiments from a laboratory soil column, against the results of a mechanistic model and against soil cores from two potato fields on Long Island. In the first test, the model's prediction of the movement of butylate, alachlor and metolachlor were close to the laboratory results. In the second test where aldicarb leaching under a Long Island potato field was predicted, the model produced almost identical results to that predicted by the mechanistic model developed by Intera (1980). However, the MOUSE simulation required about fifteen minutes on a microcomputer while the Inter model required a large computer with considerable operating cost. In the third test, the model correctly predicted that all of the aldicarb had been moved into the ground water from the first soil core. In the second soil core, the model and observed concentration started near the same depth but the variation in concentration with depth was higher in the model's predictions than was actually observed. These tests showed that the model contains enough detail to produce results that are realistic enough for planning and management applications. The other submodels were similarly validated.

Models Which Predict Leaching and Runoff

The CREAMS (Chemicals, Runoff and Erosion from Agricultural Management Systems) model was developed by USDA-ARS to test the effectiveness of different management strategies for controlling soil and chemical losses in agriculture (Knisel et al., 1980). The daily simulation model predicts losses of pesticides, phosphorus and nitrogen through both run-off and leaching from field-sized areas. Input requirements for the model are extensive, requiring over 100 parameters (Balek, 1983). The model contains a hydrology component which provides input for an erosion-sediment component which in turn supplies the inputs for the two chemical components for plant nutrients and chemicals.

The model has been used for a large number of field-scale sites to compare land use practices and conservation measures (DeCoursey, 1985). For example, Crowder et al. (1985) developed an economic linear programming model with water pollution constraints to determine the effects of various conservation practices on economic returns. CREAMS was used to simulate the necessary environmental inputs.

Although the model is reported to require no calibration, Lorber and Mulkey (1982) tested CREAMS along with two other models for the ability to predict the movement of toxaphene and atrazine. They found that the performance of all of the models was noticeably improved with adjustment of initial parameter estimates. Although the calibrated version of CREAMS underpredicted erosion losses by 25 percent, the predicted total toxaphene loss was within 10 percent of the actual value.

The Environmental Protection Agency developed the Pesticide Root Zone Model (PRZM) to predict the movement of pesticides within and below the rootzone (Carsel et al., 1984a and 1984b). The model contains a hydrology component and a chemical transport component. The hydrology component calculates runoff and erosion. The chemical transport component calculates pesticide uptake by plants, surface runoff, erosion, decay, vertical movement, foliar loss, dispersion and retardation.

The model was partially tested against data from a New York study on the application of the pesticide aldicarb to potato fields. Although the hydrology component could not be tested due to lack of data, the pesticide transport was found to be realistic. The model was tested using parameters from the literature and then calibrated to local conditions and tested again. Before calibration, the model's predictions were similar to observed results except that the peak concentrations did not match. After calibration, the model predicted soil profiles of concentration which agreed closely with observed profiles. The authors suggest that more testing will be necessary in order to fully validate the model.

Although the model was originally programmed in Fortran for a minicomputer, it has since been converted to Basic for a microcomputer (Bretas, 1986).

Decision Models

Mathematical programming and modeling have been integral to research in agricultural economics since World War II. Economists have used a variety of programming techniques to evaluate alternatives. Here, we will review the relevant applications of mathematical programming models to pest management decisions. Types of models to be considered are simulation[1], linear programming, dynamic programming, and risk programming. Although systems analysis may be successfully applied to regions or industry-wide concerns, the focus of this review will be field or farm level decision-making.

Simulation

Simulation has been widely used, both by itself and in conjunction with optimization techniques, in the development of efficient pest management practices. Simulation models have the advantage of being flexible with respect to the number and character of variables which can be used to describe the dynamics of crop growth and pest and/or predator relationships. As pointed out by Shoemaker (1981), optimization models typically have fewer variables for describing biological relationships because of computational

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[1] Simulation is not an optimization technique, but is often used in conjunction with optimization in mathematical programming and can be used with search techniques to choose the "best" alternative from a finite set.

difficulties. Conversely, the primary disadvantage of simulation models is the computer expense for solving these relatively large models. This is becoming less of a consideration due to advances in microcomputer technology in which larger amounts of random access memory are available for a relatively low initial cost.

Successful applications of simulation to decision-making in pest management are too numerous to review comprehensively. Rather, a few examples which may offer useful approaches to the New York State potato modeling effort will be reviewed.

The research group at Cornell envisions an integration of pest models with a plant model in which defoliation is the most likely link between gross revenue (as determined by yield, quality, and price) and pest damage. Stochastic elements (such as temperature, rainfall, and humidity) affect the level of pest damage, while farmers have a number of management options (choice of varieties, rates and timing of pesticides, rotation, etc.) to manage pest densities. Each of the management options has a cost and a predicted impact on gross revenue. Due to the uncertainties inherent in agricultural production, the impacts on gross revenue may be in the form of a probability density function rather than a single value.

Given such a specification of a system, a range of economic outcomes can be generated by a simulation model. Greene, et al. (1985) used a model to examine the economically optimal pest management strategies for a Virginia soybean farm. Boggess et al. (1983), used this approach with the Florida Soybean Integrated Crop Management Model. In each of these applications, multispecies of pests were modeled. In both instances a large number of net revenue outcomes were generated (100 in Virginia, 40 in Florida). Merely by observation, one could choose the strategy which maximizes net revenue. However, in each of these studies, the researchers were not interested solely in the level of net returns, but in the variability of returns as well. We will consider these approaches in the later discussion of risk programming.

As described in the section on late blight models, Fohner et al. (1984), used a late blight simulator (Bruhn and Fry, 1981) and models of fungicide effectiveness, (Bruhn and Fry 1982a and 1982b), to compare the economic efficiency of scheduling fungicide sprays by the forecasting system Blitecast versus the traditional grower practice of regular interval spraying for potatoes in New York. The scope of the economic analysis in this research was somewhat limited since the link between pest damage and yield and quality of potatoes (gross revenue) was not yet developed. Comparisons for 10 simulated seasons were made for percent defoliation and number of fungicide applications. By assuming that a lower percent defoliation was preferable to higher defoliation, the economic performance of the two decision rules could be inferred. Research into the selection of optimal decision rules for potato pest management would be greatly facilitated by a model which incorporates several pest species and yield and quality effects of management practices. The results of Fohner et al. were quite provocative in that Blitecast did not schedule fungicide applications more effectively than the traditional seven-day schedule in locations typified by late blight favorable microclimates.

Linear Programming

Linear programming (LP) has been widely used as a research tool by agricultural economists to specify the optimum organization of resources and enterprises on farms. Linear programming has three quantitative components:

an objective, alternative methods or processes for attaining the objective, and resource or other restrictions (Heady and Candler, 1958). The objective function is typically specified as profit maximization or cost minimization. Alternative methods or processes may be different enterprises, buying and selling activities, or investment alternatives. Within enterprises, there may be several different crop production or cultural practices specified. For example, four potato enterprises could be included as activities, each with a different intensity of pest management practices. Resource constraints in typical applications are acres of land, hours of labor, dollars of capital, and hours of machinery capacity. Linear programming has been used in many applications in which environmental constraints are modeled. In these applications, LP selects the optimal activities given that tons of soil loss, pounds of nitrates, or pounds of active ingredients of pesticides, may not exceed a certain level.

Lazarus and White (1983) utilized LP to investigate the economic impact of crop rotations as an Integrated Pest Management (IPM) tactic for Long Island (New York) potato farms. Rotations with various field crops and vegetable crops were included in the alternatives to continuous potato production. Parametization of potato acreage was performed to evaluate the trade-offs between net returns and environmental quality, as indicated by total pounds of insecticides, fungicides, and herbicides.

In a related application, Warner (1985) used multiperiod LP to analyze the economic potential for diversification into perennial crops (grapes and peaches) on Long Island potato farms. The multiperiod model was chosen because the path of adjustment, not just the final optimal farm plan, was of interest. The model used in this research covered a time horizon of 15 years. While it was not attempted to restrict the amount of pesticides and fertilizer used on the model farm, accounting equations tracked loading rates and risk indices (for pesticides only) for the various optimal farm plans. If some basis for restricting the amounts of fertilizer or pesticide or the risk index could be devised, then the constraints could easily be added to this model. The objective function was maximization of net returns over the 15 year time horizon subject to constraints on capital and labor availability, pesticide use, family living expenses, and capital constraints.

While LP is a useful programming technique which can be applied to a number of different situations, it does have several limitations in devising a systems analysis approach to potato pests (and for many other pest management problems). One very appropriate use in potato pest management is studying the optimal cropping system when a number of resource and environmental constraints are important. Two of its characteristics which are limiting in the proposed potato-pest model are (1) linearity, and (2) single-valued expectations. Linearity refers to the assumed linear relationship between inputs and outputs within the various activities. If 1,000 pounds of fertilizer and 20 pounds active ingredients of fungicides are used to produce 300 hundredweight of potatoes on one acre of land, then 2,000 pounds of fertilizer and 40 pounds active ingredients of fungicide will be used to produce 600 hundredweight of potatoes on two acres. A more interesting problem in the context of our potato-pest system is optimizing intensity of pest management on a given acre of land. In this application, response between inputs and output is not usually linear. While various techniques are available to creative modelers to introduce diminishing returns in production processes, only a few can be accommodated within a single model without being cumbersome.

The second limitation, single-valued expectations, is perhaps the most limiting assumption. Linear programming is deterministic, but potato-pest interactions are inherently stochastic. Farm management researchers have recognized that farmers often do not employ what LP models indicate are optimal farm plans. Concern was then directed toward risk and uncertainty. Not only the level of net returns, but also the variability of returns is important in farmer decision-making. In the following sections of the review, the focus is on mathematical programming techniques which explicitly consider optimal decisions when the outcome of decisions is uncertain.

Dynamic Programming

Dynamic programming is a general mathematical approach that can be used to solve pest management problems having certain characteristics. It is particularly appropriate to use when management decisions are implemented at discrete points in time, when predictive equations are nonlinear, and when weather variables are assumed to be random variables. In this setting, the potato farmer faces transitions to alternative states over a time horizon. The end result is that maximization of immediate returns may not be consistent with maximization of long-term returns. An example in which this was an important consideration is Taylor and Headley (1975) who used dynamic programming to analyze the control of an insect population which was developing resistance to an insecticide.

Shoemaker and associates have used dynamic programming in a number of pest management applications, especially with respect to optimizing control strategies for insect pests of alfalfa (Shoemaker and Onstad, 1983; Onstad and Shoemaker, 1984; Onstad, Shoemaker, and Hansen, 1984). The optimization techniques involved linking a complex management system containing many variables to a dynamic programming model with a few variables. Decision variables were typically when to spray and when to harvest. Long-run profits are maximized over a multiyear period.

One limitation of the approach of Shoemaker and associates is that they have focused on income maximization, but stability of income is also a consideration. Dynamic programming has been used in risk applications (see Burt and Johnson [1967] for a model of wheat diversification). A more serious limitation is that the number of decision variables has to be held to a bare minimum for computational ease. Perhaps that reason precludes the use of dynamic programming for optimizing multipest species potato models.

Risk Programming

Risk programming is a rather general term we have applied to several types of mathematical programming models. The common element is that the objective function explicitly recognizes the trade-off between the level of net income and the variability of net income. Risk modeling involves selecting the optimal choice of activities for a subset of decisions (pest management strategies for potatoes in the intended application). Most empirical applications have been at the farm level, although plot or field level applications would be appropriate. Some analyses have required the specification of utility functions which are maximized, while others rely on solving for risk-income efficient sets. Because of the intended focus of our research efforts, it is proposed to limit consideration to those approaches which do not require eliciting utility functions.

Hazell (1971) developed an alternative which can be solved by conventional LP programming algorithms that gives similar (although not identical) results to the E-V frontiers resulting from quadratic programming. In our case, any added reliability of establishing the efficiency frontier is probably too costly both in terms in complexity and computational ease. The application of Hazell's Minimization of Total Absolute Deviation (MOTAD) model would require simulation of a net income matrix (gross margin in Hazell's terminology) for potatoes produced for a period of several years. Data requirements would be weather (daily or weekly observations of temperature, rainfall, and relative humidity) and potato prices. The generation of the net income matrix would be accomplished using the proposed potato-pest simulation model. Constraints in the early modeling efforts could be relatively simple, perhaps consisting of land, labor, and pesticide and nutrient accounting equations. In this formulation of solving for the optimal strategy, the primary challenge would be in keeping the range of management alternatives small enough to restrict the complexity of the simulation model to a manageable level.

Tauer (1983) proposed a model, "Target MOTAD", for generating risk-return frontiers for farmers who wish to maximize expected return but are concerned about net returns falling below a critical target level. This model has the advantages of being solvable by LP algorithms, but also generates a second degree stochastically dominant solution. That is, the solution set is comprised of acceptable choices for risk-averse farmers.

Conclusion

We reviewed a number of mathematical techniques (both simulation and optimization) which could be used to optimize potato-pest management decisions. Given the multipest orientation of our proposed work, simulation is a necessary part of any mathematical programming technique that might be considered.

Optimization techniques reviewed were linear programming, dynamic programming, and risk programming. Linear programming was provisionally rejected for our work, primarily because of its deterministic nature. Risk is an important element of potato pest management decisions. Dynamic programming can be adapted to risky choices, but has not been widely used in risk applications probably because of the complexity involved. Dynamic programming may also be limiting because very few management variables can be included due to computational difficulties.

MOTAD or Target MOTAD optimization linked to simulation appears to be the best choice for optimizing pest management practices in a multispecies situation. The optimization is computationally simple, but has the advantages of generating theoretically defendable (though not perfect) risk-return frontiers and avoids the problem of eliciting utility functions or assuming utility functions of a certain functional form.

MANAGEMENT STRATEGIES

A wide range of control measures, can be considered involving various combinations of chemicals, application methods and schedules, scouting and forecasting, resistant cultivars, rotations and biological agents. In reviewing strategies we tried to be particularly sensitive to the multiple-pest effects of controls. For example, the fungal agent *Beauveria bassiana* is a fungus that attacks the Colorado potato beetle and could be introduced as a biological control. Fungicides applied for the control of late and early blight could destroy the fungus. Another example is the use of crop rotation to control the golden nematode. Wright (1984) found that the first generation of CPB were significantly reduced following crop rotations. Such a reduction could have an impact on decisions regarding late season sprays. Several researchers (Hare, 1980; Wellik et al., 1981, Ferro et al., 1983) have found that late season defoliation has no significant effect on yield. Thus, late season sprays followed by crop rotation could possibly be eliminated.

The following discussion will describe the management alternatives which can be considered in the control of the Colorado potato beetle, early blight, late blight, and Golden Nematode.

Variety Selection

<u>Resistant Cultivars</u>

The development of cultivars resistant to pests is generally the best means of control of a specific pest. Unfortunately, a cultivar resistant to one pest is usually susceptible to others. Furthermore, development of resistant cultivars with marketable qualities takes years. Advanced breeding lines resistant to CPB have been identified (Tingey, 1980). Although significant progress is being made, CPB resistant cultivars are still several years away from commercial availability. Until these clones have been fully characterized for yield, tuber quality and susceptibility to other pests, they cannot be considered as a viable alternative.

Resistant cultivars are being used commercially, however, as the primary control of golden nematode. Fields in which the golden nematode have been found are required to grow a resistant cultivar such as Hudson, Rosa, Belchip, Wauseon, Yankee Chipper, Sunrise, Islander or Atlantic; or, switch to a nonhost crop such as cauliflower. According to a 1985 survey of Long Island growers (Kain and Moyer, 1985), Hudson has become the preferred Golden nematode resistant variety. Based on yield trials conducted between 1981 and 1984 Hudson has yields comparable to those of the popular non-resistant variety Katahdin (Webb, 1982..1985). The cultivar Rosa is of special interest because it has also shown moderate resistance to late blight. The yield of Rosa, however, was considerably lower than that of Katahdin (Webb, 1982..1985).

While cultivars which are resistant to the golden nematode provide full resistance to that pest, those cultivars which have been developed for resistance to late blight provide only partial resistance to the disease. Cultivars are usually classed as susceptible, moderately susceptible or moderately resistant with regard to late blight research.

Cornell Recommends (1985) suggests the following time intervals for a regular interval protective spray program for control of late blight: 7 days for susceptible varieties, 8-10 days for moderately susceptible varieties and 10-14 days for moderately resistant varieties.

Although cultivars have not been similarly developed for early blight resistance, Holley et al. (1983) tested the three cultivars Chieftain, Kennebec, and Norchip, and found that the rate of disease progress was significantly different. Kennebec showed greater resistance than Chieftain which in turn had greater resistance than Norchip. Kennebec was also moderately resistant to late blight but the other two were susceptible.

Cultivar Maturity

The length of maturity of the cultivar grown has an impact on the pesticide use. For example, early maturing varieties can reduce insecticide usage since the crop matures before the CPB population achieves damaging levels. In preliminary tests, Casagrande and Sullivan (1986) found that a crop of the early maturing cultivar Caribe could be produced in New Jersey with no insecticide usage. Attempts at double cropping the variety were unsuccessful since the second crop was unacceptably defoliated by the insect.

Another advantage of early maturing varieties could be the improved prices of potatoes earlier in the season. On the other hand, one disadvantage of early maturing cultivars is their increased susceptibility to early blight. Other considerations in regard to cultivar maturity in choosing the variety include labor availability and relative yields of the varieties.

Crop Rotation

Crop rotation is a practice which contributes to control of CPB, golden nematode and early blight along with numerous other pests. The USDA Handbook of Potato Diseases (Obrien and Rich, 1976) recommends crop rotation as a means of disease control for thirteen of the sixty-nine potato diseases listed.

Wright (1984) showed that crop rotation on Long Island, New York could reduce insecticide requirements by reducing early season populations.

Lashomb and Ng (1984) found that oviposition and first appearance of larvae were significantly delayed in a wheat-potato rotation. The rotation was scheduled so that a potato field was planted next to a wheat field which had been in potatoes the previous year. The wheat fields provided an environmental and mechanical barrier that delayed the emigration of over wintering adults long enough to reduce the number of spray applications by three.

An economic study on the impact of introducing rotations to the potato farms on Long Island was reported by Lazarus and White (1984). The environmental impact was also considered and total pesticide application was tabulated along with economic results. The linear programming model found that as potato acreage was reduced, total pesticides decreased by significant amounts, indicating a probable improvement in environmental quality. However, the results also indicated a strong economic incentive for growers on Long Island to continue growing potatoes intensively as opposed to field crop rotations. A cauliflower-potato rotation produced high returns but because of managerial problems with seasonal labor this option was limited to 25 acres of cauliflower on a 150 acre farm. They concluded that if the labor problem can be overcome, the potato-cauliflower rotation could be a good alternative to the potato monoculture.

Brodie (1976) found that rotation with a nonhost crop such as cabbage at least once in two years is an effective control for managing golden nematode populations. However, this method is not as effective as growing resistant cultivars. Fields in which the golden nematode have been found are placed under regulation by the New York State Department of Agriculture and given the options described earlier in the section on model reviews.

Pesticide Treatments

The frequency of pesticide treatments can be decided in three ways:

1. Calendar scheduled fixed interval sprays which are scheduled according to a seemingly appropriate (but often inappropriate) interval of time such as weekly.

2. Action or economic thresholds which are based on the level of pest populations which are economically damaging.

3. Forecasts which are based on the relationship between certain environmental conditions and the spread of plant diseases.

Calendar Scheduled Sprays

It is the common practice in the control of certain pests to spray at regularly scheduled intervals. In the case of late blight, sprays are traditionally scheduled on a weekly basis although sprays for the resistant varieties are sometimes scheduled at longer intervals of ten to fourteen days. This type of schedule doesn't require any extra equipment or labor for monitoring. Furthermore, labor and equipment planning for the spraying operation is easier. For growers who utilize custom sprayers, a calendar schedule can be a necessity because of the rigidity of the timing. However, over-spraying frequently results when sprays are scheduled with no regard to insect densities or disease progress. The following discussion on the use of economic thresholds and forecasts will illustrate this point.

Economic Threshold

The concept of an economic threshold is an important aspect of an integrated pest management program. The economic threshold determines the highest number of pests that crops can sustain before control action must be taken. The economic threshold as defined by Stern (1959) is "the density at which control measures should be determined to prevent an increasing pest population from reaching the economic injury level" where the economic injury level is that population at which the cost of damage caused by the pests exceeds the cost of pesticides to control them. Once an economic threshold is known for an insect, fields are monitored and sprayed only when the insect population exceeds the economic threshold.

The economic threshold is not always easy to determine. Insect populations fluctuate greatly with time and average population density as described by Luckmann and Metcalf (1975) is known as the equilibrium. The CPB belongs to a group of insects whose economic injury level is only slightly higher than the populations equilibrium position (see Figure 2). Intervention is required at every upward fluctuation of the population for control (Luckmann and Metcalf, 1975). The economic threshold for the CPB is therefore difficult to define.

Fohner et al (1982) studied the value of economic thresholds for pest management and concluded that a threshold rule is unlikely to be justified if the cost of pesticide is much lower than the crop value and the economic threshold is difficult to estimate. Potatoes would fit in this category. However, they recommended that in such a case the threshold rule could still be favored if the external and long term cost of pesticides is high. Giving due consideration to the environmental impact and the development of increasing resistance of the CPB to insecticides, this rule could certainly be applied to potatoes.

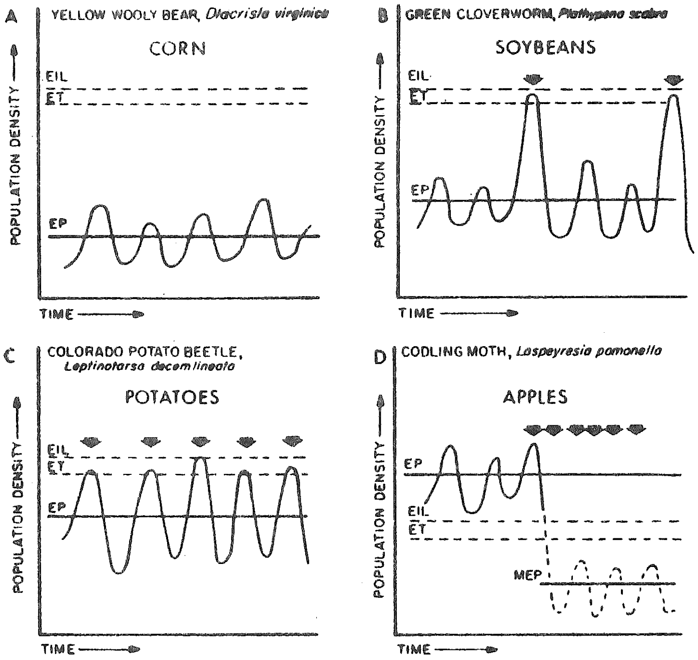

Figure 2. Economic injury levels and economic thresholds for typical insect pest situations. EIL, economic injury level; ET, economic threshold; EP, equilibrium position; MEP, modified equilibrium position; arrowheads, pest-control intervention (modified after Stern, 1965 by Luckman and Metcalf, 1975).

In a discussion of the reality and practicality of economic thresholds by Poston et al. (1983), thresholds are given four classifications:

1. Non-threshold are decisions based on other methods than thresholds to determine control tactics. Regular spray schedules are the best example.

2. Nominal thresholds are based on experience rather than actual research. This type of threshold tends to be conservative and is often used in extension publications.

3. Simple thresholds are calculated on the basis of a crude quantification of the relationship between pest and host. This approach typifies the best current practice.

4. Comprehensive thresholds result from research conducted to develop economic thresholds which incorporate multiple pests and stress factors.

The Long Island Potato IPM Pilot Program recommends the following threshold for CPB (Wright, 1985a):

Insect Stage	No CPB/50 vines
Adults	25
Small larva	200
Large larva	75

These numbers were based in part on defoliation studies of Shields and Wyman (1984) (Wright 1985b). This threshold can thus be classified as a simple threshold (No. 3) using Poston's system. Results of the program for 1984 in which thirty growers participated showed that those growers who followed the thresholds to determine spray schedules saved an average of 2.7 sprays on early varieties and 1.4 sprays on late varieties (Kain, 1985).

Forecasting

Many plant diseases including both early and late blight are governed largely by weather conditions. The development of late blight is favored by cool wet weather. Because of the importance of the weather in the development of late blight, forecasts have been developed to predict the spread of the disease according to local environmental conditions. One such system is BLITECAST, a computer forecast system for late blight of potatoes developed by Krause et al. (1975). BLITECAST assigns severity units based on relative humidity and temperature. Fungicide spray recommendations are made on a weekly basis according to rainfall and total weekly severity units. However, BLITECAST does not take cultivar resistance into account and thus often results in over spraying. Furthermore, BLITECAST assumes an initial amount of disease is present and if the actual initial infection varies greatly from this assumption, the accuracy of the prediction suffers. Mackenzie (1981) suggested that the risks of the system are unacceptably high unless high quality seed is used and good sanitation procedures are followed.

Because of the uncertainty regarding forecasting, regularly scheduled sprays adjusted for varietal resistance described earlier are probably preferable to relying on forecasts. This is especially true in areas such as the Northeast where the weather conditions generally favor late blight development.

Madden et al (1978) developed the forecast system, FAST, for early blight on tomatoes. The system assigns severity values which are dependent on environmental conditions. Disease severity data from epidemics subjected to FAST generated spray schedules were compared with weekly spray schedules and also with an unsprayed check. Although both the FAST generated and weekly spray schedules resulted in significantly lower disease than the check, the FAST schedule required significantly fewer sprays than the weekly schedule.

Pscheidt and Stevenson (1982) tested several different spray programs for effectiveness in controlling early blight on potatoes. The programs included weekly spray treatments started 0-6 weeks after row close or after 1000 growing degree days (GDD) had accumulated or after a sudden rise in airborne spores; schedules based on BLITECAST, FAST and a combination of the two forecasts. Although control generally improved as the number of applications increased, the weekly schedules didn't show different behavior. While the sprays initiated on the basis of spore count, GDD, BLITECAST and FAST all resulted in good control, the combination of BLITECAST and FAST resulted in the best control. A later study by these same authors (1983) found that prediction methods that use weather vane spore trap data or growing degree day accumulation were not consistently effective. Two other methods, however, did consistently predict the rise in air borne spores: FAST and a method based on an accumulation of 300 physiological days. These two methods required 2-3 fewer sprays for control.

Mechanical Control

Growers on Long Island have recently implemented the use of heavy duty ground maintenance vacuums to reduce overwintering adult CPB populations in the spring. Although the method resulted in varying degrees of control, it has shown good potential as a nonchemical control. A vacuum manufacturer as well as agricultural engineers at Cornell University have shown interest in pursuing development of the method (Moyer, 1984a).

Biological Control

Predators

Tamaki and Butt (1978) studied the potential impact of the predator *Perillus bioculatus* on the CPB. They found that the number of predators necessary to provide significant control with large populations of CPB are not present in potato fields. Tamaki (1980) observed that the predator was limited still further in its effectiveness due to its feeding habits--it never wastes food, feeding upon the prey until it is sucked dry, and it prefers not to eat alone so that two predators will feed on the same CPB larva even though hundreds of other larvae may surround them. Thus this predator can not be considered as a possible management alternative.

Fungal Pathogens

Galaini (1984) applied the fungus *Beauveria bassiana* for CPB control in potato fields on Long Island. The applications were made on a four-day schedule while small larvae were present. Although high levels of mortality were obtained during the first generation, the resulting potato yields were not commercially acceptable. Because of an extremely high initial population, the surviving beetles were numerous enough to inflict substantial damage. Thus, although *Beauveria* may be effective in areas of lower beetle density, its use should be coupled with insecticide treatments where a high population exists.

Campbell et al. (1985) reported management of the CPB in Long Island with *Beauveria*. Yields of the cultivar Katahdin from plots controlled by *Beauveria* were compared to treatment with the insecticide fenvalerate. Although yields were somewhat lower with the *Beauveria* treatment, they were economically acceptable. They concluded that *Beauveria* used in combinations with varying levels of insecticide depending on the CPB populations could provide a comprehensive management program.

Since potatoes are frequently sprayed with fungicides to control late blight, the effect of such sprays on *Beauveria* are a key to its effectiveness as an alternative control for CPB. Although some fungicides seemed to inhibit the growth of *Beauveria* in laboratory studies, field studies usually showed less inhibition and sometimes none at all.

Several researchers have tested the effects of various fungicides and insecticides on *Beauveria bassiana*. In two separate studies (Clark et al., 1982 and Loria et al., 1983) mancozeb was found to have significant detrimental effects on the fungus. The study by Loria and associates concluded that both metiram and metalaxyl are inactive against *Beauveria*. Clark reached similar conclusions regarding metalaxyl (then an experimental fungicide, CGA 48988) and chlorothalonil. The insecticide permethrin showed significant inhibitory action while azinophos methyl and carbofuran were not (Anderson and Roberts,1983). Thus, the fungicides metiram, chlorothalonil or metalaxyl could be effectively used in a pest control program which utilizes *Beauveria bassiana* for control of CPB. However, metalaxyl used alone is not recommended since it is ineffective against *Alternari solani* (Loria et al., 1983).

Egg Parasitoids

The egg parasitoid *Edovum puttleri* is another potential candidate as a biological control for CPB. Schroeder and Anthanas (1985) reported that they released the parasites in test plots of potatoes in Maryland. Parasitism averaged 48-65 percent for the season with egg kills averaging 85-95 percent. The parasite had been found in earlier studies to have a restricted host range, thus making it an excellent biological control agent for CPB. However, Obrycki et al. (1985) found that *E. puttleri* is not well suited for the climates of the Northeast. Since the parasite can not overwinter, an effective control program would have to include facilities for rearing large numbers of the parasite. An efficient rearing program has been established by the USDA ARS laboratory in Maryland so this problem appears to be surmountable.

Nematodes

The use of microscopic nematodes which attack the CPB was reported by Wright (1985c). When the nematodes were applied to the soil in water, they were effective in reducing the number of summer adults beetles. In field studies conducted on Long Island in 1985, the reduction was as high as 80 percent. At the present time, the cost of the large number of nematodes required for control would be prohibitive. However, several potential commercial producers are conducting research on large-scale production.

Conclusion

Of the biological agents discussed, the most promising seems to be *Beauveria bassiana*. Research has shown *Beauveria* to be an effective control agent, especially when used in combination with other means of control. Furthermore, it is the only agent for which the commercial means is available for production at this time.

Sanitation

Sanitation procedures are important in the control of disease. Because disease free seed is a critical step in the control of most diseases, the use of certified seed is generally recommended. The storage of cull piles away from the fields is another important sanitation procedure. Vine-killing two weeks before harvest is important to reduce late blight tuber rot. These procedures should most likely be considered as assumptions in a systems study since it would be difficult to accurately measure their effect.

CONCLUSIONS

Integrated pest management has been defined as "the selection, integration, and implementation of pest control based on predicted economic, ecological, and sociological consequences". If this definition is to be taken seriously, comprehensive problem-solving approaches such as systems analysis must play an important role in plant protection. We have shown how systems analysis could be applied to the development of an IPM program for potatoes and have reviewed applicable mathematical models.

The nature of the review was dictated by management objectives: income maximization, environmental protection, and risk reduction. Accordingly, a wide range of models and modelling approaches are needed. These include not only pest population models capable of predicting plant damage, but also plant growth, water pollution, and decision models. Furthermore, the models must be able to link to one another in order to evaluate alternative pest control options.

It can be concluded that available models for plant growth, water pollution, and decision making are probably adequate for systems analysis of potato IPM. This is not true for pest models. For two of the four pests, Colorado potato beetle and early blight, the necessary models for prediction of plant damage could not be found. It is apparent that further modelling research for these pests is required before they can be included in a systems analysis of potato IPM.

Mathematical modelling is essential to most applications of systems analysis. However, the modelling needs for a given problem are seldom obvious. We feel that a preliminary systems analysis comparable to that described in this report is a necessary prior condition to models' evaluation. This leads to models selection based on their perceived value in the systems analysis. It may also identify important research needs that must be met to satisfy the goals of the systems analysis and, hence, lead to problem solutions.

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