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SELECTION OF OPTIMAL PEST MANAGEMENT STRATEGIES UNDER UNCERTAINTY: A CASE STUDY IN MICHIGAN APPLE PRODUCTION

By

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ABSTRACT

SELECTION OF OPTIMAL PEST MANAGEMENT STRATEGIES UNDER UNCERTAINTY: A CASE STUDY IN MICHIGAN APPLE PRODUCTION

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Mark J. Cochran

This study focused on the problems of optimal pest management strategies used in Michigan apple orchards. A case study analysis of three common pests was performed which allowed the examination of the interrelationships between the controls of each pest. The three pests selected were scab, codling moth and mites. In addition to the pests, a natural predator of the plant feeding mites was included as well. A large systems simulation model was constructed to analyze the implications of various alternative pest management strategies. A number of sources of uncertainty were introduced and the performances of the strategies were simulated for twenty different single seasons or states of nature. Cumulative probability functions of net revenue were calculated for each control strategy.

Strategies which are risk efficient (highest expected utilities) for different risk preferences were identified. Rankings of the strategies consistent with the preferences of several classes of decision makers were performed using various stochastic dominance techniques. The superiority of Stochastic Dominance With Respect to a Function was demonstrated over Second Degree Stochastic Dominance since the latter results in both Type I and Type II errors. When a risk preference interval for SDWRF was defined to include the risk attitudes of all agricultural decision makers, the resulting efficiency

sets remained relatively large. Convex Set Stochastic Dominance could be employed to reduce the efficiency set without imposing further restrictions on the already specified risk preference interval. CSD provides a more complete ranking of the action choices without increasing the probability of either a Type I or Type II error.

The analysis using the simulation model and the stochastic dominance techniques was used to make a series of nine predictions about pest management in the specified production system. The model predicts that the expected net revenues and the expected utilities in general are higher for the IPM strategies when compared with conventional calendar spray programs. Two notable exceptions occurred in the scab and codling moth scenarios. For risk averse decision makers, the conventional scab control strategy may be risk efficient. When the codling moth population is high, the conventional calendar spray program results in a comparable expected net revenue and a higher expected utility for some decision makers.

FOR ALICIA

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I. INTRODUCTION

1.1 Problem Setting

In recent years the intensive use of chemical pesticides has become questioned more and more. It is of great interest to those who are concerned about the environmental damage that can result when residues surface in organisms other than the target species and to those who fear the long term repercusions of the continued consumption of commodities that have been sprayed during the production or marketing processes. Water quality is being increasingly affected by chemical pesticides and raises concerns about their uses as well. However, even the traditional users are reviewing their utility and are searching for alternatives as pest resistance and the rising costs of chemicals become a problem at the farm level.

In the last decade, mounting concerns about the consequences of prolonged use of chemical pesticides have brought the entire area of pest management under close scrutiny. Both agricultural producers and environmentalists are concerned about efficient use of chemicals, although not always for the same reasons. Environmentalists are concerned about the disruption of local ecologies by chemical pesticides and the presence of potentially (or in some cases actually) harmful residues in a variety of living organisms not intended as targets of the sprays. These concerns have resulted in governmental regulations to control indiscreet uses and prevent abuses of pesticides. However, further reductions in pesticide uses are desired by many environmentalists and they are interested in ways to minimize their usage. Prolonged chemical usage has produced consequences which concern farmers as well. Increased incidences of resistance in both target species and secondary pests have generated outbreaks of traditional pests and emergence of minor insects and diseases at population levels which pose major threats to agricultural production. The resistance reduces the efficiency of the pesticides and when coupled with the outbreaks, often results in increases in the total amounts of chemicals that are introduced into the environment, while lowering the profitability of the crop production to the farmers involved (2).

For many crops, pest management accounts for a sizable share of the costs of production. It has been estimated that well over one third of the variable costs of producing apples in Michigan are pest management related (70,71). While conventional control practices, with some exceptions, have been fairly successful in protecting plants from pest damage, there are a number of factors which are motivating interest in alternative methods of control which may reduce chemical usage. Increases in prices of chemicals have substantially raised the costs of the conventional spray programs. Resistance has become a problem as pest populations have been exposed more and more to chemicals that are structurally similar (2). Indiscriminate suppression of natural predators by conventional spray programs enhances the difficulties of controlling major pests and may result in significant infestations of secondary pests which are usually of little interest (2).

Conventional spray programs which have been used historically, are frequently based on a calendar schedule where a chemical treatment is applied at a fixed time interval without regard to the probability that the pest populations are likely to be high enough to warrant such applications. Conventional programs have been designed to minimize the risk of pest damage by applying doses of chemicals strong enough to control major pest infestations without regard to the actual population density in that year. As a result, some chemical applications can only be justified as insurance against the uncertain occurence of significant pest populations. Apparent over-applications arise from these risk considerations or from unavailable and inadequate information at the time control decisions are made. Other problems arise from faulty calibration procedures and estimates of these losses run into the millions of dollars annually (137).

An alternative set of control practices known under the general title of Integrated Pest Management (IPM) techniques began to evolve in the 1950's (135) but really became popular in the last decade. IPM is a conceptual approach to crop protection based upon ecological principles. Management strategies include an integration of well-timed chemical applications, biological controls, resistant plant varieties and cultural practices. Reductions in pesticide usage often result from following IPM strategies as information, natural and introduced predators, and cultural practices are substituted for chemical treatments. An improved understanding of the plant/pest system is the cornerstone of IPM strategies which use this knowledge to increase the efficiency of a wide array of inputs.

While information can increase the efficiency of pesticides (and in some cases actually substitute directly for them in the production process), timely information is not cost free. It is frequently the acquisition costs of up to date information that forces farmers to accept strategies which in a perfect knowledge situation would yield inappropriate rates of application. Collective action in the form of government programs, the extension service, or pest management cooperatives is a common way to provide groups of individuals information which individually they could not afford to acquire.

1.2 Concerns of Pest Management

The problems involved in pest management can be categorized into two basic concerns. The first concern lies at the farm level and focuses on determining the most appropriate control strategy for a given farmer with a particular risk preference. It considers the efficiency of the control strategies in generating outcomes favorable to the farmer. It involves the evaluation of control strategies using different decision rules, different types of chemicals, different rates of spray, different timings of sprays, the use of monitoring and the use of biological control. The second concern ensues from a group of consequences that result from the strategy selection decisions at the farm level but do not necessarily influence these decisions. This concern includes such matters as environmental degradation, health hazards and the impacts that one farmer's control decisions have on the pest management decision environment of a second farmer or group of farmers (i.e., migration of pests from an unsprayed field of one farmer to a field of a second farmer).

A basic requirement to addressing the problems of the two concerns will be an understanding of the decision processes by which individual farmers select pest management strategies. The interrelationships of the market conditions, the farmer's perspective on risk and the biological dynamics of the pest populations, the predator populations and the crop will need to be understood before useful prescriptions to the problems of either concern can be made. This research shall address these factors and their role in pest management strategy selection.

Although pest management has varying importance in different crops, the basic selection and decision processes should be common to the production of almost all agricultural commodities. In fact, it will be shown that much of the knowledge about decision making under risk that developed in areas completely distinct from pest management has relevant applications for pest control for all agricultural crops. Obviously, though, the largest contributions that the research can make to alleviating either of the concerns will be found in investigations with direct applications to those crops which have received the most intensive treatments of chemical pesticides, or which contribute significantly to a region's agricultural production.

1.3 Experience in Apple Pest Management

Apples have historically been one of the most heavily sprayed of all agricultural crops. In a study done by Eichers in 1970, (17) it was found that in the forty-eight continental states, apples have more pounds of active insecticide ingredient applied to them than any other crop (Tables 1 and 2). The same study concluded that apples have one of the lowest ratios of average value of commodity to pounds of pesticide applied.

This illustrates the point that more pounds of pesticides are used to produce one dollar's worth of apples than is used in the production of one dollar of most other commodities. In Michigan, pest management accounts for about 45% of the variable costs and almost 20% of the total costs of the operation of an apple orchard (71,72).

The intensive use of pesticides in apple production would seem to create a large potential for IPM strategies to contribute to the amelioration of the concerns arising from traditional pest management

Table 1. Insecticide Usage in Production of Selected Agricultural Commodities.

Crop	Pounds of Active Insecticide Ingredient per Acre*
Cotton	6.27
Corn	0.36
Soybeans	0.09
Alfalfa	0.12
Potatoes	1.99
Apples	12.58

*As presented in Carlson and Castle (17).

Table 2. Average Crop Value per Pound of Pesticide--1966*

Crop	Insecticide	Fungicide
Cotton	19.25	896.98
Apples	23.16	19.00
Peanuts	49.14	16.44
Potatoes	208.54	175.52
Corn	215.19	NA
Alfalfa	502.84	NA
Soybeans	683.27	NA
Wheat	2,322.13	NA

*As presented in Carlson and Castle (17).

controls. In other states, experiences with IPM programs are indicating that in fact net revenues can be increased and pesticide usage decreased by adopting IPM strategies in apple production systems.

In Massachusetts, a study was conducted comparing the performance of IPM programs in sixteen blocks of eleven orchards to conventional strategies applied in nine blocks (28). All blocks were in commercial orchards and the average per acre yield was 550 bushels. A variety of pests were monitored in the IPM blocks. They included the tarnished plant bug, European apple sawfly, apple maggot, codling moth, leafrollers, plum curculio, green apple aphids, woolly apple aphids, fruitworms, tentiform leafminer, spider and rust mites and apple scab. All figures are from 1979 and are in nominal dollars. It was discovered that the increase in net revenue per acre was $122.83 with a $82.37 per acre savings resulting from lowered pest management costs and $40.96 per acre arising from less insect damage. No charge was included for the monitoring service. The full does equivalents of insecticides were 42% less with the IPM blocks and aphicide use was reduced 60%. Further reductions were experienced with miticides (76%) and fungicides (12%).

In North Carolina, 45 apple orchard blocks were part of a research effort which extensively monitored the orchards from 1976 to 1980 (20). In the first four years, no advice was given and conventional spray programs were followed. In 1980, IPM programs were introduced. In the last year insecticide expenditures were reduced 25% but fungicide expenditures were up 30% due to a large scab infection. Using the 1980 fresh fruit utilization percentage and the 5-year average price for fresh and processed fruit, the IPM programs produced gross and net revenues 35% higher than the average conventional spray programs. These blocks had an average yield of approximately 775 bushels per acre.

In New York, a study was conducted examining 1978 records of 33 commercial blocks using IPM strategies and 23 commercial blocks which followed non-IPM programs (143). The average spray materials costs were $25 per acre less for the IPM blocks than the orchards using conventional techniques. The IPM strategies used one fewer spray per season on the average. When machinery and labor costs and a $12.00 participation charge for IPM orchards were considered, the savings per acre were calculated to be about $16. It was found that no discernable difference in fruit quality existed between the IPM group and the control group. Prices are in terms of 1978 dollars. It should be noted that most pest damage in apples results in a lower quality not a lower quantity.

These results do indicate that the adoption of IPM strategies does have a potential for reducing the concerns surfacing about conventional pest management but they deal with limited observations, different production systems and largely ignore the considerations that risk may have on the selection of control practices. To more thoroughly investigate the potential of IPM, a more complete understanding of the decision process is necessary.

1.4 Need for the Research

There are at least three major areas which warrant further research in the field of pest management. There has been a general neglect of the decision making process at the farm level in the selection of control strategies. The neglect of this selection process hinders recommendations of a problem solving nature that are provided for a specific farmer and the understanding of more aggregate problems such as environmental damage, health hazards and production externalities. There is a definite need to apply the relevant decision theory developed in other fields to farm level pest management to provide a clearer understanding of the process by which control strategies are selected.

The majority of analyses of farm level pest management problems focus on one pest at a time. Interrelationships between the population dynamics of various pests and their controls are often not addressed. The simultaneous management of more than one pest deserves more attention than what it has acquired in the past. Optimal strategy selection could easily be affected by these interrelationships. Therefore, there is a real contribution to integrated pest management that a multi-pest systems study would provide by enabling the analysis of the interrelationships between pests and controls. Apple production in Michigan suffers from pest damage caused by a number of different species. Three predominant apple pests in Michigan are apple scab, mites and codling moth. They could serve as a basis for a case study in such a systems project. These pests are suitable for a case study since there exists an adequate data base on each and the controls for scab and codling moth can impact on the mites and mite predators.

There is evidence that recommendations based on economic thresholds derived from marginal analysis may be misleading due to the omission of risk. Economic literature suggests that the presence of risk adds an additional cost which should be considered in determining optimal input use patterns. There is a need to develop a theoretical procedure by which the economic threshold could be defined with risk included. The procedure should be applied to an actual problem with real data to demonstrate its utility.

While it is proposed that a case study of three apple pests serve as the basis of the research, the resulting theoretical constraints, the research framework and the analytical procedures should be applicable to a variety of uses within the general area of pest management. The research should be useful to extension personnel in recommending prescriptions to specific problems of specific farmers. By predicting system behavior, it should also produce valuable subject matter information to researchers involved in the more aggregate problems of pest management like environmental damage, health hazards, impact analysis of regulations and production externalities.

1.5 Objectives

The specific objectives of the study are:

A. Identify the important determinants which influence apple producers' decisions in the selection of pest management strategies used to control scab, codling moth and mites.

B. Identify the important alternative strategies which are available for apple pest control relevant to apple scab, mites and codling moth.

C. Integrate the biological and economic implications of pest management strategies into analytical and simulation models which can simulate the decision making environment and evaluate these management alternatives and develop probability density functions for the outcomes associated with each strategy.

D. Predict which pest management strategies and economic thresholds may be preferred for decision makers with various risk preferences.

1.6 Organization of the Study

The study is organized into seven remaining chapters. Due to the multi-disciplinary nature of the work, there are sections which may be more relevant to some than others. Some discussion may be redundant but are repeated to facilitate the use of the study by non-economists who may be interested in only selected topics. Redundant discussions will be identified so readers may proceed to other sections. Chapter II presents a general discussion of the problem and reviews previous work related to the topic. It begins with a basic discussion of efficient input usage under conditions of certainty, which should be a review for economists. Next, it demonstrates that the importance of risk and shows how optimal input use patterns can be changed when it is considered. This is followed by a discussion of how optimal decisions can be made under uncertainty using the Expected Utility Hypothesis (EUH) and reviews a number of techniques to implement EUH. The discussion of decision analysis is then directed towards defining the economic threshold and optimal pest management strategy selection under uncertainty.

In Chapter III, the research procedures are described. There is a discussion on the appropriate role of simulation models in scientific research. A description of the actual system and an overview of the computer model are presented. The justification and credibility of the model and results are discussed as well. A list of statements about the anticipated system behavior are constructed from current knowledge available about the system. They will be compared with model predictions later in the study.

In Chapters IV, V and VI, the results from the three pests studied are described. These chapters have been written to include short descriptions of their model components and a synopsis of the risk analysis methodology. There may be redundant material in these discussions, but it is hoped that individuals interested only in the control of one pest may read these chapters without referring in detail to the remainder of the text.

Chapter VII is a summary of the comprehensive model results which investigate the interrelationships between the control of each of the three pests. In Chapter VIII the model predictions are compared with the statements on the anticipated system behavior. Discrepancies are attributed to model errors for improvements to the understanding of the system. The implications of the model predictions for extension, research and policy are discussed as well. Finally, future research and extensions are posed.

II. PROBLEM REVIEW

2.1 Introduction

The problem of selecting pest management strategies really focuses on efficient input usage. The design of both conventional and IPM control strategies attempts to combine various inputs into concise decision rules. These decision rules guide the application of the inputs into what should be a pattern of efficient input usage. The selection of the control strategy to be followed is then a choice between different decision rules which may use different inputs.

Conventional calendar spray programs generally develop a pattern of use which will provide crop protection in a "typical bad year." The spray schedule is designed to apply pesticides in a manner which will insure protection even if conditions are suitable for large pest infestations to occur. In traditional uses, little effort is made to incorporate information on the current conditions into these strategies.

Alternatively, one of the major inputs of IPM programs is information on the current conditions. The decision rules of these strategies are flexible so that the application of the other inputs can often be adjusted to meet the current conditions of the orchards.

It will be useful for discussion purposes to briefly highlight some of the foundations of optimal input usage. Readers not requiring this review can skip sections 2.2 and 2.3. One of the decision rules most commonly used in IPM programs is the economic threshold. This concept shall be discussed, followed by a section on defining the economic threshold under uncertainty.

2.2 Efficient Input Usage

A series of sequential choices between two hypotheses[1] are made to determine the optimal amount of a control (perhaps a chemical pesticide) that will be in the benefit of the farmer. Typically, choices are conceptualized as a production function relationship where the horizontal axis measures the amount of the input applied and the vertical axis is the amount of output (fruit or crop) produced for each level of input. This analysis, of course, holds all other inputs held constant at some specific level(s).

In pest control analysis, however, the pests are a negative input only indirectly under the control of a decision maker. The input can be defined as the post-application pest population which of course contains as a component the amount of control applied. Thus, the post-application pest is dependent on the control. It should be noted that there will be a distinct production function for each level of the pre-application pest population. So there exists a series of production functions displaying the relationship between the output and the post-application pest population which may differ by parallel or non-parallel shifts depending upon the interrelationships between the control, the "pre" and "post" application pest population and the growth process of the plant.

In Figure 1, the total physical production function (TPP) is displayed, illustrating that under many circumstances it can be expected to increase first at an increasing rate, then increase at a decreasing rate and finally reach a maximum before it begins to decrease. The

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[1]The hypotheses could be formulated as:

H_0: The amounts of net revenue associated with two different levels of input usage are equal.

H_A: The amount of net revenue associated with one level of input usage is significantly greater than the net revenue associated with an alternative level of input usage.

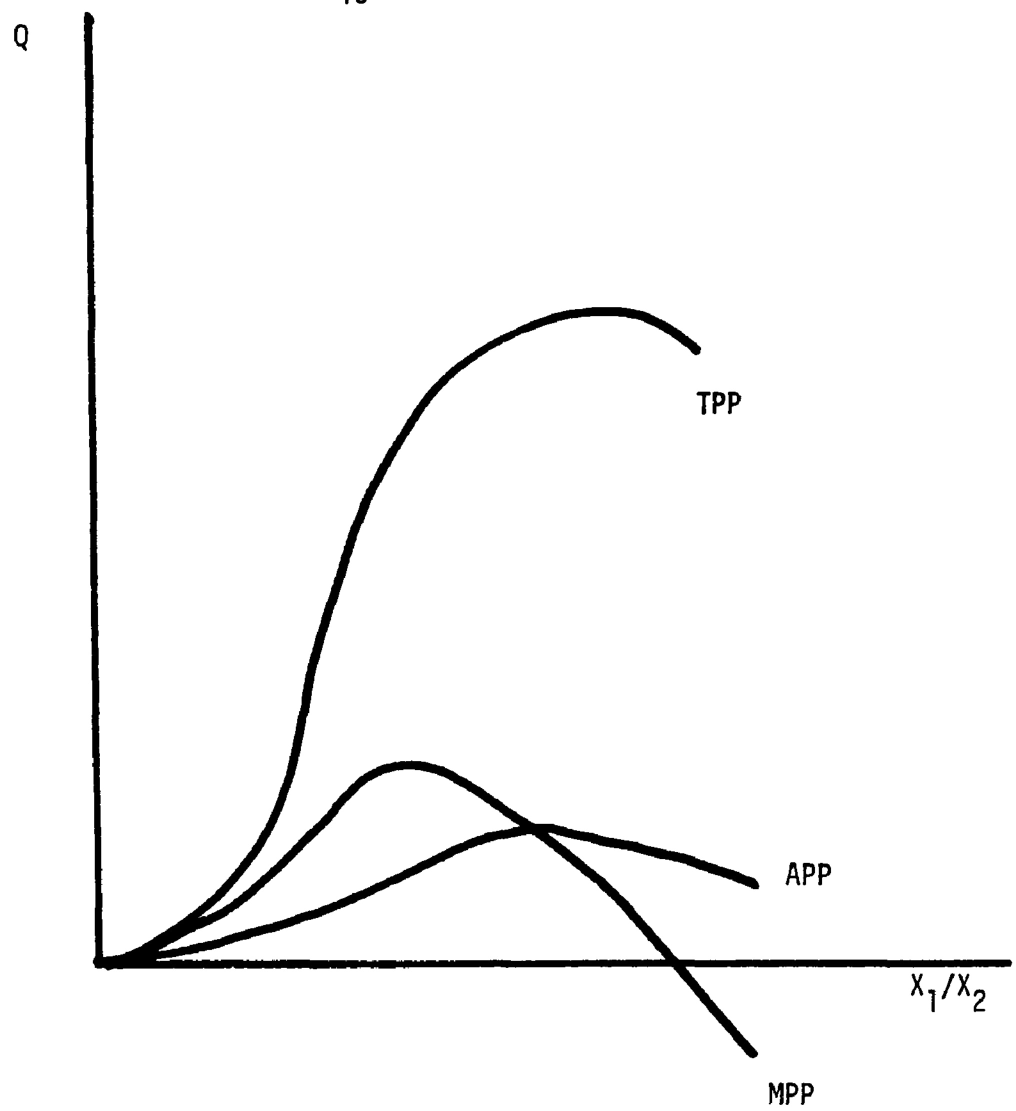

Figure 1. Total Physical Product, Average Physical Product and Marginal Physical Product.

average physical production function (APP) is derived by dividing the total physical production by the number of units of input applied. The marginal physical production function (MPP) is determined by calculating the difference in the total physical production by applying one additional unit of the input.

In this example, no prices or costs have been introduced, but their inclusion does not alter the procedures to find an optimum. When prices do not vary with output or input usage, value productivity functions can be determined by multiplying the physical production functions by the price of the output (Py). If prices vary with output or input usage, the value productivity functions must consider the functional relationship between the output and the price. If the product price is a function of output ($P_y = f(Y)$), then the value productivity functions can be defined as:

2.1 $VTP = Y * f(Y)$

2.2 $VAP = \frac{Y * f(Y)}{X_1}$

2.3 $MVP = f(Y)\partial Y/\partial X_1 + y \frac{\partial f(Y)}{\partial X_1}$

The last function has been renamed the marginal value product (MVP). The MVP is used to describe the change in the value of the output by changing the input while the VMP is the value of the change in total physical product arising from an incremental change in the input. When product prices are constant, of course, the two terms are identical. These functions appear in Figure 2.

In the case of complete knowledge, an optimum case may be found here by equating the marginal value product to the price of the input. This point will identify the amount of the input which should be utilized and the corresponding amount (and value) of the output that can be

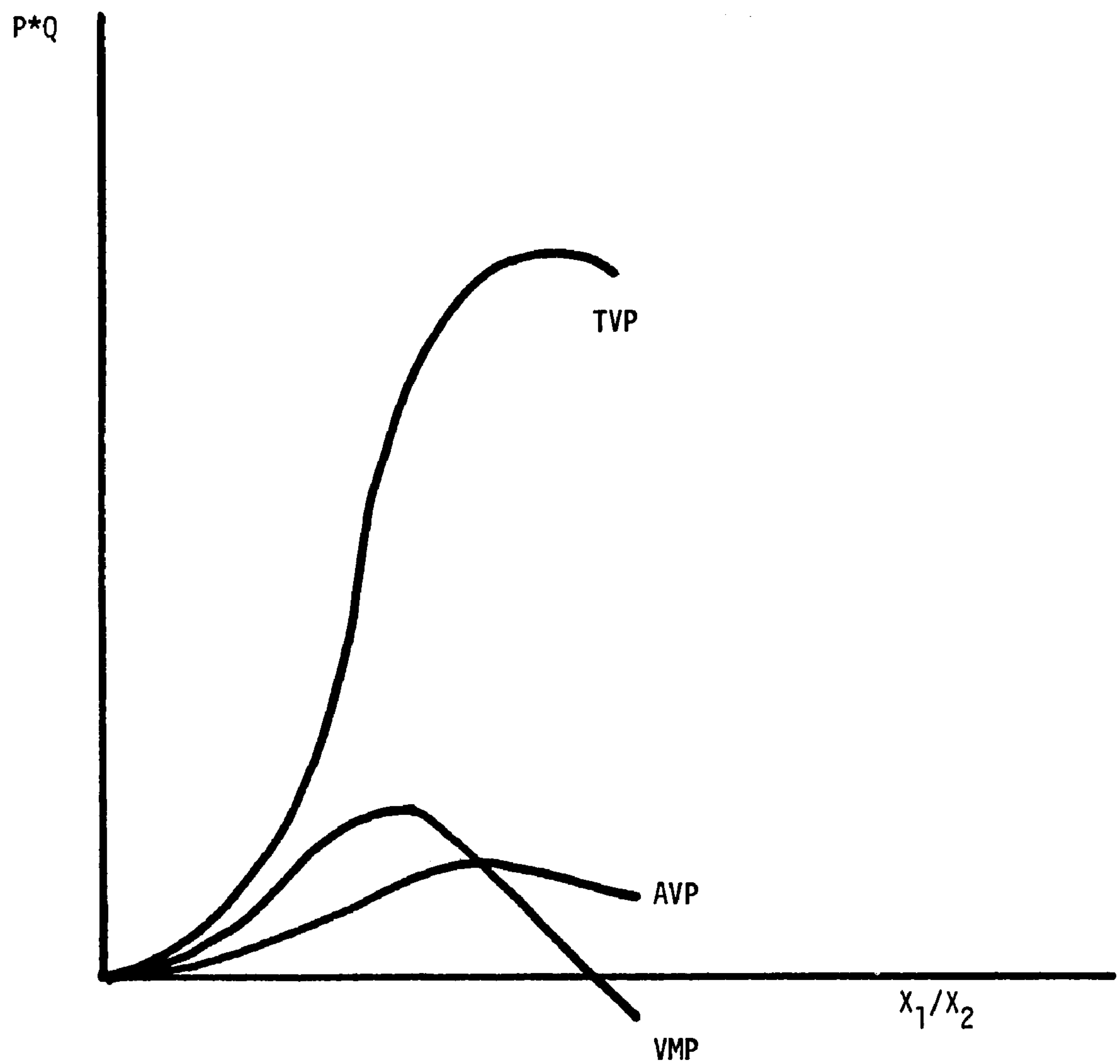

Figure 2. Total Value Product, Average Value Product and Value of the Marginal Product.

expected to be produced.

The contribution that the agricultural economist can make is in the area of identifying the appropriate values (prices and costs) to convert the physical productivity curves into value productivity curves which permit optimization of income. Although this task is quite important, it is not the only contribution that the economist has to offer in determining the most efficient control strategy for a given decision maker. Marginal analysis is quite useful for situations of subjective certainty, but economics can provide many insights into decision making in the uncertainty situations as well. Decision criteria are changed and the resulting decision rules for optimization often produce different solutions for the same problem addressed in a certainty context. Under these circumstances the role of the economist in the multi-disciplinary analysis of management is greatly expanded. The decision process under uncertainty has been studied by economic and management experts for a number of years and several insightful analytical techniques have been developed. Application of some of these techniques should prove to be helpful in the case of pest management.

2.3 Theory of Firm Under Uncertainty

Risk imposes an additional cost on the operation of a producing firm which depending upon its source and the production function, changes substantially the optimal production decisions. Sandmo (120) has investigated the impact of risk on production decisions when the output price is uncertain. He concludes that for a risk averse firm under perfect competition the optimal output level is characterized by marginal cost being less than the expected price. This implies that the risk of uncertain product prices adds additional costs to the conventional production costs. Similar results have been obtained by different authors examining other sources of uncertainty. Blair (12) explored the case with input price uncertainty and Leland (76) analyzed the situation of a firm faced by uncertainty in the demand for its output. Technological uncertainty has drawn attention from several authors such as Ratti and Ullah (106), Robison and Black (114) and Pope and Just (99), who have reached similar conclusions. These results suggest that the optimal input patterns determined by marginal analysis under certainty may not be appropriate indicators of optimal input usage under uncertainty.

2.4 Decision Analysis Under Uncertainty

In the 1920's, Frank Knight (75) distinguished between risk and uncertainty by designating the former as a condition where outcomes of an action choice can be assigned a probability of occurring while in the latter case insufficient information exists to construct such a probability function. The Knightian definitions of risk and uncertainty have often been interpreted to imply that risk is the situation where objective (measurable) probability distributions can be assigned and uncertainty is the case where the probability distributions are subjective (unmeasurable). About ten years after Knight, F.P. Ramsey (105) deduced that probabilities were personal and subjective since they are in reality "degrees of belief" rather than objective facts.

The terms risk and uncertainty are now commonly used interchangeably in a context that describes a decision situation where each choice may result in more than one outcome.

One of the easiest ways to evaluate the alternative choices under uncertainty is to calculate the expected value of each choice by weighting the outcomes expressed in monetary terms by their associated probabilities.

However, this completely ignores differences in variances in the distributions of the outcomes and relies on the mean as the only criterion for selection. The variance in the distribution of outcomes is often used as an indicator of the amount of risk involved with a particular alternative.[1] Only if decision makers are risk neutral will the ranking of the action choices determined by the size of the expected value be consistent with actual preferences. Risk aversion, a common reaction to uncertainty, may generate a different ranking. The expected value or expected net returns is therefore limited in addressing questions of selecting amongst alternative choices under uncertainty.

If under uncertainty, the expected net revenues cannot be used to rank alternative courses of action consistent with risk preferences, the problem arises as to what is an appropriate procedure. For cases where a decision maker is faced with a situation where he must select from several action choices with varying outcomes, the expected utility hypothesis (EUH) can be used to permit evaluations beyond the simplistic maximum expected net revenue rule. The EUH can be implemented by following a six step process which will insure that consideration of both the expected net returns and the uncertainty or risk.[2] These steps are:

1. Identify the possible action choices.

2. Identify the possible outcomes for each of the action choices.

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[1]The variance is an appropriate measure of risk only when the distributions are normal. Otherwise other moments of the distribution are important as well.

[2]The EUH legitimacy is often based on the axions of the vonNeumann and Morgenstern (131) utility function. These axioms include:

1) Ordering - if a decision maker is indifferent between distributions h_1 and h_2, and h_1 is preferred to h_3 then h_2 is preferred to h_3 as well;

2) Continuity - if an individual prefers the probability distribution h_1 to h_2 to h_3, then there exists a unique probability, p, such that he will be indifferent between h_2 and a lottery of $p \cdot h_1$ and $(1-p)h_3$;

3) Independence - if h_1 is preferred to h_2, then a lottery with h_1 and h_3 will be preferred to the same lottery with outcomes h_2 and h_3 (113).

3. Identify a probability density function for the outcomes.

4. Derive utility measures for the outcomes.

5. Determine the expected utility for each action choice by summing the utility measures for the outcomes which are weighted by the associated probability that each outcome will occur.

6. Select the action choice which produces the highest expected utility.

The Bernoulli six step EUH process can be consolidated into a decision matrix as displayed in Table

The outcomes expressed in terms of utility values appear in a m x n matrix. The action choices with the highest expected utility determined by summing the columns weighted by the relevant probability will be selected as the best alternative by this method.

The question arises as to whether or not decision makers actually follow the EUH and if not, should they. Two excellent reviews of the validity of the EUH have recently appeared. Schoemaker (123) has identified four general uses for the EUH and examines the uses from the perspective of four classes of evidence. The uses of the EUH that are identified are descriptive, predictive, postdictive and prescriptive while evidence is summarized in the four categories of: a) tests on axioms, b) field research, c) information processing studies and d) context effects. Schoemaker argues that the descriptive and prescriptive uses may be evaluated with all four types of evidence but the postdictive and predictive uses are more concerned with the results of field research. He concludes that as a descriptive model, the EUH fails to serve except for "well-structured repetitive tasks, with important stakes, and well-trained decision makers " (123, p. 552). As a predictive model, although he concedes that interpretation of the evidence is complicated, Schoemaker suggests that the EUH is more the exception than the rule. The postdictive

Table 1. The EUH Decision Matrix.

States of Nature	Probability	A_1	A_2	A_3		A_n
N_1	P_1	0_{11}	0_{12}	0_{13}	. . .	0_{1n}
N_2	P_2	0_{21}	0_{22}	0_{23}	. . .	0_{2n}
.	.	.	.	.	. . .	.
.	.	.	.	.	. . .	.
.	.	.	.	.	. . .	.
N_m	P_m	0_{m1}	0_{m2}	0_{m3}		0_{mn}

use is dismissed largely on the basis of problems that it encounters with the foundations of scientific reasoning. Evidence to evaluate this model is also difficult to appraise. Finally, the prescriptive use suffers from difficulties in operationalizing the elicitation of preferences consistent with the axioms and from the lack of evidence on whether or not basic preferences are really compatible with the EUH axioms.

Despite the somewhat pessimistic appraisal of the EUH, Schoemaker concludes the review with the following statement: "nevertheless, until richer models of rationality emerge, EU maximization may well remain a worthwhile benchmark against which to compare, and towards which to direct behavior" (123, p. 556).

The second review of the EUH arrives at about the same conclusion, but expends more effort on the evaluation of the tests of the EUH. Robison (116) outlines the characteristics of a good test and then proceeds to review the literature to appraise if there is justification for the use of the EUH as a descriptive, predictive or prescriptive model. He concludes that although there has been inadequate testing of the EUH, it can be surmised that, based on the available evidence, the model is a useful but far from perfect predictor of choice behavior. Under experimental conditions, the Type I accuracy of the EUH is about 65% when based on a single argument. Refinements in the basic model can increase the Type I accuracy but usually at the expense of increased Type II errors. Robison implies that the deficiencies of the EUH should be recognized, but that it is the best of available models and can still provide insights in descriptive, predictive and prescriptive uses.

It can be concluded on the basis of these reviews that the EUH is an imperfect model but provides a useful function in approximating how decision makers order risky alternatives; in predicting what the rankings of the alternatives in a choice set are; and in prescribing what alternatives will be preferred given information about the risk attitudes of decision makers.

2.5 Implementation Efforts of EUH

Three major problems arise in the application of the EUH analysis: the measurement of risk preferences; the estimation of probability density functions associated with the occurrence of the outcomes; and violations of the axioms. The first concern has by far received the most attention in research conducted in the last 40 years. This discussion will be no exception of that trend. The latter two problems can be reviewed in Robison (116), Schoemaker (123) and Spetzler and Stael vonHolstein (134).

However, before proceeding into the discussion on elicitation of risk preferences, it will be useful to make some brief comments about these other concerns. The problem of estimating the probability density function have been practically addressed by such authors as Ramsey (105), Anderson (3) and King (73), who follow the subjectivist's school of thought. As King (73) describes, the decision makers use probability distributions based on their expectations of what is likely to occur. These expectations are subjective (105) and can be drawn on logical deductions, on inferences from empirical data, on personal intuitions or on some combination of the three. After the stochastic exogenous variables have been distinguished from the endogenous control variables, information can be collected from the decision maker that will allow the representation of a cumulative probability function. Three basic classes of encoding procedures frequently used to elicit information that can be converted into a cumulative probability function have been identified by Spetzler and Stael vonHolstein (134). These classes are:

1) Procedures which fix the value of stochastic variable(s) and the decision maker is asked to specify the probability level: what is the probability that the variable X will be less than X*?

2) Procedures which fix the probability and the decision maker is asked to specific a value for the variable X which will be less than X*: What is the value of variable X that will be less than X* with the given probability?

3) Procedures which fix both the value of the stochastic variable and a probability value associated with it by examining historical data.

With the completion of the encoding process, several points on the cumulative distribution function should have been identified. Following the procedure described by Schlaiffer (122), the observations can be arranged in order of the size and the k-th observation can be considered a reasonable estimate of the k/(n+1) fractile of the distribution. A smooth curve can then be drawn through the selected points or regression techniques can be used to fit a specific form if it is suspected that the distribution of the stochastic variable is from a known family of distributions.

Of course, the more data points that are available, the more reliable will be the representation of the probability distribution. Anderson (3) has examined this relationship and concludes that while estimational reliability increases with the number of observations, in many cases good estimates of the distribution can be achieved with as few as three to five observations.

When more than one source of uncertainty is present in the decision environment, the encoding process will have to be accomplished for each stochastic variable. However, care must be taken to recognize any dependencies or influences that may exist between various stochastic variables. When the stochastic variables are correlated, a multivariate distribution should be estimated from the correlations and the appropriate marginal distributions.

The violation of the axioms of the EUH and the recent advances in the proofs of the EUH are discussed in Schoemaker (123). It should be pointed out that the axioms are intended to demonstrate the existence of numerical utilities for outcomes whose expectations for the risky action choice preserve the ordering of alternatives. Recent advances have reduced the necessity of including the independence and transivity axioms, two of the most frequently violated axioms (123).

In the years of research that have been conducted in attempts to measure risk attitudes, several approaches have been developed with varying degrees of success. Young (150) has identified four classes of approaches to measuring risk preferences. They are: 1) direct elicitation of utility functions (D.E.U.); 2) experimental methods (E.M.); 3) observed economic behavior (O.E.B.); and other methods.

The direct elicitation approach is commonly associated with the three most popular interview methods which Officer and Halter (93) refer to as the von Neumann-Morgenstern; the modified von Neumann-Morgenstern; and the Ramsey methods. These three models may also be referred to respectively as the standard reference contract, the equally likely/ certainty method and the equally likely but risky outcome method (113). Criticisms of these techniques include bias introduced by different interviewers, preferences for or against gambling, the exclusion of other important variables in addition to monetary gains and losses, and the accuracy of a "parlor game" in reflecting actual risk preferences when outcomes will really be experienced.

The experimental approach used by Binswanger (150) in rural India involves the actual financial compensation of survey participants. The compensation is the outcome of choices amongst eight gambles and the selections are an indication of the risk preferences of the participants. Binswanger argues that the approach more realistically approximates a farmer's normal decision environment and thus is superior to the D.E.U. techniques.

Observations on actual economic behavior (O.E.B.) in situations under uncertainty can be used to indirectly measure risk preferences. The first order conditions in the case of expected utility maximization under risk can be defined following Magnusson (150) as

2.4 $E(MVP_i) = MFC_i + R_a I_r, \; i = 1, \ldots n$

Where $E(MVP_i)$ = expected marginal value product of input i

MFC_i = nonstochastic marginal factor cost of input i

$R_a I_r$ = a risk adjustment

R_a = local risk aversion coefficient $(d\mu/d\sigma^2)$ EU = constant

I_r = marginal contribution to risk of additional input use (I_r)

With observations on the input usage and I_r, the MVP_i can be calculated and R_a could be solved for. Moscardi and deJanvry (150) have used similar techniques.

While the observed economic behavior approach to measuring risk preferences can be acknowledged as having solved the problem that preferences revealed during the survey process are not representative of actual behavior, it does suffer from the difficulty of measuring the stochastic influences (I_r). Generally, this is accomplished only by the adoption of very restrictive assumptions on the sources and functional forms of uncertainty. It also designates the entire discrepancy between the certainty profit maximizing equilibrium conditions $(MVP_i = MFC_i)$ and the observed behavior as being attributable to risk while other factors such as incomplete market information, different resource endowments, capital constraints, different objective functions, different subjective probability assessments, ex-post uncertainty adjustments and measurement errors could easily account for some part of the difference.

Other approaches to risk preference measurement are often focused on constructing risk aversion indices based on adoption of risk management strategies or on psychological or sociological criteria assumed to be related to willingness to bear risk. As Young, et al. (150) discusses, these measures are difficult to incorporate into predictive models since they do not generate coefficients of risk preference derivable from explicit theories of decision making and are even less relevant for prescriptive uses. More complete reviews of the methods used to implement the EUH and the general validity of the hypothesis appear in Robison (113) and Schoemaker (123).

Single Valued Utility Functions

The D.E.U. and experimental approaches produce estimations of single valued utility functions. Besides from the estimation problems already discussed, single valued utility functions inherenetly have a high probability of a Type I error. That is to say that there is a tendency to reject the null hypothesis that the expected utility of an alternative for any perceived difference, whether it results from an actual difference or from some measurement error (113).

The concept of the single valued utility function is rooted in the classical description of the problem (43). The logic of the argument can be illustrated graphically. In Figure 3, the classical utility function is displayed. In this case, the utility is a function of income and the first derivative (marginal utility of income) is positive while the second derivative is negative. This indicates that marginal utility of income is increasing at a decreasing rate.[1] This case would represent a risk averse decision maker. The concave curvature of the function will indicate the degree of risk aversion. Risk aversion can be described as the willingness to pay a premium to avoid an actuarially fair lottery. A straight line would represent a risk neutral individual. A convex curvature indicates risk preferring or risk loving behavior. If a decision maker with this utility function is faced with a lottery of receiving (x+a) 50% of the time and receiving (x-a) 50% of the time, the expected utility of the lottery, $[.5 * u(x-a) + .5 * u(x+a)]$ would be less than utility of the expected value of the lottery $(U(x))$. A risk neutral individual would receive the same utility from the lottery and the expected value of the lottery while for a risk-loving decision maker, the expected utility would be greater than the utility of the expected value of the lottery.

Most risk averse decision makers would be willing to pay an insurance premium to eliminate the uncertainty. The amount of premium depends on the degree of the decision maker's risk aversion, reflected by the curvature of the utility function. The premium, π, that could be paid and leave the decision maker indifferent between the sure outcome $(x-\pi)$ and the lottery with outcomex x-a and x+a is indicated in Figure 3. It is the difference between the expected value of the lottery, x, and the income level $(x-\pi)$ which produces a utility identical to the expected utility of the lottery. This sure outcome level $(x-\pi)$ is the certainty equivalent. The size of the certainty equivalent and the risk premium will depend on the curvature of the utility functions and the characteristics of the lottery. More risk averse decision makers will have

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[1]The abstraction of utility here may not always be analagous to the concept of utility derived under certainty. See Schoemaker (123, p. 535) for discussion of difference.

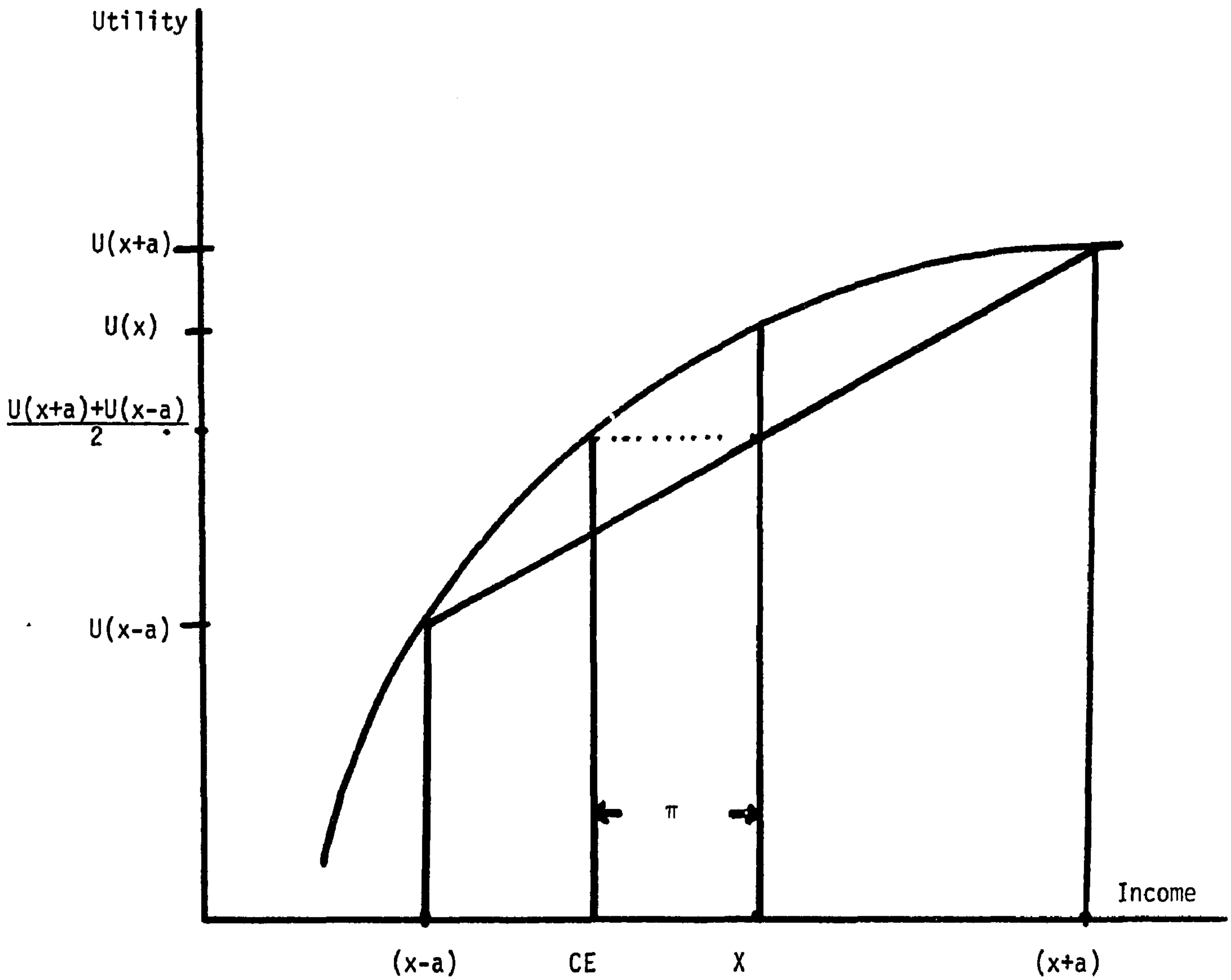


Figure 3. Risk Premium and Certainty Equivalent.

lower certainty equivalents than less risk averse decision makers while for a given decision maker, less risky lotteries will have higher certainty equivalents than more risky lotteries.

Alternative action choices can then be ranked by the size of the certainty equivalents and the rankings will be consistent with the EUH when a single valued utility function has been properly measured. However, measurement errors may lead to inaccurate rankings since the certainty equivalents will be derived erroneously. Since the single value utility function implies an exact measurement, a tendency for a Type I error is quite high. This has lead to the development of more flexible techniques.

Alternatives to the Single Valued Utility Function

The O.E.B. approach generates a risk aversion coefficient rather than attempting to directly estimate a utility function. The risk aversion coefficient generated in this manner belongs to an alternative class of methods to the single valued utility functions which can also be used to evaluate action choices. This second class of evaluation methods are referred to as efficiency criteria since they reduce the opportunity set of alternative action choices to a smaller subset in a manner that insures that the expected utility maximizing action choice is included in the reduced subset. These efficiency criteria are contrary to the single valued utility functions in that they have a tendency towards a high probability of making a Type II error. Efficiency criteria may fail to recognize a difference between the expected utilities of two alternative action choices leading to the acceptance of the null hypothesis that the two alternatives are of equal utility to the decision maker.

The O.E.B. generated risk aversion coefficient is only one of several efficiency criteria. Jock Anderson (5) has identified fourteen additional efficiency criteria. He groups them into three categories: 1) stochastic dominance; 2) utility family-specific and 3) others. The first category consists of criteria which employ rules to order action choices on the basis of characteristics of the cumulative probability distributions. The second group adopt rules which are based on very general assumptions about the nature of utility functions. The final category is a miscellaneous grouping containing E-V criteria, its offshoots and such alternatives as Baumol's E-L safety criteria.

Anderson's classification is somewhat superficial since all efficiency criteria are based upon utility function characteristics. E-V criteria are a special case of Second Degree Stochastic Dominance, where the utility function is quadratic or all distributions are normal. Stochastic Dominance techniques all impose constraints on the form of the utility function which allow the ordering of alternatives by comparing the cumulative probability distributions. While the classification is superficial, it is useful to distinguish between some of the more common criteria.

Generally, efficiency criteria are constructed by limiting the types of utility functions that will be considered or by the adoption of some assessment rules on the characteristics of the probability density functions. Examples of the types of utility functions often used as efficiency criteria are the log utility function, the negative exponential utility function and the quadratic utility function. The latter function is frequently used to generate an expected value--variance (EV) sets using quadratic programming. This EV efficiency set includes all action choices which for identical expected returns have the smallest variance. That is, for an expected return the variance is minimized.

Tobin (144) and Samuelson (118) have respectively shown that EV criteria can be consistent with the postulates of expected utility theory only when the utility function is quadratic or when outcomes are distributed normally. As such, EV analysis is a special case of Second Degree Stochastic Dominance. Examples of efficiency criteria that are based on characteristics of the probability density functions are stochastic dominance techniques. These efficiency criteria have definite rules used to compare the cumulative probability distributions of each action choice's set of outcomes. They can have differing underlying assumptions and various degrees of restrictiveness. The Stochastic Dominance techniques are by far the most useful as the other efficiency criteria suffer from more restrictive assumptions.

Efficiency criteria developed due to two deficiencies in the EUH analysis conducted with single valued utility functions. First, it is difficult to make statements about the preferences of classes of decision makers with the former method unless each individual's risk attitude has been measured or it is assumed that everyone has an identical utility function. Second, due to the measurement problems inherent in the elicitation of single valued utility functions, relatively inaccurate predictions result from implementing the EUH in this fashion. Most efficiency criteria, but not all, are designed to circumvent these problems. They are constructed to represent the preferences of a class of decision makers and do not use an exact measure for these risk attitudes. The two points are related. Rather than using a single valued utility function, a class of utility functions (or decision makers) are defined by setting an interval around possible values. This is done in a manner which reduces the choice set of all alternatives into a smaller subset in a fashion that insures that the action choice with the highest expected utility is a member of the subset. The remaining subset is denoted as the efficiency set since its members are risk efficient. The alternatives that are rejected from the subset are risk inefficient and have a lower expected utility for the entire class of decision makers. Efficiency criteria, in general, decrease the probability of a Type I error but increase the probability of a Type II error. The larger the efficiency set, the greater will be the Type II error. There is a positive relationship between the size of the efficiency set and the size of the class of decision makers represented by the criteria. With the exception of Convex Set Stochastic Dominance, efficiency criteria require that a consensus among all individuals in the class of decision makers be reached before an action choice can be rejected as inefficient. Since they operate by making pairwise comparisons, these efficiency criteria require that everyone agree on which single action choice is preferred to some alternative before the alternative can be removed from the efficiency set. So if individual A prefers action choice 2 to 1 and individual B prefers 3 to 1 but not 2 to 1, then action choice 1 cannot be declared risk inefficient for most efficiency criteria.

Efficiency criteria often reformulate the traditional EUH problem using cumulative probability functions rather than probability density functions. The construction of cumulative probability functions has been previously discussed. It is a process where the outcomes are ordered from smallest to largest and a probability of receiving each outcome level or less is established (pp. 24-26). These functions can be defined as:

2.5 $F(x) = p(y \leq x) \; \forall \, y \in R.$

They also have the following characteristics:

2.6 $F(x) = 0$ as $x \to -\infty$

2.7 $F(x) = 1$ as $x \to \infty$

and F(x) is nondecreasing and right continuous.

The probability density function associated with F(x) is denoted f(x) and satisfies the following:

2.8 $F(x) = \int_{-\infty}^{x} f(y)dy$

2.9 $f(x) = dF(x)$

First Degree Stochastic Dominance

The earliest of the stochastic dominance techniques to surface was First Degree Stochastic Dominance, FSD (104). It imposes rather mild restrictions on the utility function and does it in a fashion which should not exclude any possible preferences from the interval. The restriction placed on the utility function is that the first derivative must be positive, $U'(x) > 0$. This defines the class of all decision makers who prefer more income to less.

The efficiency criteria of FSD can demonstrate that one action choice has a higher expected utility than another if it offers a greater outcome in at least one level of the cumulative probability and at no probability level is the outcome less than the outcome of the other. The cumulative probability function of the preferred action choice must never be to the left of the dominated choice and must lie to the right of it in at least one probability level. This insures that the rankings will be consistent with the only characteristic known about preferences--that decision makers prefer more to less.

It should be obvious that FSD is limited in its ability to order action choices since most choice sets will have few alternatives whose cumulative probability functions do not cross. Intuitively, this makes sense because FSD represents the class of all decision makers (all possible increasing utility functions) and can reject an action choice as having a lower expected utility only if all individuals agree.

Mathematically, the decision rules for FSD can be stated as

Cumulative probability function F(x) stochastically dominates cumulative distribution G(x) in the first degree if

2.10 $G(x) - F(x) \geq 0 \ \forall \ x \in [0,1]$.

Second Degree Stochastic Dominance

The inability of FSD to discriminate between alternative action choices resulted in large efficiency sets and high Type II errors. To improve on this efficiency criteria, Second Degree Stochastic Dominance, SSD was developed. It imposes the same restriction on the first derivative of the utility function as FSD, $U'(x) > 0$. In addition, it also places a restriction on the second derivative: $U''(x) < 0$. It identifies the class of all risk averse decision makers. On one extreme, it includes the decision maker following the maxi-min decision rule while on the other extreme, it includes the risk neutral individual as well. However, no convex utility functions ($U''(x) > 0$) which indicate risk loving behavior are included in this interval.

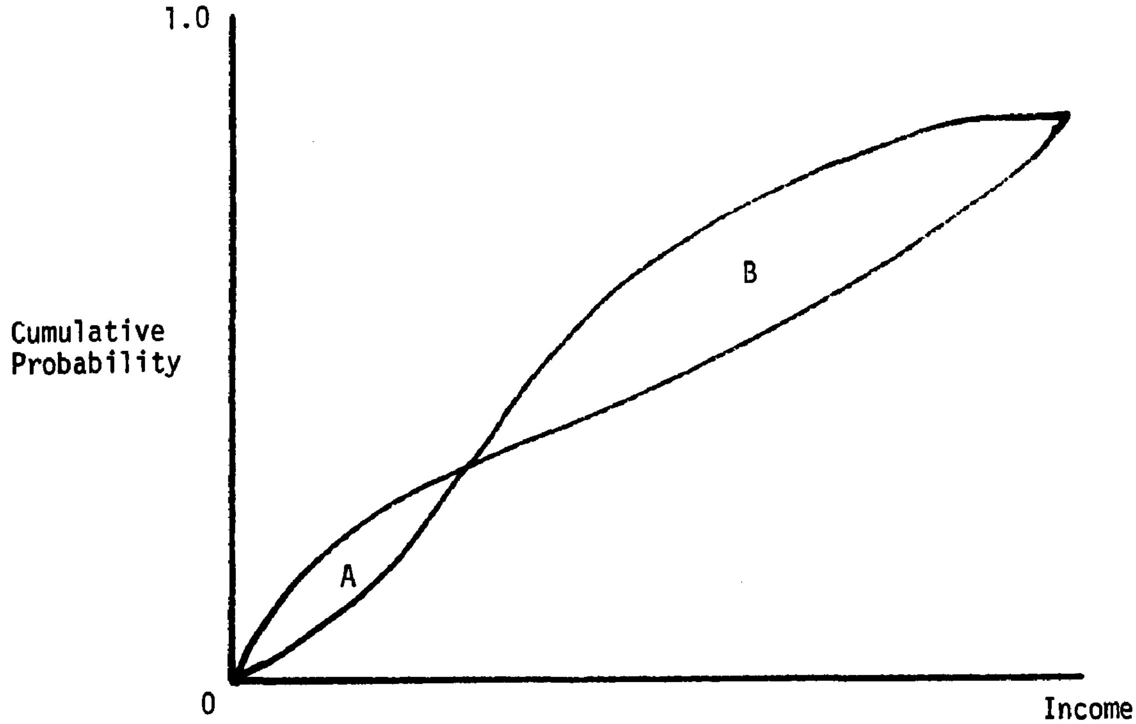
This criteria is expected to produce large efficiency sets although they should be smaller than the sets identified for FSD. The probability of Type II error remains large because of the difficulties of reaching a consensus in the comparisons of expected utilities of action choices for a diverse group of decision makers. The preferences represented by this interval range from the maxi-min individual on one extreme to the decision maker who approaches risk neutrality on the other. It should be difficult to get these individuals to concur on rankings.

In addition to the high probability of a Type II error, there is a possibility of a Type I error as well with this efficiency criteria. Since it excludes the possibility of any risk loving behavior, it may reject an efficient action choice for any decision maker with a convex portion of the utility function. The probability of a Type I error will depend on the choice set and the actual risk attitudes of the decision makers in the study.

With SSD it can be demonstrated that one action choice (F) has a higher expected utility than another (G) if the area under the cumulative probability distribution of F never exceeds the area under cumulative probability distribution of G and for at least some income level, G is above F. All action choices which are risk efficient for SSD are also risk efficient for FSD but not necessarily vice-versa.

An example is presented in Figure 4. In 4a, F does not dominate G because area A is not greater than area B. In 4b, F just the opposite result is observed. F is preferred to G since the area A is greater than the area B. Intuitively it should be obvious that A must be equal to or greater than B for F to dominate G because we know that the marginal utility is declining ($U'(x) > 0$; $U''(x) < 0$). If A and B were equal, the utility of each unit of income in A is greater than the utility of each unit of B and the expected utility of F is greater than that of G. On the other hand, if A were less than B, the two restrictions imposed on the utility function by SSD are inadequate to prove that F has a larger expected utility than G.

One additional point is made about SSD. For F to be preferred to G, at the lowest income level where the two cumulative probability distributions are not equal, F must lie below G. If this condition is not met, SSD cannot demonstrate that F is preferred to G regardless of the areas under the cumulative probability functions. This is referred



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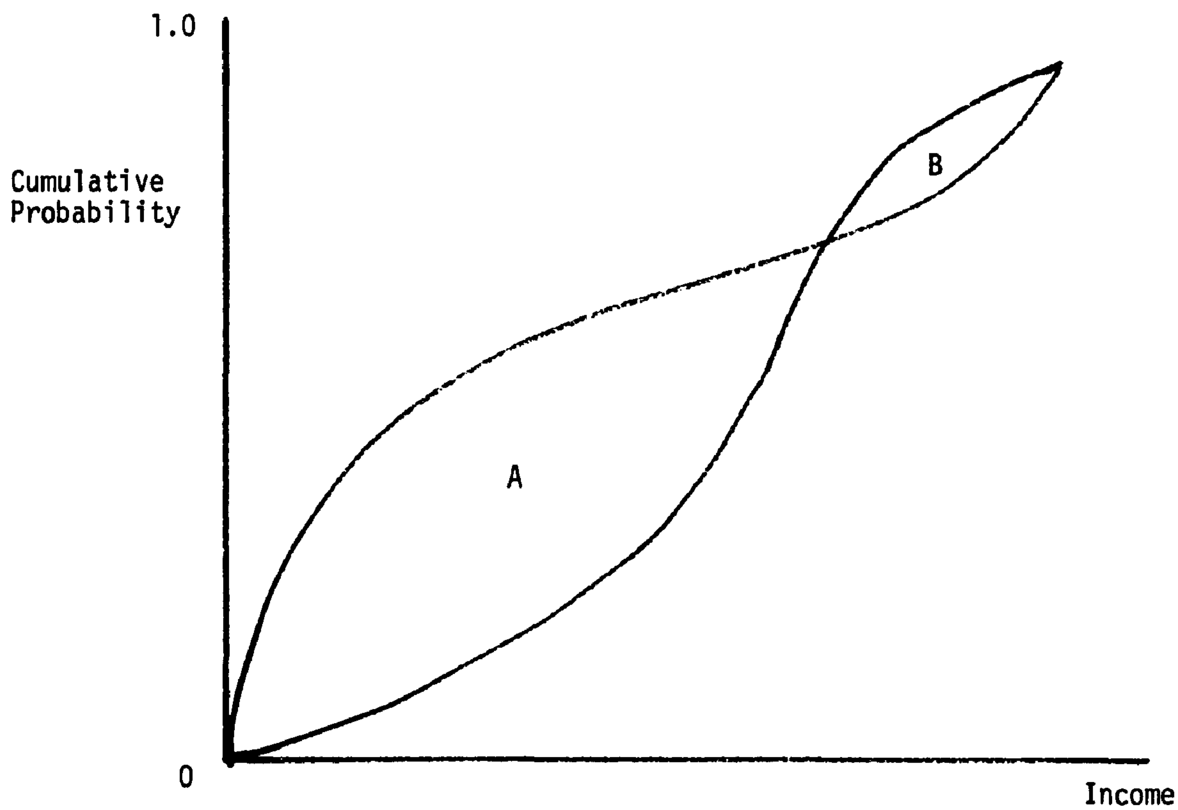

b

Figure 4. Second Degree Stochastic Dominance and Cumulative Probability Functions.

to as the left hand tail problem and results from the inclusion of the maxi-min individual in the class of decision makers. Since SSD requires a consensus amongst all decision makers in the class for F to be declared as preferred to G, any action choice which does not meet this condition will not be preferred by the maxi-miner and hence cannot be rejected from the efficiency set.

The mathematical description of the decision rule of SSD is as follows:

F(x) stochastically dominates G(x) in the second degree if

2.11 $\int_0^y [G(x) - F(x)]\, dx \geq 0$ for all $y \in [0,1]$.

Third Degree Stochastic Dominance

The next efficiency criteria to surface was Third Degree Stochastic Dominance, TSD (135). It refines the efficiency set identified by SSD as imposing a third restriction on the utility function. In addition to the previous restrictions ($U'(x) > 0$; $U''(x) < 0$), TSD requires that the third derivate be positive $U'''(x) > 0$. This interval represents the the class of risk averse decision makers whose risk aversion is diminishing as income increases. It reduces the probability of the Type II error but maintains the same possibility of a Type I error as SSD. TSD is not frequently used because of the lack of a theoretical justification for its assumptions on the shape of the utility function. There is no conclusive evidence to suggest that most decision makers in fact, exhibit diminishing risk aversion (81, 113). Furthermore, for many choice sets, TSD may produce the same efficiency set as SSD.

Stochastic Dominance with Respect to a Function

The next development in the Stochastic Dominance efficiency criteria produced a more flexible procedure where the restrictions on the utility function are not necessarily rigidly set by assumption, but can be set to reflect actual preference measurements as well. Stochastic Dominance with Respect to a Function,[1] SDWRF (85, 87) allows the setting of the upper and lower bounds that define the risk preference interval at any level. Rather than expressing the restrictions in terms of the derivatives of the utility function, it uses the Pratt absolute risk aversion coefficient, R(x).

The Pratt absolute risk aversion coefficient was developed as a measure of risk preferences which is unaffected by positive linear transformations. As stated earlier, since utility functions are constructed using an arbitrary origin and unit of scale, it is not valid to make comparisons of utility values between decision makers. To categorize decision makers by their risk preferences requires a measure which is not influenced by the arbitrary origin and unit of scale or by positive linear transformations. A possible measure is the size of the risk premium. A more general measure which is consistent with the risk premium measure is the Pratt absolute risk aversion coefficient defined as:

$$2.12 \quad R(X) = -\frac{U''(X)}{U'(X)}$$

where U(X) is the utility function of income X (101).
This measure contains all the useful information about the risk preferences but eliminates everything arbitrary about the utility function. It can be considered a measure of concavity of the utility function at X (and hence is consistent with the risk premium measure) but is unchanged--

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[1]There are two versions to this problem, a closed form solution and an optimal control algorithm. Meyer originally designated the former as Stochastic Dominance with Respect to a Function and the latter as Choice Between Distributions. The optimal control formulation is now commonly known as Stochastic Dominance with Respect to a Function.

like behavior--when the utility function is multiplied by a positive constant. The latter feature is not obtained if alternative measures like $U''(X)$ or the curvature of the function, $U''(X)\ (1 + [U'(x)]^2)^{-3/2}$ are used.

The Pratt risk aversion coefficient can be used for risk neutral, risk averse and risk loving attitudes. Positive coefficients indicate risk aversion while negative coefficients represent risk loving behavior. A coefficient equal to zero denotes risk neutrality. It can be expressed as a function of income and handle diverse preferences like the Friedman-Savage utility, i.e., it can capture the decision maker which is sometimes risk averse, risk neutral and risk preferring over the domain of values. It should be remembered that the measure is actually a function of income as in the case of utility functions.

SDWRF is a procedure where the utility functions (decision makers) represented by the risk preference interval are bounded by an upper and a lower risk aversion, $r_1(x)$ and $r_2(x)$ respectively. The expected utilities are compared in a pairwise fashion which necessitates the consensus by all decision makers. SDWRF is a systematic search process where the utility function within the interval that is most likely not to prefer F to G is identified. If it can be said that for this utility function the expected utility of F is still greater than the expected utility of G, then it is known that F is preferred by the entire class of decision makers. This procedure is in essence used by FSD, SSD and TSD as well and is the reason that all stochastic dominance techniques discussed so far require that a consensus on the ranking of action choices be met before any alternative is rejected from the efficiency set.

SDWRF is really a general version of the earlier stochastic dominance efficiency criteria. If $r_1(x)$ and $r_2(x)$ are set equal to positive and negative infinity respectively, SDWRF becomes FSD and its interval will represent the class of all decision makers.[1] If $r_1(x)$ and $r_2(x)$ are set at zero and positive infinity respectively, SDWRF will identify the same efficiency set as SSD. These relationships are displayed in Figure 5. It should be remembered that SDWRF can use values for $r_1(x)$ and $r_2(x)$ that can vary with income and that can define intervals of different widths.

The relative probabilities of Type I and Type II errors are related to the width of the risk preference interval. The wider the interval a larger Type II error would be expected. The narrower the interval is, the larger will be the expected Type I error. SDWRF is flexible in regard to the Type I and Type II errors since the interval can be adjusted to meet the needs of the researcher.

Efforts to document the size of the relative Type I and Type II errors of the various utility measures have demonstrated that, as expected, the size of the errors is related to the width of the interval (74). The single valued utility function accurately predicted the rankings of action choices 65% of the time while SSD was accurate 98% but only was able to order 7% of the action choices. SDWRF with intervals of various widths produced a range of accuracy from 98% to 72% and a percentage of choices ordered that ranged from 9% to 91%. An inaccurate prediction of orderings reflects a Type I error and an inability to order the action choices represents a Type II error. These results are presented in Table 2.

The mathematical representation of SDWRF is contained in Meyer's theorem (85):

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[1] This can be seen by reviewing the restrictions of FSD: Since $U'(x) > 0$ and $U''(x)$ is unrestricted, $r(x) = U''(x)/U'(x)$ could be positive or negative infinity depending on $U''(x)$.

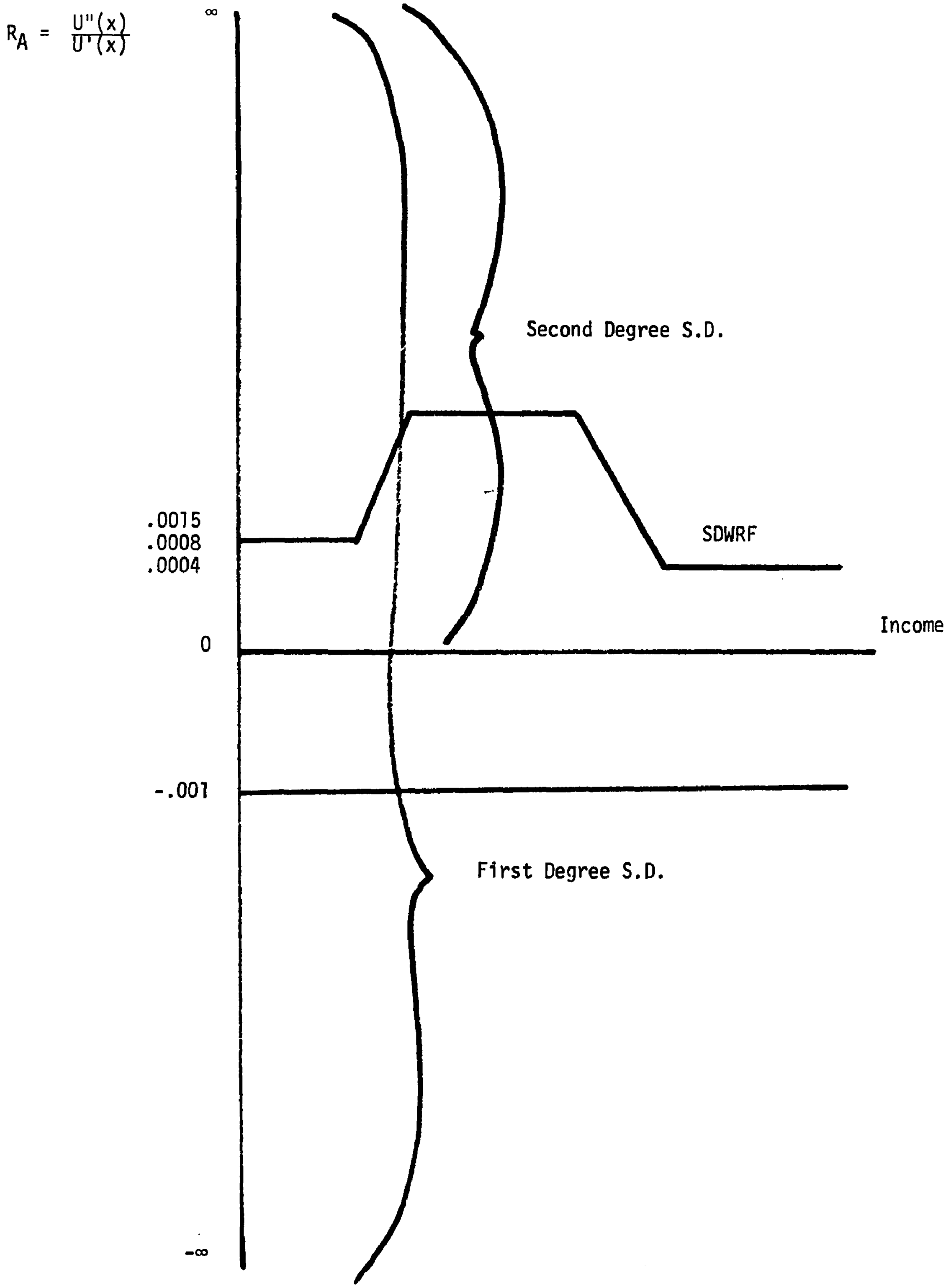

Figure 5. Risk Preference Intervals for Various Stochastic Dominance Techniques.

Table 2. Performance Indicators for Alternative Preference Measures.

Performance Indicator	Interval Measurement: Number of Questions 1	2	3	4	Single-Valued Utility Function	First-Degree Stochastic Dominance	Second-Degree Stochastic Dominance
1. Percentage of choices predicted correctly	98	88	78	72	65	100	98
2. Percentage of choices ordered	9	50	83	91	100	0	7

SOURCE: King and Robison. "Measuring Decision Maker Preferences." American J. Agr. Econ, Vol. 63, No. 3, p. 519.

An optimal control $-U_o''(y)/U_o'(y)$ which minimized

2.13 $\int_0^1 [G(y) - F(Y)]u'(y)dy$[1]

subject to

2.14 $r_1(y) \leq [u_o''(y)/u_o'(y)] \leq r_2(y)$

2.15 $$-\frac{U_o''(y)}{U_o'(y)} = \begin{cases} r_1(y) \text{ if } \int_y^1 [G(x) - F(x)]U_o'(x)\,dx < 0 \\ r_2(y) \text{ if } \int_y^1 [G(x) - F(x)]U_o'(x)\,dx \geq 0 \end{cases}$$

Convex Set Stochastic Dominance

A most recent advance in the area of Stochastic Dominance efficiency criteria relaxes even further the necessity of obtaining precise measures or risk preferences (or the utility function). Convex Set Stochastic Dominance, CSD, (39, 86, 80) can be used to refine the efficiency sets identified by FSD, SSD, TSD or SDWRF. It can be used to further discriminate between the expected utilities of the action choices without imposing further restrictions on the utility function (narrowing the risk preference interval). It can accomplish this by relaxing the previous requirement that a concensus of all the decision makers is necessary to reject an action choice as being risk inefficient. With FSD, SSD, TSD and SDWRF, if the interval identified a class of two decision makers, A and B, and A preferred action choice 2 to 1 but not 3 to 1 while B preferred action choice 3 to 1 but not 2 to 1, it was impossible to reject action choice 1 from the efficiency set. Since every decision maker does not prefer some alternative to 1, even though there is no concensus, with CSD it <u>could be rejected</u> as risk inefficient since it does indeed have a lower

[1]This result can be from comparisons of expected utilities: $\int_0^1 f(y)u(y)dy - \int_0^1 g(y)u(y)dy = \int_0^1 [f(y) - g(y)]\, u(g)dy$ and integrating by parts, $[F(y) - G(y)]\, u(y) \Big|_1^0 \quad \int_0^1 [F(y) - G(y)]U'(y)dy = \int_0^1 [G(y) - F(y)]u'(y)dy$ since $[F(0) - G(0)]$ and $[F(1) - G(1)] = 0$.

expected utility than some alternative for everyone in the class. CSD is unique of the efficiency criteria in that it identifies an efficiency set which contains only the action choices that at least one decision maker would actually prefer from the choice set and removes all alternatives that no one would select.

CSD is able to relax the consensus requirement because rather than comparing two action achoices (F and G) in a pairwise fashion, it compares one action choice G, to a convex combination of several other, F_i. Each F_i that remains in CSD efficiency set will be the action choice with the highest expected utility for some utility function in the interval. The use of CSD is a two stage process where an efficiency set is identified for the relevant risk preference interval (using either FSD, SSD, TSD or SDWRF) and then CSD is applied to further reduce the number of efficient choices. This can be done since no action choice which is inferior to the entire group would be preferred by any single decision maker in the class so any F rejected in the first stage will not appear in the optimal F_i.

Graphically, CSD can be depicted as a process which constructs a convex combination of the F_i distributions weighted by a λ that will dominate G. The idea is to discover the λ which will produce the combination that is as far to the right as possible for each probability level. That is to say that the ideal combination is the one that has the highest possible income for each probability level. It should be remembered that λ is a constant and cannot vary in income. In Figure 6 it can be seen that no combination could lie to the right of the bottom of the OABC of the envelope OABCDO. Feasible values for λ will depend upon the risk preference interval being used. For FSD, the selected λ will have to produce a combination of F_i which never lies

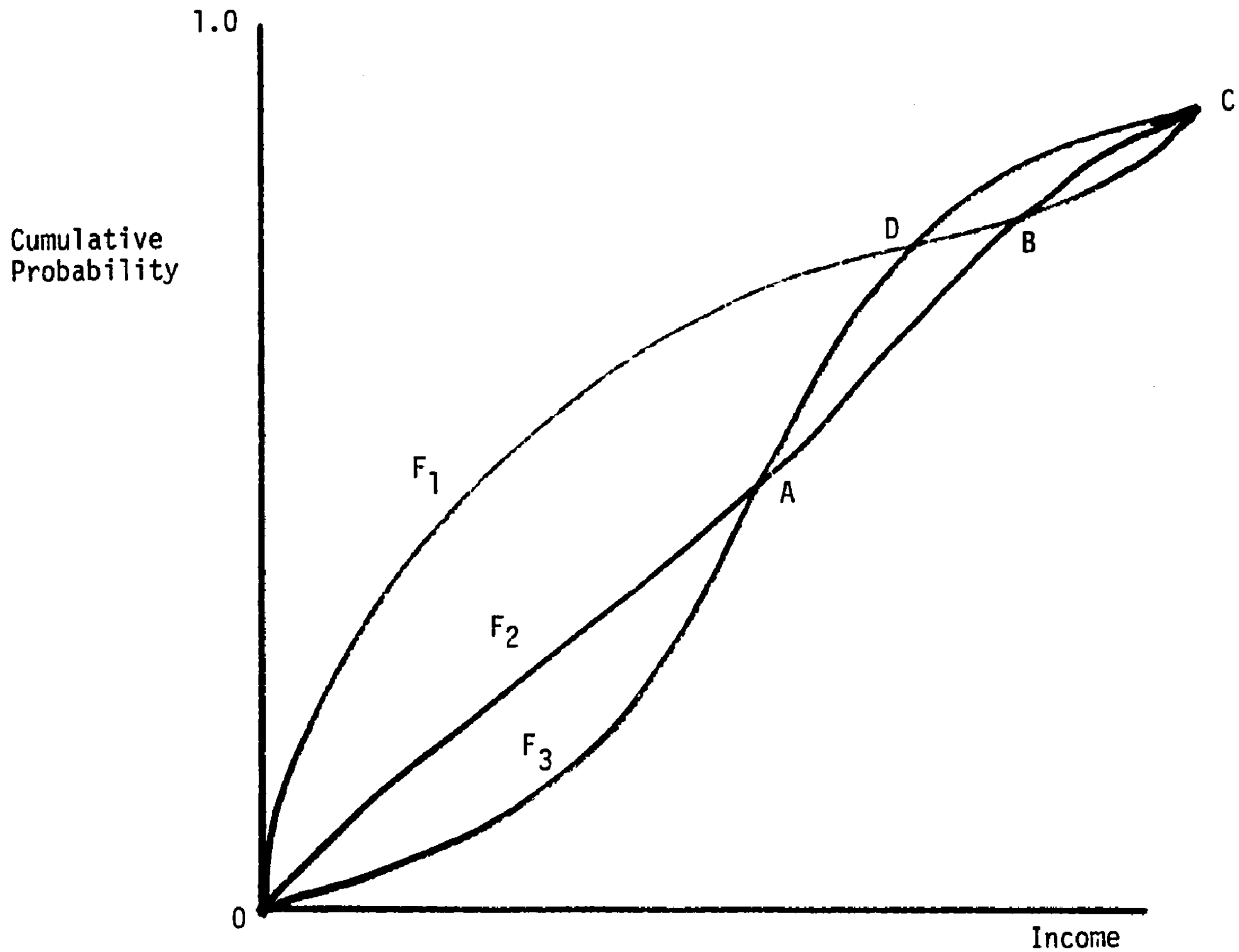

Figure 6. The Envelope of Curves for Convex Set Stochastic Dominance.

above the distribution G and for some income level the combination must be below G. For SSD, the selected λ will need to result in a cumulative probability function whose area is less than the area of G and which has no left hand tail problem.

The difficulty in implementing CSD is identifying the smallest set of F_i and developing a systematic searching process for discovering a feasible λ out of the set Λ_n. An iterative process of reducing the first stage efficiency set is necessary to test whether the set of F_i excluding F_j can dominate $F_j(G)$. A discussion of an operational algorithm to perform CSD can be found in Cochran, Lodwick and Robison (25).

In summary, the implementation of the EUH has been facilitated greatly by the recent advances in preference measurement (74) and of efficiency criteria. These developments enable the prediction of rankings of alternative action choices for classes of decision makers without requiring exact measurements of the utility functions. This greatly enhances the accuracy of the EUH and increases its usefulness for predictive and prescriptive purposes.

2.6 Economic Thresholds

A key component of many IPM programs are decision rules employing the concept of the economic threshold. This concept is a process where information on the pest population levels is used as an indicator of the need for some control and the appropriate time to begin that control. The identification of such threshold population levels has been the focus of research from a variety of disciplines such as entomology, botany, plant pathology, animal science and agricultural eocnomics. The development of this research spans some twenty to thirt years.

Vernon Stern in his article "Economic Thresholds" (135) credits Shortwell as being the first to establish a relationship between the population density of a pest and potential crop damage. Stern, et al. (135) originally consolidated the biological and economic variables into a concept known as the economic threshold. These authors begin by defining economic damage as the amount of injury that will justify artificial control measures. The economic injury level is the "lowest population density that will cause economic damage," and finally, the economic threshold is defined as "the density at which control measures should be determined to prevent an increasing pest population from reaching the economic injury level."

Edward and Hueth (36) refined the concept to arrive at their definition of the economic threshold as the pest popualtion large enough to cause damages valued at the cost of practical control.

The concept was put into the framework of marginal economic theory by Headley (51). He developed a simple model with a pest population growth function, a pest damage function, a crop yield function and a control cost function. The model determines the economic threshold at the population level where the marginal benefit derived from the pest control program is equal to the marginal cost of realizing that population through the pest control program. This, of course, is the traditional optimizing criteria for the use of any input.

Further refinements were made to the basic Headley model by a number of authors such as Hall and Norgaard (48), CArlson and Main (19), Hueth and Regev (62), Regev, Gutierrez and Feder (107), Talpaz and Borosh (138), and Talpaz and Frisbie (140). Most of these improvements result from including more variables in the basic Headley framework and/or application of more sophisticated methodological procedures. Hueth and Regev merit special mention here since their definition of the economic threshold is the most complete. It is defined as the level of input (control) usage that equates the sum of the marginal benefit from increasing the potential plant product in the future, the marginal benefit from decreasing the pest population density now, and the marginal benefit from decreasing the pest population density in the future with the sum of the marginal costs of materials, the marginal costs of increasing pest resistance to chemical input and the marginal costs of additional inputs needed in the future due to resistance to maintain some level of control.

Headley (52) presented the importance of consideration of risk and intertemporal cumulative effects in the determination of the economic threshold. He constructs a technique which permits the derivation of the expected benefits from a pest control in a dynamic, decision tree framework. Newton and Lueschner (91) also incorporate the probability of various outcomes occurring for different actions and while they propose the use of an utility scale for cases where monetary values are difficult to obtain, they really do not extend their analysis beyond a maximum expected returns decision rule.

Explicit recognition that in addition to expected returns, risk can also influence farm level pest management decisions dates at least to Carlson (16) and Hellebrant (56). Although Carlson did not directly examine the impact that the consideration of risk has on the economic threshold, he did introduce several firm objective functions that incorporate risk into a decision maker's utility function used to evaluate alternative spraying strategies to control brown-rot of peaches. By refining his definition of control strategies to focus on the economic threshold, Carlson could have determined the impact that risk could have on the threshold for each of the given objective functions. He did recognize though that the expected returns analysis is simplistic and ignores the insurance aspects of pest controls and the risk aversion of decision makers.

Two other attempts to incorporate risk into the pest management decision framework are the works of Carlson (18) and Feder (38). Carlson presents a production function that could be used to maximize expected income or expected utility when utility is expressed in terms of the mean and variance of the pest damage function. This production function is:

2.16 $Y = P_y\, Q^*(1-q) - P_x X - P_l L - F$

Where: Y = firm's net returns

Q^* = potential crop yield without pest damage

X = quantity of chemical pest controls

L = quantity of non-chemical pest management resources used

P_x = price per unit of X

P_y = price per unit of Y

P_l = price per unit of L

F = fixed costs

q = percent of potential crop lost to pests

and

$$(1-q) = S = S(X,L,R,\Theta)$$

where Θ and r are random variables denoting respectively pest numbers and pest types.

$$\partial S/\partial X > 0 \qquad \partial S^2/\partial X^2 < 0$$

$$\partial S/\partial L > 0 \qquad \partial S^2/\partial L^2 < 0$$

and $E(Y) = P_yQ^*[1-E(q)] - P_xS - P_1L - F$

$$\sigma^2_y = [P_yQ^*]^2 \quad \sigma q^2$$

Using this production function and a general utility function where $\partial U/\partial y > 0$ and $\partial U/\partial \sigma^2 y < 0$, Carlson concludes that such inputs as monitoring and informational services should reduce the variability in Y and hence increase the utility.

Feder (38) uses a production function similar to that of Carlson. His function is:

2.17 $\Pi = (\Pi_0 - C_0) - \delta N[1 - k(x)] - cx$

Where: Π = profits

C_0 = fixed costs

δ = damage per pest

N = size of pest population

k(x) = kill function

x = pesticide

cx = cost of pesticide treatment

Feder assumes a concave utility function,[1] depicting risk aversion on the part of the farmers and concludes that the objective is the maximization of expected utility as follows:

2.18 Max EU $(\Pi_0 - C_0) - \delta N[1 - k(x)] - cx$

He then sequentially considers the impact of allowing δ, N and k to be stochastic variables. He shows that increases in the variances of N and δ while maintaining their means at initial levels will increase pesticide use and lower the economic threshold. The case of the effectiveness of the pesticide is more difficult since the variance is likely to be heteroskedastic. Feder identifies two situations: a) the variance

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[1]A concave utility function is defined by $\partial U/\partial y > 0$ and $\partial U^2/\partial y^2 < 0$ and implies risk aversion.

in pest response to the pesticide declines for higher dosages; and b) the variance increases with the dosage. For the first situation, the increase in uncertainty increases the pesticide usage and decreases the economic threshold. In the second case, the use of the pesticide will decrease and the economic threshold will increase as the variance in k increases.

Most attempts to measure the economic threshold either do so under the assumption of certainty or rely on the expected returns criteria to handle risk. Consequently, they simplify the decision making process to such an extent that they likely derive misleading results in many cases. Feder and Carlson have extended the discussion into the realm of expected utility analysis but have imposed only general conditions (risk aversion) on the utility function. In the fields of economics and management science, recent advances in implementation techniques of EUH have evolved which should have a great potential to strengthen the existing work not only in the determination of the economic threshold but in the overall realm of pest management decisions.

Combining the insights of the work of Pope and Just (99) on the appropriate form of the production function with the Feder pest management model, the influence that risk and risk preferences will have on the economic threshold can be clearly demonstrated. Furthermore, the influence that changes in the input price and the output price will have on risk efficient thresholds can be explored as well.

A profit function can be formulated to include the risk of pest damage as follows:

2.19 $\pi = p(f(x) - dN\,\varepsilon(1-k(z)) - p_x x - p_z z - B$

where π = profit

p = profit

x = variable inputs

d = damage per pest

N = pest population density

ε = random element

$k(z)$ = kill function

z = pesticide

P_x = price of variable inputs

P_z = price of pesticide

B = fixed costs

and ε is assumed to have a distribution of 1 and σ^2.

This model conforms to the form of the Pope and Just (99) production function since $f = f(x)$ and $h = -dN\varepsilon(1-k(z))$. The expected profits for the function can be expressed as

2.20 $E(\pi) = p(f(x) - dN(1-k(z)) - P_x x - P_z z - B.$

The certainty equivalent can be derived using $\lambda/2$ as the expected profit-variance of profit trade-off at equilibrium. It is:

2.21 $$CE = p(f(x) - dN(1-k(z)) - P_x x - P_z z - B - (\lambda/2)\,[pdN(1-k(z))]^2\sigma^2.$$

The model now has two control variables x and z, with the latter being the risk reducing input which in this case is the pesticide. The first order conditions with respect to x and z are:

2.22 $\partial CE/\partial x = p'(x) - px = 0$

2.23 $\partial CE/\partial z = tpdNk^1(z) - P_z + \lambda pdN(1-k(z))k^1(z)\sigma^2 = 0.$

The output decision is independent of the pest control decision. The pesticide is applied until the cost of the pesticide is equal to the value of the reduction in profit variability and the reduction in expected profit. It should be noted that this point will depend upon the risk preferences of the decision maker. This can be clearly demonstrated by rewriting the first order condition as:

2.24 $\lambda pdN(1-k(z))\, k'(z)\sigma^2 + pdNk'(z) = P_z.$

The greater λ, the more risk averse the decision maker will be and more value will be placed on the risk reducing capabilities of the pesticide. So $dz/d\lambda$ should be positive and totally differentiating the above first order condition proves this hypothesis. This result appears below.

2.25 $$\frac{dz}{d\lambda} = \frac{-pdN(1-k(z))\, k'(z)\sigma^2}{[(\lambda pdN\,(1-k(z))\, k''(z)\sigma^2 - \lambda pdNk'(z)^2\sigma^2 + pdNk''(z)]} > 0$$

where $k''(z) < 0$

$pdN(1-k(z)) > 0$

$k'(z) > 0$

$\sigma^2 > 0$

$\lambda > 0$

The economic threshold can be determined by searching for the point when the application should begin -- where the marginal costs are equal to the marginal benefits. This point is found by setting z equal to zero and resolving the first order conditions.

2.26 $dNk''(0) - P_z + \lambda pdN(1-k(0))\, k'(0)\, \sigma^2 = 0$

2.27 $$\frac{P_z}{dk'(0) + \lambda pd(1-k(0))\, k'(0)\, \sigma^2} = N$$

It is hypothesized that as the cost of the pesticide increases, the economic threshold will decrease. The differentiation of the equation defining the economic threshold supports this claim. The sign of dN/dP_z is negative.

2.28 $$\frac{dN}{dP_z} = \frac{-p_z\, \partial\lambda/\partial E(\pi)^* \frac{\partial E(\pi)}{\partial Px}\, pd(1-k(0))\, k'(0)\, \sigma^2}{dk'(0) + \lambda pd(1-k(0))\, k'(0)\sigma^2} > 0$$

A similar procedure can be used to derive the impact of product price changes on the economic threshold. The relationship between the latter and the former will be positive.

$$2.29 \quad \frac{dN}{dp} = \frac{-P_z \ \lambda d(1-k(0)) \ k'(0)\sigma^2}{[dk'(0) + \lambda pd(1-k(0) \ k'(0)]^2}$$

These analytical results will be extremely useful in guiding the empirical experiments designed to test the correspondence to reality of the hypothesis.

2.7 The Economic Threshold as an Investment Problem

The theoretical basis of the definition of the economic threshold needs to be extended for other reasons as well. A discussion of the deficiencies and a suggested improvement is presented here based on reformulating the question as an investment problem. The new theoretical foundation should also be useful in handling multi-pest economic thresholds and decision rules guiding resistance management strategies. The economic threshold is an approach to developing decision rules for pesticide applications based on the observed pest population, the choice criterion usually being to maximize profits. It attempts to determine the density level when chemicals should be applied that profit has been maximized.

The concept of the economic threshold has been used in a prescriptive manner to guide the development of IPM strategies. It has been based on a maximization principle that may not be validated for this application. Therefore, the predictions which are generated from this model may not be credible. Refinements in the definition of the traditional concept may be necessary to increase the credibility of the models that implement it.

Stern (122) was the first to operationalize this concept. His system defined the economic injury level to be the population density level at which damage caused by the pest exceeds the cost of controlling it. The economic threshold is the population density level at which the pest must be controlled to prevent it from reaching the economic injury level.

Since the Hillebrandt (49) article on pesticide usage, economists have typically approached the problem of optimal pest control with marginal analysis. Headley (44) converted the terminology of the entomologist into the framework of marginal analysis when he defined the economic threshold as that pest population density level where the marginal benefits are equated with the marginal costs of the pest control program. Subsequent authors such as Hall and Norgaard (41) and Hueth and Regev (53) have defined the costs and benefits more rigorously while still applying marginal analysis to determine the economic threshold. Other authors have moved into the realm of simulation models that search for economic thresholds which maximize an objective function in terms of profits. While these models recognize the dynamic nature of the problem, they do not directly address the analytics of how to determine the economic threshold, instead they rely implicitly on the results of marginal analysis. Talpaz and Borosh (125), Talpaz, Curry, Sharpe, DeMichele and Frisbie (126) and Shoemaker (115, 116, 117) all exemplify this approach.

The logic of marginal analysis is not something that can be universally applied. It is an analytical procedure that is appropriate when inputs are divisible in acquisition and use and where time is not an important consideration.

Most inputs are acquired and used in one time period; and, they can often be acquired and used in divisible amounts. There are other inputs that provide services for more than one time period and may only be obtained in lumpy quantities, but whose services are available in divisible amounts. Those assets which provide services in more than one period we define as durables. The distinguishing feature of durables is not their indivisibility in either acquisition or use but that they are not "used up" in one time period. As such they carry costs that change with time as well as with use. It should be obvious then, that the distinction between durables and non-durables depends upon the length of the time period. The longer the time period, the fewer will be the inputs that are durables. The definition of the time period is not arbitrary but should reflect the rate of change of important variables in the decision environment. Often economists define time periods on the basis of how frequently prices change. While this is convenient for many cases, there are other important factor changes that should also be considered. In pest management, the scouting interval, or the time between pest monitors may be an appropriate time period.

Traditional marginal economic analysis considers only the costs and benefits that change directly with input usage and because it considers only costs and benefits in a single period, costs associated with time do not enter in. If a situation arises that for an input whose services last more than one time period, there are changes in costs and/or benefits that result from the passage of time, rather than input usage, traditional marginal economic analysis will be an inappropriate way to find optimal input usage. Marginal analysis also assumes that all inputs are divisible in acquisition when for many inputs that is not the case. Analysis of inputs which are not divisible in acquisition is not easily handled by traditional marginal economics.

Costs and benefits may change with the passage of time in two ways -- through the time value of money[1] and through any changes in values and durable input productive capacity that follow a time related pattern and influence such decisions as optimal rates of use and replacement schedules. There are a number of costs that must be identified to solve an investment/disinvestment decision which may not surface in a recognizable fashion with a traditional marginal economic analysis. These costs can be categorized as the inventory control costs, direct user costs, capacity time costs, time depreciation costs, indirect user costs and replacement opportunity costs (102).

The capacity of a durable to provide services is often exhausted as the durable is used and as time passes. The value of lost capacity or each factor is considered a cost. Losses that result from use are direct user cost while those losses associated with the passage of time are capacity time costs.

Since a durable lasts more than one period, there are resources committed to it that could have been used in an alternative activity. The value of these resources (the remaining capacity) need to be charged an opportunity cost equal to the rate of return possible in the most productive alternative. This opportunity cost is the inventory control cost.

After acquisition, the value of the durable that should be used in cost calculations is the market or salvage value, since it should

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[1]Since each time period is a fraction of a season, the time value of money will not be too relevant in the definition of the economic threshold.

reflect the expected present value of the remaining services. Changes in the salvage value can be attributed to two sources--changes in its productive capacity and changes in the price per unit of the productive capacity which may result from the irreversible nature of the investment, the market structure or changes in the demand for the services generated by the asset. The loss of capacity due to use and time have been attributed to direct user costs and capacity time costs, but changes in the per unit price of the capacity are not included in these costs. These costs which reflect changes in market prices due to differences between acquisition and salvage values and due to changes in the demand for the asset's services are <u>time depreciation costs</u>.

When the asset in question is one of a series that may be replaced to provide a stream of services beyond the lifetime of any one durable, there are two additional costs that have important time components. First, the acquisition date and the size of the first durable can influence the costs and benefits of the subsequent durables in the series. Secondly, the option of replacing the first durable when its productive capacity has been reduced by time and use with a new second durable, imposes an opportunity cost of returns foregone that should be considered in management decisions of the first durable.

The decisions about the size, rate of use and if capacity declines with time, the date of establishment of the first durable can impact on the costs and benefits of future durables. These impacts become more and more relevant when the future costs and benefits are changing with time. As the economic life of the first durable is lengthened or shortened and since the costs and benefits of the future durables are a function of time, the life (size) of the first durable influences the net returns of future durables. The management decisions of the first durable should include these impacts. If the influences on the benefits and costs of future durables can be viewed as being favorable, these impacts can be called indirect user benefits while if they are unfavorable they are indirect user costs.

The replacement opportunity cost is a measure of the potential loss that might result when a durable is retained too long. Even though one durable may still have some productive capacity remaining, the returns from using the remaining capacity may be smaller than the returns expected from the replacement. The postponement of receiving the returns from the new durable is referred to as the replacement opportunity cost. The decision rule to determine the optimal replacement date is replace the first durable when the net returns in the last time period are less than the annualized average returns over the life of the second durable (87).

The Durable Asset Nature of Pest Control

In the case of pest management, it is not clear that the determination of the economic threshold is a problem that can be solved by traditional marginal economic analysis. Rather than considering the entire season as a single period and sprays as variable inputs within that period, it appears that there are enough interactions between sprays and population dynamics from one part of the season to another that it becomes justified to consider the season as a series of decision periods and that the sprays are really durable assets that generate services which last longer than one period. Assuming that the scouting interval has already been optimally determined, the points in time when a farmer is faced with information about the pest population and he must make a spray/no spray decision can define the time periods. So for a 25 week season with a scouting interval of once a week, a season would consist of 25 time periods.

The problem also exhibits some of the other characteristics of investment problems in that some benefits and costs change as a function of time. The pest population, the plant condition and the attenuation of the chemicals are all a function of time and weather (which has a time related pattern). So the value of the spray is going to be dependent on time, through its influence on the pest population, the plant condition and the rate at which the chemical attenuates. Furthermore, since throughout the season usually some services (protection) are required and very rarely will one spray generate enough services for the entire season, the spary schedule is a durable replacement problem. The decision criteria should focus on the application (or investment) pattern of the series of sprays needed during the season not the optimal use of any one spray independent of its relation with others.

Traditional marginal economic analysis provides a synthetic solution to the problem of determining optimal input use patterns. However, the problem of determining the economic threshold is in reality not a question of the optimal rate of use of a variable input but one of determining the optimal size of a durable input and the optimal time to replace one durable with another. A dynamic investment theory is necessary to adequately address the problem. The rate of use of the spray is not under the control of the farm manager. It is the chemical attenuation rate which is basically a function of time and weather. The manager is in actuality concerned with when it is he should spray and the dosage he should apply.

Returns from Sprays

The returns from the use of the durable (spray) are directly associated with the value of the services extracted. In the case of a pesticide, the services are the avoidance of damage that would have been caused if the control had not been applied. The services are generated through time in two ways. First, in the application period there is an actual reduction in the pest population. Depending upon the chemical attenuation rate, the active ingredients of the pesticide may also reduce the population in some periods subsequent to the application. The damage avoided by the actual number of pests killed by the chemical is the first way services are generated by sprays. The second way in which services are generated is by changing the growth path of pest population. By reducing the pest population in the period of the application, the population will be reduced in the following periods until it has grown to the level that it would have obtained without the spary. Simply stated, the returns of the i-th spray can be represented as the sum over time of the difference between the value of the product without the control and the value of the product with the control. Obviously, the output with and without the control will depend on the pest population in the current time period, its growth rate and the use of all other inputs like fertilizer, drainage, land, etc. Moreover, the pest population in the current time period depends on the population level in the previous time period, the weather and the killing capacity of the spray under consideration. The larger the pest population in the current time period, the faster the growth rate and the larger the killing capacity of the spray the greater will be the benefits from the chemical application.

Cost of Sprays

As discussed earlier, there are a number of costs that may change with the use of the durable (spray) and the passage of time. These costs are inventory control costs, indirect user costs, time depreciation costs and replacement opportunity costs. Many of these costs are calculated by considering both the amount of capacity remaining and the per unit salvage value of that capacity. Since the sprays are irreversible durables with zero or negative salvage value, there are no direct user costs or capacity time costs. The value change from the acquisition price to a salvage price of zero is captured by the time depreciation cost since it is not related to changes in the physical capacity of the durable to generate services but it is due to the irreversible nature of spray.

The inventory costs are the costs of maintaining resources in the durable (spray) when they could have been employed in some alternative. By assessing an opportunity cost equal to the return in the best alternative, it is assured that those resources are invested in the most profitable option available. The acquisition price of the spray is the cost of obtaining the material, and the value of the labor and machinery time used in applying it. The inventory of services held during the life of the spray is the remaining lifetime capacity of the chemical to generate services, the "avoidance" of pest damage. This capacity, of course, will depend upon the chemical attenuation rate, the dosage, the pest population, the pest population growth rate and the stage and/or condition of the plant. The inventory control cost is calculated by multiplying the value of the inventory held in each time period by the rate of return possible from the next best alternative. Since after a spray is applied its salvage value is equal to zero, the value of the inventory is zero after the first time period regardless of the remaining lifetime capacity. So, there occurs an inventory control cost only in the first period. It can be represented as the product of the following three terms: the number of units of capacity remaining, the value per unit of that capacity and the rate of return in the best alternative.

The majority of the costs of a chemical control that functions as a durable are incurred as time depreciation costs. This cost captures changes in the value of the durable due to differences between acquisition and salvage prices which are caused by factors unrelated to the physical capacity of the durable to generate services. In this case, the major cause of the decline in value from a positive acquisition price to a zero salvage value, is the irreversible nature of the spray. Since it is impossible to alter either the location or time of use of the chemical once it has been applied, the market value of the applied chemical control is zero even though the chemical may retain the majority of its services. Whereas this decline in value is not gradual but immediate, in a discrete case the time depreciation costs can be considered to occur at the beginning of the second time period. They will be equal to the acquisition price of the chemical (the cost of the materials, and the cost of the labor and machinery used to apply them) since the decline in value is equal to the drop to the zero salvage value.

Another factor of investing in inputs that last more than one period or in determining the optimal timing and size decisions for a series of durables to be used in sequence is the indirect user cost/

benefit. This cost results from the relationship between the number of sprays that may be needed and the decision on each spray as to its optimal size (dosage) and time of application. If the timing (date of establishment) and the dosage (size of the durable) of the first spray in a series of sprays increase future acquisition costs by increasing the number of subsequent sprays needed, there is an indirect user cost. However, if these decisions result in a decrease of the future time depreciation and inventory control costs, there is an indirect user benefit. To measure the indirect user cost (benefit) it is necessary to use some arbitrary standard from which increases and decreases in future costs can be gauged. Perhaps, it would be best to select a conventional calendar based spray schedule from the myriad of alternatives to serve as this standard. A conventional calendar based spray schedule of an exact number of sprays of an exact dosage[1] could be used as a base to measure how the dosage and time of application of one spray (with information on the pest population, the population growth rate, the killing capacity of the chemical and the stage and/or condition of the plant) is likely to affect the optimal number (or dosages) of subsequent sprays. If this cost (benefit) is calculated in this manner, it is likely that most monitoring based strategies will have an indirect user benefit rather than the cost but different strategies will probably have different levels of benefits. The indirect user benefit (cost) of spray s_i will be derived from the product of two terms--the change in the optimal number of sprays in the season due to changes in the time of application or dosage of spray s_i and the average acquisition price of the subsequent sprays.

[1]I.e., 10 sprays in the season, one every 14 days with a dosage of 2 lbs/acre.

Unlike most durables, the chemical pesticide sprays will not incur all of the costs normally associated with the investment/disinvestment problem. Since the salvage value of the sprays is zero after they have been applied, the capacity time costs and the direct user costs become zero (changes in physical capacity valued at zero are zero). The relevant costs in this case are the inventory control costs (in the first period), the time depreciation costs (in the second period) and the indirect user benefit (costs).

Net Returns in Each Time Period

Using the definitions of returns and costs presented earlier, it is now possible to calculate the net returns from a durable asset and determine optimal use, size and replacement decisions. The determination of the economic threshold is really an optimal replacement problem since it deals with a decision rule that guides when a new durable should be acquired. It is an attempt to use an observable pest population level as an indication of the point in time when it is more profitable to install a new durable (spray) than to continue to extract services from the existing one. When perceived as an investment problem, the process for defining the economic threshold is quite distinct from the procedures described and used in the existing literature. Rather than following the traditional marginal economic analysis of finding the economic threshold by equating the change in benefits due to changes in input (spray) usage with the changes in costs due to changes in input usage, a new procedure is necessary since costs and benefits change with both the input usage and the passage of time. In this case the economic threshold is the density level that the pest population reaches in the time period when it becomes economical to replace (spray again). Replacement of one spray with another will occur in the time period when the net returns from the first spray are less than the average net returns over the life of the second spray.

The calculations of the net returns in each time period involve several steps. First, it is necessary to identify the life of the spray by analyzing how many periods after its application it can continue to generate services (the avoidance of damage). This requires information on the weather, the pest population and its growth rate, and the chemical attenuation rate. For each period it will be necessary to estimate the benefits or the value of damage that would have occurred if the spray had not been applied. In conjunction with the calculation of the benefits, it is necessary to estimate the per period costs of the spray as well. The majority of the costs are likely to appear in the first two time periods since inventory control costs are incurred in the first period only and the time depreciation costs are charged at the beginning of the second period. There will be no direct user costs or capacity time costs, but indirect user costs (benefits) could occur throughout the life of the durable. In each period, the difference between the benefits of the spray and its costs will determine the net returns.

After the net returns in each time period have been determined, it is necessary to determine the time period in which it is optimal to disinvest in the first spray and apply a second. This optimal disinvestment period will be determined when the net returns in the last period of the first spray are less than the average returns of the second spray. This will require the solution of the problem in a fashion similar to a dynamic programming model in that the net returns of the last durable must be assumed to determine when to disinvest in the next to last spray.

The economic threshold for the s_{i+1} spray will be the level of th pest population in the time period when it is optimal to disinvest in the s_i spray. The economic threshold will then be determined by the patterns of weather, chemical attenuation, pest populations, the stage, condition and/or stress of the plant and the related prices of the product, the chemical and the labor and machinery used in the application.

Strategies using different combinations of sprays of varying dosages could be evaluated by proceeding in the same manner to identify the economic threshold for each spray and the pattern of pesticide use that maximizes each strategy's net returns across all sprays within the season. The strategies could then be compared on the basis of the levels seasonal net returns.

Approaching the determination of the economic threshold as an investment problem rather than through marginal analysis provides a more complete analytical base for research. The logic of this definition is more consistent with economic theory dealing with production situations where time is important. As such, it passes the test of internal consistency while the traditional formulation of the problem will not. Its contribution to the identification of the elements of the argument of the theoretical hypothesis lies in the explicit recognition that it provides to the importance of the passage of time. It should increase the credibility of simulation models by increasing their validation. It should facilitate the justification of the theoretical hypotheses by explicitly identifying the maximization principle to be used. It should clarify the deduction process in analytical problems while illuminating both the recognition of which hypotheses are being tested in synthetic (simulation and optimal control) and the inductive process of inference about those hypotheses tests.

2.8 Risk and the Economic Threshold

The cost of risk is related to the utility function of decision makers. It can be perceived as the way in which individual value the trade-off between expected values and variance. The cost of risk can be defined as the amount the decision makers would pay to eliminate the risk. This is a risk premium and is conceptually analogous to an insurance premium. Pratt's coefficient of absolute risk aversion (101) approximates this premium and can be depicted as:

$$2.30 \quad \pi = -\frac{U''}{U} \qquad \frac{E(X - \overline{X})^2}{2}$$

Pratt's absolute risk coefficient approximates the risk premium since the size of the premium an individual is willing to pay depends on the degree of concavity in his utility function. The more concave the utility function, the higher a premium he is willing to pay and the higher the absolute risk coefficient. Since the risk premium is the amount the decision maker is willing to pay to be indifferent between the expected value of an uncertain outcome and the certain value of a certain outcome, it can also be defined as:

$$2.31 \quad \Pi = E(y) - CE(y)$$

where E(y) is the expected value of y and the CE(y) is the certainty equivalent.

Since the determination of the economic threshold requires a production decision that optimizes input usage and it has been shown that risk adds additional costs that must be considered in optimal production decisions, calculation of the economic threshold in a certainty case may be misleading in that it is biased from the neglect of the cost of risk. The case of pest control inputs demands more attention to risk than many other classes of inputs due to the environment of uncertainty in which they are applied. The uncertainty arises from two basic sources although input price uncertainty could also be included in some cases. These sources are the product price and the production function. As Sandmo (120) describes, product price uncertainty produces optimal conditions where output is less than the production under certainty. The impact of technological uncertainty is indeterminate without examination of the production function. When both sources of uncertainty are considered simultaneously, their impact is still a priori indeterminate without some observation or simulation of the production process.

A traditional approach to estimating aggregate level marginal value products for pest control inputs is to derive them from production functions statistically fitted from historical or cross sectional data. Two examples of this type of analysis are Headley (50) and Fisher (40). Both authors have fitted the data using Cobb-Douglas production functions. Fisher estimated marginal productivities for the pest control input and the non-pest control input variables in each of three geographic areas. For the pest control inputs, his estimates are \$5.71/\$1.00 for Quebec, \$2.34/\$1.00 for Ontario and \$12.80/\$1.00 for Nova Scotia. These estimates "indicate the returns which on the average are expected from the addition of one more unit (i.e., \$1.00)" of the inputs.

Calculations of marginal benefits in this manner assumes that the pest control inputs contribute to the production of the output in much the same way that other types of inputs do, such as capital, labor, fertilizer, etc. With pest control inputs, there appears to be two situations in which they are used. The first situation is where pests and pest damage have become a regular occurrence and need to be considered as a continual factor of the crop's growing environment. The second situation results when pest infestations and damage are an infrequent but perhaps disasterous even when they occur. In the first situation, the pest control inputs can be assumed to impact on both the expected value of the output and its variance while in the second case it can be argued that only the variance is affected since these inputs do not directly help generate output--they only prevent occassional reductions under infrequent conditions.

In both situations a special form of the production function must be used. As Pope and Just (99) have described, it is inappropriate to use any of the popular forms which employ a multiplicative disturbance term. This includes such production functions as the Cobb-Douglas, the translog, the transcendental and the generalized power function. Pope and Just (99) suggest that in the case of an input whose use decreases risk rather than increasing it, a production function which is the sum of two sub-functions, one of which is related to or multiplied by the error term and the other one independent of it, is appropriate. One example of that form might be:

2.32 $Q_t = F(x) = f(x_t) + h(x_t)\varepsilon$

where $E(\varepsilon) = 0$, $f_x > 0$, $h_x < 0$.

This form of a production function allows the use of an input to both impact on the expected value of the output and decreases its variance.

The above production function is acceptable for the first situation since pest infestation can be considered a normal part of the crop's environment and pest control would be anticipated to affect both the expected value of the output and the associated variance. However, if pest infestations are so infrequent that the use of pest control has a relatively insignificant effect on the expected output but can reduce the variance, then the pest control inputs should not appear in the first sub-function (f) but remain in the sub-function (h) which is multiplied by the error term. This second case is rare for most commercial crops.

A production function which pe... .s the calculation of the effect which an input can have on the expected output and on the technological uncertainty of production will be useful in the determination of the economic threshold. Such a function will be useful in determining the marginal benefits generated by the pest control--benefits which can arise from increased crop yields or decreased risks. The decrease in risks could not be derived using the more conventional functions with multiplicative error terms.

Since the benefits now include risk, some utility consideration must be used to measure the relative value that a decision maker places on different levels of expected output with varying levels of risk. The consideration of risk introduces the utility function into the determination of the economic threshold. While each decision maker may have an unique utility function, an unique valuation of the pest control benefits and hence an unique economic threshold, there are enough similarities between utility functions that approximate solutions can be derived for groups of decision makers. Various criteria of differing degrees of restrictiveness can even be used as measures of the utility functions. King (72), King (73) and Robison and King (112) describe procedures to accomplish such an analysis.

Using the common procedures to estimate the economic threshold in a certainty context, the threshold under risk can be calculated in the same way. Of course, there will be additional data demands. Historical data could still be used to estimate the threshold in a "positivistic" sense by statistically fitting an appropriate production function and deriving the necessary information for the calculation in much the same way that Talpaz and Frisbie (140) used for the certainty case. However, the physical productivities measured in terms of changes in expected output and in the variance would need to be converted to a standard denominator to allow comparison. This could be accomplished by employing a utility function specific to a given decision maker or by comparing the outcomes of alternative pest control measures with one (or more) of the efficiency criteria. It should be noted that as Robison (113) illustrates, the probability of making a Type I as opposed to a Type II error is different for a single value utility function and an efficiency criteria (or amongst the various efficiency criteria).

2.9 Optimal Pest Management Strategy Selection Under Uncertainty

Rather than optimizing and viewing the selection of pest management controls as a case similar to other traditional inputs that can be applied in continuous manners, these inputs are often combined into now-continuous packages built around various decision rules. The pest management decision then becomes a choice between the control strategies that implement the decision rules. An alternative to an optimizing model is a Monte Carlo simulation model which may be mathematically simpler to solve. These models have the advantages that its use is not as restricted by burdensome assumptions and they easily analyze the complexity of the control strategies.

The use of Monte Carlo simulation models to produce the probability distributions necessary to apply the stochastic dominance techniques in an evaluation of the alternative control strategies is also recommended. With the SDWRF and CSD, risk efficient strategies which are preferred by all members of the class of decision makers can be identified.

Monte Carlo simulation can approximate the economic threshold by comparing different runs which have varied the decision rules regarding the timing and/or dosage of the pest control. Using stochastic dominance techniques as an efficiency criteria, the alternative strategies could be evaluated for a given class of decision makers. Depending upon the refinement of the risk preference interval, the alternative strategies can be ordered for a class of decision makers consistent with the preferences of each member of the class. The preferred strategies can then be interpreted as having the "optimal" economic thresholds (decision rules). If enough runs are generated, an approximation of the true economic threshold will be generated. The economic threshold does not address problems of deciding between alternative controls, but it is related. Strategies which are risk efficient are preferred because their decision rules (economic thresholds) perform better than the alternatives. Better performing decision rules imply a preferred pattern of input usage. In summary, Monte Carlo simulation can be used to determine not only the economic threshold under uncertainty but can evaluate the entire set of control strategies at the same time.

III. RESEARCH PROCEDURES

3.1 Use of Simulation Models and Philosophy of Research

The compilation of the information necessary to construct the decision matrices used in the selection of "optimal" pest management strategies is a complex process. There are many factors which may influence the states of nature, their probability of occurring and the outcomes associated with each state. Problems of great complexity are often analyzed using a systems approach.

A systems approach to pest management should contribute to both the evaluation of the farm management alternatives and the analysis of the broader problems of production externalities, environmental damage and health hazards. It provides a perspective which facilitates the classification of the problem into more manageable components. The systems approach is extremely useful in the problem formulation because it forces the identification of boundaries of the problem, the essential elements of the problem, the interactions between the elements and the performance criteria for the system. The boundaries of the problem will define the system and distinguish it from its environment. They identify the limits to be placed on the problem. The essential elements of the system can be classified as environmental (uncontrollable) inputs, the controllable inputs (management variables), the system outputs (desired and undesired), and system and design parameters. The organization of the essential elements into components and the interactions among the components comprise the structure of the system. The outputs of the components can be described as state variables which may indicate the condition of the system at a particular time or stage. The system can be structured in a deterministic fashion where all conversions of inputs to outputs are exact relationships or the structure may be a stochastic one where these conversions may contain random error terms. Likewise, the environmental inputs may be stochastic or non-stochastic.

The structure of a system can be perceived as being hierarchical as each component could be considered as a subsystem. The more detail that is maintained in the structure and the more components the system contains, the system will be more process oriented and approaches a mechanistic model. The less detail in the structure and the fewer components the system has, the system is more opaque and is described as a "black box" model.

The systems approach can be used to perform three basic functions of research. These functions are:

1) an analysis function where the system structure and the input variables are specified and the system output is to be determined;

2) a control or management function where given the system structure, the inputs are determined which will produce the specified outputs; and

3) a design function where the available system inputs and the desired system outputs are specified while the system structure that will convert the inputs into the desired outputs is to be determined (83).

While not all research using a systems approach needs to construct a computer simulation model, it is often convenient to do so. The computer can be an aid in processing the information about a complex system where such an activity may be too tedious or too involved for most mental processes. It is often said that a computer model does not produce any new information but simply organizes existing information into a format more easily understood.

Besides from the benefits of organizing complex data bases, other advantages of using computer system simulation models have been stressed. Dent and Blackie (33) identify four advantages of these models. They are:

1) They allow the study of systems where the real-life experimentation would be either impossible, inordinately costly or disruptive;

2) The synthesis of systems in a model-form permits the study of systems that do not currently exist;

3) They allow the study of long-term effects since the time horizon over which a model is run is within the control of the researcher while that of the actual system may not meet the demands of research schedule; and

4) The modelling process forces those concerned with building the simulation model to examine the system objectively and consequently undertake a thorough and critical review of knowledge concerning the system (33).

These advantages of computer simulation models have led to their widespread application in a variety of types of research. Glenn Johnson (65) has categorized research into three basic types: disciplinary, subject matter and problem solving. The purpose of disciplinary research is to extend the theoretical knowledge and/or methodology of a particular discipline. Subject matter research is concerned with providing knowledge about a related series of problems that deal with a particular topic. It is multi-disciplinary in nature and is unlikely to provide enough information on a single problem to solve it but it emphasizes the inter-relationship between problems. Problem solving research is problem specific, generally multi-disciplinary and if successful, should provide a solution to the identified problem. System simulation models can be used as a framework for all three types of research.

Regardless, which type of research is being conducted or the reason for which a system simulation model is selected, there are some universal guidelines of scientific reasoning which must be adhered to. The use of a computer model to conduct experiments does not require a unique philosophy of research. It is imperative, however, that attention be paid to the basic procedures of scientific reasoning or the conclusions derived from the model will be spurious.

Since the object of research is to generate knowledge, it should be recalled that there exists three types of knowledge: positive, normative and prescriptive. Positive knowledge is information describing the characteristics of a condition, situation or thing without regard to the values associated to those characteristics. Normative knowledge, by contrast, is information about values (the goodness and badness of the characteristics). Prescriptive knowledge is the solution to a given problem and relates the normative to the positive (65).

Although often forgotten,it should be recognized that it is possible (and necessary) to generate all three kinds of knowledge in an objective fashion. The basic procedures of scientific reasoning insure that knowledge is obtained objectively. Four tests of objectivity have been proposed by Glenn Johnson (65). The first test that a model must pass is a test of logical consistency. This test insures that the generation of knowledge from the research is done in a manner consistent with basic logic and the theories of the disciplines involved. It is alternatively known as validation. The second test is one of correspondence to reality. The model must be able to simulate the behavior of the real system and make accurate predictions. Johnson describes this as verification. The third test is one of clarity which insures that the model and its theories are understandable and unambiguous. Workability is the final test. This test is concerned with the prescriptive capability of the model and measures its ability to solve real world problems.

While these general guidelines may serve as a framework for the reasoning process and identify the important components required to obtain credibility for the results, more detailed guides are necessary to actually direct the research. Giere (45) presents a procedure which will insure that the four tests of objectivity are fulfilled when using a computer simulation model as a research tool.

Giere perceives a model as being a theory or a definition of a system. A theoretical hypothesis is a contingent statement asserting that some designated real system fits the definition of the system described by the theory (model). The construction and testing of theoretical hypotheses is often the purpose of using a system simulation model for once the theoretical hypothesis is justified, the model can be used to predict or explain how a system behaves. However, this step is frequently not explicitly recognized and the elements of the argument used to justify the hypothesis are not clearly described. The argument will contain the conclusion and premises that relate both to the experiment and to its results. The conclusion will be the justification of the hypothesis or its negation.

The basic elements of the argument are the hypothesis, the prediction, the initial conditions and the auxiliary assumptions. The hypothesis is that some real system follows the definition of the model. The prediction describes the occurrence of a possible state of the system at an inidcated time. The initial conditions describe the state of the system at the beginning of the experiment. Auxiliary assumptions are additional characteristics of the system or its environment that may be necessary to conduct the experiment.

These elements are all necessary components to the construction of the argument. Giere describes the need to form two arguments or to have two conditions of a good test. Condition 1 tests to see if there is a conditional relationship between the hypothesis and the prediction. It infers that if the auxiliary assumptions, initial conditions and hypothesis are true (premise), then a correct prediction will likely follow (conclusion). The second condition insures that an alternative theory would yield a completely different prediction with the same initial conditions and auxiliary assumptions. The two conditions can be depicted by the following statements:

Condition 1:

If [H and IC and AA], then P.

Condition 2:

If [Not H and IC and AA], then probably not P.

P and IC and AA.

Thus, H.

where H = theoretical hypothesis

IC = initial conditions

AA = auxiliary assumptions

P = prediction

The Giere guidelines of a good test should be useful to model builders and users in that they will force an explicit statement of the hypothesis being tested with the model and insure that the four general tests of objectivity are addressed. The justification of the hypothesis using this procedure will require the passage of the test of correspondence to reality through the experiment dealing with the prediction. The clear definition of the elements of the argument and condition II will meet the requirements of the test of clarity. The rigor of the procedure will force the research to address the test of internal consistency.

3.2 Description of the Actual System

The system can be perceived to consist of several major parts or components. Such characteristics as the location of production, market prices, costs of production, yields, tree growth and pest management problems are all vital components of the system which should be relevant to a model building exercise. Before the model can be constructed these components needed to be understood and precisely described.

Production System

The production system of Michigan apple orchards is a complex one. Apple production in Michigan is most heavily concentrated in three counties, Kent, Berrien and Van Buren, although orchards are common throughout the other counties bordering Lake Michigan. The varieties which have the highest number of trees in the state are Red Delicious with 27.4 percent of the state's total, Jonathan with 18.1 percent, Golden Delicious with 9.8 percent and McIntosh with 9.6 percent. However, when the percentage of the state's total production is considered, the varietal ranking is quite different because of the influence of yields. McIntosh enjoys a high productivity in Michigan while Red Delicious suffers from erratic yields. The largest percentage of the state's production is accounted for by Jonathans (24.3%), followed by Delicious (20.7%), McIntosh (17.5%) and Northern Spy (8.6%) (24).

Historically, about 40 percent of the Michigan crop goes for fresh uses and the rest is processed. Of the amount processed, approximately 30 percent is canned, 40 to 50 percent goes to juice and 20 to 25 percent ends up in frozen processing. In the last few years, juice has become more and more important (24).

During the ten year period from 1969 to 1978, the Michigan season average price for all apple sales averaged 6.01 cents per pound with a standard deviation of 2.24. For the same time period, the fresh consumption sales price averaged 8.70 cents per pound with a standard deviation of 2.40 while the all processing price had a mean of 4.25 cents per pound and a standard deviation of 2.19. Relatively, the aggregate data indicate that the fresh market experiences much more price variation than does the processing market (24).

The farm value of the Michigan apple crop was $67,640,000 in 1978. Of that the fresh market sales accounted for 56.9 percent. Juice processing contributed 15.8 percent of the state's total value while canned and frozen processing respectively generated 15.5 percent and 12.5 percent of total value (24).

The best available information on the costs of producing one acre of apples in Michigan estimates that total costs per acre are about $1,040. Of that, about 30 percent are in overhead charges, 40 percent in the growing operation and 30 percent in harvesting activities. These estimates are for a semi-dwarf orchard with a density of 108 trees per acre and an average yield of 400 bushels per acre. The prices are listed in 1978 dollars (24).

There are a number of pests which are present in commercial orchards where pests are defined to be insects, diseases and mites. The most common pests which cause problems are European red mites, climbing cutworms, San Jose scale aphids, tarnished plant bugs, oblique-banded leafroller, green fruitworm, plum curculio, red-banded leafroller, white apple leafhopper, codling moth, tentiform leafminer, apple maggot, powdery mildew, fire blight, and scab (66).

Conventional calendar control programs can apply from 12 to 15 sprays a year and per acre pest management costs can reach extremes of $600 per acre. Control costs may be higher in Michigan than in other regions due to the climate and problems with abandoned orchards. Chemicals designed to control specific pests are often applied together in "cocktail" sprays which decrease machinery and labor costs but which might exacerbate problems by impacting on natural predators and secondary pests or by promoting the development of resistance.

Three of the most important pests of the entire complex are scab, codling moth and European red mites. These pests will serve for the case study. Scab is a fungus and is an early season problem. Codling moth is an insect with high migration potential and usually is a late season problem. Mites usually surface in the pre-bloom stage and are somewhat unique due to the complex of natural predators which can provide effective biological control. Both the mites and the mite predators can be affected by some fungicides applied for scab control and by some insecticides used to prevent infestations of codling moth.

Mites

In Michigan apple orchards, one common pest that has considerable potential for the application of Integrated Pest Management (IPM) strategies is the European red mite, Panonychus ulmi. Mites are common and destructive pests of a variety of plants including most deciduous fruit trees. They use sharp mouth parts to pierce plant tissue, suck up sap and destroy the chlorophyll. This results in a gray or brown mottling of the foliage or in the formation of galls or growths. Plants or their fruits are stunted, but in extreme cases, defoliation can occur. In apples, mite damage usually results in smaller and discolored fruit which can impact on both the quality and the quantity of the harvest.

The life cycle of the mite can be completed in 15 or 20 days under favorable conditions and since active females may lay a few eggs each day for about 2 weeks, populations can increase quite rapidly. Mites flourish during warm, dry weather and do not generally reach serious levels during cool, wet seasons (103, pp. 66-70).

The mites overwinter in eggs laid on the underside of twigs and small branches. At bloom immature mites emerge from the winter eggs and adults soon become active on the apple leaves. There can be as many as 6 to 8 generations a season and populations can reach as high as 100 mites per leaf in June to August. In the fall, the mites return to the tree base or ground litter to overwinter (31).

The potential for IPM programs in mite control exists since a number of natural predators are common in commercial orchards. These include a predaceous black ladybird beetle, Stethorus punctum, and predaceous mites such as Amblyseius fallacis, Agistemus fleschneri and Zetzellis mali (31). Of these the most important is Amblyseius fallacis.

These predators have the capability of completely controlling the plant feeding mites in some years and since they may react differently than the mite pests to certain pesticide dosages, they may complement a spray program designed to take advantage of their predation. The combination of reduced dosages and natural predation may result in substantial savings.

While miticide applications may only be made two or three times a season, their materials cost are quite high and can account for as much as 20-30% of the annual cost for pest control (31). Two full dose applications of carzol (2 lbs/acre) would cost approximately $65/acre if carzol could be purchased for about $16.50 per pound.

Some miticides applied at reduced dosages will be less toxic to the predators than to the mite pests. This differential impact can be extremely beneficial since full dose applications disrupt the biological control because the pest populations will recover much faster from most chemical treatments than the predator populations. It should be possible to take advantage of this differential impact and to promote a predator/prey ratio that will allow more biological control to occur than what would result when both populations are substantially reduced from a full strength application. The use of these miticides at reduced dosages play an important role in IPM strategies designed to control spider mites.

While miticides usually do not effectively control other pests, the pesticides applied to control such pests as apple scab, powdery mildew, codling moth, plum curculio, apple maggot and redbanded leaf-roller can disrupt the populations of the mite pests and/or their predators. Once again, the pests and predators may react differently to certain chemicals, so that it is essential for the success of IPM strategies that all pesticides be selected with a recognition of their impact on both the mite pests and the mite predators. Those chemicals which are less toxic on the predators are generally encouraged for use in IPM spray schedules (31).

Scab

The most important disease of apples in the humid-temperate climates is apple scab, a fungus caused by Venturia inaequalis. The fungus overwinters in fallen infected leaves with perithecia being produced during the winter in these leaves. By spring, the perithecia contain mature ascospores which are the primary source of inoculum for the disease each year. Rain is essential for the discharge of the spores which once discharged, are carried by air currents to adjacent trees, branches, and fruit. Within a few hours upon landing, the spores germinate and cause infections if they stay wet. The rate at which the spores germinate and result in infections is partially determined by the temperature and the length of the wetting period. Discharges of primary ascospores may continue two to four weeks after petal fall but they usually are all gone by the first cover stage of the development.

Primary scab infection can also result in the production of secondary spores. Secondary spores, or conidia, can occur from 7 to 18 days after a primary scab infection, depending upon the temperature range in the time period following the initial infection. Conidia are usually spread by dropping or splashing water but can be wind borne as well. Wind borne conidia do have a lesser impact, though. Conidia, therefore, generally infect nearby fruit and foliage. It is a matter of discussion as to whether or not conidia require a shorter wetting period for an infection to occur (21).

Apple scab can result in infected fruit which usually must be culled or sold for juice (no scab is permitted in U.S. Utility while intermediate grades permit a defect area of 1/4 inch in diameter). It can also cause early fruit and leaf drop that may seriously affect yields. Trees seriously defoliated for two or three consecutive years are weakened and susceptible to low temperature damage. If the scab infection is severe in early summer, flower bud production is often poor the following season and the crop can be lost for two years. In addition to the losses incurred from quality damage and reductions in yields, in many instances growers who suffer a greater than 10% infection rate must pay the costs of sorting the undamaged fruit from the damaged.

Common control practices for apple scab involve the use of fungicide sprays during the period of primary ascospore production in spring and early summer. Spray programs are often selected from one of three distinct approaches to controlling apple scab: single application treatment, a calendar based protective spray program and a post-infection IPM program. The three general approaches arise from differences in the performances of classes of chemicals. The single application treatment employs a chemical treatment early in the season (green tip) that protects new growth from scab infection for several weeks. Late season control can then be obtained from a protective calendar spray program or a post-infection IPM program. The protective calendar spray program involves the use of chemicals which must be applied in 5 to 14 day intervals to insure adequate control of apple scab. This time interval will depend upon the chemical compound used, the dosage applied and the part of the season that it is intended to protect. The post-infection IPM program employs chemicals which have the capacity to eradicate any infection which started 2 to 3 days earlier. These chemicals, rather than being applied at a predetermined time or a fixed time interval to protect the orchard regardless of the infection potential (like the first two approaches do), are sprayed only when indications of disease development have been observed or the weather conditions suitable for an infection period have been experienced. It should be noted however, if it rains 2 days in a row, it may not be possible to cover the orchard in time to insure that the chemicals eradicate the spores.

In general, the control measures for apple scab are aimed at disrupting the development of the ascospores into scab infections. It is known that leaf wetting by rain is an absolute requirement for significant ascospore release. The length of leaf wetness (number of hours), the temperature during the wetting period, the relative humidity and the level of incoculum present are key determinants of infection periods. Information on the relationship between scab infection, the length of the wetting period and the temperature has been incorporated into the Mills table which can be used to identify when weather conditions have been suitable for the completion of the innoculation and incubation stages of the fungus and an infection might occur. The Mills table has been used in many spray programs to predict when scab infection periods have occurred. However, the Mills table assumes that a high level of inoculum are present which probably does not represent the situation in most commercial orchards (67).

Information is also available on the probability density function of ascospore productivity. Knowledge on the general pattern of the percentage depletion of ascospores from overwintered leaves can be used to direct when protective sprays should be applied to avoid any dangers of scab infections.

However, complete epidemiological understanding of the disease is still lacking. The development of economic control programs has resulted more from the emergence of efficient fungicides than from epidemiological advances (67).

Gilpatrick and Szkolnik have concluded a recent article with the following note:

> Information on the real impact of measured incoclum potential (spore discharge and dose in air) in relation to scab potential, dosage responses of fungicides, choice of fungicides, and timing of sprays is virtually non-existent. Thus, it is impossible and,

> indeed, hazardous at this time to interpret inoculum potential estimates in terms of practical spray recommendations except in broad and conservative ways (67).

Codling Moth

The codling moth, Laspeyresia pomonella, is a pest common to wherever apples are grown in the world. It was introduced to the United States from southeastern Europe beginning in the middle of the 18th century. By the 1880's, the codling moth had become a major pest causing nearly total loss in some areas while destroying some 20% of the fruit in the northern apple and pear producing areas. Codling moths frequently attack apple, pear, English walnut, quince, crab apple, hawthorn and wild apple.

Codling moths overwinter under the bark or in the ground in waterproof cocoons. In April or May, the larvae which have overwintered change into pupae. After about four to six weeks of cool, spring weather, the pupae stage comes to a close and an adult moth emerges from the cocoon. Usually male moths emerge first, about a week earlier than the females. In Michigan, emergence commences in late May and extends until early July. Oviposition begins when the temperatures are above 60° in the afternoons and early evenings. Eggs can be laid on leaves, twigs and the fruit itself. In the first generation, eggs normally take 12 to 14 days to hatch but with warmer weather it may be quicker. First generation larvae enter the fruit over a period of the next five to six weeks. The larvae usually enter the fruit through the calyx end and eat their way to the center of the fruit to feed on the seeds and core. Stings can occur on the fruit when a larva bites into a fruit treated with an insecticide and dies. After the larvae have hatched and before they have entered the fruit, the young larvae are extremely vulnerable and suffer high losses due to wind, rain and predation. This is one critical point in the life cycle for control measures because the larvae must be stopped from reaching the fruit and causing injury.

The caterpillars will feed in the fruit for about three weeks and then tunnel out to find a place to spin their cocoons. Around 25% of the caterpillars will remain in their cocoons until the following spring. The remainder will become pupae within four to six days. In about two weeks the pupae stage ends, the new adults will emerge and and the process continues. In some warm climates, as many as five generations can occur (98). In Michigan, it is not uncommon for a second and a partial third generation to be observed (111).

In Michigan the potential for biological control of the colding moth is not high. There are a number of natural enemies such as a barconid wasp, Ascogaster earpocapsae, but they are incapable of preventing the pest population from reaching intolerable levels. It is rare that in unsprayed orchards the rate of parasitization would exceed 10% to 20%. It is necessary to rely on some form of chemical treatments to insure control of the codling moth (111).

Preventive spray programs often involve around a half dozen cover sprays spaced about two weeks apart during the summer months when the codling moth is usually most active. A high quality fruit is usually insured with these programs but they do introduce some additional problems. By not monitoring or attempting to predict the phenology of the pest, the preventive spray programs often result in more spray applications than are incurred in IPM programs. This can increase control costs and by introducing more chemicals in the orchard, the rate of resistance build-up is faster and the probability that the natural predator complex of other fruit pests will be disrupted is increased.

By combining biological and environmental monitoring, predictions can be made about the phenology of the codling moth and sprays can be timed to be most effective. The number of sprays can potentially be reduced in most seasons by better timing. The biological monitoring performed with the use of pheromone traps will indicate the population density of adults which are active. It is known that 210 degree days (base 50°) after the emergence of the adults, the target larvae population will be observed. It is then possible to develop economic thresholds for the number of captured adults that will indicate when a spray should be applied to effectively time the chemical treatment. The economic thresholds can be adjusted by the number of degree days that have accumulated to match the relationship between the number of generations expected and the amount of damage anticipated. The economic thresholds should be set at a level that will balance the costs of the spray with the value of the damage avoided by the treatment.

Phenological Stages of Apple Trees

The important stages of tree growth and fruit development can be described by several benchmark events. Common benchmarks are green tip, tight cluster, pink, bloom, petal fall, and fruit set. Green tip occurs when the first green tissue begins to push through the bud scales while tight cluster is observed when the spur leaves are showing but not fully expanded, and the flower buds are exposed but still tightly clustered. In pink, the flower buds have separated in the cluster and the pink undersides of the petals are showing. When the flowers open, bloom has arrived. In petal fall, about three-fourths of the petals have fallen. Finally, fruit set transpires when the receptacles of the successfully pollenated flowers have begun to swell and the unpollenated flowers have begun to yellow and drop (8). The trees will pass from one stage to the other depending on the passage of physiological time usually related to the accumulation of degree days.

3.3 Description of the Simulation Model

To analyze the problem identified in a manner which would permit the achievement of the stated objectives, a stochastic Monte Carlo simulation model was selected as the appropriate analytical approach. The analysis of the problem necessitates the generation of information on the cumulative probability distributions of net revenue associated with each pest management strategy. This requires that the performance of the various strategies be monitored over a number of different states of nature. Unfortunately this data is not available from field observations nor is it likely that an experiment could be designed to economically provide it. Furthermore, even if the expenses and the time horizon were not a problem, it would be difficult to perform valuable sensitivity analysis with field experiments.

A simulation model can be used to conduct the experiments necessary to provide this information while substantially reducing both the time and the costs involved. In this case, of the four advantages of systems simulation models identified by Dent and Blackie, only the second one is irrelevant. There appears to be no need to study any systems that do not currently exist. However, a model can be used to provide information in a timely and economical fashion and the construction of the model will force a critical review of the current knowledge of the system.

System Bounds

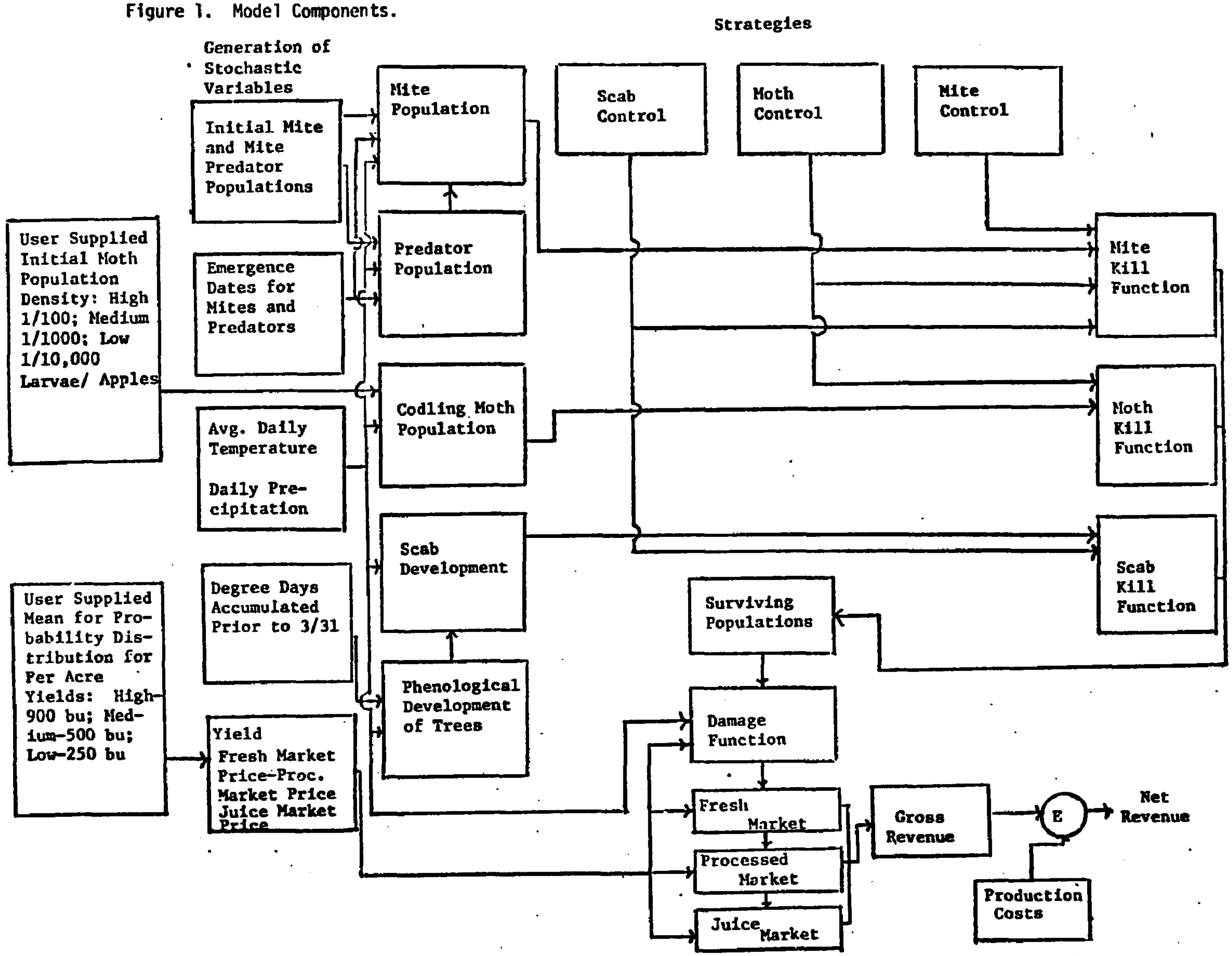
The system to be modelled is one which must have some limits imposed upon it. It will consist of a ten acre orchard block with semi-dwarf rootstock planted at a density of about 100 trees per acre. The geographical location of the orchard will be specified to be East Lansing, Michigan. The system will include three pests: scab, red mites and codling moth. The natural predators of the mites will be present in the system as well. The remaining complex of pests and predators are not considered. The fruit produced in the orchard will be assigned to three possible uses: fresh market, processed market and the juice market. The proportion going to each use is set equal to the statewide ten year average. However, as pest damage occurs, the fruit can be reassigned. Significant damage from the codling moth is assumed to result in the infected fruit being culled. Three yield levels will be analyzed with the model: 900 bushels per acre, 500 bushels per acre and 250 bushels per acre. With the exception of the market prices and the possible in-migration of adult codling moth the model will consider the system as being closed. No externalities will be included in the analysis.

Model Components

This model can be described in terms of its major components. The structure of the model is displayed in Figure 1. The components can be classified into seven categories. There are components which are designed to facilitate the introduction of the user supplied environmental inputs. These inputs are the mean of yield distributions[1] and the initial codling moth population density. There are components designed to generate the stochastic environmental inputs which include prices, yields, weather, mite emergence dates and the mite initial population density. One series

[1]Yields are randomly generated using probability distributions based on historical data but using the mean supplied by the model uses.

Figure 1. Model Components.



of components simulates the phenological development and population dynamics for the system. A fourth class of components implements the decision rules of the management strategies. There is another group of components which handles the mortality functions of the pests and predators when they are exposed to the chemical pesticides. The remaining two classes deal with the estimation of pest damage and the calculation of the net revenue. The season begins at the right of Figure 1 with the user supplied inputs. The stochastic elements are then generated for the entire season. Each day, the growth of pests, predators and trees are simulated. The decision rules of the control strategies are implemented and when sprays are applied then the population densities are adjusted to reflect the mortality rates. At the end of the season, damage, gross revenue and net revenue are all calculated.

System Inputs

The inputs in the system can be categorized into environmental and controllable. The environmental inputs, in turn, are either stochastic or deterministic. The stochastic environmental inputs are the initial mite and mite predator population densities, the emergence dates for the mites and mite predators, the average daily temperature and the daily precipitation, the degree days accumulated prior to the end of March for each season, the yields, the apple market prices and the random sampling error. The deterministic environmental inputs are the production costs, prices of chemical inputs, scouting fees and the initial population density for the codling moth. The latter is user supplied as is the mean of the probability distribution for the yields. The controllable inputs are the decision rules of the alternative pest management strategies. The various rules will monitor different stage variables (degree days, pest population densities, growth stages of trees, calendar days, precipitation, etc.) and at designated values for these variables, alternative actions will be implemented.

System Outputs

The outputs of the system can be divided into desirable and undesirable categories. The former are the variables which should be maximized while the latter are ones that should be minimized. The desirable outputs are the net revenue while examples of the undesirable are the control costs, the pest damage, the quantities of chemicals applied and the number of trips through the orchard to apply sprays.

Stochastic Elements

The stochastic elements of the model have been generated by the use of a random processor developed by King (72). In many cases, the variables have been generated from multivariate probability distributions which allow the preservation of the correlations between the various elements. Such multivariate probability distributions are constructed by first deriving the marginal distributions for each variable from historical data. The correlation coefficients and the marginal distributions are then merged to construct the multivariate distributions.

Two sets of multivariate distributions were constructed for this model. They are: 1) a distribution generating values for the apple market prices and the per acre yield; and 2) a series of eight distributions to generate values of the average daily precipitation and the daily precipitation. There are eight weather distributions, each one covering 21 days to allow for seasonal variations in the distributions and to reducce the number of correlations to a manageable number. Each day's temperature and precipitation is correlated with the temperature and precipitation of the day immediately preceding it.

The Yield and Frost Components.

The model has the option of calculating the yield in two manners. It can be randomly generated from a multivariate distribution with the fresh and processed apple prices or a calculation of the frost damage can be used to reduce a potential yield to the end of season final estimate. The former procedure maintains the relationship between the yield and the prices while ignoring the relation between the frost damage and the pest damage. The latter procedure ignores the correlation between the yield and prices while it preserves the relationship between the pest and frost damage. The algorithm used to calculate the frost damage has not been validated or verified.

The random generation of the yield involves the use of an historical series of per acre yields in the State of Michigan from the years 1970 to 1979. The shape of the cumulative probability distribution discerned from the historical data is always preserved but can be shifted to allow the model to simulate the orchard at three distinct yield levels. The mean of the distribution can be set equal to 250 bushels per acre, 500 bushels per acre or 900 bushels per acre.

To exercise the option of employing the algorithm to calcualte the frost damage, the subroutine FROST must be called on a daily basis from the main program. The algorithm has been adapted from an original version developed by Arneson (8 pp. A34-A35). The version currently used in the model was adapted to produce a distribution of yields that matched the variance of the distribution calculated from data collected for the years 1975-1979 (24). To derive a distribution with a mean of about

400 bushels per acre, the potential yield should be set at the beginning of each season to a value of 500.

The algorithm calculates the amount of frost damage that occurs each day by examining the stage of the plant and the average daily temperature. A daily low is inferred from the average temperature by assuming that the low is always a constant number of degrees below the average. The original algorithm deducted 10° F from the average to produce the daily low temperature but it has been adjusted to 7° F in the current model. The model starts the season with a potential yield of 500 bu/acre and deducts the frost damage from that figure on a daily basis. The routine produces an after frost distribution of the yield with a mean of 403 bu/acre and a standard deviation of 104.

Due to the lack of validation of the frost routine and the desire to maintain the relationship between the prices and the yield, the analysis has been performed using the randomly generated yield estimates.

Model Hierarchy

The model is constructed in a hierarchial manner so that each pest could be analyzed independently of the other two or in combination as an entire system. The stochastic environmental inputs and the controllable inputs have been introduced in a fashion to insure that each action choice is exposed to the same twenty states of nature. The major linkages of the three pest subsystems are through the impacts that the various chemical pesticides have on the non-target species. In the system defined by the model, there are two such cases. The pyrethroid insecticides applied to control the codling moth are also lethal to both the mites and the mite predators. The fungicide, benomyl will affect the mites as well. However, its effect is less on the mite predator than it is on the mites themselves. The model does assume that the damage resulting from each pest occurs on fruit previously undamaged by either of the other two pests.

The model components will be discussed in more detail in the chapters describing the analysis of each of the pests independent of the others. The pests were studied independently first to reduce the number of strategies to be examined to a small, manageable subset. The complete system was then analyzed using combinations of the strategies appearing in the subsets. In this manner, predicitons on the extent of the benefits that could be gained by integrating the single pest strategies into a comprehensive system strategy could be examined.

Evaluation of the Desired Outputs

The stochastic Monte Carlo simulation model will produce an estimate of the net revenue for each pest management strategy examined for each season. In this case, there are twenty seasons and each season has been constructed to serve as a state of nature. The net revenue observed for each season will thus be assigned a probability of .05 (1/20) and cumulative probability distributions can be estimated for each pest management strategy. So the simulation model can be used to generate two of the three components of the decision matrix necessary for the implementation of the EUH. It identifies the outcomes of the action choices and assigns the probabilities of their occurrence.

The remaining component is an estimate of the risk preferences or a utility measure that can be used to evaluate the alternatives. As described earlier, there are definite advantages to using an interval approach to utility measures rather than a single valued function. For this study, five different intervals will be used to measure risk preferences.

Four of the intervals will be defined by assumption and will function for comparative purposes. The remaining interval has been inferred from survey data of 30 farmers across the state of Michigan (81). A small survey of a group of fruit growers from Belding, Michigan was conducted as part of this research to confirm the validity of the results of the larger survey for apple producers. The results of this smaller survey of fruit growers are presented in Appendix III. This interval is defined to represent the preferences of 80% to 90% of the growers in the state of Michigan.

The intervals can be used to rank the alternative strategies and comparisons between the rankings can then be made. Differences in the rankings will indicate the importance that the risk preference can make on possible strategy selection. Similarities in the rankings will indicate how sensitive the expected utilities are to changes in the control practices. By varying the yields, prices, weather probabilities or initial pest population densities, the rankings can be checked for stability across different production situations.

The rankings of the strategies will be conducted in a two stage process. First, SDWRF will be used to identify an efficiency set for each risk interval and each production scenario. These efficiency sets can be further refined in the second stage to insure that only strategies which will actually be selected by members of each class of decision makers are declared as being risk efficient. This will be accomplished by the application of CSD rules.

Form of the Results of the Analysis

The final results of the analysis will be in the form of distributions of the desired and undesired outputs. The distributions can be described by the means, variances, standard deviations or the cumulative probability functions. The results will also include the efficiency sets identified for each pest management strategy under each production scenario. Efficiency sets will be derived using both SDWRF and CSD. The production scenarios will vary due to changes in the number of pests considered, the mean of the marginal probability distribution for the per acre yields and the initial pest population densities.

3.4 The Tests of Model Hypotheses

Following the Giere guidelines (45), the model defined for the actual system is in reality a theory. The theoretical hypothesis proposed by the research is that the actual system is accurately described by the model. The model can be used to make predictions about the performance and behavior of the system. If the theoretical hypothesis is justified, then there is reason to have a great deal of confidence in the predictions of the model. If it cannot be fully justified, then the predictions serve the valuable function of identifying one of the possibilities that could occur and the situation from which the possibility will arise.

It should be remembered that there are several elements to a good argument. These include the hypothesis, auxiliary assumptions, initial conditions and the predictions.

In reality, since there are a number of different uses of the model because of the treatment of subsystems as independent systems for some analyses and the generation of several forms of the outputs, there is more than one theoretical hypothesis inherent in the research. There will be a theoretical hypothesis for each single pest subsystem. There will be another hypothesis dealing with the comprehensive three pest model. Finally, there will be another theoretical hypothesis for the use of the

EUH to evaluate the performances of the alternative control strategies.

Each theoretical hypothesis needs to be tested. Justification for one will not necessarily imply justification for the others. However, due to the hierarchial nature of the research approach, if one of the early hypotheses is not justified, it is unlikely that subsequent hypotheses which are based on models using the subsystems as components will be justified either.

For each theoretical hypothesis, it is necessary to clearly identify the elements of the agreement. The case of the mite model(s) will be used as an example to demonstrate the procedure. The first theoretical hypothesis that should be discussed since it is part of the foundation of the larger system, is the biological model of the mite system. In this case, the hypothesis is that the actual mite system is accurately described by the model that simulates the population growth, predator consumption, chemical mortality rates and damage. The predictions of the model are levels of final season damage and population densities at various time periods. The auxiliary assumption of the argument are that: 1) the other pests and predators present in the orchard do not affect the mites; 2) the extent of damage caused by the mites is a function of only the mite population density; 3) mite damage can be measured in a lower quality fruit represented by a decrease in the value of the harvest; and 4) that multi-seasonal effects are marginal allowing the system to be accurately described by a series of independent single seasons. The initial conditions can be described in terms of both stochastic and deterministic variables. For the stochastic variables, the initial conditions are contained in the probability distributions defined for each variable. They describe the likelihood of occurence for the possible values of the stochastic variables. The deterministic variables with initial conditions of import are the age, health and productivity of the trees in the orchard. The trees are from a healthy, mature, bearing orchard and the productivity is user supplied at a low yield of 250 bushels per acre; a medium yield of 500 bushels per acre; or a high yield of 900 bushels per acre.

The justification of the model is discussed in two articles. Dover et al. (35) discusses the predictions related to population growth patterns, population densities and predator/prey ratios. Hoyt et al. (61) discusses the prediction relating the fruit damage to mite population densities. From the results of these discussions, it can be seen that there exists reason to believe that the model accurately defines the actual system.

When prices are introduced into the subsystem, using Giere's strict definition, a new model is constructed. In this case, all the previous components of the argument are still present but an additional prediction and two additional auxiliary assumptions are included as well. The new prediction is based on the net income associated with each control strategy examined. The auxiliary assumptions are: 1) that the historical probability distributions of the market are accurate indicators of what can be expected of the present system; 2) that the non-price terms of market transactions are incidental; and 3) the costs of production vary only with yields and pest management decisions. The initial conditions require that the system is described by the levels of costs for the non-pest management activities. The justification of the theoretical hypothesis of this model is difficult to establish because there are few accurate records of the performance of the actual system with which distributions of net revenue could be constructed. In this case, the hypothesis is less than fully justified. In the terms of Johnson's four tests of objectivity (65), the model has been validated but not verified. It then becomes a matter that there exists some evidence to believe the model and its predictions but the evidence is not overwhelming. The logic of the process of validation may even suggest that for relative comparisons between strategies, the predictions have more basis for credibility than for uses requiring the absolute values of the net income estimates.

If an ordering of the strategies as to the preferences of the apple growers is made, a new model is constructed by adding the EUH to the previously discussed model. The prediction of the model is now the rankings of the alternative strategies. The new auxiliary assumptions center on the validity of the EUH. The initial conditions now must include both the current wealth position of the decision makers and some statement about the choice set of growers with respect to the strategies. Unfortunately, there is not enough evidence to justify the EUH (116). Furthermore, the initial conditions cannot be justified either. However, despite the fact that the theoretical hypothesis cannot be fully justifed, it produces the best predictions about the behavior of the system that are currently available. The EUH based model is probably closer to being justified than any of its alternatives (116). As an unjustified model, the predictions are still useful since they uncover relationships between situations and possible outcomes. Besides, the actual system is one that is not particularly conducive to the testing of theoretical models. It may be that no model, regardless of its merits, will ever be fully justified for this system. The need for predictions is not lessened, but care must be exercised that the accuracy of the predictions can at best be discussed in probabilistic terms. The risk preference intervals were tested for a small group of apple growers in a hypothetical decision setting and in this setting the EUH predicted well. The relevance of the results in this setting for actual decisions has yet to be determined.

The other subsystems all will have similar hierarchical theoretical hypotheses. A review of the entire set of predictions produced by the study will appear in Chapter VIII.

3.5 Comparison of Model Predictions With A Priori Statements of Anticipated System Behavior

Since the theoretical hypothesis of the comprehensive model will not be fully justified, the predictions of the model should be used in a cautious manner. Prior to generating the predictions with the model, it will be beneficial to make some statements about the behavior of the system which can be anticipated based on the current understanding of its operation. Discrepancies between the predicted and anticipated behavior can then be analyzed for: 1) improvements in the understanding of the system provided by the modelling process; and/or 2) problems with the model due to oversimplification or misspecification.

A series of ten statements can be raised with regard to system behavior that is anticipated from existing information on the system. They are:

1) The expected net revenue from the IPM strategies should exceed the net revenue from conventional control strategies.
2) The expected utility of the conventional control strategies should be greater than the expected utility of the IPM strategies for at least some decision makers with strong risk aversion.

This result could explain why some decision makers do not adopt IPM strategies.

3) By changing the level of the economic threshold in different IPM programs, the amount of risk associated with each program will be different. More risk averse decision makers should prefer IPM strategies with lower economic thresholds. Less risk averse decision makers will prefer IPM strategies with higher economic thresholds.

4) If pest population densities are estimated at discrete time intervals, the efficiency of a given economic threshold will depend in part in the amount of population growth between estimates and there should exist a relationship between the economic threshold and the scouting interval.

    a) The expected net revenue of IPM strategies with low economic thresholds will be higher with longer scouting intervals.

    b) With shorter scouting intervals, IPM strategies with higher economic thresholds will have larger expected net revenues.

    c) With longer scouting intervals the expected utilities of the IPM strategies with lower economic thresholds will be larger than the expected utilities of the IPM strategies with higher economic thresholds.

    d) With shorter scouting intervals, the expected utilities of the IPM strategies with higher economic thresholds will be larger than the expected utilities of the IPM strategies with the lower economic thresholds.

5) With larger yields (or higher value of the crop due to higher prices), the differences in the expected net revenues (and expected utilities) of the conventional control programs and the

IPM strategies will be lower. Likewise, as yields increase, the expected net revenues (and expected utilities) of the IPM strategies with low economic thresholds will increase relative to the expected net revenues (and expected utilities) of the IPM strategies with high economic thresholds.

6) By ignoring any possibility of Friedman-Savage utility functions, Second Degree Stochastic Dominance should identify an efficiency set which is biased. The bias introduced by using the class of all risk averse individual to represent agricultural decision makers could result in both Type I and Type II errors.

7) The expected value of the amounts of chemicals introduced into the environment by conventional spray programs will exceed the expected value of the amount of chemicals introduced by IPM strategies.

8) The expected crop damage under the IPM strategies should be larger than the expected damage of the conventional spray programs. The expected damage of the IPM programs with the low economic thresholds should be lower than the expected damage of the IPM programs with higher economic thresholds.

9) There are significant gains to be realized by refining the IPM decision rules and accurately defining the economic threshold. Sampling errors incurred in the monitoring process should detract considerably from the efficiency of IPM programs.

10) The efficiency sets identified by SDWRF can be further refined by CSD as strategies which would not be selected by any decision maker are rejected from the efficiency set.

These statements will be compared with the predictions on the model in Chapter VIII.

IV. MITE MODEL RESULTS

4.1 The Simulation Model

The mite model is an adaptation of a model that was originally written by Dover, Croft, Welch and Tummala (35). The model uses a time interval of one day and is driven by the average daily temperature.

The model has a number of components but the main three subroutines are those which simulate the population dynamics of the European red mite, Panonychus ulmi, and its principal predator, Amblysesius fallacis. These subroutines are PRED, ERPOP and AFPOP. They are designed to be called each day and respectively calculate the predation, the red mite population growth and the predator mite population growth. The subroutines operate using the daily average temperature. The temperature influences the rate of development in the population and the predation rate. Below 50° F predation, growth and reproduction stop. For average temperatures above 80° F, the feeding and growth rates may not be accurate.

The subroutine AFPOP advances the predator population each day by calculating the fraction of individuals in each of 10 age classes which should mature in the next class and by determining the number of eggs oviposited. The ten age classes appear in Table 1. The population can be decreased by natural mortality, starvation or exposure to toxic chemicals. The subroutine is depicted in a flow chart appearing in Figure 1.

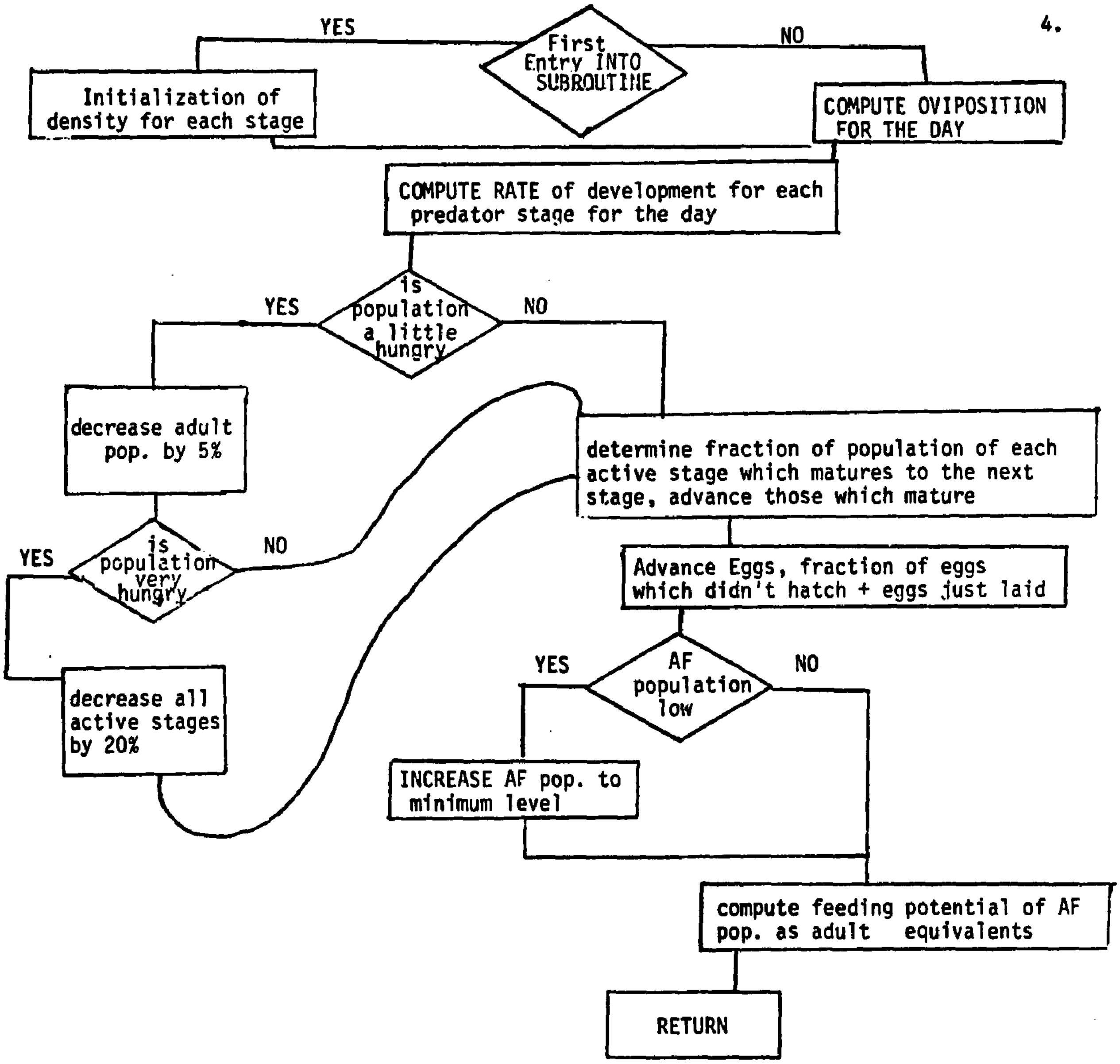
The subroutine ERPOP functions in much the same way and uses the same age classes. It proceeds each day by calculating the oviposition, the fraction of individuals not eaten and the fraction of individuals

Table 1. Age Classes for Mite and Predator Populations.

Age Class	Description
1	egg
2	larva
3	protonymph
4	deutonymph
5	preoviposition
6	oviposition, first quintile
7	oviposition, second quintile
8	oviposition, third quintile
9	oviposition, fourth quintile
10	oviposition, fifth quintile

Figure 1. Subroutine AFPOP: The Population Dynamics of the Predator.

4.



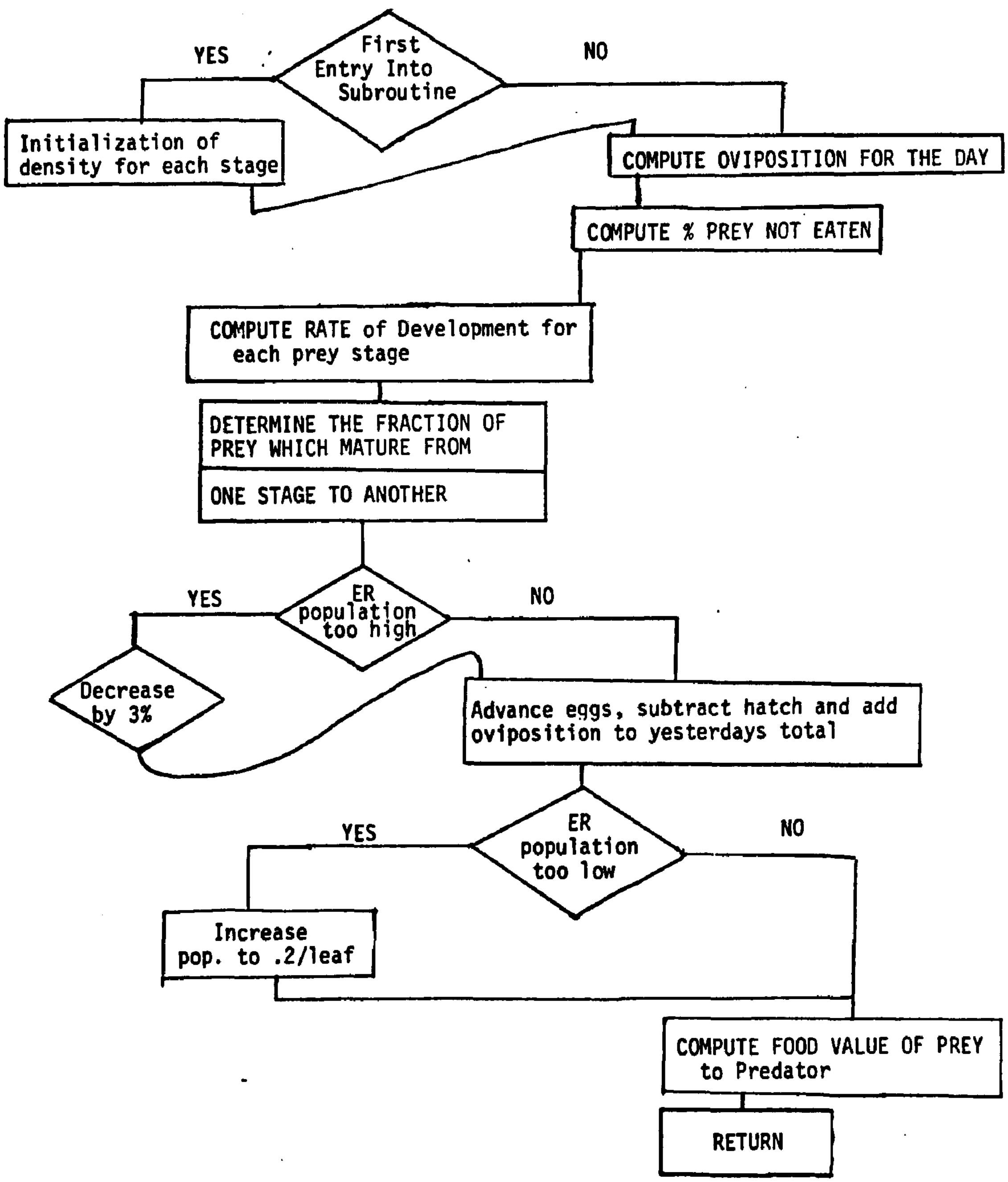
in each of the ten classes which should mature and graduate to the next class. It is assumed that food is unlimited for the red mites at densities below 35 mites/leaf and that at densities above 70 mites/leaf oviposition ceases. At densities greater than 35 mites/leaf, the population is reduced at a rate of 3% per day. The subroutine is depicted in a flow chart in Figure 2.

The species populations are both measured in terms of the female population. It is assumed that the male population is 1/3 the size of the female population for the red mites and that there are 4 females for each one of the male mite predators. The males are included in the model where the food value of the prey is calculated, when the predation rate of Amblyesius fallacis is determined and when the total number of members in the active stages are estimated for either species. The food value of the prey is converted into Tetranychus urticae egg equivalents (EPY).

A more complete description of the model and a discussion of its validation appear in Environmental Entomology (35). The major differences between the original model and the adapted version lie in several simplifying assumptions. First, the cohorts are not maintained but rather, a fraction from each of the 10 age classes is matured each day. The negative binomial distribution is not used to compute the predation and the red mite population is converted into prey equivalents which is then used to compute predation. The final change is the imposition of the assumption that at densities of greater than 70 mites/leaf oviposition ceases entirely.

Using these three subroutines as a base from which the population dynamics can be simulated, the complete model can be constructed to incorporate mortality caused by pesticides treatments, the application of different pest management strategies, the random generation of initial

Figure 2. Subroutine ERPOP: The Population Dynamics of Mites.



population densities and emergence dates and the estimate of fruit damage that would be caused each season by mites.

The subroutine MMORT determines mortality of both the plant feeding mites and the predator mites when they are exposed to different dosages of two miticides (plictran and carzol), one fungicide (benomyl and/or an insecticide pyrethroid). The mortality rates are a function of the time that has elapsed since the application.

The initial population densities for the two species are randomly generated by a subroutine entitled INTMITE. This model component uses a uniform distribution to randomly select one of twenty different starting population levels. The twenty levels occur at irregular intervals and have been designed to simulate the historical distribution on initial densities. Both species use the same procedure but the predator population is determined by an independent draw from the uniform distribution and is set equal to 1/10 of the starting level selected by that draw.

This subroutine selects the emergence dates for the populations in much the same fashion. It uses a uniform distribution to randomly select from a number of emergence dates designated to reproduce the observed historical pattern. In this case, the two species do not use the same data on the emergence dates. The predator population uses an independent draw from the uniform distribution to select from ten dates peculiar to its own emergence pattern while the mite population is randomly selected from 20 possible dates. The probability is high that the mite population should emerge much sooner than its predators.

Each season will have a unique, random combination of two emergence dates and two initial population densities.

The mite injury and subsequent fruit damage are handled in two subroutines. First, in the component entitled MITEINJ the number of mite days for each of three parts of the season are computed. A mite day is a measure of the number of mites present and the length of time that they feed. In this case, it is the sum of the number of mites per leaf by which the population exceeds the specified threshold each day. The threshold is set at 15 mites/leaf since it is believed that European red mite populations can be tolerated at this level without the feeding adversely affecting fruit production or tree vigor (31, p. 4). The mite days are accumulated for each of three parts of the season. The first third of the season ends at June 15, the middle part runs from June 16 to August 15 and the final third begins on August 16 and extends to the end of the season.

The number of mite days is converted to a damage figure using information from a study appearing in Recent Advances in Acarology (61) and from unpublished data collected by Croft. Hoyt et. al concluded that "an estimated 3,000 mite-day (peak of about 120 mites per leaf) was required to produce a loss of one box size or approximately 12% loss in yield" (61, p. 11). This conclusion has been adapted to the situation in Michigan by Croft. The peak has been adjusted to 2000 mite-days and a curvilinear function is used to estimate damage at lower densities. Since the damage results in both discolored and small sized fruit, it was felt converting the expression of percentage loss to terms of value of the harvest rather than number of bushels would more closely capture the damage of both quality and quantity. The earlier in the season that the mite injury occurs, the more affected will be the fruit production and tree vigor. Therefore, the maximum damage expected in each part of the season will be progressively smaller. On the first part, a sum of

2000 mite-days will reduce the value of the crop by 12% while the same population density in the middle third of the season will only result in an 8% decline. In the final time interval, the peak population of 2000 mite days would produce a 3.432% reduction in the value of the fruit. Under the worst possible conditions the maximum amount of damage could account for just under 24% of the value of the potential, non-mite damaged yield. These calculations are performed in the subroutine ESMITES which is designed to be called once a year, at the end of each season.

The model implements the decision rules which are dictated by the various strategies in the subroutine MSCOUT. This subroutine has been designed to handle strategies which are based on calendar spray schedules or IPM programs of varying degrees of sophistication. In the case of a strategy which follows a strictly biological control program, this subroutine would not be called. In the case of calendar based strategies, the subroutine is called on the days designated for sprays by the specified time intervals. It is called whenever the orchard is to be monitored by a professional scout when any of the IPM strategies are being examined.

There are three classes of strategies examined by the model. They are biological control, calendar and IPM. The biological control relies entirely on the efficacy of the natural predators to control the plant feeding mites and applies no chemical miticdes regardless of the population densities experienced. The calendar programs included in the model are the full dose applications of two different chemicals (plictran and carzol) at specified dates. In this case, sprays are applied at the end of June and again at the beginning of August. The IPM strategies have varying degrees of sophistication and can apply full or reduced dosages depending upon the decision rule exercised and the ratio of population densities of the mites and the mite predators. Reduced dosages are designed to minimize the impact of the chemicals on the predators and promote the biological control of pests. When the chemical carzol is employed, the potential for reduced dosages is not great since even at less than full strength it remains very toxic to the predators. The IPM strategies which do not have the option of applying reduced dosages are fairly simple. Whenever the mite population is monitored and it exceeds the economic threshold, a full dose of the miticide is applied. However, when a more sophisticated strategy is employed, the decision rule becomes more complex. These strategies have at least two key management variables--the economic threshold for a full dosage (FET) and the economic threshold for a lower dosage (HET). If the red mite population is less than HET, no spray is applied, while if it exceeds FET, a full dosage is recommended. If the red mite population lies between HET and FET, the ratio of the prey to the predator becomes important. If the predator population is greater than TRP1, then no spray is applied. If it falls between TRP1 and TRP2, a third dosage is recommended while for levels between .08 predator mites/leaf and TRP2, a half dosage is required. TRP1 and TRP2 are defined as follows:

1) TRP1 - .099 * AER - .3

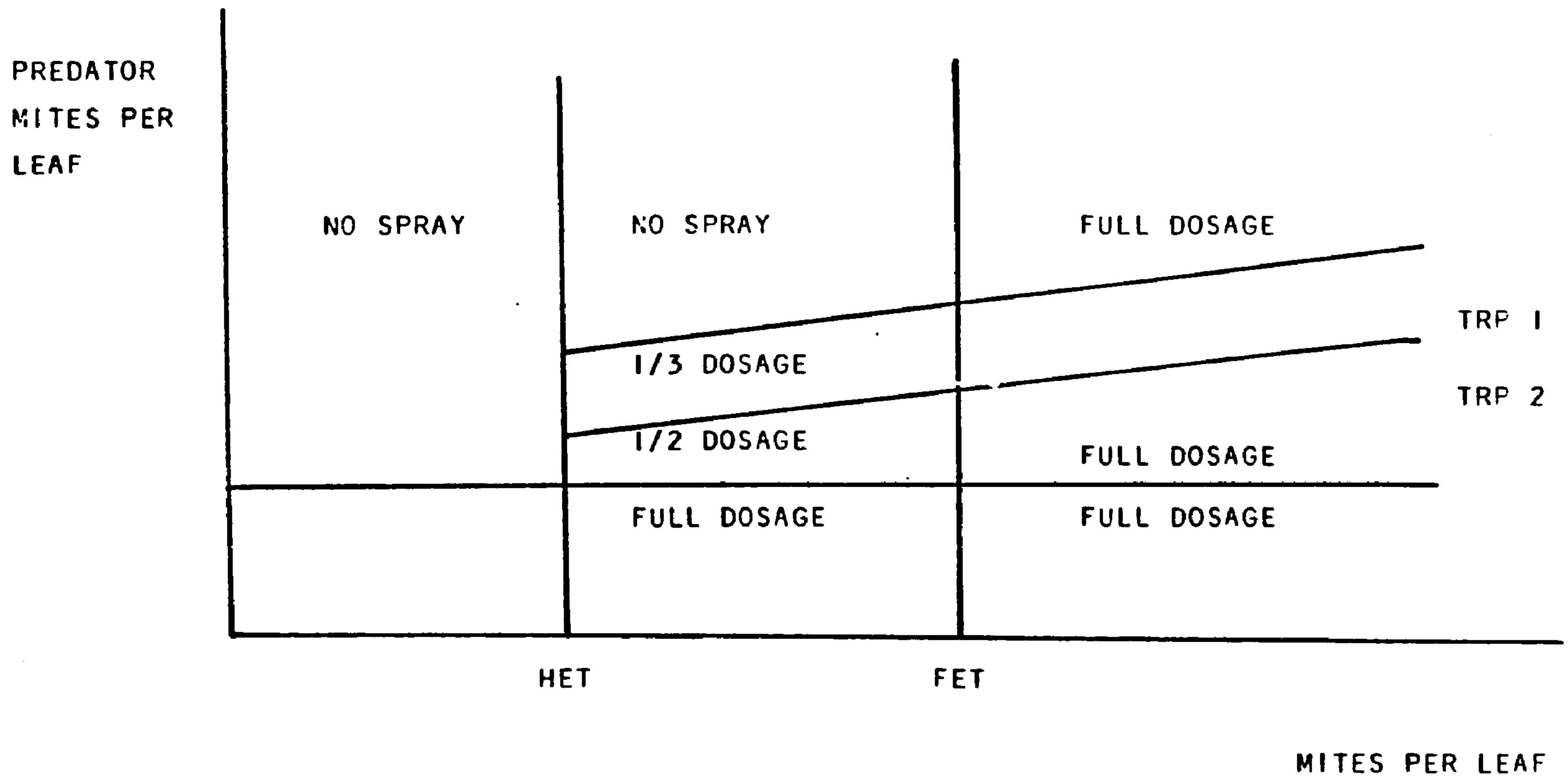
2) TRP2 = .08267 * AER - .34

AER = red mite population density (mites per leaf)

This decision framework is displayed in Figure 3.

The basic framework can be slightly revised to promote even more biological control. If the decision rule is adjusted to dictate a half dosage for the first spray regardless of the predator prey ratio, the possibility of saving some chemicals would exist. Strategies based on

Figure 3. Decision Framework for IPM Mite Control Strategies.



this revised rule are dependent upon the subsequent monitoring, biological control and future sprays to avoid losses if a full dosage should have been applied first. Therefore, even with the possibility of some savings on the chemical costs, it might result that the risk of employing one of these strategies may be increased by the danger of increased mite damage.

The model compares the sophisticated IPM strategies both with the automatic half dosage-first spray rule and without it. The strategies examined by the model are presented and described in Table 2.

The performance of the IPM strategies have been simulated under two assumptions about the size of sampling error associated with scout's estimate of mite population. First, the model operated as if the sampling error was zero--that the scout's estimate was exactly accurate. Then, the model repeated the simulations but with the assumption that 95% of the time the scout's estimate was within 50% of the true population.

Another factor which can influence the performance of the strategies is the scouting interval. The model currently has two options by which the scouting interval can be defined. Each has its advantages for certain circumstances. The first option can be defined as scouting on a request basis. With this option, whenever the growers perceive that there is a problem in the orchard with mites, they request a visit from a professional scout who then estimates the population densities. This information is then used by the decision rule of the appropriate IPM strategy and some action is implemented. It is assumed that there is a three day delay between when the scout is requested and when the visit is actually made. The scout will visit the orchard twice for each request--an initial visit and a check three days later. For this service a charge

Table 2. Mite Model Strategies.

Strategy	Chemical	Type of Control Program	Decision Rule	Monitoring Error
1	--	Biological control	No chemicals are applied, but control relies on natural predators	--
2.	Plictran (1 1/2 lbs/acre	Calendar	Apply full dose at the end of June and at the end of July	None
3	Carzol (2 lbs/acre)	Calendar	Apply full dose at the end of June and a* the end of July	None
4	Plictran-Full Dose (1 1/2 lbs/acre)	IPM	Full dosage Economic threshold-15 mites/leaf. No reduced dosages applied	None
5	Plictran-Full Dose (1 1/2 lbs/acre)	IPM	Full dosage Economic threshold-28 mites/leaf. Reduced dosage economic threshold-22 mites/leaf	None
6	Plictran-Full Dose (1 1/2 lbs/acre)	IPM	Full dosage economic threshold 28 mites/leaf Reduced dosage economic threshold 7 mites/leaf	None
7	Plictran-Full Dose (1 1/2 lbs/acre)	IPM	Full dosage economic threshold-35 mites/leaf Reduced dosage economic threshold 25 mites/leaf	None
8	Carzol-(2 lbs/acre)	IPM	Full dosage economic threshold 28 mites/leaf No reduced dosages applied	None
9	Carzol (2 lbs/acre)	IPM	Full dosage economic threshold 15 mites/leaf No reduced dosages applied	None
10	Carzol (2lbs/acre)	IPM	Full dosage economic threshold 35 mites/leaf No reduced dosages applied	None
11	Plictran-Full dose (1 1/2 lbs/acre)	IPM	Full dosage economic threshold 15 mites/leaf No reduced dosages applied	95% of time estimated population is within 50% of true population
12	Plictran-Full dose (1 1/2 lbs/acre)	IPM	Full dosage economic threshold 28 mites/leaf Reduced dosage economic threshold. 22 mites/leaf	95% of time estimated population is within 50% of true population
13	Plictran-Full dose (1 1/2 lbs/acre)	IPM	Full dosage economic threshold 38 mites/leaf Reduced dosage economic threshold. 7 mites/leaf	95% of time estimated population is within 50% of true population
14	Plictran-Full dose (1 1/2 lbs/acre)	IPM	Full dosage economic threshold 35 mites/leaf Reduced dosage economic threshold. 25 mites/leaf	95% of time estimated population is within 50% of true population
15	Carzol (2 lbs/acre)	IPM	Full dosage economic threshold 28 mites/leaf No reduced dosage applied	95% of time estimated population is within 50% of true population
16	Carzol (2 lbs/acre)	IPM	Full dosage economic threshold 15 mites/leaf No reduced dosage applied	95% of time estimated population is within 50% of true population
17	Carzol (2 lbs/acre)	IPM	Full dosage economic threshold 35 mites/leaf No reduced dosage applied	95% of time estimated population is within 50% of true population

is assessed at the rate of $5.00 per ten acre block per request. The model has been simulated with growers perceiving a mite problem at two different densities. First, it was assumed that they recognized a problem at 5 mites per leaf and then later is was adjusted to 9 mites per leaf. It has been determined from historical record analysis that growers first detect mites at densities between 3 and 10 per leaf (148, pp. 46-48).

When the error terms are introduced for the sampling of the mite population they are also included in the growers detection of mite problems. The errors would be the same for both variables--the sampling and the problem perception.

The second option is the standard weekly interval where every seven days a professional scout visits the orchard and samples the pest populations.[1] The charge for this service is $12.00/acre, but it is assumed that the sampling of more than just the mite population occurs. This option is more relevant when more than one pest is being monitored. When a single pest is considered independently from the complex of pests whose control would likely benefit from the weekly scouting, it is difficult to assess the appropriate charge to control of the single pest for the scouting service.

The Stochastic Elements of the Model

The model is a Monte Carlo simulation of twenty independent seasons for each strategy. Each season begins on April 1 and ends on September 15. For each strategy, the model simulates twenty seasons so that the performance of the various control programs can be evaluated under different circumstances. As the conditions in the orchard and the market change, it is unlikely that strategies will produce the same outcomes.

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[1]In some analyses the interval was changed to one visit every 14 days.

The uncertainty about which conditions will occur influences the variability in the outcomes and hence the amount of risk associated with each strategy. The change in conditions in the model is governed by the random generation of the values for the stochastic variables. The random generation of values is, in turn, determined by the underlying probability distributions for the variables which are usually based on historical data records.

The mite model has six major sources of uncertainty. They are: 1) the product prices; 2) the average daily temperature; 3) the number of degree days accumulated prior to April 1; 4) the emergence dates of the populations; 5) the initial population densities; and 6) the random sampling error for monitoring and the detection of mite problems by growers.

The product prices are randomly generated for both the fresh and processed markets using a multivariate random processor (63). These stochastic variables are drawn from a multivariate distribution which has incorporated the correlation coefficients between the two market prices and the yield. This maintains the observed relationships of the variable in the random draws. The yield can be drawn from three alternative marginal distributions which each have a different mean value. The multivariate distribution was constructed from historical data from 1970 to 1979.

This multivariate random processor is also used in the generation of the random weather variables. Although the mite model does not directly use daily precipitation, it is drawn from a multivariate distribution with the average daily temperature which the model does use. The correlations which are important in these distributions are the correlation coefficients between the temperature and precipitation for each day within the time interval, the autocorrelation between the precipitation for each day and the previous day. Since the season was divided into 8 parts of 21 days each, there are 8 distinct multivariate distributions. The probability of a given temperature being drawn is different in the 8 parts of the season but it is identical for all 21 days within any part of the season. The distributions were developed from historical weather records from the East Lansing weather experiment station for the years between 1910 and 1979. An alternative set of distributions was also developed from data from Grand Rapids (1944-1979).

As was previously discussed, the number of degree days (base 43° F) that have accumulated prior to April 1 is randomly generated from a normal distribution with a mean of 580 and a standard deviation of 80. The degree day count influences the phenological stage of the trees, the amount of frost damage and certain components of the codling moth model.

The random generation of the emergence dates of the populations and the initial population densities has been previously discussed in this chapter. The probability distributions of these variables are based on historical data.

The random sampling error is an option which can be used in conjunction with two processes in the model. It can adjust the accuracy of the estimate of the mite population that is provided by the professional scout. It can also influence the accuracy of the perception of the grower as to when the potential of a mite problem exists and a request for a professional scout should be made. The random error is drawn from a normal distribution with a mean equal to the actual population density and a standard deviation inferred by the confidence interval defined by the user of the model. In this case the error insures that the estimate will be within 50% of the true population 95% of the time.

4.2 The Mite Model Results

The performance of a pest management strategy could be measured in several different ways. The expected net revenue would obviously be an important one since it indicates how on the average, the farmer who adopted a strategy would do financially. However, it is not a complete measure of the value that the income would have for the farmer since it ignores any value that may be placed on the risk associated with the strategy. The variance in net revenue could be used as a measure of the inherent risk of the strategy but often it is necessary to examine other moments of the distribution as well to truly estimate the impact that risk can have on optimal decisions. The model reports the expected value and variance in the per acre net revenue and provides enough information that all other important moments of the distribution can be estimated if needed.

The number of sprays applied and the amounts of the chemicals used are of interest not only for analysis of the on-farm impact that the adoption of strategies could have but because of the implications for environmental quality as well. The model reports the use of chemicals in terms of full dose equivalents. For carzol, a full dose is an application of 2 lbs. per acre while for plictran it is a rate of 1 1/2 lbs. per acre. The price per pound for the two chemicals which the model currently uses is \$16.50/lb. for carzol and \$18.50/lb. for plictran. The spray costs appear in Table 3.

Another important performance variable is the estimate of mite damage. Mite damage is assessed in terms of dollars per acre since it is calculated as a percentage reduction in the value of the potential non-

Table 3. Spray Costs for Mite Control Strategies.

Spray	Chemical Price Per Unit	Chemical Cost Per Application	Labor Cost Per Application	Machinery Cost Per Application	Cost Per Application
Carzol (2 lbs/acre)	$16.50/lb	$33.00/acre	$.70/acre	$.70/acre	$34.40/acre
Plictran (1 1/2 lbs/acre)	$18.50/lb	$27.75/acre	$.70/acre	$.70/acre	$29.15/acre
Plictran (3/4 lb/acre)	$18.50/lb	$13.875/acre	$.70/acre	$.70/acre	$15.275/acre
Plictran 1/2 lb/acre)	$18.50/lb	$9.25/acre	$.70/acre	$.70/acre	$10.65/acre

SOURCE: Pest Control Branch, NRED, ERS, USDA.

mite damaged harvest. Since the figures for mite damage are heavily influenced by the assumptions that directly influence the determination of the yield, caution must be exercised in using the numbers as an absolute estimate. They were designed more for relative comparisons with each other.

Another vital statistic is one which attempts to balance the expenditures on pest control with the amount of pest damage that is experienced. If the two measures are considered independently the potential for some spurious conclusions is high. It would not be at all infeasible to imagine cases where small amounts of damage are observed but large expenses for pest control have been incurred, or vice versa. The variable, "Control Costs," tries to account for this measure. It is the sum of the mite damage, and the costs of the chemicals applied, and the labor and machinery used in the spray applications.

For each of the strategies, the expected values and standard deviations appear for each performance variable in Table 4. It should be noted that these results are for a weekly scouting program where a monitoring charge of $12/acre has been assessed to the IPM strategies for the control mites. The performance of strategies with the option which provides a scout on request from the grower will be discussed later. It should also be remembered that strategies 4-10 have no sampling error while strategies 11-17 have a random error in the estimates of the population densities provided by the professional scout. The strategies were simulated with the medium or low yield levels.

Medium Yield and Weekly Scouting

At the medium yield level, of those strategies with the zero sampling error, strategy 6 has the highest expected net revenue. It has a very low reduced dosage economic threshold (HET-7 mites per leaf)

Table 4. Mite Model Results with Medium Yield and Weekly Scouting.

Strategy	Potential Yield (bu/acre)	Mite Damage ($/acre)	Number of Sprays	Plictran (F.D.E.*)	Carzol (F.D.E.*)	Total Control Costs ($/acre)	Net Revenue ($/acre)
1	502.1 (47.5)	112.0 (115.2)	---	---	---	482.7 (48.0)	296.4 (618.3)
2	502.1 (47.5)	26.1 (64.2)	2 (0.0)	2.0 (0.0)	---	369.3 (128.4)	323.9 (689.9)
3	502.1 (47.5)	27.7 (65.5)	2 (0.0)	---	2.0 (0.0)	383.0 (131.1)	311.8 (690.3)
4	502.1 (47.5)	1.4 (5.1)	2 (1.8)	2.0 (1.8)	---	319.8 (51.8)	348.7 (685.9)
5	502.1 (47.5)	3.6 (6.8)	2 (1.6)	1.7 (1.6)	---	314.9 (53.1)	355.8 (685.7)
6	502.1 (47.5)	1.1 (5.1)	2 (1.8)	1.6 (1.5)	---	308.0 (44.8)	360.2 (692.1)
7	502.1 (47.5)	4.5 (8.5)	2 (1.5)	1.5 (1.5)	---	311.7 (55.2)	359.9 (687.7)
8	502.1 (47.5)	7.2 (9.2)	2 (1.7)	---	2.0 (1.7)	340.2 (73.1)	334.1 (681.1)
9	502.1 (47.5)	1.4 (5.1)	2 (1.9)	---	2.2 (1.9)	337.2 (64.5)	331.3 (680.9)
10	502.1 (47.5)	13.5 (14.2)	2 (1.7)	---	1.8 (1.7)	347.7 (81.2)	332.9 (679.5)
11	502.1 (47.5)	1.8 (5.1)	2 (1.8)	2.0 (1.8)	---	319.1 (53.1)	349.7 (687.8)
12	502.1 (47.5)	3.2 (6.5)	2 (1.8)	1.8 (1.8)	---	317.0 (57.7)	353.3 (688.7)
13	502.1 (47.5)	1.1 (5.1)	2 (1.6)	1.6 (1.5)	---	307.5 (43.7)	360.7 (692.8)
14	502.1 (47.5)	4.5 (6.8)	2 (1.7)	1.7 (1.6)	---	317.5 (55.3)	354.2 (688.5)
15	502.1 (47.5)	7.2 (9.5)	2 (1.7)	---	1.9 (1.7)	338.5 (69.9)	335.8 (683.9)
16	502.1 (47.5)	1.7 (5.0)	2 (1.9)	---	2.1 (1.9)	334.5 (65.7)	334.3 (679.1)
17	502.1 (47.5)	13.0 (13.0)	2 (1.7)	---	1.9 (1.7)	348.5 (80.0)	331.6 (681.9)

* Full Dose Equivalents

and a moderate full dose economic threshold (FET-22 mites per leaf). The strategy with the highest economic thresholds, strategy 7 (FET-35, and HET-25), has an expected net revenue of only $.30/acre less than strategy 6. There is more damage experienced with strategy 7 but strategy 6 uses slightly more of the miticide.

All of the IPM strategies have expected net revenues greater than the conventional calendar spray program. The conventional programs suffer considerably more damage and use more chemicals than the IPM strategies. The carzol strategies produced net revenues from $26 to $13 an acre below their plictran counterparts. These differences reflect the higher spray costs and the disruption of the natural predation. The biological control strategy has an average net return below the calendar spray programs but the natural predation completely prevents the mites from causing damage in 7 of the 20 seasons.

The introduction of the random sampling error has a greater impact on the IPM strategies with the high economic thresholds than on the ones with the lower thresholds. In fact, strategies 4 and 6 display a marginal improvement while strategies 5 and 7 experience declines in their expected net revenues. Strategy 7 has a reduction in net income of over $5/acre. A similar pattern is exhibited by the carzol strategies.

When the decision rules are revised to always apply a half dose on the first spray regardless of the predator/prey ratio, the plictran IPM strategies all unveil higher expected net revenue estimates. The results of the simulation appear in Table 5. With the exception of strategy 7, the increase in the net revenue is about $8/acre. Strategy 7 experiences only a $2/acre increase which is probably because its reduced dose economic threshold is so high that it previously applied a

Table 5. Mite Model Results with Medium Yield, Weekly Scouting and Revised Decision Rules Which Always Apply a Half Dose on First Spray.

Strategy	Potential Yield (bu/acre)	Mite Damage ($/acre)	Number of Sprays	Plictran (F.D.E.)*	Carzol (F.D.E.*)	Total Control Costs ($/acre)	Net Revenue ($/acre)
4	502.1 (47.5)	1.5 (5.0)	2 (1.8)	1.7 (1.7)	----	312.4 (48.4)	356.1 (684.0)
5	502.1 (47.5)	3.5 (5.4)	2 (1.6)	1.4 (1.4)	----	307.8 (44.1)	362.8 (688.5)
6	502.1 (47.5)	1.1 (5.1)	2 (1.6)	1.3 (1.3)	----	300.2 (38.4)	368.1 (694.6)
7	502.1 (47.5)	5.8 (10.2)	2 (1.6)	1.4 (1.4)	----	311.0 (55.5)	361.8 (689.1)
11	502.1 (47.5)	1.8 (5.1)	2 (1.9)	1.8 (1.7)	----	314.5 (50.2)	354.3 (684.2)
12	502.1 (47.5)	2.8 (5.3)	2 (1.6)	1.5 (1.4)	----	307.1 (44.0)	362.8 (691.3)
13	502.1 (47.5)	1.1 (5.1)	2 (1.6)	1.3 (1.3)	----	299.5 (37.9)	368.7 (695.1)
14	502.1 (47.5)	4.3 (6.1)	2 (1.7)	1.3 (1.4)	----	306.6 (48.3	364.8 (689.4)

*Full Dose Equivalent

half dose on the first spray on a regular basis. In most cases, the amount of chemical applied is reduced while the amount of damage remains almost unchanged. Strategy 7 does have its damage increase over $1/acre but the savings from the reduced miticide usage exceed this amount by $2/acre. The introduction of the random sampling error has a marginal impact on the expected net revenues. The largest change is observed in Strategy 7 and it is an increase in the average net income of $3/acre.

Low Yield and Weekly Scouting

The low yield scenario produces model results slightly different than the previous scenario. The results are shown in Table 6. The strategy with the highest expected net revenue is strategy 7. Its net income is $15 higher than the net income of strategy 6. The IPM strategies have average net revenues $14 to $27 per acre higher than the conventional calendar spray programs. All strategies apply the same amount of chemicals as with the previous scenario but the damage estimates are lower reflecting the change in the yield. The strategy using exclusively biological control generates an expected net revenue higher than the conventional calendar spray programs, the simple plictran IPM strategy and all of the carzol IPM strategies. The conventional program applying plictran is slightly more profitable than the carzol IPM strategy with the lowest eocnomic threshold. The latter strategy applies the most sprays on average of any of the strategies examined.

The presence of the random sampling error influences the relative performances of the strategies in much the same way as was uncovered earlier. The changes in expected net revenue are small except for those strategies with large economic thresholds. The plictran IPM strategy with the highest economic thresholds suffers almost a $6/acre decline in

Table 6. Mite Model Results with Low Yield and Weekly Scouting.

Strategy	Potential Yield (bu/acre)	Mite Damage ($/acre)	Number of Sprays	Plictran (F.D.E.)*	Carzol (F.D.E.*)	Total Control Costs ($/acre)	Net Revenue ($/acre)
1	248.0 (50.8)	52.1 (55.2)	--	--	--	362.9 (110.4)	-346.6 (301.3)
2	248.0 (50.8)	14.5 (36.1)	2 (0.0)	2 (0.0)	--	346.1 (72.1)	-367.4 (321.3)
3	248.0 (50.8)	15.4 (36.8)	2 (0.0)	-- --	2.0 (0.0)	358.3 (73.5)	-378.7 (321.3)
4	248.0 (50.8)	.6 (2.2)	2 (1.8)	2.0 (1.8)	--	318.3 (51.6)	-353.5 (324.1)
5	248.0 (50.8)	1.7 (3.4)	2 (1.6)	1.7 (1.6)	--	311.1 (49.3)	-345.2 (321.6)
6	248.0 (50.8)	0.5 (2.3)	2 (1.8)	1.6 (1.5)	--	306.8 (44.4)	-342.1 (324.1)
7	248.0 (50.8)	2.2 (4.4)	2 (1.5)	1.5 (1.5)	--	307.0 (49.6)	-340.6 (322.8)
8	248.0 (50.8)	3.5 (4.9)	2 (1.7)	--	2.0 (1.7)	332.9 (66.5)	-365.2 (321.3)
9	248.0 (50.8)	0.6 (2.2)	2 (1.9)	--	2.2 (1.9)	335.7 (64.4)	-370.9 (319.6)
10	248.0 (50.8	6.6 (7.4)	2 (1.7)	--	1.8 (1.7)	333.9 (69.5)	-363.1 (318.6)
11	248.0 (50.8)	0.8 (2.2)	2 (1.8)	2.0 (1.8)	--	317.2 (52.4)	-352.2 (324.7)
12	248.0 (50.8)	1.6 (3.2)	2 (1.8)	1.8 (1.8)	--	313.7 (54.4)	-348.0 (322.2)
13	248.0 (50.8)	0.5 (2.3)	2 (1.6)	1.6 (1.5)	--	306.2 (43.3)	-341.5 (325.0)
14	248.0 (50.8)	2.2 (3.3)	2 (1.7)	1.7 (1.6)	--	312.8 (51.7)	-346.4 (321.3)
15	248.0 (50.8)	3.5 (4.9)	2 (1.7)	--	1.9 (1.7)	331.1 (64.1)	-363.4 (322.9)
16	248.0 (50.8)	.8 (2.3)	2 (1.9)	--	2.1 (1.9)	332.6 (65.2)	-367.6 (319.5)
17	248.0 (50.8)	6.4 (6.8)	2 (1.7)	--	1.9 (1.7)	335.1 (69.3)	-364.6 (321.4)

*Full Dose Equivalents

net income when the sampling error is considered. The majority of strategies experience a change in net revenue of $2/acre or less which cannot be viewed as very large when the size of the sampling error is considered.

The expected net revenues of most of the plictran IPM strategies can be increased by $7 to $8 per acre by revising the decision rules to apply a half dose on the first spray regardless of the predator/prey ratio. This provides the predators more of a chance to become established before a full strength treatment is applied. The exception to this observation is strategy 7 which previously applied a half dose first spray due to its high reduced dose economic threshold. It displays a per acre increase in net income of $2. These results are presented in Table 7.

Medium Yield and Biweekly Scouting

When the scouting interval is changed from every seven days to every 14 days, the expected net revenues of the plictran IPM strategies with the high economic thresholds decline substantially. These results are displayed in Table 8. The strategies examined used the revised decision rules which automatically apply a half dose on the first spray. Strategy 7 suffers a decrease in its average net income of over $11/acre while strategy 6 enjoys a slight increase in its net revenue. It appears that the longer the scouting interval, the less efficient are the strategies with the high economic thresholds.

Medium Yield and Scouting on Request with a Grower Problem Perception at 5 Mites Per Leaf

In this scenario the scouting program is changed to a system where the scout visits the orchard only when a grower perceives a mite problem

Table 7. Mite Model Results with Low Yield, Weekly Scouting and Revised 7 Decision Rules.

Strategy	Potential Yield (bu/acre)	Mite Damage ($/acre)	Number of Sprays	Plictran (F.D.E.)*	Carzol (F.D.E.*)	Total Control Costs ($/acre)	Net Revenue ($/acre)
4	248.0 (50.8)	.7 (2.2)	2 (1.8)	1.7 (1.7)	--	310.8 (48.2)	-346.0 (321.3)
5	248.0 (50.8)	1.6 (2.3)	2 (1.6)	1.4 (1.4)	--	304.0 (41.9)	-338.2 (322.7)
6	248.0 (50.8)	.5 (2.3)	2 (1.6)	1.3 (1.3)	--	298.9 (38.1)	-334.2 (326.8)
7	248.0 (50.8)	2.8 (5.5)	2 (1.6)	1.4 (1.4)	--	305.1 (48.2)	-338.1 (324.3)
11	248.0 (50.8)	.8 (2.3)	2 (1.9)	1.8 (1.7)	--	312.6 (49.6)	-347.6 (321.5)
12	248.0 (50.8)	1.3 (2.4)	2 (1.6)	1.5 (1.4)	--	304.2 (42.7)	-338.7 (325.2)
13	248.0 (50.8)	.5 (2.3)	2 (1.6)	1.3 (1.3)	--	298.2 (37.6)	-333.5 (326.8)
14	248.0 (50.8)	2.0 (2.9)	2 (1.7)	1.3 (1.4)	--	302.1 (44.9)	-335.8 (322.4)

*Full Dose Equivalents

Table 8. The Influence of the Scouting Interval on Net Revenue.

Strategy	Expected Net Revenues	
	7 day	14 day
4	356.1	353.0
5	362.8	355.8
6	368.1	369.6
7	361.8	350.3

developing. The grower of the typical orchard perceives a problem when the population density is at 5 mites per leaf. There is a 3 day lag between the time that request for the scout is made and the visit to the orchard is actually paid. The scout estimates the mite and predator populations and an action is implemented following the decision rules of the control strategies. Three days after the first visit the scout returns for a second visit. The charge for the series of two visits is $5.00 per 10 acre block. The model results from this scenario are presented in Table 9.

In this scenario the plictran IPM strategies with the higher economic thresholds produce the highest expected net revenues. Strategies 5 and 7 are on the average $1.5 to $4.5 per acre more profitability than strategy 6. They apply less miticde but suffer more damage. All of the IPM strategies have expected net revenues higher than the biological control and the conventional calendar based programs. The average net incomes of the carzol strategies are $12 to $28 lower than their plictran counterparts.

The introduction of the random sampling error has the surprising result of increasing the expected net revenue of the majority of the strategies. Of the seven IPM strategies examined, only three strategies had a decline in net revenue with the sampling error. The sampling error is present in both the scout's estimate of the mite populations and in the density at which the grower perceives a probelm developing. The increases in net revenues may be indicating that there exists a potential to further refine the decision rules of the strategies. All of the changes in the revenue estimates due to the sampling errors are less than $2/acre.

Table 9. Mite Model Results with Medium Yield and Grower Problem Perception at 5 Mites per Leaf.

Strategy	Potential Yield (bu/acre)	Mite Damage ($/acre)	Number of Sprays	Plictran (F.D.E.*)	Carzol (F.D.E.*)	Total Control Costs ($/acre)	Net Revenue ($/acre)
1	502.1 (47.5)	112.0 (115.2)	---	---	---	470.7 (230.4)	308.4 (618.3)
2	502.1 (47.5)	26.1 (64.2)	2 (0.0)	2.0 (0.0)	---	357.3 (128.4)	335.9 (689.9)
3	502.1 (47.5)	27.7 (65.5)	2 (0.0)	---	2.0 (0.0)	371.0 (131.1)	323.8 (690.3)
4	502.1 (47.5)	1.1 (4.8)	2 (1.7)	2.0 (1.7)	---	308.2 (51.2)	359.9 (687.2)
5	502.1 (47.5)	1.5 (4.7)	2 (1.6)	1.5 (1.5)	---	296.1 (46.2)	372.4 (690.6)
6	502.1 (47.5)	1.1 (4.8)	2 (1.7)	1.6 (1.5)	---	297.4 (45.4)	370.7 (686.4)
7	502.1 (47.5)	2.1 (4.8)	2 (1.5)	1.4 (1.4)	---	294.0 (46.8)	375.2 (685.9)
8	502.1 (47.5)	2.9 (4.9)	2 (1.8)	---	2.0 (1.8)	322.6 (66.1)	347.3 (684.2)
9	502.1 (47.5)	1.1 (4.8)	2 (1.8)	---	2.2 (1.8)	325.3 (63.7)	342.9 (678.9)
10	502.1 (47.5)	5.8 (6.2)	2 (1.7)	---	1.9 (1.7)	325.0 (70.2)	347.8 (680.5)
11	502.1 (47.5)	1.1 (4.8)	2 (1.7)	1.9 (1.7)	---	306.8 (51.7)	361.3 (686.1)
12	502.1 (47.5)	1.6 (5.3)	2 (1.6)	1.4 (1.5)	---	294.5 (46.7)	374.2 (688.3)
13	502.1 (47.5)	1.1 (4.8)	2 (1.7)	1.5 (1.5)	---	295.4 (46.7)	372.2 (691.2)
14	502.1 (47.5)	2.1 (4.7)	2 (1.5)	1.4 (1.4)	---	294.1 (46.4)	375.1 (687.6)
15	502.1 (47.5)	3.8 (5.8)	2 (1.7)	---	2.0 (1.7)	324.5 (65.8)	346.4 (676.2)
16	502.1 (47.5)	1.2 (4.7)	2 (1.8)	---	2.2 (1.8)	325.7 (64.0)	342.6 (678.9)
17	502.1 (47.5)	7.4 (3.9)	2 (1.7)	---	1.8 (1.7)	324.9 (72.8)	349.6 (677.0)

* Full Dose Equivalent

Revising the decision rules to always apply a half dose on the first spray, increases the expected net revenue by between $8 to $10 an acre for each of the plictran IPM strategies. Table 10 contains these results. The amounts of miticideapplied in this case are the lowest for all of the scenarios examined. The damage estimates are equal to or slightly lower than the other results as well. Strategy 7, whose expected net revenue was relatively unimproved by the revised decision rules in the previous scenarios, registers one of the largest increases in this scenario. However, when the random sampling error is considered, the increase is reduced by half. Three of the four strategies experience declines in their expected net revenues of almost $5/acre due to the sampling error. This is the first time when a pattern of a significant decrease in income has been encountered when the sampling error was introduced.

Medium Yield and Scouting on Request Grower Problem Perception at 9 Mites per Leaf

In this scenario, the scouting program is very similar to the system of the previous scenario except that the growers recognize a problem developing when the mite population reaches a density of 9 mites per leaf. At this level, a request is made for a scout to visit the orchard in three days and measure the population. The scout's population estimates are then used in the decision rules of the IPM strategies. The model results for this scenario appear in Table 11. It can be seen that little has changed by adjusting the level at which growers identify a mite problem developing. Strategy 7 still produces the highest expected net revenue by applying the least amount of miticide. Strategies 4 and 6 experience the lowest damage but as expected with their low economic thresholds, they apply more chemicals than strategy 7. The carzol

Table 10. Mite Model Results with Medium Yields, Grower Problem Perception at 5 Mites per Leaf and the Revised Decision Rules which Always Apply a Half Dose on the First Spray.

Strategy	Potential Yield (bu/acre)	Mite Damage ($/acre)	Number of Sprays	Plictran (F.D.E.*)	Carzol (F.D.E.*)	Total Control Costs ($/acre)	Net Revenue ($/acre)
4	502.1 (47.5)	1.1 (4.8)	2 (1.7)	1.6 (1.5)	---	297.7 (45.9)	370.5 (679.7)
5	502.1 (47.5)	1.6 (4.7)	2 (1.6)	1.2 (1.3)	---	288.4 (41.0)	380.3 (693.7)
6	502.1 (47.5)	1.1 (4.8)	2 (1.7)	1.3 (1.4)	---	289.9 (40.6)	378.3 (690.1)
7	502.1 (47.5)	2.0 (4.8)	2 (1.5)	1.0 (1.2)	---	283.9 (39.3)	385.1 (691.0)
11	502.1 (47.5)	1.1 (4.8)	2 (1.8)	1.7 (1.7)	---	302.2 (49.6)	366.0 (680.8)
12	502.1 (47.5)	1.7 (4.7)	2 (1.7)	1.3 (1.4)	---	292.2 (45.1)	376.6 (694.1)
13	502.1 (47.5)	1.1 (4.8)	2 (1.6)	1.3 (1.3)	---	287.3 (38.6)	380.8 (694.0)
14	502.1 (47.5)	2.9 (4.9)	2 (1.6)	1.2 (1.4)	---	289.4 (44.7)	380.6 (690.9)

*Full Dose Equivalents

Table 11. Mite Model Results with Medium Yield and Grower Problem Perception at 9 Mites per Leaf.

Strategy	Potential Yield (bu/acre)	Mite Damage ($/acre)	Number of Sprays	Plictran (F.D.E.)*	Carzol (F.D.E.*)	Total Control Costs ($/acre)	Net Revenue ($/acre)
1	502.1 (47.5)	112.0 (115.2)	--	--	--	470.7 (230.4)	308.4 (618.3)
2	502.1 (47.5)	26.1 (64.2)	2 (0.0)	2.0 (0.0)	--	357.3 (128.4)	335.9 (689.9)
3	502.1 (47.5)	27.7 (65.5)	2 (0.0)	--	2.0 (0.0)	371.0 (131.1)	323.8 (690.3)
4	502.1 (47.5)	1.1 (4.8)	2 (1.7)	2.0 (1.7)	--	306.9 (51.1)	361.2 (691.1)
5	502.1 (47.5)	1.6 (4.7)	2 (1.6)	1.5 (1.4)	--	295.7 (45.1)	372.9 (691.9)
6	502.1 (47.5)	1.1 (4.8)	2 (1.7)	1.5 (1.5)	--	294.5 (44.9)	373.6 (690.7)
7	502.1 (47.5)	1.9 (4.7)	2 (1.5)	1.4 (1.4)	--	292.5 (43.8)	376.5 (689.2)
8	502.1 (47.5)	2.8 (4.7)	2 (1.7)	--	1.9 (1.7)	319.9 (63.6)	350.0 (683.7)
9	502.1 (47.5)	1.1 (4.8)	2 (1.8)	--	2.1 (1.8)	320.6 (61.0)	347.6 (686.7)
10	502.1 (47.5)	5.5 (6.3)	2 (1.7)	--	1.8 (1.7)	322.1 (67.6)	350.4 (681.1)
11	502.1 (47.5)	1.2 (4.7)	2 (1.7)	1.9 (1.7)	--	306.2 (52.3)	362.1 (688.3)
12	502.1 (47.5)	1.7 (4.7)	2 (1.7)	1.6 (1.6)	--	299.7 (50.1)	369.1 (684.8)
13	502.1 (47.5)	1.1 (4.8)	2 (1.7)	1.5 (1.5)	--	293.7 (44.8)	374.4 (691.8)
14	502.1 (47.5)	2.8 (5.3)	2 (1.7)	1.5 (1.5)	--	296.8 (50.2)	373.0 (686.7)
15	502.1 (47.5)	3.5 (5.5)	2 (1.8)	--	1.9 (1.8)	321.5 (67.0)	349.1 (693.1)
16	502.1 (47.5)	1.2 (4.7)	2 (1.9)	--	2.2 (1.9)	326.5 (65.6)	341.8 (679.3)
17	502.1 (47.5)	7.4 (8.7)	2 (1.7)	--	1.8 (1.7)	324.3 (72.4)	350.2 (674.2)

*Full Dose Equivalent

strategies are once again less profitable than the plictran strategies and all of the IPM strategies generate more income on the average than the conventional calendar programs.

The introduction of the random sampling error once again has a larger, detrimental effect on the strategies with the high economic thresholds. Strategies 5 and 7 both have the reductions in net revenue of more than $3/acre while strategies 4 and 6 display marginal improvements in their average income. The sampling error can change the amount of miticides applied and the amount of damage incurred.

The revision of the decision rules to automatically apply the first spray at half dose enhances the profitability of the plictran IPM strategies by $5 to $10 per acre. Strategy 5 has the highest expected net revenue because it applies the least amount ofmiticides applied and suffers less damage than strategy 6. With the exception of strategy 7, all of the strategies experience the same amount of damage as before but apply considerably less pesticide. Strategies 5, 6 and 7 have expected net revenues all within $0.80/acre of each other even though there is substantial difference between their economic thresholds. Consistent with this result is the observation that the random sampling error changes the net revenue of none of the strategies by more than $2/acre. These results are exhibited in Table 12.

The results from the various scenarios are compared for classes of strategies in Table 13. There are some basic patterns which can be discerned from the comparisons. With the exception of the low yield scenario, the biological control strategy has the lowest expected net revenue. The calendar programs and the carzol IPM strategies are less profitable than the simple plictran IPM strategy. All other IPM strategies produce more income on the average than this strategy, except

Table 12. Mite Model Results with Medium Yield, Grower Problem Perception at 9 Mites per Leaf and Revised Decision Rules which Always Apply a Half Dose on the First Spray.

Strategy	Potential Yield (bu/acre)	Mite Damage ($/acre)	Number of Sprays	Plictran (F.D.E.)*	Carzol (F.D.E.*)	Total Control Costs ($/acre)	Net Revenue ($/acre)
4	502.1 (47.5)	1.1 (4.8)	2 (1.7)	1.6 (1.5)	--	296.4 (45.0)	371.7 (688.9)
5	502.1 (47.5)	1.6 (4.7)	2 (1.5)	1.2 (1.3)	--	286.7 (40.8)	382.0 (690.8)
6	502.1 (47.5)	1.1 (4.7)	2 (1.7)	1.3 (1.3)	--	287.0 (39.1)	381.2 (694.4)
7	502.1 (47.5)	2.0 (4.7)	2 (1.5)	1.2 (1.3)	--	287.5 (40.8)	381.6 (690.4)
11	502.1 (47.5)	1.1 (4.8)	2 (1.7)	1.6 (1.5)	--	296.7 (46.2)	371.4 (684.1)
12	502.1 (47.5)	1.6 (4.7)	2 (1.6)	1.2 (1.2)	--	286.7 (38.7)	382.0 (693.6)
13	502.1 (47.5)	1.1 (4.8)	2 (1.7)	1.3 (1.5)	--	288.8 (44.9)	379.3 (690.8)
14	502.1 (47.5)	2.2 (4.9)	2 (1.5)	1.1 (1.2)	--	286.5 (41.3)	382.7 (690.1)

*Full Dose Equivalents

Table 13. Relative Comparisons of Classes of Strategies by Differences from the Expected Net Revenue of the Simple Plictran IPM Strategy.

Scenarios	Biological Control (1)	Plictran Calendar (2)	Carzol Calendar (3)	Carzol IPM (8-10)	Carzol IPM w/Error (15-17)	Simple Plictran IPM (4)	Simple Plictran IPM w/Error (11)	Sophisticated Plictran IPM (5-7)	Sophisticated Plictran IPM w/Error (12-14)	Revised Plictran IPM (H4-H7)	Revised Plictran IPM w/ Error (H11-H14)
Weekly Scouting	-52/acre	-25/acre	-37/acre	-17/acre to -15/acre	-17/acre to -13/acre	--	+1/acre	+7/acre to +12/acre	+5/acre to +12/acre	+7/acre to +19/acre	+6/acre to +20/acre
Weekly Scouting Low Yield	+7/acre	-14/acre	-25/acre	-17 acre to -10 acre	-14/acre to -10/acre	--	+1/acre	+8/acre to +13/acre	+6/acre to +12/acre	+8/acre to +19/acre	+6/acre to +20/acre
Biweekly Scouting	-49/acre	-22/acre	-34/acre	a	a	--	a	a	a	-3/acre to +17/acre	a
Request Scouting: Grower Perception @ 5 mites per leaf	-52/acre	-24/acre	-36/acre	-17/acre to -12/acre	-17/acre to -10/acre	--	+1/acre	+11/acre to +15/acre	+12/acre to +15/acre	+11/acre to +25/acre	+6/acre to +21/acre
Request Scouting: Grower Perception @ 9 mites per leaf	-53/acre	-25/acre	-37/acre	-14/acre to -11/acre	-20/acre to -11/acre	--	+1/acre to	+12/acre to +15/acre	+8/acre to +13/acre	+11/acre to +21/acre	+10/acre to +22/acre

[a]Unavailable

for one revised plictran IPM strategy in the biweekly scenario. The revised decision rules generally improve expected net revenue by $5 to $10/acre.

4.3 Risk Analysis

The following section is divided into two parts. The first part describes the analytical procedures while the second presents the model results. Readers familiar with the risk analysis should skip the discussion of the analysis procedure and proceed to the part describing the results.

Analysis Procedure

Evaluating mite management strategies by the single criteria of the expected net revenue may ignore some other important performance variables. The amounts of chemicals introduced into the environment is certainly of interest to more individuals than just the individual grower who selects which strategy to implement. However, there are still some performance variables which are of concern to only the grower making the decision. These involve the amount of risk which he is willing to bear. The willingness to bear risk is a concept which attempts to measure how willing individuals are to experience a higher probability of a loss in order to have a higher probability of a gain. Individuals who forego higher probabilities of more income to avoid higher probabilities of a loss are less willing to bear risk and are referred to as risk averse. On the other extreme, are the individuals who decide to experience higher probabilities of less income if they can increase the probabilities of earning a higher income. These individuals are risk lovers. It is recognized that the willingness to bear risk is greatly influenced by the amount of income involved and that there currently does not exist a great enough understanding to identify relationships between risk preferences--and personal attributes such as age, education, financial debt, etc. However, it is apparent that risk preferences are a function of personality and that they are likely to vary considerably from individual to individual.

If individuals are either risk averse or risk loving for the range of income relevant to a particular decision, the criteria of the expected value for the net revenue will not be an adequate representation of their preferences. Simplistically, the situation is often described as a trade-off between the mean and the variance of the distributions of income. Of two distributions with the same mean and different variances, risk averse decision makers will prefer the distribution with the smaller variance. This analysis assumes that the variances is the only relevant measure for risk (or that all distributions are normal) but it is naive since other moments of the distribution can be as important as well. The skewness of the distribution can influence the decisions of some indivduals just like the variance.

The preferences that individuals hold for the amount of risk that they are willing to bear vary from individual to individual. Furthermore, the preferences of a single individual usually change for decisions that involve different amounts of money. The willingness to bear the risk of an investment which has a 50% chance of winning and a 50% chance of losing is likely to be different if the possible gains and losses are $10 rather than $10,000.

The manner in which the individuals value the uncertainty of which of the possible outcomes will result from selecting an alternative is different for different individuals. It is possible that for some individuals, the worst possible outcome of each alternative is so important that little attention is paid to the other possible outcomes. These individuals are some of the most risk averse that are possible. They are so concerned about minimizing the probability of a major loss that they do not even consider the probabilities of earning the higher incomes (the best outcomes). They compare the minimums of the distributions of the alternatives and select the alternative which has the best "worst" outcome. These individuals follow a decision rule known as maxi-min.

The other extreme is the decision rule called maxi-max. This decision rule is followed by individuals who are the most risk loving that is possible. In this case, the only outcomes which concern the decision makers are the outcomes with the highest incomes. They are so eager to earn the high incomes that they will bear any amount of risk to increase the probability of receiving the best outcome. They examine the maximums of the distributions and select the alternative with the best "best" outcome.

Between these extremes is another classical behavior model which is the maximization of the expected profit. This decision rule places no value on the risk in the distributions but averages the possible outcomes weighted by their probability of occurring and selects the alternative with the highest expected value.

Survey results (81) would indicate that it is unlikely that nay individuals would exhibit any one of the three of these classical behavior models, but over certain income ranges they may approach one. Some individuals may even approach different models in different income ranges. It is expected however, that most individuals will display a lower degree of risk aversion than the maxi-min over some part of the income range and that they will be risk loving at some degree for at least some other section of their income range. The classical models are important because they aid in the interpretation of many of the analytical techniques developed to evaluate choices between various alternatives.

Early attempts to evaluate these decisions focused on the specification of single-valued utility functions from which risk preferences could be inferred. The utility function is a concept designed to measure the amount of satisfaction that an individual receives from such items as income, risk, leisure, consumption, etc. However, it is impossible to construct a single valued utility function which can represent the preferences of more than one individual and it is difficult to avoid measurement errors in specifying the function for even one decision maker. To circumvent these problems, a series of technqieus commonly referred to as efficiency criteria have been developed. Efficiency criteria do not attempt to directly measure utility functions but instead construct intervals, similar to statistical confidence intervals, around the possible utility functions for a class of decision makers and/or the possible shape of the utility function for a specific decision maker. The size of the interval is related to the relative probability of making a Type I or Type II error on the hypothesis that the expected utilities of two distributions are equal. The narrower the interval is, the greater will be the probability of a Type I error while the wider the interval is, the higher will be the probability of a Type II error. The more decision makers that are included in the class represented by the interval, the more difficult will it be to identify which strategy is preferred.

Efficiency criterion examine the distributions of the alternatives and reject as inefficient any distribution about which it can be said that for every decision maker (every utility function) within the class defined by the interval, there is at least one other distribution which is preferred. After all distributions that can be possibly rejected as being inefficient are eliminated, the remainder are designated as the efficiency set. The efficiency set will not always be reduced to one strategy, in fact for large intervals it may be as large as 50% of the total number of the alternatives examined.

A general class of efficiency criterion is the family of techniques known as Stochastic Dominance. There are four types of Stochastic Dominance which are relevant to this study. They are First Degree, Second Degree, Stochastic Dominance with Respect to a Function and Convex Set Stochastic Dominance. First Degree Stochastic Dominance has the widest possible interval and is intended to include every individual. It suffers from large Type II errors and usually produces very large efficiency sets. Second Degree Stochastic Dominance narrows the interval by excluding from the class of decision makers any individuals who are risk loving over any part of the income range. It is bounded on the one extreme by the maxi-min individual and on the other by the risk neutral decision maker. It is more discriminating than First Degree Stochastic Dominance but still can produce large efficiency sets.

Stochastic Dominance with Respect to a Function is more flexible than the other two. It allows the researcher to define the size of the interval and the class of decision makers to be represented. First and Second Degree Stochastic Dominance are really special cases of the more general Stochastic Dominance with Respect to Function. The interval does not need to be constant across all income values and it can be set to include (exclude) the maxi-min, the maxi-max, the risk neutral or any other preferences.

Convex Set Stochastic Dominance is a technique which can be used with any of the other efficiency criteria to examine the possibility of whether some combination of two alternatives can dominate (be preferred to) some other alternative. It can be used to reduce large efficiency sets without having to narrow the risk interval or reduce the class of decision makers.

The various strategies for controlling the European red mite have been examined by the Stochastic Dominance efficiency criteria. From the infinite number of possible intervals, five were selected for the analysis. The first intervals appear in Table 14. They are briefly described in the table and are listed in order of the risk aversion of the lower limit on the interval. The coefficients of the intervals refer to the lower and upper bounds and are in terms of the Pratt Risk Aversion Coefficient which is defined as the negative ratio of the second derivative of the utility function to first derivative of the utility function $(-u''(x)/u'(x))$.

The values of the coefficients can be interpreted as to the risk preferences which they represent. Risk neutrality is indicated by a risk aversion coefficient of 0.0. The most risk averse individual would be represented by a risk aversion coefficient of $+\infty$ while on the other extreme, the most risk loving individual would be depicted by a coefficient of $-\infty$. Positive coefficients indicate some level of risk aversion and negative coefficients display a preference towards risk.

The first interval is the widest one considered. It approximates Second Degree Stochastic Dominance since it ranges from 0 to .1. It is an approximation because it does not include the ranges from .1 to ∞ but it assumed that the .1 is of a large relative magnitude and the efficiency set identified will be identical to the one with Second Degree Stochastic Dominance. Since the interval represents a class of decision makers including the maximin and the risk neutral individual, it is expected that the efficiency set for this interval would contain at least the alternative with the largest minimum value and the alternative with the greatest expected value.

The next interval is almost identical to the first except that the lower bound has been adjusted to exclude the risk neutral and slightly risk averse individuals. The upper bound remains unchanged. It represents a class of decision makers which includes the individual who follows the maxi-min decision rule and those individuals who are not less risk averse than the level implied by the .0003 risk aversion coefficient.

In the third interval, the extremely risk averse individuals have been eliminated from the class of decision makers and the lower bound has been adjusted to include individuals who are more than slightly risk averse. The maxi-min decision rule has been removed from consideration.

The fourth interval includes individuals who are slightly risk loving to those who are slightly risk averse. It does include the risk neutral case but excludes both extremes--the maxi-min and the maxi-max. It should have an efficiency set consisting of at least the strategy that produces the greatest expected net revenue.

The final interval is an attempt to define an interval which would represent a class of decision makers that should include 80-90% of the farmers in Michigan. It is an interval which has been inferred from survey results (81) measuring the risk preferences of a group of Michigan farmers. The width of the interval varies by the income level although the lower bound is constant at -.0001. The upper bound adjusts to the size of the income involved in a decision and is represented by three points from an estimated function. At zero income, the upper bound is .0008 while at $10,000 it increases to .0015 and at $25,000 it decreases to its lowest level .0004. The three levels on the upper bound represent various degrees of moderately strong risk aversion. The lower bound implies a moderately strong risk loving position. The interval does include the risk neutral case but does not include the extreme cases of maxi-min or maxi-mum. It is a fairly wide interval since it is intended to represent a large class of decision makers and it is expected to produce a large efficiency set. The other intervals, with the exception of the first one should have efficiency sets consisting of 1 to 3 members.

Results

The various intervals were used to examine different groups of strategies and identify which strategies are risk efficient for the classes of decision makers represented by each interval. The strategies have been grouped by the type of scouting program, the level at which growers detect a mite problem developing, the presence or absence of the random sampling error and the inclusion or exclusion of the revised decision rules which automatically apply the first spray at half strength. The efficiency sets for each of the scenarios are presented in Table 14.

The efficiency sets identified for the scenario using the weekly scouting program and the medium yield as dominated by the presence of the IPM strategies with the revised decision rules. Only two strategies without the revised decison rules are risk efficient. They are strategies 7 and 13 and they appear in the efficiency set identified for the last interval, the one representing the preferences of the class of Michigan agricultural decision makers. There are 8 strategies which are risk efficient for the interval, including four with the random sampling error. It appears that the simple plictran IPM strategy and the one with the highest economic thresholds (H4, H11 and H7) may only be preferred by the more risk averse

Table 14. Risk Analysis Results for Mite Control Strategies.

Risk Interval	General Description	Weekly Scouting and Medium Yield	Weekly Scouting and Medium Yields excluding Revised Strategies	Weekly Scouting and Low Yield	Weekly Scouting and Low Yield excluding Revised Strategies	Grower Perception at 9 Mites/Leaf and Medium Yield
1) 0.0 to 0.1	Approximates Second Degree Stochastic Dominance: Includes risk neutral and maxi-min	H4, H5, H7, H11, H12, H13, H14	5, 7, 10, 12, 13	1, H4, H5, H11, H12, H13	1, 5, 7, 13	H5, H7 H14, 7
2) .0003 to 0.1	Ranges from maxi-min to moderately strong risk aversion	H4, H5, H11, H12	10, 13	1	1	H7, H14, 7
3) .0001 to .0003	Ranges from slight risk aversion to moderately strong aversion	H5, H13, H14	7, 13	1, H13	1, 7	H14
4) -.0001 to .0001	Ranges from slightly risk loving to slightly risk averse; includes risk neutrality	H13	7.13	H13	7, 13	H5, H6, H12, H14
5) -.001 to .0008 at $0 -.001 to .0015 at $10,000 -.001 to .0004 at $25,000	Interval changes as income increases; ranges from moderately strong risk loving to various levels of moderately strong risk aversion; includes risk neutrality; represents preferences of 85% of Michigan farmers	7, 13, H4, H5, H7, H12, H13, H14	7, 12, 13, 14	1, H5, H7, H13, H14	1, 5, 7, 13	H5, H6, H7, H12, H13, H14

- Strategies denoted with an H indicate revised decision rules which always apply a half dose first spray.

Table 14. Continued.

Grower Perception at 9 mites/leaf and Medium Yield excluding Revised Strategies	Grower Perception at 5 Mites/Leaf and Medium Yield	Grower Perception at 5 mites/leaf and Medium Yield excluding Revised Strategies
7, 14	1, H4, H5, H7, H11, H12, H13, H14	1, 5, 7, 12, 15, 17
7	1, H5, H7, H12	1, 5, 12, 15, 17
7	H7	7, 12
7, 13	H7	7, 12, 13, 14
5, 6, 7, 11, 13, 14	H5, H6, H7, H12 H13, H14	5, 6, 7, 12, 13 14

decision makers since they are not risk efficient for intervals 3 and 4. These intervals do not include the preferences of strongly risk averse decision makers.

If the revised decision risk strategies are excluded from consideration, the efficiency sets are changed. Strategy 7, the plictran IPM strategy with the highest economic thresholds, may be risk efficient for decision makers who are less than moderately risk averse. It appears in the efficiency sets of all intervals except the second one. Strategy 10 which is the carzol IPM program with the highest economic thresholds may be risk efficient for very risk averse indiviudals, but is not preferred by any of the decision makers represented by the last interval. There are four strategies which appear in the efficiency set identified for the class of Michigan decision makers. They are strategies 7, 12, 13 and 14. Three of the four have the random sampling error which may indicate that the decision rules of the strategies without the sampling error could be improved.

The next scenario considered is the one consisting of the weekly scouting program and the low yield. The efficiency sets contain the strategies with the revised decision rules and the biological control option. In fact, the biological control strategy is the unique member of the efficiency set generated for the second interval, indicating that it is preferred by the most risk averse decision makers - probably because in the worst years, the risk of applying too much pesticide is greater than the risk of mite damage with uninterrupted natural predation.[1] The strategies which would be preferred by Michigan farmers appear in the efficiency set for the last interval. They are the biological control

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[1]This result, of course, is predicated on the assumption no other pesticides targeted for other pests are applied which may impact the natural predators.

option (1) and the sophisticated plictran IPM strategies (H5, H7, H13, H14). None of the carzol IPM strategies or the plictran strategies without the revised decision rules are risk efficient for any of the intervals. Furthermore, even at this low yield level, the conventional calendar programs are dominated by at least one of the IPM strategies. The most predominant strategy is H13 which is the sophisticated plictran IPM program with the lowest economic thresholds. It uses the revised decision rules and has the random sampling error.

When the strategies with the revised decision rules are excluded from consideration, strategies 7 and 1 become the strategies which appear in the most efficiency sets. The individuals in the class of Michigan farmers would prefer one of four strategies: 1, 5, 7 or 13. It appears that more risk averse individuals would prefer 1 or 5 while less risk averse ones may select 13. Strategy 7 may be preferred by the widest group of individuals as it only can be said that it si not preferred by anyone whose risk aversion coefficient is .0003 or greater.

The scenario using a medium yield and an on-request scouting program with growers detecting a problem developing at mite densities of 9 mites per leaf produces an efficiency set for the last interval which is more as expected. This efficiency set consists of six strategies - the three sophisticated plictran IPM strategies with no sampling error and their counterparts with the random sampling errors. All six strategies use the revised decision rules. This was somewhat as expected since these strategies had the highest expected net revenues and the introduction of the random sampling error did not greatly change their performances.

The only strategy which is risk efficient that does not use the revised decision rules is strategy 7 but it appears to be preferred by only extremely risk averse decision makers and it is not likely that any Michigan farmers would be so risk averse that they may select it above the alternatives on the basis of its risk efficiency.

However, if the revised decision risk strategies are ignored, strategy 7 becomes the predominant control program, appearing in every efficiency set. There are five other strategies which are risk efficient for the last interval so growers may prefer any one of several alternatives dependent upon their risk attitudes. The strategies which are risk efficient are 5, 6, 7, 11, 13 and 14. Half of these strategies have the random sampling error - once again indicating how little of a detrimental effect it exerts on the IPM programs.

The last scenario to be discussed is the one using a medium yield and scouting system where growers request a visit when the mite population reaches a density of 5 mites per leaf. The strategies preferred by individuals in the class of Michigan agricultural decision makers are all examples of the sophisticated plictran IPM strategies with the revised decsion rules. The efficiency set identified for the class of decision makers includes the three strategies without the sampling errors and the same three strategies with the sampling error. This result demonstrates the insensitivity of the system to changes in the economic threshold, either by design or by way of the sampling error.

The biological control program is risk efficient for some preferences but they are more risk averse than what can be expected of any actual decision maker. This program produces a minimum value in the worst year, higher than the other alternatives and would be preferred by individuals approaching the extreme attitude of the maxi-min decision criteria.

Ignoring the revised decison risk strategies produces an efficiency set for the last interval of all the counterpart strategies which do not use the revised decision rules. That is to say that each revised strategy which was risk efficient is replaced by the original version of the strategy. This result is observed only for the last interval. The efficiency set for the four intervals which represents the class of decision makers who approach risk neutrality is interesting because it contains four members. Usually this set has a single member but in this case, the four strategies have expected net revenues so similar that slight diversions in the risk attitude from risk neutrality may influence the ranking of the alternatives.

Some general conclusions can be reached about the strategies which may be consistent with growers' risk preferences. First, in none of the scenarios were either the conventional or the carzol IPM strategies risk efficient for the class of Michigan agricultural decision makers. The biological control program may be preferred by some decision makers but only at low yield levels and with weekly scouting systems. The revised decision rule strategies are generally preferred to the original versions of those same strategies. The sophisticated plictran IPM strategies are the most frequent members of the efficiency sets and their risk efficiency for the class of decision makers as a whole appears to be somewhat insensitive to the level of the economic threshold or the presence of the random sampling error. Finally, the changes in the production system represented by the various scenarios examined can influence the rankings of the strategies.

V. SCAB MODEL RESULTS

5.1 The Simulation Model

The apple scab model has been constructed by employing a number of assumptions that facilitate the simulation of a very complex biological process by a simplified model that stillcaptures the essential elements of the process. The model has several components or subroutines which perform the important functions of the biological and chemical processes that direct the development of apple scab in commercial orchards.

The model has been constructed in a Monte Carlo framework which permits the analysis of the performance of each of the strategies under a variety of different conditions. In this case the model simulates the performance of the strategies under twenty different states of nature. In each state of nature, the stochastic variables all have different values drawn at random from the appropriate multivariate probability distributions. The major stochastic variables are the product prices, the temperature, the precipitation, the infection periods and the damage coefficients. The twenty states of nature can be viewed as twenty independent seasons. The model in its current version does not incorporate any multi-seasonal relationships.

The model operates on a daily basis and uses randomly generated observations for the average daily temperature and the amount of precipitation. The temperature and precipitation are randomly drawn by a multivariate random generator from distributions constructed from historical data from the East Lansing weather station. The observations are generated while maintaining three critical sets of correlations. The correlation between the temperature and precipitation for each day is preserved in the random draws. Likewise, the correlations between the temperature on one day and the previous day and between the precipitation on a given day and on the preceeding day are also preserved. The season is divided into eight 21-day parts so that seasonal influences can be captured. There is, therefore, one multivariate distribution for each part of the season.

The product prices, both fresh market and all processing prices are randomly generated in a similar fashion with a multi-variate random generator. The distributions used by the random generator have been constructed from historical price series for the state of Michigan during the years 1969 to 1979. They are expressed in constant 1979 dollars. The correlations between the fresh and processed markets are preserved in the random generation. The generator can also produce yield estimates which are correlated to the randomly drawn prices. The yield estimates are drawn from a series of distributions based on historical Michigan data from the years 1969 to 1979. The series of yield distributions are derived by maintaining the shape of the historical distribution but setting the mean at three distinct levels. There is a low level yield which has a mean of 250 bu/acre and a medium level which corresponds to an average yield of 500 by/acre. The high level has a mean of 900 bu /acre. The user can select the yield level that is desired. A juice price is inferred from the random processed price through the use of the ten year average ratio of the two prices. The juice price in each year is set at a level which is 72.5% of the all processed price.

At the beginning of each year, in addition to the random weather pattern and product prices, the number of degree days that have accumulated previous to April 1 are randomly generated from a normal distribution with a mean of 580 and a standard deviation of 80. Each season is assumed to begin on April 1 with the random starting degree days and proceeds to September 15.

The randomly generated variables are all entered into the model in the subroutine GETWET.

Those variables which must be initialized at the beginning of each year are initialized in a subroutine INIT while the subroutine DDAYS calculates the accumulated degree days each day on a base of 43° F.

The subroutine STAGE determines the progression of the apple trees in their various physiological stages. The algorithm is taken from a pedagogic model developed by Arneson (8). The number of accumulated degree days determines the stage which the trees will be in. At 700 degree days it is assumed that the trees are at green tip. When 750 degree days are reached, they are at 1/2 inch green while 800 degree days is the transition point to tight cluster. Pink and bloom occur respectively at 900 and 1,000 degree days. At 1,100 degree days, etal all is assumed to occur. Seven calendar days following petal fall, the model has fruit set occurring.

Fungicides lose their effectiveness as a function of the amount of time that has elapsed since application, their exposure to the weather and the rate of growth in the tree. However, the model has been greatly simplified due to two reasons. First, the attenuation process of the different chemicals and their associated impact on the fungus is little understood. Secondly, the model could become quite large, unwieldly and extremely expensive to operate if all the detail was incorporated. Therefore, some simplifying assumptions have been made about the rate at which the chemicals lose their effectiveness. Following the recommendations which appear in the 1979 Fruit Pesticide Handbook (66, pp. 38-47) the time for which each chemical remains active and will effectively control apple scab is calculated. The model reacts as if the chemicals either control the disease or they do not. There is no continuous decrease in the effectiveness considered. However, different dosages have different rates of attenuation. The attenuation rates will also change by the time of the season to reflect changes in scab activity, tree and fruit growth and other factors. There are three chemicals with two dosages for each chemical in the current model. The chemicals are: captan, benomyl and captafol. The lengths of protective and eradicant actions for each chemical and dosage appear in Table 1.

Scab infection periods are calculated by considering the probability that given a combination of precipitation, the average daily temperature, the part of the season and the previous infections, that an infection of a light, moderate or heavy level will occur. The probabilities were constructed from data on field observations from a number of different sites across the state of Michigan. The original data contained the level of infection, and the weather experienced during the wetting period. However, the model simulates on a daily basis, not on an hourly one, so the infection levels for each day were matched with weather records on a daily precipitation and average temperature. To simulate the apple season on an hourly or even a three hour basis for a Monte Carlo model which will be run for a minimum of 20 years for each strategy to be evaluated would be extremely expensive. It is especially expensive when the apple scab model is coupled with additonal pest models to allow the evaluation of IPM strategies. Therefore, the biology was simplified, but hopefully not compromised, to allow the model to focus on the central objective of the study--the evaluation of pest management strategies under uncertainty.

Table 1. Chemical Attenuation Rates.

Chemical	Dosage	Protective Action Before Petal Fall	Protective Action Petal Fall to 6/15	Protective Action After 6/15	Eradicant Action
Captan	8 lbs/acre	7 days	7 days	14 days	1 day
Captan	6 lbs/acre	5 days	7 days	14 days	--
Captan	4 lbs/acre	5 days	5 days	14 days	--
Captafol	5 gal/acre	Green Tip to Petal Fall	--	--	--
Captafol	3 gal/acre	Green Tip to Pink	--	--	--
Benomyl	16 oz/acre	7 days	7 days	14 days	2 days
Benomyl*	12 oz/acre	7 days	7 days	--	--

*When applied with Captan @ 4 lbs/acre.

The probabilities derived from the field data were then adjusted to produce a distribution of infection periods similar to the distribution of ascospore depletion reported from New York State (67, p. 4). This assumes, perhaps heroically, that there is a direct relationship between the ascospore production and the number of infection periods, but it does provide a guide to introducing the seasonal nature of the life cycle of the fungus to the model.

It is known that 15% of the ascospores which have overwintered are depleted by the end of April, 70% by the middle of June, and 99% by July 31. The probabilities of a scab infection period were adjusted for the model by first dividing the season into four parts as follows: April 1 to April 31, May 1 to June 15, June 16 to July 31 and the remainder of the season after the end of July. Thus, it was assumed that the field data represented most closely the second part of the season, so the probabilities in parts 1 and 3 were adjusted to conform to the documented pattern of ascospore production. This was accomplished by multiplying the observed probabilities by the ratio of the percentage depletion of ascospores in that time period to the percentage depletion of ascospores in the second part of the season. This resulted in the probability that any scab infection might occur in the first time period as being about one fourth of the probability of an infection in the second part of the season.

The last part of the season was assumed to be free of any primary spores and, hence, any infection must result from conidia produced by a primary infection. If the controls are completely successful and no significant primary infection occurs, the probability of infection during this time period is zero. However, if two or more infections of moderate or heavy levels occur, the probability of a secondary infection is exactly equal to the probability of a primary infection during the second part of the season.

The cumulative probabilities of scab infections simulated by the model are compared to the pattern observed for ascospore production in Table 2. It should be noted that by assumption all simulated primary scab infections have occurred by the end of July. With the exception of the first time interval, the simulated pattern for all years is within 5 percentage points of the pattern of ascospore depletion.

The determination of the scab infection periods is handled within the subroutine SCABINF. This subroutine also determines when weather conditions have been right for an infection to occur. The information is used by strategies which attempt to eradicate any existing infections rather than protecting the orchard from future attacks. An infection does not always result when the weather conditions have been suitable since there is almost always some probability that no infection will occur. The level of infection (none, light, moderate or heavy) will depend upon the random draw and the probabilities of each event.

The current model examines the performance of eleven control strategies. The strategies consist of different decision rules as to when certain chemicals at specific dosages should be applied. As mentioned before, there are three chemicals which were employed in the model: benomyl, captan and captafol. The application costs for the chemicals at different dosages are presented in Table 3. The first strategy applies no chemical control at all and is used as a baseline for comparison. The second strategy consists of applying captafol (5 gal/acre) at green tip followed by weekly application of captan (8 lbs/acre) starting at petal fall and lasting until the middle of June. After that, a biweekly

Table 2. Cumulative Probability Functions of % Ascospore Depletion.

Date	Gilpatrick & Szkolnik	All Years	Simulated Years 1	2	3	4	5	6	7	8	9	10
4/6	0	0	0	0	0	0	0	0	0	0	0	0
4/30	.15	.084	.038	.059	.125	0	.136	.143	0	.017	.067	.15
5/14	.30	.323	.192	.235	.50	.429	.318	.357	.20	.385	.333	.35
5/31	.55	.605	.423	.529	.625	.714	.636	.643	.70	.462	.667	.75
6/7	.667	.701	.517	.588	.625	.786	.727	.643	.90	.692	.80	.80
6/30	.90	.892	.923	.765	.813	.929	.818	.786	.90	1.00	1.00	1.00
7/31	.99	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00

Table 3. Spray Costs for Chemical Applications Considered.

Spray	Chemical Price per Unit	Chemical Cost per Application	Labor Cost per Application	Machinery Cost per Application	Cost per Application
Captafol (5gal/acre)	$24.00/gal	$120.00/acre	$.70/acre	$.70/acre	$121.4/acre
Captafol (3gal/acre)	$24.00/gal	$ 72.00/acre	$.70/acre	$.70/acre	$ 73.4/acre
Captan (8lbs/acre)	$ 1.85/lb	$ 14.8/acre	$.70/acre	$.70/acre	$ 16.2/acre
Captan (6lbs/acre)	$ 1.85/lb	$ 11.1/acre	$.70/acre	$.70/acre	$ 12.5/acre
Captan (4 lbs/acre)	$ 1.85/lb	$ 7.4/acre	$.70/acre	$.70/acre	$ 8.8/acre
Benomyl (16 oz/acre)	$.659/oz	$ 10.54/acre	$.70/acre	$.70/acre	$ 11.94/acre
Benomyl (12 oz/acre)	$.659/oz	$ 7.91/acre	$.70/acre	$.70/acre	$ 9.31/acre
Benomyl (16 oz/acre)	$ .9/oz	$ 14.4/acre	$.70/acre	$.70/acre	$ 15.8/acre
Benomyl (12 oz/acre)	$ .9/oz	$ 10.8/acre	$.70/acre	$.70/acre	$ 12.2/acre

Source: Pest Control Branch, Natural Resource Economics Division, Economic Research Service, USDA.

program of captan (4 lbs/acre) is pursued. The third strategy applies captan (8 lbs/acre) every 7 days until the 15th of June and then the full dosage of captan is applied every 14 days. The fourth strategy is similar in that it follows the same spray schedule but a half dosage of captan (4 lbs/acre) is applied instead of the full dosage. The next strategy is a post infection program which applies benomyl (16 oz/acre) whenever observations of average daily temperature and daily precipitation indicate that weather conditions have been suitable for an infection. In this strategy weather conditions suitable for an infection to occur are assumed to be whenever the average daily temperature exceeds 34° F and the precipitation is greater than .01 inches. An application will not be made if the orchard has been treated by benomyl within the last week. The sixth strategy is an example of the use of benomyl in combination with captan in a protective mode. It applies benomyl (12 oz/acre) and captan (1 lb/acre) on a weekly basis. The conventional spray program commonly used in Michigan is represented by strategy 7. This strategy involves the application of a full dosage of captan (8 lbs/acre) every 7 days until petal fall, after which a lower dosage is applied. Between petal fall and June 15, captan (6 lbs/acre) is applied every 10 days. After June 15, captan (4 lbs/acre) is applied every 14 days. The next three strategies use captafol for the first part of the season and either eradicate with benomyl or protect with captan for the remainder of the year. Captafol is applied with all three strategies at green tip. When strategy 8 is followed, after pink captan (8 lbs/acre) is applied weekly until June 16 and then a half dosage of captan (4 lbs/acre) is applied on a biweekly basis. This strategy begins the season with a treatment of captafol (3 gal/acre). With strategy 9, captafol (5 gal/acre) is applied at green tip and after petal fall, benomyl (16 oz/acre) is applied every time that the weather conditions have been suitable for an infection (except when benomyl has been applied within the last 6 days). The tenth strategy is identical to the previous one except the dosage of captafol is reduced (3 gal/acre) and the post-infection program commences at pink. The final strategy is a hypothetical one used for demonstrative purposes. It is an example of a post-infection program with perfect knowledge about the incidence of infections. Since the accuracy of the infection predictions based on weather conditions is likely to influence the efficiency of post-infection control programs, this strategy demonstrates the potential that this type of post-infection can have. This strategy applies benomyl (16 oz/acre) whenever an infection actually occurs rather than just whenever the weather conditions have been suitable for an infection. The strategies are more fully described in Table 4.

For all the control strategies, there are two adjustments to the normal spray schedule. If the rainfall exceeds .02 inches on the day designated for a spray, the application is postponed until the next day. The second adjustment involves the special sprays which are necessary if an infection occurs. Two benomyl sprays (16 oz/acre) 7 days apart are necessary to eradicate scab lesions that have developed. The special sprays eliminate light infections and substantially reduce the spread of moderate or heavy infections. If these eradicant sprays are required, normal applications are postponed.

The normal sprays are handled in the subroutine APPLY while all of the special sprays are administered in another subroutine called SPSPRAY.

The last of the major components of the simulation model is the subroutine SCABDAM. This subroutine estimates the amount of damage that

Strategy	Green Tip to Pink	Pink to Petal Fall	Petal Fall to 6/15	6/15 to 8/7	8/7 to 9/1
1	Do Nothing	Do Nothing	Do Nothing	Do Nothing	Do Nothing
2	Captafol (5 gal/acre) at green tip or 4/9	------	At petal fall, apply captan (8 lbs/acre) every 7 days (for 3 cover sprays)	After 3 weekly full dose captan cover sprays, apply captan (4 lbs/acre) every 14 days	Do nothing unless at least 2 infections have developed previously then apply captan (4 lbs/acre) every 14 days
3	Captan (8 lbs/acre) every 7 days starting on 4/10	Captan (8 lbs/acre) every 7 days	Captan (8 lbs/acre) every 7 days	Captan (8 lbs/acre) every 14 days	Do nothing unless at least 2 infections have developed previously; then apply captan (8 lbs/acre) every 14 days
4	Captan (4 lbs/acre) every 7 days starting on 4/10	Captan (4 lbs/acre) every 7 days	Captan (4 lbs/acre) every 7 days	Captan (4 lbs/acre) every 14 days	Do nothing unless at least 2 infections have developed previously, then apply captan (4 lbs/acre) every 14 days
5	Benomyl (16 oz/acre) when weather conditions have been suitable* for an infection--unless benomyl has been applied within the last week	Benomyl (16 oz/acre) when weather conditions* have been suitable for an infection--unless benomyl has been applied within the last week	Benomyl (16 oz/acre) when weather conditions* have been suitable for an infection--unless benomyl has been applied within the last week	Benomyl (16 oz/acre) when weather conditions* have been suitable for an infection-unless benomyl has been applied within the last week	Do nothing unless at least 2 infections have developed previously, then apply benomyl (16 oz/acre when weather conditions* have been suitable for an infection unless benomyl has been applied within the last week
6	Benomyl (12 oz/acre) and captan (4 lbs/acre) every 7 days starting on 4/10	Benomyl (12 oz/acre) and captan (4 lbs/acre) every 7 days	Benomyl (12 oz/acre) and captan (4 lbs/acre) every 7 days	Benomyl (12 oz/acre) and captan (4 lbs/acre) every 14 days	Do nothing unless at least 2 infections have previously developed; then apply benomyl (12 oz/acre) and captan (4 lbs/acre) every 7 days
7	Captan (8 lbs/acre) every 7 days starting on 4/10	Captan (8 lbs/acre) every 7 days	Captan (6 lbs/acre) every 10 days	Captan (4 lbs/acre) every 14 days	Do nothing unless at least 2 infections have previously developed; then apply captan (4 lbs/acre) every 14 days
8	Captafol 3 gal/acre) at green tip or 4/9	Captan (8 lbs/acre) every 7 days (for 5 cover sprays)	Captan (8 lbs/acre) every 7 days for 5 cover sprays	After 5 cover sprays, apply captan (4 lbs/acre) every 14 days	Do nothing unless at least 2 infections have previously developed; then apply captan (4 lbs/acre) every 14 days
9	Captafol (5 gal/acre) at green tip or 4/9	------	Benomyl (16 oz/acre) when weather conditions have been suitable for an infection*--unless benomyl has been applied within the last week	Benomyl (16 oz/acre) when weather conditions have been suitable for an infection*--unless benomyl has been applied within the last week	Do nothing unless at least 2 infections have previously developed; then apply benomyl (16 oz/acre) when weather conditions have been suitable for an infection*--unless benomyl has been applied within the last week
10	Captafol (3 gal/acre) at green tip or 4/9	Benomyl (16 oz/acre) when weather conditions have been suitable for an infection*--unless benomyl has been applied within the last week	Benomyl (16 oz/acre) when weather conditions have been suitable for an infection*--unless benomyl has been applied within the last week	Benomyl (16 oz/acre) when weather conditions have been suitable for an infection*--unless benomyl has been applied within the last week	Do nothing unless at least 2 infections have previously developed; then apply benomyl (16 oz/acre) when weather conditions have been suitable for an infection*--unless benomyl has been applied within the last week
11	When an infection actually occurs, benomyl (16 oz/acre)	When an infection actually occurs, benomyl (16 oz/acre)	When an infection actually occurs, benomyl (16 oz/acre)	When an infection actually occurs, benomyl (16 oz/acre)	When an infection actually occurs, benomyl (16 oz/acre)

* Weather conditions suitable for an infection are assumed to be when the average daily temperature has exceeded 35°F and precipatation is greater than .01 inches.

Table 4. Description of Scab Control Strategies

results from each infection. This calculation is guided by the assumption that the scab is experienced in the fruit intended for the fresh market. Following the historical statewide average use pattern, 40% of the yield is designated as being intended for the fresh market at the beginning of each season with the remainder going to processed uses. Scab damaged fruit is sold only in the juice market. In severe scab seasons, the entire fresh market crop can be damaged and some of the fruit to be marketed for processed uses can be infected as well. A light infection results in 5% of the fruit damaged. The moderate and heavy infections produce damages that are randomly drawn from uniform distributions. The distribution for moderate infections has a range of .05 to .10 while the range for the distribution of heavy infection damage is from .05 to .70.

The damage suffered at each infection is summed at the end of each year and cannot exceed 100%.

Stochastic Elements of the Apple Scab Model

The model was used to simulate the performance of 11 different strategies under twenty different conditions. Each condition can be perceived as a state of nature with a random value for each of the stochastic variables. There are a number of sources of uncertainty in the apple scab model. Each source of uncertainty is represented by a stochastic variable. As previously discussed the fresh and processed market prices are also random variables. The average daily temperature and the daily precipitation are also randomly drawn from multivariate distributions based on historical data. The number of degree days that have accumulated previous to April 1 when the simulated season is assumed to commence is a random variable from a normal distribution with a mean of 580 and a standard deviation of 80. The determination of scab infection periods is also based upon a random variable. Each day a random variable between 0 and 1 is drawn from a uniform distribution. This random variable is compared to the probabilities of no infection, light infection, moderate infection or heavy infection determined by the combination of average precipitation, average daily temperature and the part of the season. Hence, for a given set of weather conditions, the development of an infection is not deterministic but a stochastic process. The calculation of the percentage of fruit damaged by moderate and heavy infections is handled in a similar fashion. A uniformly distributed variable between 0 and 1 is randomly drawn each day. If an infection occurs on that given day, the random variable is used to calculate the amount of damage that will result. The damage of light infections is deterministic and always set equal to 5%. However, the damage resulting from moderate and heavy infections is stochastic and is calculated at follows:

For Moderate Infections : Damage = 0.10 - R *0.05

For Heavy Infections : Damage = 0.75 - R *0.70

Where R = random variable

The late season damage estimates for moderate and heavy infections are adjusted to account for the length of time early in the season that no scab is allowed to develop. If no infections have occurred, the estimates are adjusted by the percentages appearing in Table 5. The adjustment factors are derived from the percentage depletion of ascospores in each stage of the development (58, p. 4). The damage estimates for selected strategies are statistically compared to results observed in experimental orchards in Appendix I.

Table 5. Adjustment Factors for Late Season Infections.

Stage When Infection Occurs	Damage Adjustment
Tight Cluster	78% of Original Estimate
Pink	70% of Original Estimate
Bloom	58% of Original Estimate
Petal Fall	45% of Original Estimate
Fruit Set to Harvest	35% of Original Estimate

5.2 Apple Scab Model Results

The model produces a number of performance variables which could be used to evaluate the various strategies. The performance variables range from those which measure net revenue to those which monitor the amounts of the chemicals applied. Some performance variables may be more relevant to potential users of the model than others, but the model tries to report all that may be of interest. For the private firm, the average net revenue over the twenty simulated seasons could often be used as a principal criteria, but it ignores the value which might be attributed to risk. The variance in the net revenue can be used to capture some of the costs of risk but frequently other moments of the distribution must be considered to truly reflect the entire realm of the effects that risk can have on optimal decisions. The model reports both the expected value and the variance of the net revenue and the distribution itself can be constructed from the twenty years of data.

The number of sprays applied could be of interest in some cases while the amount of the chemicals applied should be important in almost all cases. Captan is measured in pounds per acre and defolatan is recorded in gallons per acre while benomyl appears in terms of ounces per acre. The price per pound of captan used in the model is $1.85 while the prices for the other two chemicals are $24/gallon for difolatan and $.659/ounce for benlate.

The number of bushels lost each year to apple scab is of importance, but given the structure of the model the more relevant variable is probably the percentage of the potential harvest which becomes infected since the actual yield is influenced greatly by the assumptions inherent in the frost damage calculation. The figures should not be used as an absolute estimate but rather were designed more for relative comparison with each other.

A variable which balances the costs incurred in a control program with the value of the fruit lost is the variable "control costs." It is the sum of a) the costs of the chemicals applied; b) the cost of the labor and machinery used in the spray applications; and c) the value of the fruit damaged by the fungus.

For each of the eleven strategies the values for the various performance variables appear in Table 6. The standard deviations appear in parenthesis below the expected values. These results were obtained when the yield level was set with a mean of 500 bushels per acre. The three strategies with the highest expected revenue per acre are different forms of the post infection, IPM program. Strategy 11 which applied benomyl only after an infection actually occurred produced the highest net revenue of $430/acre. It was followed by strategy 5 which predicts infection periods by observing the daily temperature and precipitation. When an infection period has been predicted, benomyl is applied. This strategy applied more chemicals but suffered less damage than strategy 11. The strategy with the third highest net return was number 10. It follows a Reduced Single Application Treatment (RSAT) early and a post-infection IPM program similar to strategy 5 late in the season. It is approximately $20 per acre less effective than strategy 5.

The conventional spray program represented by strategy 7 has the fourth highest expected net revenue. As displayed in Table 7, holding everything else constant, it would take a 36.7% increase in the price of benomyl to make the conventional program as effective on an expected net revenue basis as the post-infection IPM program of strategy 5.

Table 6. Scab Model Results with Medium Yield.

Strategy	Potential Yield (bu.)	Scab Damage (bu)	Scab Damage (%)	Net Undamaged Yield	Number of Sprays	Benomyl (oz)	Captan (lbs)	Captafol (gals)	Control Costs ($)	Production Costs ($)	Net Revenue ($)
1	502.1 (47.5)	502.1 (47.5)	100.0	--	--	--	--	--	1107.6 (168.3)	1302.8 (48.0)	-440.5 (592.1)
2	502.1 (47.5)	0.0 (0.0)	0.00	502.1 (47.5)	8 (.8)	4.8 (11.7)	36.6 (5.4)	5.0 (0.0)	293.3 (8.4)	1504.3 (50.5)	373.8 (701.0)
3	502.1 (47.5)	1.3 (5.8)	0.3	500.8 (47.4)	14 (.5)	3.2 (9.8)	107.6 (5.5)	--	317.1 (23.5)	1523 (47.8)	349.9 (692.4)
4	502.1 (47.5)	26.7 (60.7)	5.3	495.5 (45.6)	15 (1.1)	67.2 (25.2)	45.0 (4.1)	--	341.1 (212.0)	1451.9 (47.2)	326.0 (702.0)
5	502.1 (47.5)	6.6 (14.7)	1.3	500.8 (47.4)	11 (.9)	175.2 (14.2)	--	--	247.2 (53.5)	1433.6 (44.6)	419.8 (705.5)
6	502.1 (47.5)	1.3 (5.8)	0.3	499.5 (47.0)	14 (.5)	164.6 (6.9)	53.8 (2.7)	--	324.0 (23.4)	1529.9 (47.8)	343.1 (692.5)
7	502.1 (47.5)	2.6 (8.0)	0.5	499.5 (47.0)	14 (.7)	17.6 (19.4)	82.1 (6.3)	--	285.7 (39.7)	1485.3 (47.0)	381.4 (690.3)
8	502.1 (47.5)	2.6 (8.1)	0.5	499.5	10 (1.5)	11.2 (15.7)	50.2 (7.0)	3.0 (0.0)	288.2 (41.3)	1488.5 (48.9)	378.9 (692.9)
9	502.1 (47.5)	7.0 (31.3)	1.4	495.1 (56.5)	6 (.7)	85.6 (10.7)	--	5.0 (0.0)	309.2 (142.7)	1488.1 (49.4)	357.9 (719.0)
10	502.1 (47.5)	5.4 (14.1)	1.1	496.7 (45.5)	8 (1.0)	110.4 (16.3)	--	3.0 (0.0)	266.5 (51.0)	1458.6 (48.0)	400.6 (704.0)
11	502.1 (47.5)	16.1 (27.4)	3.2	486.0 (44.8)	7 (1.0)	110.4 (16.3)	--	--	237.2 (109.2)	1385.2 (47.5)	429.9 (694.6)

Table 7. Scab Model Results with Medium Yield and an Increase in the Price of Benomyl of 36.7%.

Strategy	Potential Yield (bu.)	Scab Damage (bu.)	Scab Damage (%)	Net Undamaged Yield (bu.)	Number of Sprays	Benomyl (oz)	Captan (lbs.)	Captafol (gals.)	Control Costs ($)	Production Costs ($)	Net Revenue ($)
2	502.1	0.0	0.0	502.1	8	4.8	36.6	5.0	294.5	1505.4	372.6
	(47.5)	(0.0)		(47.5)	(.8)	(11.7)	(5.4)	(0.0)	(9.2)	(50.8)	(701.8)
3	502.1	1.3	0.3	500.8	14	3.2	107.6	-	317.9	1523.8	349.2
	(47.5)	(5.8)		(47.4)	(.5)	(9.8)	(5.5)		(25.1)	(48.0)	(691.6)
4	502.1	26.7	5.3	475.4	15	67.2	45.0	-	357.3	1468.1	309.8
	(47.5)	(60.7)		(76.3)	(1.1)	(25.2)	(4.1)		(209.6)	(49.3)	(700.9)
5	502.1	6.6	1.3	495.5	11	175.2	-	-	289.5	1475.8	377.6
	(47.5)	(14.7)		(45.6)	(.9)	(14.2)			(53.8)	(44.0)	(704.3)
6	502.1	1.3	0.3	500.8	14	164.6	53.8	-	363.6	1569.6	303.4
	(47.5)	(5.8)		(47.4)	(.5)	(6.9)	(2.7)		(24.5)	(48.0)	(692.2)
7	502.1	2.6	0.5	499.5	14	17.6	82.1	-	289.9	1489.5	377.2
	(47.5)	(8.0)		(47.0)	(.7)	(19.4)	(6.3)		(42.6)	(46.1)	(689.1)
8	502.1	2.6	0.5	499.5	10	11.2	50.2	3.0	290.9	1491.2	376.2
	(47.5)	(8.1)		(46.8)	(1.5)	(15.7)	(7.0)	(0.0)	(43.4)	(49.7)	(692.8)
9	502.1	7.0	1.4	495.1	6	85.6	-	5.0	329.8	1508.7	337.3
	(47.5)	(31.3)		(56.5)	(.7)	(10.7)		(0.0)	(142.6)	(50.2)	(718.9)
10	502.1	5.4	1.1	496.7	8	110.4	-	3.0	293.1	1485.2	374.0
	(47.5)	(14.1)		(45.5)	(1.0)	(16.3)		(0.0)	(52.0)	(48.7)	(702.6)
11	502.1	16.1	3.2	486.0	7	110.4	-	-	263.8	1411.8	403.3
	(47.5)	(27.4)		(44.8)	(1.0)	(16.3)			(110.9)	(48.1)	(694.2)

It should be noted that benomyl is used in every control program even though it is not a principal chemical of many. This is because at least during some season each strategy allowed an infection to develop that required the special eradicant sprays. One series of eradicant sprays will apply 32 ounces of benomyl. So for example, strategy 3 will allow one infection to develop every ten years (3.2/32).

If it is assumed that all strategies provide complete control of the disease and the damage estimates are ignored, the strategies could be ranked on the basis of their spray costs. These results are presented in Table 8. The same three strategies (11, 5, 10) are still the most effective.

When the yield level is lowered to a mean of 250 bushels per acre, the post-infection IPM programs are relatively more effective. These results are presented in Table 9. The IPM programs are relatively more effective since they generally incur higher percentage damage losses than conventional programs and since yields are less, the value of the damage is lower resulting in a more favorable comparison between the spray costs and value of damage avoided for the IPM programs.

When yields are raised to an average level of 900 bushesl per acre, an opposite result is observed. The conventional programs become relatively more effective than before. However, the post-infection IPM programs, strategies 5, 10 and 11 are still producing the highest expected net revenues. These results appear in Table 10.

The performances of the strategies were simulated under five different scenarios: medium yield, low yield, high yield, medium yield and high benomyl price, and medium yield and no damage assumed. The rankings of the strategies by the size of expected net revenues remains fairly stable across the scenarios with two important exceptions. When no damage is

Table 8. Scab Model Results with Medium Yield and No Damage Assumed.

Strategy	Potential Yield (bu.)	Scab Damage (bu.)	Scab Damage (%)	Net Undamaged Yield	Number of Sprays	Benlate (oz)	Captan (lbs)	Captafol (gals)	Control Costs ($)	Production Costs ($)	Net Revenue ($)
2	502.1	--	--	--	8	4.8	36.4	5.0	293.3	1504.3	373.8
	(47.5)				(.8)	(11.7)	(5.4)	(0.0)	(8.4)	(50.3)	(701.0)
3	502.1	--	--	--	14	3.2	107.6	--	312.1	1523.0	355.0
	(47.5)				(.5)	(9.8)	(5.5)		(7.7)	(47.8)	(702.1)
4	502.1	--	--	--	15	67.2	45.0	--	241.0	1451.9	426.1
	(47.5)				(1.1)	(25.2)	(4.1)		(13.4)	(47.2)	(699.3)
5	502.1	--	--	--	11	175.2	--	--	222.6	1433.6	444.5
	(47.5)				(.9)	(14.2)			(10.6)	(44.6)	(698.2)
6	502.1	--	--	--	14	164.6	53.8	--	318.9	1529.9	348.2
	(47.5)				(.5)	(6.9)	(2.7)		(8.0)	(47.8)	(702.2)
7	502.1	--	--	--	14	17.6	82.1	--	274.3	1485.3	392.8
	(47.5)				(.7)	(19.4)	(6.3)		(10.2)	(47.0)	(702.3)
8	502.1	--	--	--	10	11.2	50.2	3.0	277.5	1488.5	389.6
	(47.5)				(1.5)	(15.7)	(7.0)	(0.0)	(15.4)	(48.9)	(639.5)
9	502.1	--	--	--	6	85.6	--	5.0	277.1	1488.1	390.0
	(47.5)				(.7)	(10.7)		(0.0)	(8.0)	(49.4)	(701.9)
10	502.1	--	--	--	8	110.4	--	3.0	247.6	1458.6	419.5
	(47.5)				(1.0)	(16.3)		(0.0)	(12.2)	(48.0)	(697.5)
11	502.1	--	--	--	7	110.4	--	--	174.2	1385.2	492.0
	(47.5)				(1.0)	(16.3)			(12.2)	(47.6)	(699.9)

Table 9. Scab Model Results with Low Yield.

Strategy	Potential Yield (Bu.)	Scab Damage (bu.)	Scab Damage (%)	Net Undamaged Yield	Number of Sprays	Benomyl (oz)	Captan (lbs)	Captafol (gals)	Control Costs ($)	Production Costs ($)	Net Revenue ($)
1	248.0	248.0	100.0	--	--	--	--	--	593.3	1046.1	-629.1
	(50.8)	(50.8)							(118.9)	(51.3)	(278.8)
2	248.0	0.0	0.0	248.0	8	4.8	36.6	5.0	293.3	1247.6	-329.1
	(50.8)	(0.0)		(50.8)	(.8)	(11.7)	(5.4)	(0.0)	(8.4)	(53.1)	(332.3)
3	248.0	.4	0.2	247.6	14	3.2	107.6	--	313.6	1266.4	-349.4
	(50.8)	(1.8)		(51.6)	(.5)	(9.8)	(5.5)		(10.1)	(50.9)	(333.8)
4	248.0	12.0	4.8	236.0	15	67.2	45.0	--	286.4	1195.3	-322.2
	(50.8)	(26.6)		(60.7)	(1.1)	(25.2)	(4.1)		(89.9)	(53.3)	(339.6)
5	248.0	2.7	1.1	245.3	11	175.2	--	--	232.6	1176.9	-268.4
	(50.8)	(5.7)		(51.6)	(.9)	(14.2)			(21.1)	(47.2)	(337.2)
6	248.0	.4	0.2	247.6	14	164.6	53.8	--	320.5	1273.2	-356.3
	(50.8)	(1.8)		(51.6)	(.5)	(6.9)	(2.7)		(10.2)	(50.9)	(333.9)
7	248.0	1.0	0.4	247.0	14	17.6	82.1	--	278.6	1228.7	-314.4
	(50.8)	(3.1)		(51.9)	(.7)	(19.4)	(6.3)		(19.6)	(49.6)	(334.9)
8	248.0	1.1	0.4	246.9	10	11.2	50.2	3.0	282.1	1231.8	-317.9
	(50.8)	(3.7)		(51.0)	(1.5)	(15.7)	(7.0)	(0.0)	(26.3)	(56.0)	(329.6)
9	248.0	3.7	1.5	244.3	6	85.6	--	5.0	294.1	1231.4	-329.9
	(50.8)	(16.6)		(52.0)	(.7)	(10.7)		(0.0)	(75.6)	(52.3)	(339.8)
10	248.0	2.0	0.8	246.0	8	110.4	--	3.0	254.5	1201.9	-290.3
	(50.8)	(5.2)		(51.8)	(1.0)	(16.3)		(0.0)	(19.5)	(50.6)	(336.3)
11	248.0	6.4	2.6	241.6	7	110.4	--	--	199.3	1128.5	-235.2
	(50.8)	(10.0)		(54.8)	(1.0)	(16.3)			(42.7)	(50.2)	(343.2)

Table 10. Scab Model Results with High Yield.

Strategy	Potential Yield (Bu.)	Scab Damage (bu.)	Scab Damage (%)	Net Undamaged Yield	Number of Sprays	Benomyl (oz.)	Captan (lbs)	Captafol (gals)	Control Costs ($)	Production Costs ($)	Net Revenue ($)
1	898.7 (50.3)	898.7 (50.3)	100.0	--	--	--	--	--	1920.6 (326.8)	1703.4 (50.8)	-105.9 (1179)
2	898.7 (50.3)	0.0 (0.0)	0.0	898.7 (50.3)	8 (.8)	4.8 (11.7)	36.6 (5.4)	5.0 (0.0)	293.3 (8.4)	1904.9 (49.8)	1521.4 (1443.8)
3	898.7 (50.3)	2.2 (10.0)	0.2	896.5 (51.4)	14 (.5)	3.2 (9.8)	107.6 (5.5)	--	320.9 (39.7)	1923.7 (51.9)	1493.8 (1430.9)
4	898.7 (50.3)	48.1 (114.1)	5.4	850.6 (121.3)	15 (1.1)	67.2 (25.2)	45.0 (4.1)	--	421.2 (403.7)	1852.6 (52.8)	1393.5 (1445.8)
5	898.7 (50.3)	10.9 (22.8)	1.2	887.8 (60.5)	11 (.9)	175.2 (14.2)	--	--	263.4 (87.1)	1834.2 (53.5)	1551.3 (1454.0)
6	898.7 (50.3)	2.2 (10.0)	0.2	896.5 (51.4)	14 (.5)	164.6 (6.9)	53.8 (2.7)	--	327.7 (39.5)	1930.5 (52.1)	1487.0 (1431.0)
7	898.7 (50.3)	4.4 (13.6)	0.5	894.3 (53.5)	14 (.7)	17.6 (19.4)	82.1 (6.3)	--	293.4 (63.2)	1885.9 (50.7)	1521.3 (1430.2)
8	898.7 (50.3)	4.5 (14.0)	0.5	894.2 (51.3)	10 (1.5)	11.2 (15.7)	50.2 (7.0)	3.0 (0.0)	295.9 (64.3)	1889.1 (52.1)	1518.8 (1433.4)
9	898.7 (50.3)	12.3 (54.9)	1.4	886.5 (76.5)	6 (.7)	85.6 (10.7)	--	5.0 (0.0)	333.4 (251.2)	1888.7 (50.5)	1481.3 (1474.5)
10	898.7 (50.3)	8.7 (22.5)	1.0	890.0 (59.5)	8 (1.0)	110.4 (16.3)	--	3.0 (0.0)	278.2 (80.4)	1859.2 (80.4)	1536.5 (1451.7)
11	898.7 (50.3)	27.1 (46.7)	3.0	871.6 (70.3)	7 (1.0)	110.4 (16.3)	--	--	280.2 (182.6)	1785.8 (55.5)	1534.5 (1446.4)

assumed, the program which applies a half dosage of captan throughout the season, strategy 4, becomes one of the three most effective programs. This occurs because strategy 4 has a relative low total spray cost but suffers the most damage of any of the control programs examined. The other exception is that at high yields the hypothetical post-infection program, strategy 11 slips from being the most effective strategy to the third most effective strategy. This result probably is observed since strategies 5 and 10 by inaccurately predicting infection periods and applying more sprays are benefiting from some of the protective capacity of each of the benomyl applications. The rankings are compared for the various scenarios in Table 11.

5.3 Risk Analysis

The following discussion is divided into two sections--a description of the analytical procedures and the presentation of the results of the analysis. The first section may be redundant to most readers and they should proceed directly to the section presenting the results. For readers interested only in the scab model, this discussion may be pertinent.

Analytical Procedures

The very nature of crop protection implies that decisions about pest management are not always made on the basis of the expected values of net income but that the avoidance of risk is important as well. Simplistically, the situation can be depicted as being a trade-off between the mean and the variance of the distribution of net income where the variance is often used as a measure of risk. However, this can be naive since other moments in the distribution can be important as well. The

Table 11. Rankings of Scab Control Strategies by Size of Expected Net Revenues.

Strategy	Medium Yield	Low Yield	High Yield	High Benomyl Price and Medium Yield	Medium Yield and No Damage
1	11	11	11	11	11
2	6	7	4	6	8
3	8	9	7	7	9
4	9	6	10	9	3
5	2	2	1	2	2
6	10	10	8	10	10
7	4	4	4	3	5
8	5	5	6	4	7
9	7	8	9	8	6
10	3	3	2	5	4
11	1	1	3	1	1

skewness of the distribution can influence the decisions of some individuals just like the variance.

The trade-off between the expected value, the variance and/or other measures of risk is likely to be rather personal. Different individuals have different perspectives about how much risk they are willing to bear and each individual is likely to alter his/her risk preference as the amount of money involved in the decision changes. The willingness to participate in an investment that has a 50% chance of earning $10 and 50% chance of losing $10 is likely to change if the outcomes were the chance to win or lose $10,000,000 rather than just $10. However, the adjustment of the risk preference to changes in income is not expected to be identical for all individuals. Many individuals will display risk aversion, risk preference and risk neutrality over at least some sections of their relevant income range.

The manner in which individuals value the uncertainty in the outcomes which result from their decisions is an area that is still little understood. It is hypothesized that for some individuals the worst possible outcomes of each possible action choice are the most important. These individuals are the most risk averse that is possible. They compare the minimums of the cumulative probability functions associated with each action choice and select that action choice which has the highest minimum value. In essence they compare the worst possible outcomes and choose the alternative which has the best "worst" outcome. They ignore the rest of the outcomes and the expected values since they are interested only in minimizing the impacts of any possible disasters. These individuals follow a decision rule known as maxi-min.

Another classical behavior model is that of maximization of expected profit. The individuals who follow this decision rule ignore any risk or uncertainty associated with the action choices and select only on the basis of the expected values. The alternative with the largest expected value is chosen as the best.

These two extreme cases are important because of the way which some analytical tools that are commonly used to evaluate alternative action choices for classes of decision makers operate. Since it is impossible to construct a single function which can represent the risk preferences of more than one individual, a series of analytical techniques referred to as Stochastic Dominance has developed. These efficiency criteria set upper and lower bounds on the risk preferences of a class of decision makers. The wider the interval defined by the bounds, the larger the class of decision makers will be. However, the larger that the class of the decision makers is, the more difficult it will be to discard alternative action choices as inefficient. The procedure examines all of the possible alternatives and rejects any alternative for which it can be said that for every member of the class of decision makers, there exists at least some other alternative that is preferred. The remaining alternatives are referred to as the efficiency set. The efficiency set is not always narrowed down to one alternative, in fact for wide intervals (large classes of decision makers) it may be as large as 50% of the total number of alternatives examined. For this reason, the interval of risk preferences is much like a statistical confidence interval. A wide interval has a high probability of a Type II error (claiming no difference between the expected utilities of the alternatives when one actually exists) while a narrow interval has a tendency for a Type I error (claiming there is a difference between the expected utilities of the alternatives when none actually exists).

There are four types of Stochastic Dominance which are relevant for this study. They are: First Degree, Second Degree, Stochastic Dominance with Respect to a Function, and Convex Set Stochastic Dominance. First Degree Stochastic Dominance sets the bounds on the risk preferences in such a way that its class of decision makers includes every possible decision maker. It suffers from the lack of discriminating power and produces large efficiency sets. Second Degree Stochastic Dominance narrows the interval somewhat but it still suffers from a high probability of a Type II error. It excludes all risk preferences which are risk preferring. Its class of decision makers is bounded on the one extreme by the maxi-min individual and on the other by the risk neutral decision maker.

Stochastic Dominance with Respect to a Function is a much more flexible analytical tool than the first two types. Rather than having a fixed interval like First and Second Degree Stochastic Dominance, its interval can be set by the researcher. The interval does not need to be constant across the entire income range and it can be set to include risk preferences that are risk averse, risk neutral or risk loving. The size of the class of decision makers and the relative probabilities of the Type I and Type II errors will be determined by the size of the interval. First and Second Degree Stochastic Dominance are really subsets of the more general Stochastic Dominance with Respect to a Function.

Convex Set Stochastic Dominance is a technique which when applied with one of the other Stochastic Dominance procedures will determine if the efficiency set can be further reduced by eliminating any alternatives for which there exists a convex combination of two or more other alternatives which is preferred by every decision maker within the class.

It removes from the efficiency set strategies which are not the most preferred alternative for at least one decision maker in the class.

The 11 strategies for controlling apple scab which were simulated by the model were examined by the Stochastic Dominance procedures. Of the infinite number of intervals that would be possible, five were selected for this analysis. The five intervals are displayed in Table 12. The coefficients for the intervals are in terms of the Pratt Risk Aversion Coefficient which is defined as the negative of the ratio of the second derivative of the utility function to the first derivative of the utility function $(-u''(x)/u'(x))$. The utility function is a concept which economists use to represent the amount of satisfaction or value that individuals receive from such items as income, leisure, consumption, etc.

Risk neutrality is represented as having a risk aversion coefficient of 0.0. The most risk averse individual would be represented with a coefficient of $+\infty$ while on the other extreme, the most risk loving individual would be depicted by a coefficient of $-\infty$.

The first interval approximates Second Degree Stochastic Dominance since it ranges from 0 to .1. It is an approximation since it does not extend completely to $+\infty$ but it is of a large enough magnitude to produce an identical efficiency set to the one identified for Second Degree Stochastic Dominance. It would be expected that this interval would retain as risk efficient at least both the alternative with the highest expected value and the one with the largest minimum value.

The next interval is similar to the first except that it excludes the risk neutral and slightly risk averse preferences. Its lower bound begins at .0003 which corresponds to a moderately high level of risk aversion.

Table 12. Risk Analysis Results for Scab Control Strategies.

Risk Interval	General Discription	Medium Yield (All Strategies)	Medium Yield (Excluding 11)	Low Yield (All Strategies)	Low Yield (Excluding 11)	High Yield (All Strategies)	High Yield (Excluding 11)	Medium Yield High Benomyl Price (All Strategies)	Medium Yield High Benomyl Price (Excluding 11)
1) 0.0 to 0.1	Approximates Second Degree Stochastic Dominance: Includes risk neutral and maxi-min	7, 8, 11	5,7,8,9	11	5, 7, 8	2,5,7,8,9,11	2,5,7,8,9	2, 7, 8, 11	2, 5, 7, 8
2) .0003 to 0.1	Ranges from maxi-min to moderately strong risk aversion	11	5, 7, 8	11	5, 7, 8	8, 11	2, 7, 9*	7, 8, 11	7, 8
3) .0001 to .0003	Ranges from slight risk aversion to moderately strong aversion	11	5	11	5	7, 8, 11	7, 8	11	7,8
4) -.0001 to .0001	Ranges from slightly risk loving to slightly risk averse; includes risk neutrality	5, 11	5	11	5	5, 7	2,7,8,10,11**	11	2, 5, 7, 8
5) -.001 to .0008 at $0 -.001 to .0015 at $10,000 -.001 to .0004 at $25,000	Interval changes as income increases; ranges from moderately strong risk loving to various levels of moderately strong risk aversion; includes risk neutrality	2, 3, 5, 7, 8 9, 10, 11	2, 3, 5, 7, 8, 9, 10	11	5	2, 5, 7, 8 9, 10, 11	2, 5, 7, 8, 9, 10	2, 3, 4, 5, 7, 8, 9, 10, 11	2, 3, 4, 5, 7, 8, 9, 10

*Excludes Strategy 8 as well as Strategy 11

**Excludes Strategy 5 but includes Strategy 11

The next two intervals represent a much smaller class of decision makers. The third interval excludes the decision makers who have more than moderately strong risk averse attitudes and those who are less than slightly risk averse. The fourth interval includes the risk neutral individual and those whose preferences approach risk neutrality. It does represent decision makers who are slightly risk averse and those who are slightly risk loving.

The final interval is the most complex. It is an attempt to use survey data on risk preferences (81) to construct an interval which would include the 80 to 90% of the Michigan farmers. Its upper bound varies by the income level and its lower bound is set to include the strongly risk loving individuals. At zero income, the upper bound is .0008 which represents a strong risk aversion. At $10,000 it increases to .0015 while at $25,000 it drops to .0004 which is still a moderately strong risk averse position. Since this is a wide interval, it is expected that the efficiency set will be relatively large.

Results

Efficiency sets have been identified for each of the five intervals using the distributions of net revenue generated by the simulation model under the various scenarios. For each scenario, two series of efficiency sets were identified. The first series included all 11 strategies while the second series excludes from consideration strategy 11. Strategy 11 is a hypothetical post-infection IPM program which assumes that there is no error in predicting the infection periods. The efficiency sets are compared in Table 12.

There are three major points that surface from the comparison of the efficiency sets. The first point is that strategy 11 is risk efficient for all intervals under each scenario with the exception of the fourth interval for the high yield scenario. The second point is that the conventional program represented by strategy 7 is risk efficient in the fifth interval for each scenario except for the low yield one. The final point is that the efficiency set identified for the last interval is generally quite large. In some cases, only two or three strategies can be declared as being inconsistent with the risk preferences of the majority of the Michigan farmers. If a smaller class of decision makers were used (i.e., 50-60% of the farmers) or if attitudes to risk were more homogenous, it is likely that more strategies could be removed as being risk inefficient. It should be noted, however, that there are growers in Michigan who follow programs which are very similar to each of the strategies with the exception of strategy 3.

VI. CODLING MOTH MODEL RESULTS

6.1 The Simulation Model

The codling moth model utilizes a time varying distributed delay. It was developed by slightly modifying the PETE phenology model which is widely used to predict colding moth occurrence on apples (148). The rates at which the insect population matures from one age class to another is time varying and dependent upon the accumulated degree days. The average time that it takes for the insects to pass from one stage to another is directly related to the ambient temperature.

In this case, the ambient temperature is measured in degree days accumulated from a bio-fix, a point in time fixed by the occurrence of an easily observed biological event. The bio-fix used here is the occurrence of fruit set in the apple trees. The model produces a series of phenological stages in the seasonal development of the trees based upon the number of degree days (base 43°F) that have accumulated since January 1 each year. The weather pattern for each season is randomly generated from a distribution developed from historical records from the East Lansing weather experiment station during the years 1910 to 1979. The model commences each season on April 1 so the number of degree days that have accumulated during the months of January, February and March are randomly generated from a normal distribution with a mean of 580 and a standard deviation of 80. The first stage determined by the model is green tip which occurs at 700 degree days. At 750 degree days 1/2 inch green is reached while 800 degree days is the transition point to tight cluster. At 900 and 1,000 degree days, pink and bloom respectively occur.

Petal fall is assumed to occur at 1,100 degree days and fruit set is observed seven calendar days after petal fall (8, pp. A34-A35). It should be noted that there is a difference between the degree days used to calculate the phenological stages of the trees and the days used to simulate the population dynamics of the codling moth. They have different starting points and employ different bases.

The model begins each season at fruit set by simulating the population dynamics of the codling moth by allowing a time varying distributed delay to calculate the rates at which the insects mature from one stage to the other. The model has five life stages: the eggs, the larvae, the pupae, the pre-oviposition adults and the ovipositing adults. While the same routine is used for all five life stages, there are a number of calculations which are unique to the maturation process of each stage.

The subroutine DELAY is an extemely flexible algorithm that can be used to calculate time varying distributed delays with proportional losses. It functions by dividing each delay into K cascading stages. The stages of the delay are distinct from the life stages of population since each life stage is represented by a different delay. The delay is predictated upon a series of differential equations which describes the process and can be solved by Euler's integration. The equations can be represented by:

1) $$R_i(t) = R_i(t\text{-}Dt) + Dt * \frac{K}{D(t\text{-}Dt)} * [R_{i+1}(t\text{-}Dt) - R_i(t\text{-}Dt) * (1 + \frac{1}{K} * \frac{D(t) - D(t\text{-}Dt)}{Dt} + \frac{D(t\text{-}Dt)}{K} * PLR\ (t\text{-}Dt)\ ]$$

where R_i = rate of the ith cascading stage

D = the mean time delay

K = the order of the delay process (number of cascading stages)

PLR = proportional loss rate out of each stage

Dt = integration step size (1, pp. 3-6)

The amount of time that it takes for an individual to pass completely through a delay process (life stage) depends upon three factors. As has been previously discussed, the rate at which degree days are accumulated is one factor. The other two factors are the values which are used for the variables D and K in the equations represented by Equation 1. The delay process operates with a Erlang distribution representing the amount of time necessary to complete the delay. The variable DEL is set equal to the desired mean while the variance is equal to the following expression:

2) $\sigma^2 = DEL^2/K$

The variable D is equal to DEL/K and is the time necessary to complete each cascading stage.

There are a number of interesting characteristics of the Erlang family of distributions. Where K is equal to 1, the distribution is the familiar exponential density function. As K becomes asymptotically large, the distribution approximates a normal density function. With K equal to ∞ the distribution qpproaches a normal distribution with a mean of D and a variance of zero--or a discrete delay.

By selecting the appropriate values for D and K, the algorithm can accurately simulate the pattern of maturation observed in the real population. Differences in the length of time necessary to mature from the different life stages can be handled by assigning different values for D, and/or K in each delay process (82).

Another variable which influences the number of individuals that actually emerge from each delay (life stage) is the variable PLR. This variable calculates a proportional loss from each of the K cascading stages of the delay. It reduces the number of individuals in each cascading stage by the average amount that will be lost in each delay. Usually the delay process will conserve flow-- that is to say that the number of individuals who enter the delay will be exactly equal to the number which emerge when the delay has been completed. However, in some cases there may occur a loss during the maturation process and not all of those who entered will finish the process. This phenomena can be simulated by the introduction of the proportional loss rate variable. Each time the algorithm is called, a reduction occurs in the populations of each cascading stage in direct proportion to the number of individuals that it has. Losses in the delay processes in the population dynamics of insects can be accredited to natural deaths from rain, wind and parasites. The loss rate can be set at different levels for the various life stages (82).

The model begins at fruit set by initializing the values for a number of variables which must be reset at the beginning of each season. This is performed in the subroutine CMINIT. In this subroutine, the variables that are initialized which are important for this discussion are DEL, K, R and STRG, PLR, and SCMPOP. There are of course, other initializations occurring but they are fairly standard and do not merit mention here. The variable DEL is the average time that it takes for an individual to completely mature from one life stage to the next. It is the total time to complete the entire delay process while D in equation 1 is the time necessary to complete one stage of the delay. It is equal to DEL/K. It is expressed in terms of degree days (base 50°F) that have accumulated since fruit set. For each delay (life stage) the variable is assigned a different value. For the first life stage, the egg stage, it takes an average of 145 degree days to hatch into a larva. The larval stage is expected to last 587 degree days and the pupal stage another 265 days. The pre-oviposition adult stage is by far the shortest. It lasts an average of 50 degree days. The ovipositing adult stage has an expected duration of 175 days.

In each delay, the number of cascading stages is the same. The value of K for all life stages is 15. The characteristics of the Erlang distributions governing the maturation rates from each life stage can now be inferred. The means and variances of each delay are presented in Table 1.

The next two variables, R and STRG are related to the rates of movement from one cascading stage to the next and the number of individuals that may be found in any one delay (life stage) at a given point in time. It is commonly assumed that when T = 0 and the simulation is just beginning that most initial values for R and STRG will be zero. However, it is to be remembered that in the population dynamics of the codling moth, the insect overwinters as larva and that at fruit set the overwintering population should have advanced to the later larval stages. It is therefore necessary to initialize some of the values of R and STRG for the larval stage at non-zero levels. The rates of movement out of the last ten cascading stages of the delay representing the pupal stage are assigned non-zero values. All other rates within this delay and the other delays as well are set equal to zero at the beginning of each season. At fruit set since only individuals that have overwintered as larvae can be found, all initial values for STRG are set equal to zero except for the STRG variable related to the delay for the larval stage.

The proportional loss rates assigned to each of the delays are different. For the two adult life stages, there is no loss while for the

Table 1. The Characteristics of the Erlang Distributions Representing Delay Times for the Life Stages of the Codling Moth.

Delay	Life Stage	Mean	Variance	Standard Deviation
1	Eggs	145	1402	37.4
2	Larvae	587	22971	151.6
3	Pupae	265	4682	68.4
4	Pre-oviposition Adults	50	167	12.9
5	Ovipositing Adults	175	2038	45.1

eggs, larvae and pupae a small loss exists. The losses for the three stages are respectively .00103, .00140 and .00023 per degree day in that life stage or .149, .822[1] and .061. The total natural mortality would thus be 85.8%.

The final variable whose initialization needs to be discussed is the starting population density, SCMPOP. It can be set at three levels which approximate a high, medium and low population density. A high level can be assigned by setting the value fo SCMPOP equal to 10.0 while a medium density is defined by a value of 1.0. The low population density is determined by initializing SCMPOP with a value of 0.1. The high population corresponds to density of one larva per 100 apples while the medium level is equal to a density of one larva per 1000 apples. The low population represents a density of one larva per 10,000 apples. It is assumed that the orchard produces 100 apples to the bushel and that there are 100 trees per acre.

After the initialization has been completed, the model commences with the simulation. Each day after fruit set, the subroutine CODMOTH is called. This subroutine performs seven basic functions. It calculates the number of degree days from the average daily temperature and updates the movement of the population through the various life stages. Every two degree days an iteration of the delay processes occurs so it is quite conceivable that in most days the number of times the maturation process is updated will greatly exceed one. CODMOTH also calculates the in-migration of the insect into the orchard and the amount of oviposition that occurs. The in-migration is determined by equation 3.

3) R(J,2) = R(J,2) + .002555 * Apples * .0022

---

[1]After fruit damage.

where R = rate of movement out of the Jth cascading stage in delay representing the larval life stage

Apples = the number of apples per tree

It is now possible that the number of larvae leaving a given cascading stage may acutally exceed the number which entered due to the in-migration. The oviposition is determined by the number of adults which appear in each of the 15 cascading stages of the last delay process. Only individuals in the following cascading stages actually lay eggs: 2, 3, 4, 5, 6, and 7. The oviposition rates differ for each of the cascading stages.

The subroutine calculates the mortality to the newly hatched larvae to the chemical sprays after the oviposition and in-migration are determined. The spray mortality to the adult stages and the eggs are calculated in the subroutine CMMORT which is called once by CODMOTH at the beginning of each day. The mortality to the newly hatched larvae, as well as the oviposition and in-migration are updated with the delay process every two degree days. The rate of movement out of the first cascading stage of the larval delay is the only rate adjusted for the spray mortality by CODMOTH.

After the spray mortality is calculated for the newly hatched larvae, the number of apples that are infested by worms is derived using the rate of movement out of the first cascading stage of the larval delay. This calculation is updated every two degree days with the previosly discussed operations. At the end of the day, the proportion of apples that are infested with the codling moth larvae is computed.

The last function that is performed by the subroutine is the estimation of the numbers in each of the various life stages. They are represented by the STRG variables for the five delays and are calculated by summing the rates of movement out of the cascading stages for each delay and dividing by K/DEL. The variable CMLEVEL is set equal to the number of eggs estimated divided by the number of apples per tree. These calculations are performed once a day at the end of the CODMOTH subroutine.

This model was adapted with few revisions from a widely used PETE phenology model which has been validated for a number of different regions (110; 148; and 63).

The remaining subroutine of the codling moth model is the one which implements the decision rules of the various strategies examined. It is referred to as CMSCOUT and is called on a weekly basis from the subroutine SCOUT. It executes the decision rules for both conventional calendar spray schedules and Integrated Pest Management (IPM) programs.

There are 19 different strategies which are examined by the model. The first strategy consists of applying no control and it is used as a baseline for comparison purposes. The next two strategies are conventional calendar schedules which apply respectively azinphosmethyl and pyrethroid. The sprays are applied on a bi-weekly basis from fruit set until 1700 degree days (base 50°F) have accumulated since fruit set. The remaining strategies are variations of IPM programs with different levels for three economic thresholds. For each of the two chemicals considered, there are four distinct IPM programs. Each program is examined twice, first with no sampling error assumed in the scout's estimate of the population and then later with a random sampling error that 95% of the time of the scout's estimate is within 50% of the true population density. The sampling error is randomly drawn from a normal distribution using the subroutine RAN.

The IPM programs use three economic thresholds (or perhaps more correctly one dynamic economic threshold adjusted by the observed weather pattern). A maximum of two sprays are applied for control of first generation eggs and larvae. Which economic threshold that is to be used is dependent upon the number of degree days (base 50°) experienced since fruit set and the number of sprays applied. If no sprays have been applied, the relevant economic threshold is defined by the value for the variable ECM1. If one spray has been previously applied and less than 800 degree days have accumulated since fruit set, the value of ECM2 is the threshold level to be used. If more than 1200 degree days have been observed, the threshold value of concern is ECM3. These programs will never apply more than 3 sprays per season. The population estimates are made in terms of eggs/apples/tree (CMLEVEL). The strategies are more completely described in Table 2.

Stochastic Elements of the Model

The model was constructed to perform a stochastic Monte Carlo analysis. For each strategy a simulation was made for twenty independent seasons.

The purpose of the Monte Carlo analysis was to generate enough information about the performance of the strategies under different, possible conditions that the strategies could be evaluated in a stochastic manner. Each season can be viewed as a distinct set of conditions because they are randomly generated from a series of multivariate distributions, usually based on historical records. The performances of all of the strategies are examined under the same twenty seasons.

The differences in the various seasons lie in the random draws from the multivariate probability distributions. Each stochastic variable

Table 2. Codling Moth Model Strategies.

Strategy	Chemical	Never Spray	Biweekly Sprays Until 1700 Degree Days	Spray #1 When Pop>EMC1 (Value of EMC1)	Spray #2 When Pop>EMC1 and DD <800 (Value of EMC2)	Spray #3 When Pop>EMC3 and DD >1200 (Value of EMC3)	Sampling Error
Baseline 1	—	Yes	No	-	-	-	No
Calendar							
2	Azinphosmethyl	No	Yes	—	—	—	No
3	Pyrethroid	No	Yes	—	—	—	No
IPM							
4	Azinphosmethyl	No	No	.001	.003	.005	No
5	Pyrethroid	No	No	.001	.003	.005	No
6	Axinphosmethyl	No	No	.001	.001	.001	No
7	Pyrethroid	No	No	.001	.001	.001	No
8	Azinphosmethyl	No	No	.002	.006	.01	No
9	Pyrethroid	No	No	.002	.006	.01	No
10	Azinphosmethyl	No	No	.0015	.0045	.0075	No
11	Pyrethroid	No	No	.0015	.0045	.0075	No
12	Azinphosmethyl	No	No	.001	.003	.005	Yes
13	Pyrethroid	No	No	.001	.003	.005	Yes
14	Azinphosmethyl	No	No	.001	.001	.001	Yes
15	Pyrethroid	No	No	.001	.001	.001	Yes
16	Azinphosmethyl	No	No	.002	.006	.01	Yes
17	Pyrethroid	No	No	.002	.006	.01	Yes
18	Azinphosmethyl	No	No	.0015	.0045	.0075	Yes
19	Pyrethroid	No	No	.0015	.0045	.0075	Yes

represents a source of uncertainty and it is the uncertainty within the system that necessitates the evaluation of the strategy performances under different conditions. If there were no uncertainty in the system, information from a single simulation would be sufficient to rank the strategies as to their desirability. The source of uncertainty in the independent codling moth model are the fresh market price, the processed market price, the average daily temperature, the number of degree days (base 43°F) accumulated in January, February, and March, and in some cases the random sampling error.

The apple prices are randomly generated from a multivariate distribution which was inferred from a historical time series of data from the years 1969 to 1978. The fresh market and the all-processed market prices are randomly drawn from the distribution in a fashion that should preserve the observed correlation between the two. This process is performed by an algorithm developed by King and is called MVGEN (63).

The average daily temperature is generated from a multivariate random processor which also includes probabilistic information on daily precipitation. There are a number of important correlations which are incorporated into this processor. The correlation coefficients between the temperature and the precipitation for each day are used by the algorithm, as are the autocorrelations for the precipitation and the average temperature for a given day and the day immediately preceding it. Since the season was divided into 8 parts of 21 days each, there are 8 distinct multivariate distributions with three sets of correlation coefficients incorporated to preserve important relationships in the randomly generated distributions. The probability of a given temperature being drawn is different in the 8 parts of the season but it is identical for all 21 days within any one part of the season. The multivariate distributions were developed from historical weather records from the East Lansing weather experiment station for the years 1910 to 1979.

The number of degree days (base 43°F) that have accumulated prior to April 1 is necessary to calculate the physiological progression of the apple trees through the season. The model begins each season at the beginning of April. The degree day total previous to the season's beginning is randomly generated from an univariate normal distribution with a mean of 580 and a standard deviation of 80.

The random sampling error that can be imposed on the scout's estimate of the population used in the IPM programs is also drawn from a normal distribution. The algorithm that directs this random generation uses a mean that is set equal to the actual population density and the standard deviation is inferred by the size of the confidence interval defined by the user of the model. In this case, the random error that is generated will ensure that the estimate of the scout is within 50% of the true population 95% of the time. Since it is drawn from a normal distribution, the probability that scout overestimates the population is equal to the probability of an under-estimation.

6.2 Model Results

There are a number of performance variables which are simulated by the model and which could be used to evaluate the various strategies. More than one performance variable may be necessary to thoroughly evaluate a strategy since it is unlikely that a single variable can capture all of the parameters which may be of interest to someone concerned with pest management. Of all the variables, probably the four most relevant are per acre expected net revenue, the distribution of net revenue, the amount of moth damage and the quantity of pesticides introduced into the environment. The expected net revenue can be used as an indication, on the average, of the relative profitability of following one strategy over another, but it is necessary to consider the distribution of net revenue to evaluate the risk efficiency of the strategies. The amount of moth damage and the quantity of pesticides employed are useful measures of the general efficacy of the strategies.

Other performance variables provided by the model are the number of sprays applied and a measure which attempts to balance the pest damage and the costs incurred to control it. This variable is "control cost" and is the sum of the pest damage, the pesticide cost, the scouting cost, and the cost of labor and machinery used in the application. In many cases there will exist a trade-off between the damage and the other costs--that is to say that if the application and pesticide costs are reduced, the damage is likely to increase. However, it may be possible to substitute information provided by scouting (at a lower cost) for some pesticide without greatly affecting the amount of damage experienced. This is part of the basis for many IPM strategies.

For each of the 19 strategies the model was simulated a number of times. Following the Monte Carlo format, the model was run once for each state of nature for each strategy for each initial population level. There are three population levels and 20 states of nature so a total of sixty seasons were simulated for each strategy. All strategies were simulated for the same 20 states of nature.

The strategies are all designed to use one of two chemicals--azinphosmethyl or a pyrethroid. A full dose application for azinphosmethyl is assumed to be 32 ounces per acre while the full strength spray of the pyrethroid consists of a rate of 26 ounces per acre. The price per pound of azinphosmethyl used by the model is $5.25. The pyrethroid is assumed to be available at a price of $10.50 per pound. As seen in Table 3, the cost per application is considerably less in the use of azinphosmethyl. The two chemicals have identical mortality rates for codling moth but the pyrethroid impacts on the mite predation which azinphosmethyl does not.

The expected values and standard deviations produced by the simulation of the model for the high initial population density appear in Table 4. The high initial popualtion density refers to a level of larvae per apples per tree of 10/1000. The strategy with the highest expected net revenue is strategy 8, the IPM strategy with the highest economic thresholds. The conventional calendar program based on the use of azinphosmethyl has the second highest average income. It is about $4 per acre lower but it should be noted that it prevents almost all damage while strategy 8 suffers approximately 3% damage. It should also be remembered that the calendar sprays are designed to control more pests than just the codling moth and the activity of these pests is ignored in the model. The IPM strategies only apply half the sprays that the calendar control program do, but they result in more damage. Of all the IPM strategies, only strategy 8 enjoys an expected net revenue higher than the calendar program. The IPM strategies with either the static economic thresholds or the low and medium level dynamic thresholds perform identically. This suggest that net revenue is not too sensitive to the economic threshold. The chemical price differential between

Table 3. Spray Costs for Moth Control Strategies.

Spray	Chemical Price Per Unit	Chemical Cost per Application	Labor Cost per Application	Machinery Cost per Application	Cost per Application
Azinphosmethyl 50WP 32 oz/acre	$.0328/oz	$10.50/acre	$.70/acre	$.70/acre	$11.90/acre
Pyrethroid 3EC 26 oz/acre	$.808/oz	$21.00/acre	$.70/acre	$.70/acre	$22.40/acre

Source: Pest Control Branch, NRED, ERS, USDA.

Table 4. Moth Model Results with Medium Yield and a High Density for the Initial Moth Population.

Strategy	Potential Yield (bu/acre)	Moth Damage (bu/acre)	Net Yield (bu/acre)	Number of Sprays	Azinphos-methyl (F.D.E.)*	Pyrethroid (F.D.E)*	Control Costs ($/acre)	Net Revenue ($/acre)
1	502.1 (47.5)	308.0 (79.3)	194.1 (88.9)	---	---	---	1438.1 (556.7)	-459.9 (335.1)
2	502.1 (47.5)	0.1 (0.0)	502.0 (47.5)	6 (.5)	6.4 (.5)	---	349.9 (6.7)	317.2 (702.3)
3	502.1 (47.5)	0.1 (0.0)	502.0 (47.5)	6 (.5)	---	6.4 (.5)	417.1 (12.0)	250.0 (702.7)
4	502.1 (47.5)	17.7 (6.6	484.4 (48.6)	3 (.3)	2.9 (.3)	---	369.6 (33.1)	315.3 (679.7)
5	502.1 (47.5)	17.7 (6.6)	484.4 (48.6)	3 (.3)	---	2.9 (.3)	400.1 (34.3)	284.9 (677.5)
6	502.1 (47.5)	17.7 (6.6)	484.4 (48.6)	3 (.3)	2.9 (.3)	---	369.6 (33.1)	315.3 (679.7)
7	502.1 (47.5)	17.7 (6.6)	484.4 (48.6)	3 (.3)	---	2.9 (.3)	400.1 (34.3)	284.9 (679.5)
8	502.1 (47.5)	15.8 (7.1)	486.3 (47.2)	3 (.3)	2.9 (.3)	---	362.2 (32.2)	320.9 (683.1)
9	502.1 (47.5)	15.8 (7.1)	486.3 (47.2)	3 (.3)	---	2.9 (.3)	392.6 (33.2)	290.4 (682.9)
10	502.1 (47.5)	17.7 (6.6)	484.4 (48.6)	3 (.3)	2.9 (.3)	---	369.6 (33.1)	315.3 (679.7)
11	502.1 (47.5)	17.7 (6.6)	484.4 (48.6)	3 (.3)	---	2.9 (.3)	400.1 (34.3)	284.9 (679.5)
12	502.1 (47.5)	18.6 (7.3)	483.5 (48.0)	3 (.3)	2.9 (.3)	---	372.4 (33.4)	313.5 (680.5)
13	502.1 (47.5)	18.6 (7.3)	483.5 (48.0)	3 (.3)	---	2.9 (.3)	402.8 (34.7)	283.1 (680.4)
14	502.1 (47.5)	18.6 (7.3)	483.5 (48.0)	3 (.3)	2.9 (.3)	---	372.4 (33.4)	313.5 (680.5)
15	502.1 (47.5)	18.6 (7.3)	483.5 (48.0)	3 (.3)	---	2.9 (.3)	402.8 (34.7)	283.1 (680.4)
16	502.1 (47.5)	15.6 (6.9)	486.5 (49.0)	3 (.3)	2.9 (.3)	---	362.3 (32.4)	320.6 (683.2)
17	502.1 (47.5)	15.6 (6.9)	486.5 (49.0)	3 (.3)	---	2.9 (.3)	392.7 (33.4)	290.2 (683.0)
18	502.1 (47.5)	16.6 (7.2)	485.5 (48.5)	3 (.3)	2.9 (.3)	---	364.8 (31.9)	319.1 (684.3)
19	502.1 (47.5)	16.6 (7.2)	485.5 (48.5)	3 (.3)	---	2.9 (.3)	395.7 (33.0	288.6 (684.1)

*Full Dose Equivalents

the two insecticides is great enough that all azinphosmethyl strategies are more efficient than their pyrethroid counterparts.

The introduction of the random sampling error reduces the net income of three of the four strategies (12, 14 and 16) but increases the net revenue of one (18). The reductions in the net income are all under $2/acre, indicating that the sampling error is not influencing the profitability of the IPM strategies to any great extent.

In Table 5, the performances of the strategies is depicted when the initial population is at a medium level. The medium population density is defined as one emerging moth in the spring for every 1000 apples per tree. The IPM strategy with the highest dynamic economic threshold produces the largest expected net revenue. It is however, only $.50/acre greater than the IPM strategy with the lowest expected net revenue. The four IPM strategies using azinphosmethyl are all within $.50/acre of each other. Due to higher chemical costs, the strategies using the pyrethroid have revenues considerably below these. The calendar spray program has an expected net revenue almost $40/acre below the IPM strategies. It results in slightly less damage but applies substantially more chemicals.

The introduction of the random sampling error does not influence the net incomes of the control strategies much at all. The expected net revenues are not very sensitive to the error. None of the strategies experienced more than a $1/acre decline in net revenue. This would be consistent with the observation that the expected net revenue is not affected much by changes in the economic threshold.

When the analysis is made with a low initial population density, the sensitivity of the expected net revenue to the economic threshold levels

Table 5. Moth Model Results with Medium Yield and Low Density for Initial Moth Population.

Strategy	Potential Yield (bu/acre)	Moth Damage (bu/acre)	Net Yield (bu/acre)	Number of Sprays	Azinphos-methyl (F.D.E.)*	Pyrethroid (F.D.E)*	Control Costs ($/acre)	Net Revenue ($/acre)
1	502.1 (47.5)	10.5 (4.7)	491.6 (47.5)	---	---	---	304.5 (23.2)	373.1 (686.3)
2	502.1 (47.5)	0.0 (0.0)	502.1 (47.5)	6 (.5)	6.4 (.5)	---	349.6 (6.7)	317.4) (702.4)
3	502.1 (47.5)	0.0 (0.0)	502.1 (47.5)	6 (.5)	---	6.4 (.5)	416.8 (12.0)	250.2 (702.8
4	502.1 (47.5)	2.6 (.9)	499.5 (47.3)	2 (.3)	1.9 (.3)	---	299.6 (8.0)	370.1 (697.8)
5	502.1 (47.5)	2.6 (.9)	499.5 (47.3)	2 (.3)	---	1.9 (.3)	319.5 (10.7)	350.2 (697.6)
6	502.1 (47.5)	2.6 (.9)	499.5 (47.3)	2 (.3)	1.9 (.3)	---	299.6 (8.0)	370.1 (697.8)
7	502.1 (47.5)	2.6 (.9)	499.5 (47.3)	2 (.3)	---	1.9 (.3)	319.5 (10.7)	350.2 (697.6)
8	502.1 (47.5)	2.5 (1.5)	499.6 (47.7)	2 (.5)	1.5 (.5)	---	294.0 (11.3)	375.6 (698.6)
9	502.1 (47.5)	2.5 (1.5)	499.6 (47.7)	2 (.5)	---	1.5 (.5)	309.5 (16.3)	359.9 (698.4)
10	502.1 (47.5)	3.0 (1.2)	499.1 (47.3)	2 (.3)	1.9 (.3)	---	300.9 (8.6)	369.2 (697.8)
11	502.1 (47.5)	3.0 (1.2)	499.1 (47.3)	2 (.3)	---	1.9 (.3)	320.8 (11.3)	349.2 (697.7)
12	502.1 (47.5)	2.7 (1.0)	499.4 (47.3)	2 (.3)	1.9 (.3	---	200.8 (8.0)	369.0 (697.8)
13	502.1 (47.5)	2.7 (1.0)	499.4 (47.3)	2 (.3)	---	1.9 (.3)	319.8 (10.7)	350.0 (697.6)
14	502.1 (47.5)	2.7 (1.0)	499.4 (47.3)	2 (.3)	1.9 (.3)	---	298.8 (8.0)	369.9 (697.8)
15	502.1 (47.5)	2.7 (1.0)	499.4 (47.3)	2 (.3)	---	1.9 (.3)	319.8 (10.7)	350.0 (697.8)
16	502.1 (47.5)	2.5 (1.3)	499.6 (47.3)	2 (.5)	1.7 (.5)	---	296.2 (11.6)	373.4 (697.0)
17	502.1 (47.5)	2.5 (1.3)	499.6 (47.3)	2 (.5)	---	1.7 (.5)	313.6 (16.1)	356.1 (697.0)
18	502.1 (47.5)	2.8 (1.1)	499.3 (47.2)	2 (.4)	1.9 (.4)	---	299.6 (8.4)	370.3 (697.5)
19	502.1 (47.5)	2.8 (1.1)	499.3 (47.2)	2 (.4	---	1.9 (.4)	319.1 (11.6)	350.9 (697.1)

is enhanced. The results appear in Table 6. The strategy with the highest expected net revenue is once again strategy 8. It has a net return almost $60/acre higher than the conventional calendar spray program and it exceeds its nearest IPM competitor by $5.50/acre. Strategy 8 uses less than one fourth of the insecticide applied by the conventional control. The amount of damage experienced between the two treatments is less than 0.5% of the yield. The other IPM strategies result in more damage and more control costs.

Expected net revenues decline by as much as $2/acre when the random sampling error is introduced. Strategy 10 actually increases its net revenue with the sampling error. This probably indicates that the thresholds used could be improved. The IPM strategy with the constant economic threshold performs identically to the one with the dynamic threshold set at the lowest levels.

One final point is worth mentioning in this discussion. It is that only strategy 8 produces a net revenue greater than the one expected when no controls are applied at all. It appears that with a low initial population density that the majority of the strategies apply more chemicals than what is justified by the amount of damage which they avoid. The conventional program is sone $50 to $60 per acre less efficient than the no treatment alternative in this scenario.

In Table 7 the relative comparisons of the various strategies are presented for each scenario on the initial pest population density. The strategies are categorized into classes and the strategies of each class are identified under the class titles. Even with the full change of the scouting attribute to the control of codling moth, the IPM programs generally produce higher expected net revenues than do the conventional calendar spray programs.

Table 6. Moth Model Results with Medium Yield and Medium Density for Initial Moth Population.

Strategy	Potential Yield (bu/acre)	Moth Damage (bu/acre)	Net Yield (bu/acre)	Number of Sprays	Azinphos-methyl (F.D.E.)*	Pyrethroid (F.D.E)*	Control Costs ($/acre)	Net Revenue ($/acre)
1	502.1 (47.5)	53.4 (21.6)	448.7 (52.4)	--	--	--	469.3 (116.2)	251.8 (622.1)
2	502.1 (47.5)	0.0 (0.0)	502.1 (47.5)	6 (.5)	6.4 (.5)	--	349.7 (6.7)	317.4 (702.4)
3	502.1 (47.5)	0.0 (0.0)	502.1 (47.5)	6 (.5)	--	6.4 (.5)	416.9 (12.0)	250.2 (702.8)
4	502.1 (47.5)	3.0 (1.0)	499.1 (47.3)	3 (.3)	2.9 (.3)	--	314.2 (8.1)	355.9 (697.9)
5	502.1 (47.5)	3.0 (1.0)	499.1 (47.3)	3 (.3)	--	2.9 (.3)	344.7 (10.9)	325.4 (697.7)
6	502.1 (47.5)	3.0 (.9)	499.1 (47.3)	3 (.3)	2.9 (.3)	--	314.4 (7.7)	355.7 (697.8)
7	502.1 (47.5)	3.0 (.9)	499.1 (47.3)	3 (.3)	--	2.9 (.3)	344.9 (10.4)	325.3 (697.6)
8	502.1 (47.5)	3.3 (1.4)	498.8 (47.3)	3 (.4)	2.8 (.4)	--	314.2 (8.6)	356.2 (697.3)
9	502.1 (47.5)	3.3 (1.4)	498.8 (47.3)	3 (.4)	--	2.8 (.4)	343.6 (11.7)	326.8 (697.4)
10	502.1 (47.5)	2.9 (1.0)	499.2 (47.3)	3 (.3)	2.9 (.3)	--	314.2 (8.0)	355.9 (697.6)
11	502.1 (47.5)	2.9 (1.0)	499.2 (47.3)	3 (.3)	--	2.9 (.3)	344.6 (10.6)	325.4 (697.4)
12	502.1 (47.5)	3.1 (1.0)	499.0 (47.4)	3 (.3)	3.9 (.3)	--	314.8 (8.6)	355.4 (697.3)
13	502.1 (47.5)	3.1 (1.0)	499.0 (47.4)	3 (.3)	--	2.9 (.3)	345.2 (11.4)	325.0 (697.1)
14	502.1 (47.5)	3.2 (1.0)	498.9 (47.3)	3 (.3)	2.9 (.3)	--	315.0 (8.3)	355.2 (697.1)
15	502.1 (47.5)	3.2 (1.0)	498.9 (47.3)	3 (.3)	--	2.9 (.3)	345.5 (10.9)	324.8 (696.9)
16	502.1 (47.5)	3.6 (1.0)	498.5 (47.2)	3 (.4)	2.9 (.3)	--	314.9 (9.8)	355.8 (697.0)
17	502.1 (47.5)	3.6 (1.0)	498.5 (47.2)	3 (.4)	--	2.9 (.3)	343.8 (11.6)	326.9 (697.9)
18	502.1 (47.5)	3.1 (1.0)	499.0 (47.4)	3 (.3)	2.9 (.3)	--	314.9 (8.4)	355.4 (697.4)
19	502.1 (47.5)	3.1 (1.0)	499.0 (47.4)	3 (.3)	--	2.9 (.3)	345.3 (11.0)	325.0 (647.2)

*Full Dose Equivalents

Table 7. Relative Comparisons of Classes of Strategies by Differences from the Expected Net Revenue of the Calendar Spray Program for Codling Moths.

Initial Population Density	Strategy Classes			
	No Control (1)	Calendar (2,3)	IPM Constant Economic Threshold (6,7,14,15)	IPM Dynamic Economic Threshold (4,5,8-13,16-19)
Low	+56 to+123	---	+33 to+53	+33 to +59
Medium	-66 to +2	---	+38	+38 to +40
High	-710 to+777	---	-2 to -4	-4 to +4

6.3 Risk Analysis

This discussion is divided into two sections -- one describing the analytical procedures and another presenting the results of the analysis. This material may be redundant for all readers except those interested exclusively in the control of codling moth. It should be pertinent to these readers, while the others can proceed to the next section.

Analytical Procedures

While the expected values for net revenue are certainly an important performance variable vital to evaluating strategies, they are not a complete criteria. The expected value does not provide any information about the amount of risk associated with any of the strategies. Crop protection by its very nature implies that risk is an important ingredient to the decision making process. Simplistically, the situation is often depicted as a trade-off between the mean and the variance, with more risk averse individuals assumed to accept lower means if the variance is reduced as well. The variance is viewed in this case as a measure of risk. However, this is an oversimplification since other moments in the distribution may be important as well.

The value that individuals place on risk is extremely personal and it is almost impossible to make precise statements about the risk preferences of large groups of decision makers. It is possible, though, to draw some general conclusions and discuss preferences of many individuals which may fall within wide bounds of possibilities. It is known that risk preferences are a function of income but different individuals adjust their preferences differently to changes in the amount of money involved in a decision.

A method of defining intervals which will allow the preferences to change by income level and to be a valid representation of the risk preferences ofa class of decision makers has been developed under the name of Stochastic Dominance with Respect to a Function. Before the actual intervals are discussed, it will be useful to review three extreme cases of preferences.

The extreme case of risk aversion is referred to a maxi-min behavior. Individuals following this decision rule are the most risk averse possible because they are only interested in the lowest income possible from each strategy. After identifying minimum return possible for each alternative they prefer the strategy with the largest minimum-- hence they maximize the minimum return.

Another extreme case of behavior is the risk neutral individual who is completely unaffected by the risk involved in the alternative strategies. This person's only criteria is the size of the expected net revenue.

The final extreme case to be discussed here is the maxi-max decision maker. This is the polar case to the maxi-min individual discussed previously. In this case, only the highest possible returns are of interest to the decision maker. These individuals will prefer the s trategy which produces the largest possible income. These decision makers are the most risk loving that can be observed.

While it is not likely that any individuals can be found that consistently follow any one of the extreme cases, they are useful in orienting one's self with the boundaries on the intervals which will be used to evaluate the pest management strategies. Stochastic Dominance with Respect to a Function uses a measure for risk preferences which is defined as the negative ratio of the second derivative of the utility function to the first derivative $(-u''(x)/u'(x))$. This measure, the risk aversion coefficient, produces a value used in this study of $+\infty$ for the risk preferences of the maxi-min decision makers. The values for the risk neutral and maxi-max decision makers are respectively, 0.0 and $-\infty$. A positive value indicates risk aversion which a negative one implies a risk loving attitude.

This analysis uses five intervals to evaluate the strategies. Each interval represents the preferences of a class of decision makers. Some of the intervals may have mutual members and others will represent distinct groups. The width of the interval will affect the number of strategies which are designated as being risk efficient for the class of decision makers being examined. Strategies which are risk efficient will appear in the efficiency set. The efficiency set will consist of all strategies for which it can be said that there is no alternative within the opportunity set (the total number of strategies examined) that is preferred by every possible decision maker within the class represented by the risk interval. Different intervals may produce different efficiency sets and the wider the interval the larger will be the efficiency set. The five intervals used are presented in Table 8.

The first interval approximates Second Degree Stochastic Dominance and its upper bound is set equal to 0.1 while its lower bound is 0.0. It is an approximation since the upper bound does not extend all the way to positive ∞ but the 0.1 is of a large enough relative magnitude to be a reasonable facsimile within this context. Since the upper bound is assumed to approximate positive ∞, this interval includes every decision maker who is not risk loving at any income level. It is bounded by the maxi-min individual on one extreme and the risk neutral one on the other extreme. Therefore, it is expected that at least the strategies which have

Table 8. Risk Analysis Results for Moth Control Strategies.

Risk Interval	General Description	Medium Yield and low Initial Density	Medium Yield and Medium Initial Density	Medium Yield and High Initial Density
1) 0.0 to 0.1	Approximates Second Degree Stochastic Dominance: Includes risk neutral and maxi-min	1, 8, 16	1, 6, 8, 10, 12	8, 16
2) .0003 to 0.1	Ranges from maxi-min to moderately strong risk aversion	1	1, 6, 8, 10, 12, 14	8, 16
3) .0001 to .0003	Ranges from slight risk aversion to moderately strong risk aversion	1	8	8, 16
4) -.0001 to .0001	Ranges from slightly risk loving to slightly risk averse; includes risk neutrality	1, 8	4, 8	2, 8, 16
5) -.001 to .0008 at $0 -.001 to .0015 at $10,000 -.001 to .0004 at $25,000	Interval changes as income increases; ranges from moderately strong risk loving to various levels risk aversion; includes risk aversion; includes risk neutrality	4, 6, 8, 12, 14 16	4, 6, 8, 10, 12	2, 8, 16

the highest expected net revenue and the one with the largest minimum value will appear in the efficiency set.

The second interval represents a class of decision makers which is a subset of the first interval. It excludes from the class any individual who has a high risk aversion coefficient less than .0003 over any point of the relevant income range. A value of .0003 for the risk aversion coefficient corresponds to a moderately strong risk aversion. This interval does include the maxi-min decision maker but excludes the risk neutral individual. It is therefore expected to include in its efficiency set the strategy with the largest minimum return and may or may not include the alternative with the highest expected net revenue.

The third interval is considerably narrower than the first two and should produce a smaller efficiency set. It also represents a class of decision makers which is a subset of the class of the first interval, so every member of its efficiency set should appear in the efficiency set of the first interval. This interval represents decision makers who range from slightly risk averse to those with moderately strong risk aversion. It excludes the risk neutral and the maxi-min individual so it may not result in the strategies with the highest expected net revenue and largest minimum income appearing in the efficiency set.

The fourth interval is of relatively narrow width but does not represent a class of decision makers which is a subset of the class of the first interval. It is bounded above by the slightly risk averse individual and below by the slightly risk loving decision maker. It does include the risk neutral case and should always declare the strategy with the largest expected net revenue as risk efficient.

The last interval is different than the previous ones in two respects.

First, it is derived from actual survey data (81) and its width is set to define a class of decision makers which should include about 85% of the farmers in Michigan. The second unique characteristic is that its upper bound is not set at a constant level but is adjusted by the income level. It ranges from the strongly risk loving decision maker to individuals with various degrees of moderately strong risk aversion. It does include the risk neutral case. It is a wide interval since it represents a large class of decision makers and is expected to produce a large efficiency set. Whether this interval results in an efficiency set larger than the one from the first interval will depend on the relative shape of the distributions of net revenue associated with the strategies.

Results

The efficiency sets are compared in Table 8. There is considerable difference in the pattern of efficiency sets between the various scenarios about the initial population density. With the low initial pest population scenario, it is interesting that the no control option, strategy 1, appears in every efficiency set. With this low density level, the risk of applying too many chemicals may be greater than the risk of moth damage. None of the pyrethroid strategies are risk efficient. The conventional calendar spray programs do not appear in any of the efficiency sets. The IPM strategy (8) with the highest dynamic economic threshold is risk efficient for the intervals that include the risk neutral decision maker. This is not surprising since it has the largest expected net revenue. For the class of Michigan agricultural decision makers there are seven strategies which are risk efficient. They include the no control option and three of the four IPM strategies. All three of the IPM strategies remain risk efficient when the random sampling error is introduced.

The no control strategy is risk efficient for only those intervals containing the maxi-min decision maker when the initial population density is set equal to a medium level. It should be preferred by extremely risk averse individuals since it has the highest minimum value of all strategies considered. Strategy 8 is the only strategy which is risk efficient for all intervals but when the random sampling error is introduced it is never risk efficient. All four IPM strategies are efficient for at least some interval. However, strategies 6 and 10 may be preferred by individuals at least more than moderately strongly risk averse while strategy 4 may be risk efficient for decision makers who are less than slightly risk averse. No pyrethroid or conventional strategies are risk efficient under this scenario.

The efficiency sets identified when the initial population density is high are significantly smaller than those of the two other scenarios. There are only three strategies which are risk efficient. The two most common ones are the IPM program with highest dynamic economic threshold and the same program with the random sampling error. They appear in all of the efficiency sets. The azinphosmethyl conventional program appears in two efficiency sets. It may be risk efficient for some decision makers who are less than slightly risk averse. All of the pyrethroid strategies are dominated by at least one of the azinphosmethyl strategies.

VII. COMPREHENSIVE MODEL RESULTS

When the three pests are considered simultaneously, there are two major interactions that must be analyzed. The pyrethroid insecticides which can be applied for the control of codling moth will affect both the mite and mite predator populations. It should be remembered that the mite population can recover from a toxic chemical treatment much faster than then predator population, so a pyrethroid application may seriously disrupt any further biological control for the remainder of the season.

The second interaction involves the use of the fungicide, benomyl, in scab control strategies. Benomyl will suppress the mite population and it is less lethal to the predators than to the mites themselves. The active seasons of the two pests (scab and mites) can overlap in most years, but the scab season usually ends substantially before the termination of mite activity. Therefore, it is possible that mite problems could be postponed to later in the season (or until the next season) if a benomyl scab control program is followed. It should be noted as well that spider mites tend to become resistant to benomyl after three to four years of intensive exposure.

The results of selected comprehensive strategies for the scenario of the medium moth population density are presented in Table 1. In general, the expected net revenues which are the highest were recorded for strategies which followed the post-infection IPM program for scab control. The strategy using this scab control practice in combination with the low economic threshold IPM moth program and the mite IPM program with the low, dynamic economic threshold produced the lowest control costs and the highest expected net revenue. The control costs of this

Table 1. Comprehensive Model Results for Medium Yield and Medium Initial Moth Population Density.

Strategy* Scab	Mite	Moth	Scab Damage (bu/acre)	Moth Damage (bu/acre)	Mite Damage (bu/acre)	Control Costs** ($/acre)	Net Revenue ($/acre)
5	13	12	6.6 (14.7)	3.1 (1.0)	0.0 (0.0)	275.0 (53.5)	395.2 (708.9)
5	4	13	6.6 (14.7)	3.1 (1.0)	0.0 (0.0)	305.4 (53.6)	364.8 (700.7)
5	5	13	6.6 (14.7)	3.1 (1.0)	0.0 (0.0)	305.4 (53.6)	364.8 (700.7)
5	13	13	6.6 (14.7)	3.1 (1.0)	0.0 (0.0)	306.9 (52.9)	363.3 (700.5)
8	13	4	2.6 (8.1)	3.1 (1.0)	0.0 (0.0)	350.2 (51.3)	319.9 (681.7)
7	13	12	2.6 (8.0)	3.1 (1.0)	0.0 (0.0)	353.9 (49.7)	316.3 (687.3)
7	13	13	2.6 (8.0)	3.1 (1.0)	1.1 (5.1)	376.8 (51.1)	294.6 (683.0)
8	13	13	2.6 (8.0)	3.1 (1.0)	1.1 (5.1)	380.6 (53.6)	290.8 (676.8
7	5	13	2.6 (8.0)	3.1 (1.0)	2.6 (1.8)	385.8 (62.2)	287.0 (678.7)
7	2	2	2.6 (8.0)	0.0 (0.0)	4.2 (12.6)	415.1 (42.6)	256.1 (688.8)

*Scab strategies are: 5-post infection, IPM; 7-conventional calendar; 8-reduced single application followed by conventional calendar. Mite strategies are: 2-calendar; 4-simple, IPM; 5-sophisticated, IPM with high economic thresholds; 13-strategy 5 with sampling error. Codling moth strategies are: 2-conventional calendar; 4-IPM with low dynamic thresholds; 12-IPM with low dynamic thresholds and sampling error; 13-IPM with low dynamic thresholds, sampling error using pyrethroid.

**Control costs include pest management expenses and the value of pest damage.

program were only two thirds of the control costs for the conventional program using scab control strategy 7, mite control strategy 2 and moth control strategy 2. The expected net revenue of this strategy is 150% greater than that of the conventional program. The damage from scab and codling moth is less with the conventional program but the mite damage is greater, signaling the value of not disrupting the natural biological control.

These results indicate that the potential savings from coordinating the control of different pests is quite large. The savings arise from two fewer miticide applications, three fewer codling moth treatments and a lower cost of scab control introduced by the IPM program. Two points of caution should be raised in conjunction with this analysis. First, the insecticide treatments considered for the control of codling moth are often applied with the expectation that they will control other pests such as apple maggot as well. The model has ignored these other insect pests and by doing so may be overstating the benefits received from the coordinated IPM program.

Second, the multi-seasonal effects are not considered. They surface in two areas - resistance and overwintering. Both the mites and scab can become resistant to benomyl after three to four years of intensive exposure. The single season model ignores this possibility. However, there are several compounds which can be used in a post-infection IPM scab program that are in the process of being registered for use. They will perform similarly to benomyl except they will not immediately face the problem of resistance. This reduces the concern raised by the omission of the resistance question in the model. A further discussion of this was previously presented in Chapter IV. Sensitivity analysis was performed to address the possibility of mite resistance developing. The mortality coefficients of benomyl for mites were reduced by 50% and the results remained essentially the same: no mite damage was experienced and on average no miticide applications were necessary. Overwintering becomes a problem when benomyl scab treatments are used to control mites because the mite population densities soar once the scab treatments cease in late summer. The mite population does not grow to a size that poses a threat to the plant vigor in that year but a large number of eggs are laid late in the season which increases the number of mites which overwinter and are present in the beginning of the following season. This increased density may not be of a magnitude which can be suppressed by the benomyl scab treatments. This multi-seasonal problem is not captured by the analysis of the model so the results once again may overstate the savings of the coordinated IPM program.

However, even if the program could save only one insecticide and one miticide application, with the IPM scab control savings the expected net revenue of the coordinated IPM program should still lower control costs, including the value of the pest damage, by about $80 per acre[1] or 20% of the control costs of the conventional program.

The amounts of the chemicals introduced into the system by the two strategies depicting the extremes of the possible combinations are displayed in Table 2. No miticide applications are made with the IPM strategy and only 45% of the insecticide conventionally used is applied in this program. The fungicide comparison is more problematic since it involves two different compounds. The actual quantity of captan applied in the conventional program is greater than the quantity of benomyl used

[1]Scab control savings are $38 per acre while one insecticide application is $12 per acre and one miticide application is $29 per acre.

Table 2. Comparison of Quantities of Pesticides Applied by Selected Control Strategies.

Strategies*			Quantities of Chemicals Applied During Season			
Scab	Mite	Moth	Captan lbs/acre	Benomyl Oz/acre	Plictran lbs/acre	Azinphosmethyl Oz/acre
5	13	12	---	175.2 (14.2)	0.0 (0.0)	92.8 (9.6)
7	2	2	82.1 (6.3)	17.6 (19.4)	3.0 (0.0)	204.8 (16)

*Scab strategies are: 5-post-infection IPM; 7-conventional calendar. Mite strategies are: 2-conventional calendar; 13-IPM with high economic thresholds and sampling error. Moth strategies are: 2-conventional calendar; 12-IPM with dynamic threshold and sampling error.

in the IPM program, but the two compounds have different chemical properties. Captan is under review for possible cancellation of its registration due to laboratory tests which produced cancer in isolated cells. However, its potential as a carcinogen has not been fully established since it has never produced cancer in tissues. In summary, the IPM program uses substantially less miticide and insecticide and a lower physical quantity of fungicides.

CHAPTER VIII. SUMMARY OF RESULTS

8.1 Predicted and Anticipated System Behavior Compared

Before the simulation runs were made a number of statements about the anticipated behavior of the system were posed (Section 3.5). These statements can now be compared with the predictions of system behavior that were generated with the model. Differences between them can be judged to arise from an increased understanding of the model or from specification on simplification errors in the model building process.

Expected Net Revenues

The model can be run for each pest independently or in any combination specified. It can also be used with different yield levels and scouting intervals. There are three yield levels which the model user can specify -- 250 bushels per acre, 500 bushels per acre and 900 bushels per acre. The implied behavior can be measured in terms of the expected net revenue or the control costs which include the costs of materials, labor and machinery used in the spray and the value of the pest damage.

When the comprehensive model under the medium yield and weekly scenario is employed to simultaneously analyze the performance of the control programs for all three of the pests, the following results are produced:

Table 1. Comparison of Expected Net Revenues: IPM and Conventional Strategies.

Strategy			Description	Expected Net Revenue
Scab	Mite	Moth		
7	2	2	Conventional Calendar	256
5	13	12	IPM With Sampling Error	395

The difference in these two extreme cases is almost $140 per acre with the savings generated by the IPM program arising from 2 fewer miticide applications, 3 fewer codling moth treatments and a lower cost of the IPM scab program. When the same comparison is made in terms of the control costs, a similar result is uncovered (Table 2).

Table 2. Comparison of Control Costs: IPM and Conventional Strategies.

Strategy	Expected Control Costs
7 - 2 - 2	$415
5 - 13 - 12	$276

The savings per acre in control costs amount to about $140 per acre.

In this case, the predicted and anticipated behavior are consistent although the generality of the statement describing the latter is somewhat unconstraining. It should be remembered that the model has two obvious simplification problems which may affect this prediction. First, additional pests for which the insecticide treatments may be jointly applied are ignored. Second, the multi-seasonal effects of resistance and increased over-wintering have been omitted.

When the control of the codling moth was considered independently under the conditions of a medium yield and a medium initial population density, the results were:

Table 3. Comparison of Expected Net Revenues for IPM and Conventional Moth Control Strategies: Medium Population Density.

Moth Strategy	Description	Expected Net Revenue
2	Conventional Calendar	317
6	IPM Constant E.T.	356

The savings of the IPM program accrue from three fewer sprays. At the low initial population density further savings result.

Table 4. Comparison of Expected Net Revenues for IPM and Conventional Moth Control Strategies: Low Population Density.

Moth Strategy	Description	Expected Net Revenue
2	Calendar	317
8	IPM Dynamic E.T.	375

The IPM program under this scenario uses four fewer sprays than the conventional calendar spray schedule.

When the initial moth population is high, the two programs produce expected net revenues which are almost identical. The IPM program applies less sprays but suffers a greater incidence of damage so if the ratio of apple prices to insecticide prices increases, the conventional calendar spray program would then produce a larger expected net revenue. A decline in the ratio will favor the expected net revenue of the IPM program in comparison.

If apple scab is analyzed separately, similar general results will be obtained. They appear in Table 5.

Table 5. Comparison of Scab Control Strategies: IPM and Conventional.

Scab Strategy	Description	Expected Net Revenue
7	Calendar	381
5	IPM Pest Infection	419

The savings are due to the fact that the IPM program needs three fewer sprays per season and the average cost per spray is lower.

Finally, when the control of the mites is considered while ignoring the other two pests, a similar conclusion can be drawn that on average the IPM programs produce higher net revenues. These results appear in Table 6.

Table 6. Comparison of Mite Control Strategies: IPM and Conventional.

Mite Strategy	Description	Expected Net Revenue
2	Calendar	324
H13	Revised IPM	368
15	IPM With Sampling Error	350

In this case, the savings arise from a lower incidence of damage and less chemical costs since reduced dosages are frequently applied.

The sum of the individual savings is from $68 to $140 per acre with the medium yield while the range for the comprehensive model is $107 to $220 per acre. This occurs because the benomyl used in the scab IPM strategies can suppress early season mites the azinphosmethyl applied by codling moth IPM strategy will not disrupt the natural predation like the pyrethroids will. If resistance in the mites to benomyl builds up to the point that the coefficients of the mortality function for the mites are halved, the savings for the comprehensive IPM strategy will be $90 to $200 per acre.

Expected Utilities IPM vs. Conventional

In the case of the medium yield when mite control is examined independently, the two conventional strategies never appear in any of the efficiency sets regardless of the type of scouting program employeed. This result supports the statement that the expected utility derived from IPM programs exceeds that of conventional control strategies. Risk preferences should not hinder the adoption of IPM strategies in mite control.

However, when scab control is considered, a different conclusion is reached. In this case, the conventional program is risk efficient under all scenarios except for when a low yield is used. With the high and medium yields the expected utility of the conventional program is greater than or equal to the expected utility of the IPM programs. Adoption of the IPM strategies may depend upon the subjective assessments of the probability distributions associated with the initial population level.

It was anticipated that the conventional strategies would be risk efficient for some decision makers. However, the model predicts this result for only scab control and one scenario for codling moth.

Risk Aversion and the Economic Threshold

Previous understanding of the system leads to an expectation that more risk averse decision makers will prefer IPM strategies with higher economic thresholds. If a weekly scouting program is adhered to with a medium yield, the mite control strategies which are risk efficient for the first two intervals (Table 14, Chapter IV) provide some evidence to support the hypothesis. These two intervals include the most risk averse individuals. In interval 1, which includes individuals with a lower degree of risk aversion than the least risk averse in interval 2, some IPM strategies with high economic thresholds are efficient. However, those strategies are dominated by strategies with a low economic threshold in interval 2. This suggests that these strategies are preferred by decision makers with low risk aversion but more risk averse decision makers prefer the strategies with lower economic thresholds.

Just the opposite result is observed in the third and fourth intervals. Here it is apparent that the strategy with the lower economic threshold is preferred by the less risk averse group while the more risk averse class of decision makers prefers the strategy with a high economic threshold. This contradicts the expectation on system behavior.

With a weekly scouting program and a low yield, a strategy with a low economic threshold is risk efficient for the intervals (1, 4 and 5) which all have possibility for low risk aversion but it is not risk efficient for the intervals which are restricted to strong risk aversion. This result suggests that the less risk averse decision makers prefer the low economic threshold while the more risk averse decision makers would select higher economic thresholds. This contradicts the statement on anticipated behavior.

An examination of the risk analysis results of the codling moth strategies (Table 8, Chapter VI) is inconclusive on this point as well. At the high initial population density, only one IPM strategy is risk efficient and it appears in the efficiency set of each interval. At the medium initial density level, both types of strategies appear throughout the efficiency sets. Strategies with low economic thresholds appear only in the efficiency set of the last interval for the low initial population density. This interval includes a range of risk loving attitudes. This result is not consistent with the anticipated behavior.

The discrepancy in the anticipated and predicted behavior may be explained by a lack of evidence to support the contention that higher economic thresholds may produce more risk. The risk of pest damage may be less but the risk of overapplication of pesticides might be greater.

Relationship Between the Economic Threshold and the Scouting Interval

It is hypothesized that the selection of the optimal economic threshold should be integrated with the design of the scouting program. One key component of the scouting program is the frequency at which the orchard is visited. As the scouting interval increases, the IPM strategies with lower economic thresholds should perform relatively better. Mite control strategies 5 and 7 have high economic thresholds while strategies 4 and 6 have lower ones. The expected net revenues are compared below for scouting intervals of 7 and 14 days. The mite model results were obtained from the medium yield scenario and the revised decision rules which automatically apply a half dose on the first spray were in effect.

Table 7. The Relation Between the Scouting Interval and the Economic Threshold: A Comparison of Expected Net Revenues.

	Expected Net Revenues Scouting Program	
Strategy	7 Day	14 Day
4	356.1	353.0
5	362.8	355.8
6	368.1	369.6
7	361.8	350.3

It can be seen that the strategies with the high economic thresholds did considerably worse when the scouting interval was doubled. Strategy 7, which has the highest economic threshold had a drop in net revenue of over $11/acre while strategy 6 slightly increased its revenue. The mite damage per acre increased by a magnitude of about 400% with strategy 7. This data definitely supports the statement on the anticipated behavior.

Relationship Between Yields and Strategy Performance

A. Comparison of Expected Net Revenues

As the yield of the crop increases, the amount of chemicals that can efficiently be applied should increase as well. The marginal benefits of avoiding damage have been increased, so more control costs can be incurred and still remain at an optimum. This result would be expected with increases in market price of apples as well. This statement is compared with data from model runs examining the performance of mite and scab control strategies independently.

The results from the scab model runs are presented in Table 8.

Table 8. Impact on Yield on Relative Performances of IPM and Conventional Scab Control Strategies.

Strategy	Expected Net Revenues Yield Levels Low (250 bu/acre)	Medium (500 bu/acre)	High (900 bu/acre)
5 (IPM)	-268	420	1551
7 (Conventional)	-314	381	1521
	46	39	30

Since the difference between the expected net revenues for the conventional and IPM programs is decreasing as the yield (value) is increasing, it must be concluded that the scab model results support the statement. This statement may become more relevant if market prices drop due to large increases in the supply of apples from recent expansions in the state of Washington and as more concentrate is imported to handle the juice market.

The mite model results can be used to make two comparisons. First, the IPM and conventional programs can be contrasted. Next, the IPM strategies using various levels of the economic threshold can be compared. These comparisons are made in Table 9.

Table 9. Impact on Yield on Mite Control Strategies.

Strategy	Expected Net Revenues Yield Level Low (250 bu/acre)		Medium (500 bu/acre)	
2 (Conventional)	-367		324	
		> 13		> 25
4 (IPM-Low E.T.)	-354		349	
		> 9		> 7
5 (IPM-High E.T.)	-345		356	
		> 9		> 4
6 (IPM-Low E.T.)	-342		360	
		> 1		> 0
7 (IPM-High E.T.)	-341		360	

The differences in the expected net revenues appear to the right of the revenue figures. In the comparison of the IPM program with the conventional one, the differences in the expected net revenues is just opposite of what the hypothesis would suggest. As yields increased, the difference increased as well.

In two of the three comparisons of the IPM strategies with various levels of the economic threshold, the difference between the expected net revenues decreased as the yields increased, as the hypothesis would suggest. However, in the third case, the difference increased. At least, this is marginal support for the hypothesis.

A possible explanation of the disparity of the test results between the scab and mite model might be the influence of the biological control provided by the mite predators. By reducing the amount of the miticide applied, the biological control is enhanced since full dose miticide treatments can impact on the predators as well as the mites. There is no biological control active for apple scab. The threat of mite damage is dampended by the existence of the natural mite predators.

B. Comparison of Expected Utilities

The efficiency sets for the various intervals can be examined across the three yield scenarios to uncover how the expected utilities of the strategies will likely change as the value of the crop changes. The conventional spray program for apple scab is risk efficient for the fifth interval for all of the yield scenarios except for the low one. So at least some farmers will prefer the conventional control program at the low yield level. This supports the statement on the anticipated system behavior.

Another approach to determining the changes in the expected utilities of the strategies is to look for changes in the efficiency sets of all five risk preference intervals as the scenarios change. These efficiency sets are displayed in Table 12 of Chapter V. The risk preference intervals represent different degrees of risk aversion and differences in their efficiency sets have implications as to which individuals will prefer which strategies.

At the medium yield level, when the hypothetical IPM strategy is ignored, the conventional spray program, strategy 7, appears in the efficiency sets for all except the third and fourth intervals. From this it can be inferred that at this yield level, the conventional program is consistent with farmers who have more than moderately strong risk aversion (.0003). At the low yield level, the conventional strategy is risk efficient only for the first two intervals. Since it does not appear in the efficiency set of the last interval, it can be concluded that it is preferred only by decision makers more risk averse than .0004, slightly higher than at the medium yield level. With the high yield scenario, there is no evidence to assume that the expected utility of the conventional program is less than any alternative for any of the decision makers included in the analysis (except for the risk neutral individual). It appears in all of the efficiency sets.

The evidence from this approach supports the statement since as the yield increases, the conventional program is risk efficient for more risk preferences. It should be recalled that a strategy is risk inefficient only if all individuals prefer one other strategy to it. With Stochastic Dominance With Respect to a Function, there must be concurrence among all decision makers as to which alternative is preferred. When more than one strategy appears in the efficiency set, it may be that some individuals in the group prefer one strategy while the others prefer the second. However, unless a strategy is rejected from the efficiency set, there is no evidence that its expected utility is less than the expected utility of the members of the efficiency set.

In the case of the mites, the evidence is inconclusive. With the weekly scouting program, neither the conventional nor the IPM program with the lowest economic threshold ever appear in the efficiency sets. The other three IPM strategies are all risk efficient for the fifth interval in both the low and medium yield scenarios. The entire set of efficiency sets are displayed in Table 14 of Chapter III.

SSD vs. SDWRF

Often inferences are made about the preferences of agricultural decision makers with an underlying assumption that all individuals are always risk averse. No attempt is made to restrict the degree of risk aversion and the conclusions reached about the rankings of the alternatives must be accurate for the most risk averse decision maker (maxi-min) and the individual approaching risk neutrality. These analyses are frequently done with Second Degree Stochastic Dominance. It is hypothesized that two problems will arise with this technique. Since the group of decision makers is so large, it will be difficult to discriminate among alternatives so large Type II errors will likely be encountered. The second problem is related to Type I errors. By excluding any possibility for risk loving behavior, this technique ignores the preferences of a large majority of agricultural decision makers (81). The results may be biased from this lack of consideration to the possible negative ranges of the risk preference functions.

The size of the Type I and Type II errors can be estimated by comparing the efficiency sets of interval 1 and 5. Interval 1 approximates

Second Degree Stochastic Dominance while interval 5 has been designed to represent the preferences of 80 to 90% of Michigan farmers. The size of the errors will depend upon the choice set of the problem and the width of the interval which includes the preferences of all members of the class of decision makers.

The examination of the efficiency sets produces the results displayed in Table 10.

In only two of the nineteen cases are the efficiency sets equal. By using Second Degree Stochastic Dominance only slightly more than 10% of the time did the technique accurately reflect the preferences of Michigan agricultural decision makers (as measured by interval 5). In five of the nineteen scenarios, Second Degree Stochastic Dominance identified some strategies as efficient when in actuality they were inefficient (Type II error). Over 60% of the time (12 of 19), Second Degree Stochastic Dominance declared some strategies as being risk inefficient when they should really have appeared in the efficiency set (Type I error). There is considerable support from this analysis that there exists a great potential for both Type I and Type II errors in the use of Second Degree Stochastic Dominance (or other techniques that ignore risk loving behavior) to represent the class of all agricultural decision makers.

Chemical Usage

Often one of the results of adopting at IPM strategy is a lower rate of use of chemical pesticides. Two comparisons are presented in Table 11 to test the hypothesis that the expected amount of chemicals used in an IPM program will be less than the expected amount of chemicals used in conventional calendar spray programs.

Table 10. Comparisons of Efficiency Sets for SSD and SDWRF.

Mites

Total Number	8
Number of Cases where Efficiency Set of Second Degree Stochastic Dominance is larger than 5th interval*	4
Number of cases where efficiency set of Second Degree Stochastic Dominance is the same as the 5th interval	1
Number of cases where efficiency set of Second Degree Stochastic Dominance is smaller than the 5th interval	3

*Fifth interval is inferred from survey data and should represent the preferences of 80-90% of Michigan's farmers.

Apple Scab

Total Number of Cases	8
Number of cases where efficiency set of Second Degree Stochastic Dominance is larger than 5th interval	1
Number of cases where efficiency set of Second Degree Stochastic Dominance is equal to the 5th interval	1
Number of cases where efficiency set of Second Degree Stochastic Dominance is smaller than the 5th interval	6

Codling Moth

Total Number of Cases	3
Number of cases where efficiency set of Second Degree Stochastic Dominance is larger than 5th interval	0
Number of cases where efficiency set of Second Degree Stochastic Dominance is equal to the 5th interval	0
Number of cases where efficiency set of Second Degree Stochastic Dominance is smaller than the 5th interval	3

Table 11. Comparison of Chemical Usage: IPM and Conventional Strategies.

Codling Moth (Medium Yield) - Azinphosmethyl

	Low Initial Population	Medium Initial Population	High Initial Population
Conventional	204.8 oz.	204.8 oz.	204.8 oz.
IPM	60.8 oz.	92.8 oz.	92.8 oz.

Mite (Medium Yield) - Plictran

	Weekly Scouting	GPP5*	GPP9**
Conventional	3 lbs/acre	3 lbs/acre	3 lbs/acre
IPM	2.25 lbs/acre	2.1 lbs/acre	2.1 lbs/acre
IPM with Revised Decision Rule	1.95 lbs/acre	1.5 lbs/acre	1.65 lbs/acre

*Scouting on request when grower perceives a mite problem developing at 5 mites per leaf.

**Scouting on request when grower perceives a mite problem developing at 9 mites per leaf.

In all cases, the IPM strategies apply less chemicals than the counterpart calendar spray programs. It ranges from a low of 30% of conventional strategy's usage to a high of 75%. The statement is definitely supported by these comparisons.

Pest Damage

It is often perceived that IPM programs result in higher pest damages than conventional programs. Conventional programs by applying more chemicals should benefit from more plant protection. However, the influence on the damage of the timing of sprays and the impacts on non-target pests and predators may disprove this contention. The expected damages can be compared from various scenarios for the scab model, the mite model, the codling moth model and the comprehensive model. The model results are presented in Tables 12 through 15.

Table 12. Expected Pest Damage for Scab Control Strategies.

	Expected Damage (%) Yield Scenario		
Strategy	Low	Medium	High
5 (Post-infection IPM)	1.1	1.3	1.2
7 (Typical Conventional)	0.4	0.5	0.5
8 (RSAT/Conventional)	0.4	0.5	0.5

Table 13. Expected Pest Damage for Mite Control Strategies (Weekly Scouting).

	Expected Damage ($/acre) Yield Scenario	
Strategy	Low	Medium
2 (Plictran Conventional	14.5	26.1
4 (IPM Low E.T.)	0.6	1.4
5 (IPM High E.T.)	1.7	3.6
6 (IPM Low E.T.)	0.5	1.1
7 (IPM High E.T.)	2.2	4.5

Table 14. Expected Pest Damage for Codling Moth Control Strategies (Medium Yield).

Strategy	Expected Damage (%) Initial Pest Population Low	Medium	High
2 (Conventional)	0.00	0.00	0.00
4 (IPM Medium Dynamic E.T.)	0.01	0.01	3.53
6 (IPM Low Constant E.T.)	0.01	0.01	3.53
8 (IPM High Dynamic E.T.)	0.01	0.01	3.15

Table 15. Expected Pest Damage for Comprehensive Control Strategies.

Strategy	Scab (%)	Mite ($)	Codling Moth (%)
7-2-2 (Conventional-Azinphosmethyl)	0.05	4.2	0.00
7-2-3 (Conventional-Pyrethroid)	0.05	17.4	0.00
5-13-12 (IPM-benomyl & azinphosmethyl)	1.31	0.0	0.06
5-13-13 (IPM-benomyl & pyrethroid)	1.31	0.0	0.06

In the case of apple scab controls, the IPM strategy suffers more damage, almost twice as much as the conventional strategies. With low and medium initial population densities, the IPM codling moth strategies experience damage only slightly different than the conventional, but at high population densities the difference is significant.

Mite control with the possibility of biological control by natural predation that can be disrupted by full dose miticide treatments displays a different pattern. In this case, the IPM strategy results in considerably less damage since it has the options of applying reduced dosages and not spraying at all when the predator-prey ratio is in balance.

In the comprehensive model results, two important results are the impacts that the pyrethroid insecticide and the fungicide benomyl have on mite control. The damage estimates for codling moth and scab are similar to the results of the independent model runs. Certainly a major component of IPM programs should be the coordination of controls for the various pests present in the system. The use of pyrethroid insecticides in apple production systems would not be an example of this coordination. The mite damage for the "conventional" program which employs azinphosmethyl is about one fourth of the damage of the similar program using the pyrethroid. The model results indicate that the benomyl of the IPM programs will completely suppress the mites. However, it should be remembered that the model simulates a single season and it is likely that mite problems will be enhanced in the second season with the benomyl program.

The data from the control of apple scab and codling moth support the expectations on system behavior but the introduction of the natural predators in the control of mites complicates the issue. It appears that IPM programs result in less mite damage than conventional treatments.

The argument that as the economic threshold increases, the pest damage should increase as well appears not to hold for the case of the codling moth control. The expected damage estimates for the three IPM programs are extremely similar. Just the opposite is observed in the results from the mite model. There is a very definite relationship between the economic threshold and the expected damage. The mite data do support this contention.

Economics of Decision Rule Refinements

The observation that the refinements to the economic thresholds will improve the benefits that are gained by adopting a crude IPM program is certainly not supported by the results from the codling moth model. These results appear in Table 16.

Table 16. Comparison of Expected Net Revenues: Sophisticated and Simple Moth IPM Strategies.

Strategy	Expected Net Revenues Initial Moth Density Level Low	Medium	High
2 (Conventional)	317.4	317.4	317.4
6 (IPM-low static E.T.)	370.1	355.7	315.3
8 (IPM-high dynamic E.T.)	375.6	356.2	320.9

In the low initial population density scenario, 90% of the difference in net revenues between the IPM strategy with the highest return and the conventional program could be captured by adopting a simple IPM program with a static economic threshold. At the medium initial population level, the percentage is almost 99%. In the scenario using the high initial moth density, the crude IPM strategy has a net revenue below that of the conventional program while the sophisticated IPM strategy is above that figure. However, all three are within $5/acre of each other.

The control of mites is somewhat more complex due to the natural predation and the marginal returns to the more sophisticated decision rules is relatively much higher. The IPM strategy with the highest expected net revenue for the medium yield and weekly scouting scenario is strategy 6 with the revised decision rule which automatically applies a half dose on the first spray. The IPM strategy with the simple decision rules and no option for applying reduced dosages can account for 56% of the difference in expected net revenue of the "best" IPM strategy and the conventional program. The IPM strategy with the decision rules guided by predator/prey ratios will produce about 82% of the maximum benefits uncovered by the model. There is about a $8 to $12 per acre return to the adoption of decision rules of each stage of sophistication.

Table 17. Comparison of Expected Net Revenues: Simple and Sophisticated Mite Control Strategies.

Strategy	Expected Net Revenues Medium Yield and Weekly Scouting
2 Conventional	324
4 Simple IPM	349
6 Sophisticated IPM	360
H6 Sophisticated IPM with revised decision rules	368

If refinements in the economic thresholds do not significantly improve the expected net revenues, it can be assumed that sampling errors associated with the population estimates generated by the scouting program should not drastically reduce the expected net revenues. The model was used to re-examine the performance of the IPM strategies when a sampling error was introduced. The sampling error was drawn from a normal distribution with the properties that 95% of the true population.

The results from the mite model are presented below for three scenarios (Table 18). With the exception of the strategy with the high economic thresholds the random sampling error does not appear to significantly change the revenue figures. In fact, in some cases the expected net revenue increased slightly. The strategy with the high economic thresholds experienced a decline of from $3 to $6 per acre when the error was introduced.

The same pattern is encountered in the case of the codling moth. The expected net revenues do not change appreciably except at the high initial population density. However, the decline in income even at this level is less than 1% of the expected net revenue with no random sampling error. These results appear in Table 19.

Table 18. Impact on Expected Net Revenues of a Random Sampling Error for IPM Mite Control Strategies.

Strategy	Expected Net Revenue: Weekly Scouting, Low Yield	Weekly Scouting, Medium Yield	Bi-Weekly Scouting, Medium Yield
4 (Simple IPM-no error)	-354	349	353
6 (IPM low E.T.-no error)	-342	360	370
7 (IPM high E.T.-no error)	-341	360	350
11 (IPM low E.T. with error)	-352	350	353
13 (IPM low E.T. with error)	-342	361	369
14 (IPM high E.T. with error)	-346	354	347

Table 19. Impact on Expected Net Revenues of a Random Sampling Error for IPM Codling Moth Control Strategies.

Strategy	Expected Net Revenue, Initial Population Density: Low	Medium	High
4 (IPM medium dynamic E.T.)	370	356	315
6 (IPM low static E.T.)	370	356	315
8 (IPM high dynamic E.T.)	376	356	321
12 (IPM medium dynamic E.T. with error)	370	355	313
14 (IPM low static E.T. with error)	370	355	313
16 (IPM high dynamic E.T. with error)	373	356	321

The expected utilities of the strategies are not changed dramatically either. As can be seen in Table 14 Chapter IV, some strategies with the random sampling errors appear in almost every efficiency set. It does not appear that the presence of the sampling error greatly changes the risk efficiency of the stratigies.

Potential of CSD

In the scenario examining the scab control strategies alone with a medium yield, the efficiency sets of two intervals appearing in Table 12, Chapter V were further refined through the application of CSD. These were intervals 1 and 5. In the case of interval 1, strategy 9 was rejected as inefficient while in interval 5, strategies 2, 3, 9 and 10 were all rejected as not being the most preferred strategy of any decision maker in the class.

The efficiency sets identified for the mite strategies in Table 14, Chapter V for the weekly scouting and medium yield scenario were not particularly reduced by CSD. Of the strategies risk efficient for the first and last intervals, only H4 could be rejected with CSD.

The codling moth efficiency sets may appear large at first glance but due to the fact that the distributions of net revenue were insensitive to changes in the economic threshold, the cumulative probability functions are almost identical for most of the IPM programs. CSD was not applied to these efficiency sets.

8.2 Implications of Model Predictions

Extension

There are four major results which should be relevant for extension efforts in apple pest management. The results are in the following areas: the comparisons of the average net revenues between strategies, the comparison of the risk efficiencies of the strategies, the relationship between the size of the economic threshold and the length of the scouting interval, and the selection of optimal economic thresholds.

The model predictions can be useful in an extension context by providing additional evidence that the expected net revenues of IPM programs will be greater than the expected net revenues of conventional calendar strategies. In some cases, the savings in control costs can amount to as much as 30% to 40%. The savings will likely increase as the ratio of apple prices to pesticide prices decreases since the IPM programs use less chemicals and may result in more damage. Increases in apple prices or yields may favor the selection of conventional strategies by strongly risk averse growers since with a higher value of the harvest, growers can afford to apply more chemicals to avoid pest damage. Furthermore, producers with lower yielding orchards probably have more to gain from IPM strategies on a per acre basis than growers with more productive farms because their ratio of crop value to pesticide prices is lower. The per acre value of the damage avoided is lower with smaller yields so less chemicals can be efficiently applied.

It appears that risk preferences will be an important consideration in the adoption of scab control strategies. For some risk averse decision makers, the conventional calendar program (strategy 7) will be preferred because it produces higher net revenues in the bad years. Other decision makers who are less risk averse will prefer alternative strategies such as the post-infection IPM program (5) or the reduced single application treatment followed by a protective calendar schedule (8). These strategies on average produce higher net revenues.

In the case of the control of mites and codling moth, it is generally true that even very risk averse decision makers will prefer the IPM programs. The model predicts that the risk of most IPM strategies, even with a large error in the scouting estimates, is less than the risk of the conventional calendar programs. Perhaps the threat of pest damage is less than the threat of applying too much pesticide. It should be noted that there were in general, several IPM strategies which were risk efficient so decision makers with different risk preferences may prefer different IPM programs. However, there did not appear to be a strong relationship between the preferred level of the economic threshold and the risk preference.

There is a relationship between the length of the scouting interval and the performance of the IPM strategies with different economic thresholds. Strategies with high economic thresholds performed considerably worse when the scouting interval was increased from one week to two weeks. Strategies with lower economic thresholds were not so drastically affected. This result is observed since the pest populations should be higher with the strategies with high economic thresholds and less frequent monitoring should enhance the probability that the density reaches an injury level between visits of the scout. The substitution of information for chemicals will be affected by the timeliness of the information and less frequent scouting does not provide as timely information.

The model predicts that in the case of the codling moth control strategies, there are a wide range of possible economic thresholds that produce similar results. The introduction of large sampling errors in the scouting program did not particularly change the rankings of the strategies by either the size of the expected net revenue or by the expected utility. Similar, but not as dramatic results were observed for the mite control strategies. However, in the case of mites there may be as much as a $10 per acre savings by always applying a half dose or less on the first spray. The economic thresholds for mites which produced the highest expected net revenues were in the range of 25 to 30 mites per leaf.

The lack of impact that the random sampling error had on the rankings of the strategies implies that elaborate scouting programs which increase the accuracy of population estimates may be producing information whose value is less than its cost.

It does not appear that either the miticide carzol or the pyrethroid insecticides should ever be used at current prices. Their impact on non-target species further detract from their overall performance.

Research

The predictions of the model are relevant for research because they demonstrate the potential for a number of recent advances. First, by considering three pests simultaneously rather than independently a further understanding of the system is enhanced and predictions can be refined. Second, the predictions dealing with the sensitivity of the strategy rankings to refinements in decision rules and sampling errors should help guide future research to areas where information can be economically generated. Third, the increased accuracy of rankings based on SDWRF should dissuade future use of SSD and E-V analyses. The use of CSD demonstrates its capability to further discriminate between alternatives without increasing the Type I error. The advent of CSD should diminish the need to attempt to accurately measure risk preferences for many purposes. Finally, the result that only in the case of scab control and high moth population scenarios is the evidence to suggest that risk preferences could account for the lack of adoption of IPM strategies, should encourage further research into the area of subjective probability assessments to explain continued use of conventional spray programs. Perhaps, the perceptions by growers of the relative performance of the strategies is a vital key to understanding the adoption process.

Policy

The IPM programs all resulted in the introduction of fewer pesticides into the environment. Furthermore, it appears that there are a number of firm level benefits from adopting these strategies. In almost all cases, the expected net revenues were higher for the IPM strategies but for some decision makers the conventional scab and moth strategies were still preferred. As the ratio of apple prices to pesticide prices increases, the conventional strategies will relatively improve in the comparison. When the value of the harvest is high in relation to the chemical costs, more pesticides can be efficiently applied. This may result in IPM strategies being slightly less attractive to risk averse growers with highly productive orchards. The value of the harvest is determined by apple prices and the yield. However, if apple prices decline, IPM programs may become more readily adopted since gross revenues will decrease and to remain profitable firms will need to decrease their costs of production. A major component of the variable production costs are related to pest management and since IPM strategies can reduce these control costs by 30 to 40%, they should be more widely adopted in this situation.

At the farm level, it appears that the promotion of IPM strategy adoption may be a cost effective policy instrument in dealing with the externality problems created by excessive pesticide use. At current prices, there are substantial benefits to adopting most IPM strategies. Public subsidies of the information (scouts and weather reports) necessary to implement IPM programs should enhance the benefits and increase the rate of adoption. Public expenditures in the form of support required to perform the technology transfer of the necessary managerial skills should be a viable option as well. These instruments are attractive since they encourage voluntary acceptance of reduced pesticide usages. The subsidies may be necessary to convince risk averse decision makers to adopt the IPM strategies. It can be perceived as subsidy to the risk premium. There should be lower administration costs and less enforcement problems than with programs using regulations or direct incentives.

It should be noted that the possibility exists that widespread adoption of IPM programs may actually lead to a higher total pesticide use. If the adoption of the IPM strategies reduces production costs to an extent that profits are increased, orchards may be expanded and even though the intensity of use has been diminished, the overall quantity of pesticides introduced into the environment may increase (141). The relevant question then becomes the importance that the concentration of the pesticide has on the severity of the externalities. This will vary with the chemicals involved and should be examined before any policy instruments are selected.

The model predictions may be relevant for the review of the registration of the fungicide captan. Captan has produced cancer in isolated cells but not in cells organized into tissues. The model predicts that two scab control strategies which use captan are preferred to some risk averse decision makers to the alternatives examined. The strategies using captan had lower average net revenues but were risk efficient for some individuals. This implies that some growers with choice sets identical to the one in the model would be hurt by the banning of captan.

The variance in the results between the three pests and the different production scenarios analyzed, stresses the point that in pest management where biological conditions can vary from one subsystem to another, it is imperative that the decision setting be considered and generalizations avoided.

8.3 Further Research and Extensions

This research has uncovered a number of areas which justify further investigation. First, the system defined by the model should be expanded to include additional pests and the problem of defining multi-pest economic thresholds to guide the use of "cocktail sprays" should be examined. The multi-seasonal problems of resistance and increased overwintering should be addressed as well as several specification problems were uncovered by comparing model predictions with the statements on anticipated system behavior.

The entire basis of the prescriptive, descriptive, and predictive work on decision making lacks credibility due to the fact that the EUH model has not been fully justified. Additional evaluations using the two conditions of the Giere test should be pursued. Further work also needs to be continued on establishing probability functions to treat the stochastic variables dealing with market prices, packout rates and yields. A yield simulator which could correlate pest damage to the health of the tree would be a major contribution. Probability functions identified by the model could be improved by refined damage estimates and error terms on the introduction of the growth functions which simulate the pest population development. Finally, the area which appears to have the greatest potential for future research in this topic is the subjective assessment of probabilities. Little work has been done in this area even though it may play a crucial role in the selection of pest management strategies. Contributions in descriptive and predictive knowledge should be readily achieved and it does appear that even prescriptive knowledge could be generated on probability assessments with substantially justified simulation models.

BIBLIOGRAPHY

BIBLIOGRAPHY

1) Abkin, M.H. and C. Wolf. "DELLVF - Distributed Delay with Storage Losses and Variable Delay Time." Mimeograph. Computer Library for Agricultural Systems Simulation.

2) Adkisson, Perry L. and et al. 1982. "Controlling Cotton's Insect Pests: A New System." Science Vol. 216 (April 2) pp. 19-22.

3) Anderson, J.R. 1974. "Sprase Data, Estimational Reliability, and Risk-Efficient Decisions." American Journal of Agricultural Economics, Vol. 56, No. 1, pp. 564-72.

4) Anderson, J.R. 1975. "Programming for Efficient Planning Against Non-Normal Risk." Australian Journal of Agricultural Economics, Vol. 19, pp. 94-107.

5) Anderson, J.R. 1976. "Risk Efficient Monte Carlo: A Manual." Miscellaneous Publication No. 6, Department of Agricultural Economics and Business Management, University of New England, Armidale, Australia.

6) Anderson, J.R., J.L. Dillion, and J.B. Hardaker. 1977. Agricultural Decision Analysis. Ames, Iowa: The Iowa State University.

7) Anderson, J.R. 1979. "Perspective on Models of Uncertain Decisions" in Risk, Uncertainty and Agricultural Development. Agricultural Council: New York.

8) Arineson,Phil A., et al. 1978. Applescab: A Pest Management Game - Student Manual. Michigan State University.

9) Baron, David P. 1977. "On the Utility Theoretic Foundations of Mean-Variance Analysis." The Journal of Finance. Vol. XXXII, No. 5 pp. 1683-1697.

10) Baquet, Alan E. 1977. "An Economic Theory of Investment and Disinvestment." Proceedings of Conference on Practice, Theory and Needed Research on Capital Investment Decisions in the Energy Supply Industry. MSU.

11) Bicksler, James L., Amir Barnea and Jair Babad. 1973. "Portfolio Choice, the Horizontal Problem and the Investment Opportunity Set." American Economic Review, Vol. LXIII, No. 2 pp. 140-144.

12) Blair, R. 1974. "Random Input Prices and the Thoery of the Firm." Economic Inquiry. Vol. 12. pp. 214-225.

13) Boulding, Kenneth. 1950. A Reconstruction of Economics. John Wiley & Sons, Inc.

14) Bradley, P. 1973. "Increasing Scarcity: The Case of Energy Resources." American Economic Review, Vol. 63, No. 2, p. 119.

15) Brunner, J.F. and D.T. Johnson. 1976. "Apple Maggot Control in Backyard Situations." Extension Bulletin E939, MSU.

16) Carlson, Gerald A. 1970. "A Decision Theoretic Approach to Crop Disease Prediction and Control," American Journal of Agricultural Economics, 52:216-233.

17) Carlson, Gerald A. and Emery Castle. 1972. "Economics of Pest Control." Control Strategies for the Future. National Academy of Sciences, Washington.

18) Carlson, Gerald A. 1976. "Pest Control Risks in Agriculture." Risk, Uncertainty and Agricultural Development. CIMMYT, Mexico, pp. 199-211.

19) Carlson, Gerald A. and C.E. Main. 1976. Economics of Disease-Loss Management. Paper No. 4912 of Journal Series of the North Carolina Agricultural Experiment Station. Raleigh, North Carolina.

20) Carlson, Gerald A. 1981. "IPM Experience in North Carolina Crops." Tar Heel Economist. Agricultural Extension Service, North Carolina State University.

21) Childers, Frank. 1976. Modern Fruit Science, New York.

22) Clark, Colin W. 1973. "The Economics of Overexploitation." Science, Vol. 181, August.

23) Cochran, Mark J. and Lindon J. Robison. 1981. "Redefining the Economic Threshold." Staff Report No. 1981-49. Department of Agricultural Economics, Michigan State University.

24) Cochran, Mark. 1982. "Characteristics of Apple Production in Michigan." Staff Report 1982-73. Department of Agricultural Economics, Michigan State University.

25) Cochran, Mark J., Weldon Lodwick and Lindon Robison. 1982. "Rankings of Action Choices Under Uncertainty: A Discussion of Stochastic Dominance Techniques." Staff Report 1982-68. Department of Agriculturla Economics, Michigan State University.

26) Cochran, Mark J., Weldon Lodwick, Alan Jones and Lindon Robison. 1982. "Selection of Apple Scab Pest Management Strategies Under Uncertainty: An Application of Various Stochastic Dominance Techniques." Staff Report No. 1982-34. Department of Agricultural Economics, Michigan State University.

27) Cochran, Mark J. et al. 1982. "Evaluation of Strategy Performance and Risk Efficiency of IPM Programs in Michigan Apple Production." Staff Report No. 1982-27. Department of Agricultural Economics, Michigan State University.

28) Coli, W.M., R.J. Prokopy and R. Hislop. 1979. "Integrated Management of Apple Pests in Massachusetts Commercial Orchards--1979 Results: Insects and Mites." Fruit Notes (Nov/Dec.) pp. 9-14.

29) Cress, D. et al. 1976. "Pesticides Manual." Extension Bulletin E-751. Farm Science Series, MSU.

30) Crocomo, Celso. 1979. "Risk Efficient Fertilizer Rates: An Application to Corn Production in the Cerrado Region of Brazil." Unpublished Ph.D. Dissertation, MSU.

31) Croft, B.A. 1975. "Integrated Control of Apple Mites." Extension Bulletin E-825, MSU.

32) Council for Agricultural Science and Technology. 1982. Integrated Pest Management. Report No. 93.

33) Dent, J.B. and M.J. Blackie. 1979. Systems Simulation in Agriculture. (London: Applied Science Publishers, LTD).

34) Donaldson, G.F. and J.P.G. Webster. 1968. "An Operating Procedure for Simulation Farm Planning - Monte Carlo Method." Department of Agricultural Economics, Wye College, University of London.

35) Dover, M.J., B.A. Croft, S.M. Welch and R.L. Tummala. 1979. "Biological Control of Panonychus ulmi (Acarina: Tetranychidae) by Amblyseius fallacis (Acarina: Phytoseiidal) on Apple: A Prey-Predator Model. Environmental Entomology. Vol. 8, pp. 282-292.

36) Edward, C.A. and G.W. Heath. 1964. The Principles of Agricultural Entomology. Charles C. Thomas, Publisher, Springfield, Illinois.

37) Eichers, Theodore R. and Paul A. Andrilenas. 1978. "Evaluation of Pesticide Supplies and Demand for 1979." USDA, ESCS Agricultural Economics Report No. 418. Washington.

38) Feder, G. 1979. "Pesticides, Information and Pest Management Under Uncertainty." American Journal of Agricultural Economics, Vol. 61, No. 1, pp. 97-103.

39) Fishburn, P.C. 1974. "Convex Stochastic Dominance with Continuous Distribution Functions." Journal of Economic Theory. Vol. 7 pp. 143-158.

40) Fisher, L.A. 1970. "The Economics of Pest Control in Canadian Apple Production." Canadian Journal of Agricultural Economics. Vol. 18, No. 3, pp. 89-96.

41) Fisher, Anthony C., John V. Krutilla and Charles J. Cicchetti. 1972. "The Economics of Environmental Preservation: A Theoretical and Empirical Analysis." American Economic Review, Vol. LXII, No. 4.

42) Flore, J.A., A.L. Jones and L.G. Olsen, eds. 1979. "1979 Fruit Pesticide Handbook." Extension Bulletin E-154, MSU.

43) Friedman Milton and L.J. Savage. 1948. "The Utility Analysis of Choices Involving Risk." The Journal of Political Economy. Vol. LVI, No. 4. pp. 279-304.

44) Gaffney, Mason. 1967. Extractive Resources and Taxation. Madison, Wisconsin: The University of Wisconsin Press.

45) Giere, Ronald N. 1978. Understanding Scientific Reasoning. New York: Holt, Rinehart and Winston.

46) Gordon, H.S. 1954. "The Economic Theory of a Common Property Resource: The Fishery." Journal of Political Economy, Vol. 62, pp. 124-142.

47) Hadar, J. and W.R. Russell. 1969. "Rules for Ordering Uncertain Prospects." American Economic Review. Vol. 59, pp. 25-34.

48) Hall, Darwin C. and Richard B. Norgaard. 1973. "On the Timing and Application of Pesticides." American Journal of Agricultural Economics, 55, pp. 198-201.

49) Hanoch, G. and H. Levy. 1969. "The Efficiency Analysis of Choices Involving Risk." Review of Economic Studies. Vol. 36, pp. 335-346.

50) Headley, J.C. 1968. "Estimating the Productivity of Agricultural Pesticides." American Journal of Agricultural Economics. Vol. 50, No. 1, pp. 13-23.

51) Headley, J.C. 1972. "Defining the Economic Threshold." Pest Control Strategies for the Future. Washington, DC: National Academy of the Sciences, pp. 100-108.

52) Headley, J.C. 1975. "The Economics of Pest Management Decision by Individual Growers." Iowa State Journal of Research. Vol. 49, No. 4, pt. 2. pp. 623-628.

53) Heal, Geoffrey. 1976. "The Relationship Between Price and Extraction Cost for Resource With a Backstop Technology." The Bell Journal of Economics. Vol. 7, No. 2. pp. 371-378.

54) Heidhues, T. 1966. "A Recursive Programming Model of Farm Growth in Northern Germany." Journal of Farm Economics, 48: 668-684.

55) Henry, Claude. 1974. "Investment Decisions under Uncertainty: The 'Irreversible Effect'". American Economic Review, Vol. LXIV, No. 6, December.

56) Hillebrandt, Patricia M. 1960. "The Economic Theory of the Use of Pesticides." Journal of Agricultural Economics. Vol. 13, pp. 464-472.

57) Hoel, M. 1978. "Resource Extraction, Uncertainty and Learning." The Bell Journal of Economics, Vol. 9, No. 2.

58) Hoel, P.G. Introduction to Statistical Analysis.

59) Hotelling, Harold. 1931. "The Economics of Exhaustible Resources." The Journal of Political Economy, Vol. 39, No. 2, pp. 137-175.

60) Hoyt, S.C. and J.D. Gilpatrick. 1976. "Pest Management on Deciduous Fruits: Multidisciplinary Aspects: in Integrated Pest Management. J.L. Apple and R.F. Smith, eds. New York.

61) Hoyt, S.C. L.K. Tanigoshi and R.W. Browne. 1979. "Economic Injury Level Studies in Relation to Mites on Apples." Recent Advances in Acarology Volume I. Academic Press, Inc.

62) Hueth, D. and U. Regev. 1974. "Optimal Agricultural Pest Management with Increasing Pest Resistance." American Journal of Agricultural Economics, 56:543-552.

63) Jorgensen, Clive D., Mark U. Martinsen, and Layne J. Westover. 1979. "Validating Michigan State University's Codling Moth Model (MOTHMOL) in an Arid Environment: A Test in Utah." The Great Lakes Entomologist. Vol. 12, No. 4, pp. 203-212.

64) Johnson, G.L. A.N. Halter, H.R. Jensen and D.W. Thomas, eds. 1961. Managerial Processes of Midwestern Farmers. Ames, Iowa: The Iowa State University Press, pp. 142-149.

65) Johnson, Glenn L. and George E. Rossmiller. 1978. "Improving Agricultural Decision Making: A Conceptual Framework." in Agricultural Sector Planning, ed. George E. Rossmiller. Michigan State University. pp. 23-51.

66) Jones, A.L. 1976. "Diseases of Tree Fruits." North Central Regional Extension Publication No. 45.

67) Jones, A.L. and John D. Gilpatrick, eds. 1976. "Proceedings: Apple and Pear Scab Workshop." Kansas City, Missouri. Special Report No. 28, New York State Agricultural Experiment Station, Cornell University.

68) Jones, A.L., S.L. Lillevik, P.D. Fisher and T.C. Stebbins. "A Microcomputer Based Instrument to Predict Primary Apple Scab Infection Periods." Plant Disease, Vol. 64, No. 1.

69) Kelley, R.D. and A.L. Jones. 1981. "Evaluation of Two Triazole Fungicides for Pest-infection Control of Apple Scab." Phytopathology. Vol. 71, pp. 737-742.

70) Kelsey, Myron and Archibald Johnson. 1979. "Costs of Apple Production in Western Michigan: Semi-Dwarf Planting - 108 Trees per Acre." Extension Bulletin E-1107. MSU.

71) Kelsey, Myron and Archie Johnson. 1979. "Costs of Apple Production in Western Michigan: Standard Orchard Planting." Extension Bulletin E-1006. MSU.

72) King, Robert. 1979. "Operational Techniques for Applied Decision Analysis Under Uncertainty." Unpublished Ph.D. Dissertation, Michigan State University.

73) King, Robert. 1980. "Implementing Choice Theory Under Uncertainty." Paper presented at EPRI Conference at Michigan State University March 6, 1980.

74) King, Robert P. and Lindon J. Robison. 1981. "An Interval Approach to the Measurement of Decision Maker Preferences." American Journal of Agricultural Economics. Vol. 63, No. 3. pp. 510-520.

75) Knight, Frank. 1921. Risk, Uncertainty and Profit. (Houghton-Mifflin).

76) Leland, H. 1972. "Theory of the Firm Facing Uncertain Demand." American Economic Review. Vol. 62, pp. 278-291.

77) Levy, H. and M. Sarnat. 1970. "Alternative Efficiency Criteria: An Empirical Analysis." Journal of Finance. Vol. 25, pp. 1153-1158.

78) Levy, H. 1973. "Stochastic Dominance, Efficiency Criteria and Efficient Portfolios: The Multi-Period Case." American Economic Review 63:986-994.

79) Levy, H. and J. Paroush. 1974. "Multi-Period Stochastic Dominance." Management Science 24:428-441.

80) Levy, H. and J. Paroush. 1974. "Toward Multivariate Efficiency Criteria." Journal of Economic Theory, 7:129-144.

81) Love, Ross O. and Lindon J. Robison. 1982. "An Empirical Analysis of the Intertemporal Stability of Risk Preferences." Staff Paper No. 1982-24, Department of Agricultural Economics, Michigan State University.

82) Manetsch, Thomas J. 1976. "Time-Varying Distributed Delays and Their Use in Aggregative Models of Large Systems." IEEE Transaction on Systems, Man and Cybernetics Vol. SMC-6, No. 8.

83) Manetsch, Thomas J. and Gerald L. Park. 1979. System Analysis and Simulation with Applications to Economic and Social Systems.

84) Merril, William C. 1965. "Alternative Programming Models Involving Risk." Journal of Farm Economics.

85) Meyer, Jack. 1977. "Choice Among Distributions." Journal of Economic Theory. Vol. 14. pp. 326-336.

86) Meyer, Jack. 1977. "Extended Efficiency Criteria and Set Stochastic Dominance." Unpublished mimeograph. Department of Economics, Texas A & M University.

87) Meyer, Jack. 1977. "Second Degree Stochastic Dominance with Respect to a Function." International Economic Review. 18: pp. 477-487.

88) Meyer, Jack. 1979. "Mean-Variance Efficient Sets and Expected Utility." The Journal of Finance. Vol. XXXIV, No. 5, pp. 1221-1229.

89) Mossin, Jan. 1973. Theory of Financial Markets. Englewood Cliffs.

90) Nautiyal, J.C. 1970. "User Cost in Renewable Natural Resources." Canadian Journal of Agricultural Economics, Vol. 18, No. 2, pp. 95-103.

91) Newton, C. and W. Leuschner. 1975. "Recognition of Risk and Utility in Pest Management Decisions." Bulletin of the Entomological Society of America. Vol. 21, No. 3. pp. 169-192.

92) Nordhaus, W.D. 1969. "Resources and Man." Report of National Academy of Sciences of the U.S. (San Francisco: Freeman).

93) Officer, R.R. and A.N. Halter. 1968. "Utility Analysis in a Practical Setting." American Journal of Agricultural Economics 50:257-277.

94) Oguchi, N. and A. Guccione. 1979. "Perfect Aggregation Conditions for Quadratic Programming Models," American Journal of Agricultural Economics.

95) Pearce, D. and J. Rose, Ed. 1975. Economic Aspects of Natural Resource Depletion.

96) Perrin, R.K. 1972. "Asset Replacement Principles." American Journal of Agricultural Economics. Vol. 54, pp. 60-67.

97) Perrin, Richard K. 1972. "Optimal Levels of Fertilizer under Risk: Comment." American Journal of Agricultural Economics, Vol. 54, No. 4.

98) Pfadt, Robert. 1971. Fundamentals of Applied Entomology. The MacMillan Company.

99) Pope, R. and R.E. Just. 1977. "On the Competitive Firm under Production Uncertainty." Australian Journal of Agricultural Economics, Vol. 21, No. 2, pp. 111-118.

100) Porter, R. Burr and Jack E. Gaumnity. 1972. "Stochastic Dominance vs. Mean-variance Portfolio Analysis: An Empirical Evaluation." American Economic Review, Vol. LXII, No. 3.

101) Pratt, J. 1964. "Risk Aversion in the Small and in the Large." Econometrica, Vol. 32, pp. 122-136.

102) Prokopy, Ronald J. et al. "Integrated Management of Insect and Mite Pests in Commercial Apple Orchards in Massachusetts." Unpublished mimeograph. Department of Entomology, University of Massachusetts.

103) Pyenson, Louis L. 1977. Fundamentals of Entomology and Plant Pathology. AVI Publishing Company, Inc.

104) Quirk, J.P. and R. Saposnik. 1962. "Admissibility and Measurable Utility Functions." Review of Economic Studies. Vol. 29, pp. 140-146.

105) Ramsey, F.P. 1931. "Truth and Probability." The Foundation of Mathematics and Other Logical Essays. Braithwaite, R.B., ed. London: Routledge and Kegan Paul.

106) Ratti, R. and A. Ullah. 1976. "Uncertainty in Production and the Competitive Firm." Southern Economics Journal. Vol. 42, No. 4, pp. 703-710.

107) Regev, Uri, Andrew P. Gutierrez and Gershon Feder. 1976. "Pests as a Common Property Resource: A Case Study of Alfalfa Weevil Control." American Journal of Agricultural Economics, Vol. 58, pp. 187-197.

108) Reichelderfer, Katherine H. and Filmore E. Bender. 1979. "Application of a Simulative Approach to Evaluating Alternative Methods for the Control of Agricultural Pests," American Journal of Agricultural Economics, Vol. 61, No. 2.

109) Reichelderfer, Katherine H. 1980. "Economics of Integrated Pest Management: Discussion." American Journal of Agricultural Economics. Vol. 62, No. 5.

110) Reidl, Helmut, B.A. Croft and A.J. Howitt. 1976. "Forecasting Codling Moth Phenology Based on Pheromone Trap Catches and Physiological-Time Models." The Canadian Entomologist Vol. 108, No. 5. pp. 449-460.

111) Riedl, Helmut and B.A. Croft. 1978. "Management of the Codling Moth in Michigan." Research Report 337. Farm Science, Agricultural Experiment Station, MSU.

112) Robison, Lindon and R.P. King. 1978. "Specification of Micro Risk Models for Farm Management and Policy Research." Agricultural Economics Report No. 349, Department of Agricultural Economics, Michigan State University, East Lansing, Michigan.

113) Robison, Lindon. 1979. "Lecture Notes for AEC 906 on Decision Making Under Uncertainty." Unpublished mimeograph.

114) Robison, Lindon and J.R. Black. 1979. "Combining Lumpy and Divisible Assets Under Uncertainty." Michigan State University Agricultural Experiment Station.

115) Robison, Lindon J. and Michael Abkin. 1981. Theoretical and Practical Models for Investment and Disinvestment Decision Making Under Uncertainty in the Energy Supply Industry. Agricultural Economics Report No. 390.

116) Robison, Lindon J. 1982. "An Appraisal of Expected Utility Hypothesis Tests Constructed from Responses to Hypothetical Questions and Experimental Choices." American Journal of Agricultural Economics. Vol. 64, No. 2, pp. 367-375.

117) Rovinsky, Robert B., Katherine H. Reichelderfer, Rueben N. Weis and William Quinby. "The Use of Policy Models to Evaluate the Effects of a Pesticide Ban."

118) Samuelson, P.A. 1967. "General Proof That Diversification Pays." Journal of Financial Quantitative Analysis. Vol. 2. pp. 401-416.

119) Samuelson, Paul A. 1971. "Generalized Predator-Prey Oscillations in Ecological and Economic Equilibrium," Prooceedings of the National Academy of Sciences 68:980-983.

120) Sandmo. 1981. "On the Theory of the Competitive Firm under Price Uncertainty." American Economic Review. Vol. 61, pp. 65-73.

121) Surhan, Mohamed E., Richard E. Horvitt and Charles V. Moore. 1979. "Pesticide Resistance Externalities and Optimal Mosquito Management." Journal of Environmental Economics and Management, Vol. 6, pp. 69-84.

122) Schlaifer, Robert. 1961. Introduction to Statistics for Business Decisions. New York: McGraw-Hill Book Company, Inc.

123) Schoemaker, Paul J. 1982. "The Expected Utility Model: Its Variants, Purposes, Evidence and Limitations." Journal of Economic Literature. Vol. XX, No. 2. pp. 529-563.

124) Scott, Anthony. 1953. "Notes on User Costs." Economic Journal, Vol. 63, pp. 368-384.

125) Scott, Anthony. 1955. "The Fishery: The Objectives of Sole Ownership." Journal of Political Economy, Vol. 63, pp. 116-124.

126) Scott, Anthony. 1967. "The Theory of a Mine Under Conditions of Certainty." in Extractive Resources and Taxation. Mason Gaffney, ed. Madison, Wisconsin: The University of Wisconsin Press.

127) Scott, John T. and Chester B. Bahec. 1972. "A Practical Way to Select an Optimum Farm Plan Under Risk." American Journal of Agricultural Economics. Vol. 54, No. 4.

128) Shoemaker, Christine. 1973. "Optimization of Agricultural Pest Management I: Biological and Mathematical Background." Mathematical Biosciences Vol. 16, No. 1 and 2, p. 143.

129) Shoemaker, Christine. 1973. "Optimization of Agricultural Pest Management II: Formulation of a Control Model." Mathematical Biosciences, Vol. 17, pp. 357-365.

130) Shoemaker, Christine. 1973. "Optimization of Agricultural Pest Management III: Results and Extensions of a Model." Mathematical Biosciences, Vol. 18, pp. 1-22.

131) Smith, Vernon L. 1968. "Economics of Production from Natural Resources." American Economic Review.

132) Smith, Vernon, L. 1961. Investment and Production Cambridge, Massachusetts: Harvard University Press.

133) Solow, R.M. and F.Y. Wan. 1976. "Extraction Costs in the Theory of Exhaustible Resources." The Bell Journal of Economics, Vol. 7., No. 2.

134) Spetzler, C.S. and C.A.S. Stael von Holstein. 1975. "Probability Encoding in Decision Analysis." Management Science, Vol. 22, pp. 340-58.

135) Stern, Vernon M., et al. 1959. "The Integrated Control Concept." Hilgardia, Vol. 29, No. 2, pp. 81-101.

136) Stevens, Guy, G.V. 1974. "On the Impact of Uncertainty on the Value and Investment of the Neoclassical Firm." American Economic Review, Vol. LXIV, No. 3.

137) Successful Farming. "Chemical Application--The Billion Dollar Blunder." Vol. 78, No. 6, pp. 23-27.

138) Talpaz, H. and I Borosh. 1974. "Strategy for Pesticide Use: Frequency Applications." American Journal of Agricultural Economics, Vol. 56, No. 4, pp. 769-775.

139) Talpaz, Hovav, G.L. Curry, P.J. Sharpe, D.W. DeMichele, and R.E. Frisbie. 1978. "Optimal Pesticide Application for Controlling the Boll Weevil on Cotton." American Journal of Agricultural Economics. Vol. 60, pp. 469-475.

140) Talpaz, H. and R. Frisbie. 1975. "An Advanced Method for Economic Threshold Determination: A Positive Approach." Southern Journal of Agricultural Economics, Vol. 7, No. 2.

141) Taylor, C. Robert. 1980. "The Nature of Benefits and Costs of Use of Pest Control Methods." Journal of Agricultural Economics. Vol. 62, No. 5. pp. 1007-1011.

142) Taylor, C. Robert and J.C. Headley. 1975. "Insecticide Resistance and the Evolution of Control Strategies for an Insect Population." Canadian Entomology, Vol. 107, pp. 237-242.

143) Thompson, Peter and G.B. White. 1982. An Economic Evaluation of the Potential for Tree Fruit Integrated Pest Management in the Northeast. A.E. Res. 82-14. Department of Agricultural Economics, Cornell University.

144) Tobin, James. 1958. "Liquidity Preferences as Behavior Towards Risk." Review of Economic Studies. Vol. 25. pp. 55-86.

145) von Neumann, J. and O Morgenstern. 1947. Theory of Games and Economic Behavior. Princeton: Princeton University Press.

146) Weisz, Reuben, Mike Lancaster and Bill Quinby. 1979. "The Interrelationship of a Pesticide Regulation to Target Prices: A Multiple Policy Approach to Pest Management Analysis." Draft of Paper submitted to 1979 Agricultural Economics Association.

147) Weisz, Reuben N., Ronald R. Miller and William Quinby. "The Stochastic Impacts of a Change in Agricultural Technology." Paper presented at Southern Agricultural Economics Meeting -- February, 1979.

148) Welch, S.M., B.A. Croft, J.F. Brunner and M.F. Michels. 1978. "PETE: An Extension Phenology Modeling System for Management of Multi-Species Pest Complex." Environmental Entomology. Vol. 7 pp. 484-494.

149) Whitmore, G.A. 1970. "Third-Degree Stochastic Dominance." American Economic Review. Vol. 60. pp. 457-459.

150) Young, Doug et al. 1979. "Risk Preferences of Agricultural Procedures: Their Measurement and Use." Risk Management in Agriculture: Behavioral, Managerial, and Policy Issues. AE-4478. Department of Agricultural Economics, University of Illinois.

151) Zenter, R.P. et al. 1981. Ordinary and Generalized Stochastic Dominance: A Primer. Staff Paper P81-27. Department of Agricultural and Applied Economics, University of Minnesota.

APPENDICES

APPENDIX I

CUMULATIVE PROBABILITY DISTRIBUTIONS

Net Income Per Ten Acre Block	Probability of Receiving Income Level or Less
-7858	.295
-4699	.658
-1541	.817
1617	.857
4775	.891
7934	.968
11092	1.00
14250	1.00
17408	1.00
20567	1.00

Table 1. Cumulative Probability Distribution for Scab Control Strategy 1: Medium Yield.

Net Income Level Per Ten Acre Block	Probability of Receiving Income Level or Less
-7858	.030
-4699	.080
-1541	.247
1617	.538
4775	.662
7934	.788
11092	.858
14250	.912
17408	.960
20567	1.000

Table 2. Cumulative Probability Distribution for Scab Control Strategy 2: Medium Yield.

Net Income Level Per Ten Acre Block	Probability of Receiving Income Level or Less
-7858	.032
-4699	.087
-1541	.270
1617	.543
4775	.662
7934	.797
11092	.863
14250	.919
17408	.974
20567	1.000

Table 3. Cumulative Probability Distribution for Scab Control Strategy 3: Medium Yield.

Net Income Level Per Ten Acre Block	Probability of Receiving Income Level or Less
-7858	.034
-4699	.119
-1541	.259
1617	.571
4775	.698
7934	.823
11092	.873
14250	.911
17408	.965
20567	1.000

Table 4. Cumulative Probability Distribution for Scab Control Strategy 4: Medium Yield.

Net Income Per Ten Acre Block	Probability of Receiving Income Level or Less
-7858	.030
-4699	.075
-1541	.224
1617	.507
4775	.643
7934	.762
11092	.851
14250	.902
17408	.962
20567	1.000

Table 5. Cumulative Probability Distribution for Scab Control Strategy 5: Medium Yield.

Net Income Per Ten Acre Block	Probability of Receiving Income Level or Less
-7858	.033
-4699	.089
-1541	.274
1617	.545
4775	.664
7934	.799
11092	.864
14250	.920
17408	.975
20567	1.000

Table 6. Cumulative Probability Distribution for Scab Control Strategy 6: Medium Yield.

Net Income Per Ten Acre Block	Probability of Receiving Income Level or Less
-7858	.030
-4699	.076
-1541	.250
1617	.525
4775	.652
7934	.786
11092	.857
14250	.911
17408	.969
20567	1.000

Table 7. Cumulative Probability Distribution for Scab Control Strategy 7: Medium Yield.

Net Income Per Ten Acre Block	Probability of Receiving Income Level or Less
-7858	.029
-4699	.074
-1541	.238
1617	.533
4775	.658
7934	.782
11092	.855
14250	.917
17408	.968
20567	1.000

Table 8. Cumulative Probability Distribution for Scab Control Strategy 8: Medium Yield.

Net Income Per Ten Acre Block	Probability of Receiving Income Level or Less
-7858	.029
-4699	.074
-1541	.294
1617	.583
4775	.656
7934	.782
11092	.856
14250	.910
17408	.955
20567	1.000

Table 9. Cumulative Probability Distribution for Scab Control Strategy 9: Medium Yield.

Net Income Per Ten Acre Block	Probability of Receiving Income Level or Less
-7858	.032
-4699	.081
-1541	.232
1617	.522
4775	.647
7934	.772
11092	.849
14250	.911
17408	.966
20567	1.000

Table 10. Cumulative Probability Distribution for Scab Control Strategy 10: Medium Yield.

Net Income Per Ten Acre Block	Probability of Receiving Income Level or Less
-7858	.025
-4699	.050
-1541	.228
1617	.488
4775	.616
7934	.759
11092	.830
14250	.921
17408	.974
20567	1.000

Table 11. Cumulative Probability Distribution for Scab Control Strategy 11: Medium Yield.

Net Income Per Ten Acre Block	Probability of Receiving Income Level or Less
-5845	.508
-3099	.767
-352	.952
2394	.976
5141	1.000
7887	1.000
10634	1.000
13381	1.000
16127	1.000
18874	1.000

Table 12. Cumulative Probability Distribution for Codling Moth Strategy 1: Medium Yield and High Initial Population Density.

Net Income Per Ten Acre Block	Probability of Earning Income Level or Less
-5845	.064
-3099	.195
-352	.397
2394	.596
5141	.681
7887	.805
10634	.860
13381	.908
16127	.946
18874	1.000

Table 13. Cumulative Probability Distribution for Codling Moth Strategy 2: Medium Yield and High Initial Population Density.

Net Income Per Ten Acre Block	Probability of Earning Income Level or Less
-5845	.081
-3099	.234
-352	.510
2394	.625
5141	.695
7887	.820
10634	.873
13381	.918
16127	.957
18874	1.000

Table 14. Cumulative Probability Distribution for Codling Moth Strategy 3: Medium Yield and High Initial Population Density.

Net Income Per Ten Acre Block	Probability of Earning Income Level or Less
-5845	.064
-3099	.195
-352	.397
2394	.596
5141	.681
7887	.805
10634	.860
13381	.908
16127	.946
18874	1.000

Table 13. Cumulative Probability Distribution for Codling Moth Strategy 2: Medium Yield and High Initial Population Density.

Net Income Per Ten Acre Block	Probability of Earning Income Level or Less
-5845	.081
-3099	.234
-352	.510
2394	.625
5141	.695
7887	.820
10634	.873
13381	.918
16127	.957
18874	1.000

Table 14. Cumulative Probability Distribution for Codling Moth Strategy 3: Medium Yield and High Initial Population Density.

Net Income Level Per Ten Acre Block	Probability of Earning Income Level or Less
-5845	.053
-3099	.150
-352	.392
2394	.607
5141	.682
7887	.807
10634	.861
13381	.911
16127	.956
18874	1.000

Table 15. Cumulative Probability Distribution for Codling Moth Strategy 4: Medium Yield and High Initial Population Density.

Net Income Level Per Ten Acre Block	Probability of Earning Income Level or Less
-5845	.060
-3099	.188
-352	.462
2394	.620
5141	.687
7887	.813
10634	.866
13381	.916
16127	.963
18874	1.000

Table 16. Cumulative Probability Distribution for Codling Moth Strategy 5: Medium Yield and High Initial Population Density.

Net Income Level Per Ten Acre Block	Probability of Earning Income Level or Less
-5845	.053
-3099	.150
-352	.392
2394	.607
5141	.682
7887	.807
10634	.861
13381	.911
16127	.956
18874	1.000

Table 17. Cumulative Probability Distribution for Codling Moth Strategy 6: Medium Yield and High Initial Population Density.

Net Income Level Per Ten Acre Block	Probability of Earning Income Level or Less
-5845	.060
-3099	.188
-352	.462
2394	.620
5141	.687
7887	.813
10634	.866
13381	.916
16127	.962
18874	1.000

Table 18. Cumulative Probability Distribution for Codling Moth Strategy 7: Medium Yield and High Initial Population Density.

Net Income Level Per Ten Acre Block	Probability of Earning Income Level or Less
-5845	.053
-3099	.150
-352	.391
2394	.607
5141	.682
7887	.807
10634	.861
13381	.909
16127	.947
18874	1.000

Table 19. Cumulative Probability Distriution for Codling Moth Strategy 8: Medium Yield and High Initial Population Density.

Net Income Level Per Ten Acre Block	Probability of Earning Income Level or Less
-5845	.060
-3099	.188
-352	.462
2394	.620
5141	.687
7887	.813
10634	.866
13381	.914
16127	.952
18874	1.000

Table 20. Cumulative Probability Distribution for Codling Moth Strategy 9: Medium Yield and High Initial Population Density.

Net Income Level Per Ten Acre Block	Probability of Earning Income Level or Less
-5845	.053
-3099	.150
-352	.392
2394	.607
5141	.682
7887	.807
10634	.861
13381	.911
16127	.956
18874	1.000

Table 21. Cumulative Probability Distribution for Codling Moth Strategy 10: Medium Yield and High Initial Population Density.

Net Income Level Per Ten Acre Block	Probability of Earning Income Level or Less
-3711	.138
-1266	.365
1179	.548
3624	.659
6070	.758
8515	.825
10960	.872
13405	.916
15850	.957
18295	1.000

Table 22: Cumulative Probability Distribution for Codling Moth Strategy 11: Medium Yield and High Initial Population Density.

Net Income Level Per Ten Acre Block	Probability of Earning Income Level or Less
-3711	.124
-1266	.350
1179	.539
3624	.653
6070	.699
8515	.820
10960	.868
13405	.911
15850	.951
18295	1.000

Table 23. Cumulative Probability Distribution for Codling Moth Strategy 12: Medium Yield and High Initial Population Density.

Net Income Level Per Ten Acre Block	Probability of Earning Income Level or Less
-3711	.124
-1266	.350
1179	.539
3624	.653
6070	.699
8515	.820
10960	.868
13405	.911
15850	.951
18295	1.000

Table 24. Cumulative Probability Distribution for Codling Moth Strategy 13: Medium Yield and High Initial Population Density.

Net Income Level Per Ten Acre Block	Probability of Earning Income Level or Less
-3711	.138
-1266	.365
1179	.549
3624	.659
6070	.758
8515	.825
10960	.872
13405	.916
15850	.957
18295	1.000

Table 25. Cumulative Probability Distribution for Codling Moth Strategy 14: Medium Yield and High Initial Population Density.

Net Income Level Per Ten Acre Block	Probability of Earning Income Level or Less
-3711	.122
-1266	.350
1179	.535
3624	.653
6070	.699
8515	.820
10960	.868
13405	.910
15850	.943
18295	1.000

Table 26. Cumulative Probability Distribution for Codling Moth Strategy 15: Medium Yield and High Initial Population Density.

Net Income Level Per Ten Acre Block	Probability of Earning Income Level or Less
-3711	.136
-1276	.365
1179	.548
3624	.659
6070	.758
8515	.825
10960	.872
13405	.914
15850	.947
18295	1.000

Table 27. Cumulative Probability Distribution for Codling Moth Strategy 16: Medium Yield and High Initial Population Density.

Net Income Level Per Ten Acre Block	Probability of Earning Income Level or Less
-3711	.124
-1266	.350
1179	.535
3624	.653
6070	.699
8515	.820
10960	.868
13405	.910
15850	.943
18295	1.000

Table 28. Cumulative Probability Distribution for Còdling Moth Strategy 17: Medium Yield and High Initial Population Density.

Net Income Level Per Ten Acre Block	Probability of Earning Income Level or Less
-3711	.138
-1266	.365
1179	.548
3624	.659
6070	.758
8515	.825
10960	.872
13405	.914
15850	.947
18295	1.000

Table 29. Cumulative Probability Distribution for Codling Moth Strategy 18: Medium Yield and High Initial Population Density.

Net Income Level Per Ten Acre Block	Probability of Earning Income Level or Less
-3711	.138
-1266	.365
1179	.548
3624	.659
6070	.758
8515	.825
10960	.872
13405	.914
15850	.947
18295	1.000

Table 30. Cumulative Probability Distribution for Codling Moth Strategy 19: Medium Yield and High Initial Population Density.

Net Income Level Per Ten Acre Block	Probability of Receiving Income Level or Less
-3559	.128
-1004	.347
1549	.556
4103	.649
6658	.750
9212	.827
11766	.910
14320	.930
16874	.953
19428	1.000

Table 31. Cumulative Probability Distribution for Mite Strategy 1: Medium Yield and Weekly Scouting.

Net Income Level Per Ten Acre Block	Probability of Receiving Income Level or Less
-3559	.127
-1004	.327
1549	.553
4103	.636
6658	.696
9212	.829
11766	.885
14320	.925
16874	.961
19428	1.000

Table 32. Cumulative Probability Distribution for Revised Mite Strategy 4: Medium Yield and Weekly Scouting.

Income Level Per Ten Acre Block	Probability of Receiving Income Level or Less
-3559	.127
-1004	.321
1549	.553
4103	.633
6658	.725
9212	.830
11766	.885
14320	.922
16874	.951
19428	1.000

Table 33. Cumulative Probability Distribution for Revised Mite Strategy 5: Medium Yield and Weekly Scouting.

Income Level Per Ten Acre Block	Probability of Receiving Income Level or Less
-3559	.127
-1004	.322
1549	.546
4103	.631
6658	.711
9212	.830
11766	.893
14320	.924
16874	.951
19428	1.000

Table 34. Cumulative Probability Distribution for Revised Mite Strategy 7: Medium Yield and Weekly Scouting.

Income Level Per Ten Acre Block	Probability of Receiving Income Level or Less
-3559	.127
-1004	.327
1549	.564
4103	.636
6658	.697
9212	.829
11766	.885
14320	.925
16874	.961
19428	1.000

Table 35. Cumulative Probability Distribution for Revised Mite Strategy 11: Medium Yield and Weekly Scouting.

Income Level Per Ten Acre Block	Probability of Receiving Income Level or Less
-3559	.127
-1004	.321
1549	.554
4103	.633
6658	.697
9212	.829
11766	.885
14320	.922
16874	.951
19428	1.000

Table 36. Cumulative Probability Distribution for Revised Mite Strategy 12: Medium Yield and Weekly Scouting.

Income Level Per Ten Acre Block	Probability of Receiving Income Level or Less
-3559	.127
-1004	.324
1549	.541
4103	.633
6658	.699
9212	.827
11766	.883
14320	.920
16874	.949
19428	1.000

Table 37. Cumulative Probability Distribution for Revised Mite Strategy 13: Medium Yield and Weekly Scouting

Income Level Per Ten Acre Block	Probability of Receiving Income Level or Less
-3559	.127
-1004	.321
1549	.528
4103	.633
6658	.699
9212	.826
11766	.890
14320	.923
16874	.951
19428	1.000

Table 38. Cumulative Probability Distribution for Revised Mite Strategy 14: Medium Yield and Weekly Scouting.

APPENDIX II

STATISTICAL TESTS ON SCAB DAMAGE ESTIMATES

A standard t-test was conducted to test if the average damage predicted by the simulation model statistically differed from the average damage observed in experimental orchards. The hypothesis was tested for two strategies: the conventional calendar (7) and the post-infection IPM (5). In both cases, there is no significant difference between the two damage estimates at .975 significance level.

These results indicate that the model is justified for damage predictions for these two strategies. Experimental data were not available for the necessary tests of the remaining strategies. It should be noted that the experimental observations were obtained from strategies which used slightly different chemicals than the model.

Conventional Program*

1) H_0: $M_1 = U_2$

The mean damage estimate for the model is equal to the observed damage in experimental orchard.

2) H_1: $M_1 \neq U_2$

The mean damage estimate for the model is not equal to the observed damage in experimental orchard.

3) Under H_0 $|T_{19}| = \frac{\bar{x} - 5.02^{**}}{s/\sqrt{19}}$

4) Reject H_0 if $|T_{19}|_{.0975} \geq 2.093$

5) $T_{19} = \frac{2.6 - 5.02}{80/\sqrt{19}} = \frac{-2.42}{8.0/4.36}$

$= \frac{-2.42}{1.83}$

$= 1.32$

H_0 is not rejected

* Compares Strategy 7 with 7 day protective treatment of bitertanol.

** Bushels damaged per acre with yield of 500 bushels per acre.

Post-Infection IPM Program*

1) H_0: $M_1 = M_2$

The mean damage estimate for the model is equal to the observed damage in experimental orchard.

2) H_1: $M_1 \neq U_2$

The mean damage estimate for the model is not equal to the observed damage in experimental orchard.

3) Under H_0 $|T_{19}| = \frac{\overline{X} - 2.51^{**}}{x\ \sqrt{19}}$

4) Reject H_0 if $|T_{19}|\ _{.0975} \geq 2.093$

5) $|T_{19}| = \frac{16.1 - 25.1}{27.4/4.36} = \frac{-9}{6.28}$

$= 1.43$

H_0 is not rejected.

* Compares Strategy 11 with post-infection treatment of bitertanol.

** Bushel damaged per acre with yield of 500 bushels per acre.

APPENDIX III

FRUIT GROWER SURVEY

A small survey was conducted with a group of fruit growers from Western Michigan at the beginning of the study for two reasons. First, it was necessary to validate for fruit growers the results of larger surveys which measured the risk preferences of farmers dealing with other commodities. Second, a more complete understanding of the perspectives of the decision makers who actually make pest management decisions was desired.

The following questionnaire was used as a guideline in an informal discussion with eight growers. The questionnaire is followed by a summary of the major points of the discussion.

PEST MANAGEMENT QUESTIONNAIRE

1. How much does pest management influence the variety you select to grow:

   ________None

   ________Little

   ________A lot

2. Do you use the same control for apple scab, mites and codling moth year in and year out?

   ________No

   ________Yes

   If no, what determines changes in controls you employ from one year to the next?

   ________Weather

   ________Expected apple prices

   ________Expected infestations

   ________Last year's experience with pest(s)

   ________Chemical prices

   ________Others

3. Do you apple the same control over the entire orchard or are some blocks treated differently than others?

   Why?

   ________Age

   ________Size of Orchard

   ________Variety

   ________Other

4. How would you ordinally rank these factors as to the importance that they usually play in your decision to select a control strategy for mites? (Use 1 through 13 with a "1" indicating greatest importance and "13" the lowest. Use each number only once.)

_________Expected apple prices

_________Decision to sell fruit in fresh or processed market

_________Expected weather patterns

_________Weather experience to date in the season

_________Last year's experience with mites in own orchard

_________Control selected for apple scab

_________Apple variety

_________Type or capacity of sprayer equipment

_________Costs of alternative chemicals

_________Amount of labor required to apply alternative controls

_________Retention (weathering) capacity of control

_________The relative probability that control will prevent substantial damage

_________Retention of toxic residue

_________Other

5. How would you ordinally rank these factors as to the importance that they usually play in your decisions to select a control strategy for codling moths? (Use 1 through 14 with a "1" indicating greatest importance and a "14" the lowest. Use each number only once.)

_________Expected apple prices

_________Decision to sell fruit in fresh or processed markets

_________Weather experienced to date in the season

_________Expected weather pattern

_________Last year's experience with codling moth in your own orchard

_________Experience with codling moth in neighboring orchards

_________Control selected for another pest (Name:_________________)

_________Capacity or type of spray equipment

_________Costs of alternative chemicals

_________Amount of labor required to apply alternative controls

_________Retention (weathering) capacity of control

_________Relative probability that control will prevent substantial damage

_________Retention of toxic residues

_________Other

6. How would you ordinally rank these factors as to the importance that they usually play in your decisions to select a control strategy for apple scab? (Use 1 through 15 with a "1" indicating greatest importance and a "15" the lowest. Use each number only once.)

__________Expected apple prices

__________Decision to sell fruit in fresh or processed markets

__________Expected weather pattern

__________Weather experienced to date in the season

__________Last year's experience with apple scab in own orchard

__________Experience with apple scab in neighboring orchards

__________Apple variety

__________Capacity or type of spray equipment

__________Costs of alternative chemicals

__________Amount of time needed to apply alternative controls

__________Amount of labor needed to apply alternative controls

__________Retention (weathering) capacity of control

__________Relative probability that control will prevent substantial damage

__________Retention of toxic residues

__________Other

7. Do you use formal monitoring of pest populations (actual counting on sample areas, traps, etc.)?

__________Routinely

__________Occasionally

__________Never

8. Do you use informal monitoring of pest populations?

(a) inspection done alone without outside "expert"

__________Routinely

__________Occasionally

__________Never

(b) inspection done with extension personnel

__________Routinely

__________Occasionally

__________Never

(c) inspection done with chemical company/distributor representative

__________Routinely

__________Occasionally

__________Never

(d) inspection done with cooperative representative

__________Routinely

__________Occasionally

__________Never

(e) inspection done with private consultant

__________Routinely

__________Occasionally

__________Never

9. To what degree do Extension recommendations influence your decisions in

(a) selecting one control method over another? ________very influential; ________moderately influential; or ________of little influence.

(b) timing of sprays? ________very influential; ________moderately influential; or ________of little influence.

(c) determining concentrations or dosages of sprays? ________very influential; ________moderately influential; or ________ of little influence.

10. Have you ever noticed a problem with resistance of pest population to a chemical you frequently use(d)?

________Yes

________No

Have you ever altered your pest management due to a resistance problem?

________No

________Yes

If yes, how?

________Discontinue use of chemical

________Use chemical in combination with another chemical which controls resistant strains, i.e., (Benomyl and Captan)

________Rotate use of chemicals in alternate years

________Reduce dosages or number of sprays to avoid problems

________Other (please explain)

11. Are there any areas of pest management were you would like to see additional information provided for your use? Comments:

RISK ATTITUDE QUESTIONNAIRE

Your attitudes about risk influence the decisions that you make in the pest management of your orchard. The attached questionnaire is designed to help you think about these attitudes. It will also help us to determine how accurately your risk preference can be measured and incorporated into the way that extension specialists may assist you in making pest management decisions.

In filling out the questionnaire you will be asked to compare distributions of numbers and indicate which you prefer. The numbers represent levels of annual net income from one 10-acre block. This income is over and above the costs of production and is available for family living expenses, expansion of your farm operation and accelerated debt repayment. Each distribution should be thought of as a range of possible outcomes that can occur under a particular management strategy. Six income levels are listed under each choice, and each income is considered to have one chance in six of actually occuring next year. The six levels of each distribution can be viewed as the six faces of a die and when the die is rolled each side has an equal probability of coming face up.

There are three sections of the questionnaire with each section focusing on a different income range.

Your answers should reflect your own attitudes and your own situation. There are no right or wrong answers.

SECTION I

1. Compare the following two distributions and circle the one you prefer.

A	B
-450	-500
-50	-450
400	-350
450	500
550	1200
950	1600

If you prefer A, go to question 2. If you prefer B, go to question 3.

2. Compare the following two distributions and circle the one you prefer.

C	D
-100	-150
350	50
400	150
400	450
550	1050
650	1100

If you prefer C, go to question 4. If you prefer D, go to question 5.

3. Compare the following two distributions and circle the one you prefer.

E	F
-500	50
50	100
350	650
900	800
950	850
1600	950

If you prefer E, go to question 6. If you prefer F, go to question 7.

4. Compare the following two distributions and circle the one you prefer.

G	H
-50	50
500	250
500	350
900	750
1050	800
1600	1400

Go to Section II.

5. Compare the following two distributions and circle the one you prefer.

I	J
50	-150
200	50
300	150
550	450
600	1050
700	1100

Go to Section II.

6. Compare the following two distributions and circle the one you prefer.

K	L
-150	-500
50	-450
150	-350
450	500
1050	1200
1100	1600

Go to Section II.

7. Compare the following two distributions and circle the one you prefer.

M	N
50	-250
200	-200
300	100
550	800
600	900
700	1100

Go to Section II.

SECTION II

1. Compare the following two distributions and circle the one you prefer.

A	B
3400	3250
3850	3300
3900	3600
3900	4300
4050	4400
4150	4600

If you prefer A, go to question 2. If you prefer B, go to question 3.

2. Compare the following two distributions and circle the one you prefer.

C	D
3550	3000
3700	3550
3800	3850
4050	4400
4100	4450
4200	5100

If you prefer C, go to question 4. If you prefer D, go to question 5.

3. Compare the following distributions and circle the one you prefer.

E	F
3550	3050
3700	3950
3800	4000
4050	4050
4100	4150
4200	4200

If you prefer E, go to question 6. If you prefer F, go to question 7.

4. Compare the following two distributions and circle the one you prefer.

G	H
3700	3450
3750	4000
3900	4000
4450	4400
4450	4650
4600	5100

Go to Section III.

5. Compare the following two distributions and circle the one you prefer.

I	J
3350	3000
3450	3050
3550	3150
3700	4000
4150	4700
4300	5100

Go to Section III.

6. Compare the following two distributions and circle the one you prefer.

K	L
3550	3250
3700	3300
3800	3600
4050	4300
4100	4400
4200	4600

Go to Section III.

7. Compare the following two distributions and circle the one you prefer.

M	N
3700	3250
3750	3900
3900	4100
4450	4150
4450	4250
4600	5050

Go to Section III.

SECTION III

1. Compare the following two distributions and circle the one you prefer.

A	B
14000	14650
14550	14850
14850	14850
15400	15100
15450	15250
16100	15500

If you prefer A, go to question 2. If you prefer B, go to question 3.

2. Compare the following two distributions and circle the one you prefer.

C	D
14550	14050
14700	14950
14800	15000
15050	15050
15100	15150
15200	15200

If you prefer C, go to question 4. If you prefer D, go to question 5.

3. Compare the following two distributions and circle the one you prefer.

E	F
14400	14250
14550	14600
14650	14650
14950	15050
15550	15150
15600	16000

If you prefer, E, go to question 6. If you prefer F, go to question 7.

4. Compare the following two distributions and circle the one you prefer.

G	H
14550	14250
14700	14300
14800	14600
15050	15300
15100	15400
15200	15600

You have completed the questionnaire. Thank you.

5. Compare the following two distributions and circle the one you prefer.

I	J
14350	14000
14550	14050
14250	14150
14950	15000
15550	15700
15600	16100

You have completed the questionnaire. Thank you.

6. Compare the following two distributions and circle the one you prefer.

K	L
14340	14000
14450	14550
14550	14850
14700	15400
15150	15450
15300	16100

You have completed the questionnaire. Thank you.

7. Compare the following two distributions and circle the one you prefer.

M	N
14000	14050
14050	14400
14150	14750
15000	15000
15700	15100
16100	15150

You have finished the questionnaire. Thank you.

MAJOR POINTS OF GROWERS

1) Unlike pest management decisions dealing with other commodities, it appears that expectations on apple prices and the yield to not influence the selection of pestmangement tactics because of two important factors: 1) marketing institutions and 2) the long term consequences of controls in any one given year.

The general strategy employed by the Belding growers is to produce a high quality of fruit (at whatever cost) regardless of whether or not it is intended for the fresh or processed markets, whether or not there has been frost damage or whether or not the price/yield outlook is favorable. The rationale for this strategy is centered on marketing and long term control concerns.

In a good yield/poor price year it is necessary to harvest high quality fruit to insure that it will be marketed. In a poor yield/good price year it is beneficial to produce high quality fruit to pack-out higher and to receive the higher premiums that are paid for top grades. The consensus among the growers was that they attempt to produce high quality for both the fresh and processed markets. (Gerbers especially was noted as a processing firm demanding high quality apples.) Only juice apples were indicated as being a possible case where quality was less important in the marketing of fruit.

The control necessary to produce a high quality fruit is pursued throughout the season regardless of any possible short term gains from reducing control costs when reductions in the value of the harvest is likely to warrant such cutbacks (perhaps due to frost damage, poor prices, etc.). This is the case because of the long term consequences of pest controls. By cutting back on the controls (and saving some control costs) in one year, it is felt by the growers that the increased pest problems in future years stimulated by the cutbacks will produce much higher control costs in the future and offset any gains by adjusting to the conditions of each particular year.

2) It is unrealistic to isolate out a single pest and discuss its management since the entire orchard is operated as a system and it is necessary to discuss interrelationships between pests, predators and controls.

3) Pest management does not influence the varieties grown but variety can influence the pest management. Market conditions dictate variety. Varietal differences between susceptibilities to pests can be an important determinant in identifying control needs.

4) Controls are adjusted from one year to the next by information on the previous year's experience with the pest(s), chemical prices and the expected level of infestation. The weather pattern and the development of new chemicals are also important factors which may change the controls applied.

5) Different blocks are often treated differently. Two common factors for differential treatments are the overall size of the orchard and the varietal mix of each block. If blocks are in different locations, the distance between blocks could result in a different treatment. Proximity to neighbor's orchard which always has problems would influence treatment as well.

Occasionally, some growers may apply an eradicant program to some blocks while pursuing a protective program to other blocks to insure that they will be able to spray all the blocks in the eradicant program within the necessary time limit. By following a protective program in some blocks, the total number of acres that need to be sprayed in a timely fashion is reduced. This practice can circumvent restrictions imposed by the available sprayer capacity. However, most of the growers do not use this tactic since they have sufficient equipment for their orchard size. They have matched the needed machinery to the desired controls and/or have needed to match a control to the existing machinery. It was noted that at least one of the growers used a duster in some cases when he was in a hurry since he could cover the orchard faster, spray in the wind and the diesel fuel costs were substantially less.

Each block will have "hot spots" which usually require extra attention. The size and frequency of the hot spots in each block may result in differential treatment of the various blocks. Hot spots could be caused by the differences within the orchard as to site, micro-climate, wind pattern, age and variety of trees, water table, etc.

6) Factors that were selected by the growers as being the most important for the control of mites were last year's experience with mites in their own orchard, the relative probability that new controls will prevent substantial damage and the costs of alternative chemicals. Of secondary importance was the apple variety. Apple prices and the decision to sell the harvested fruit in the fresh as opposed to the processed market were deemed as being relatively unimportant. It was mentioned by one of the growers that possible disruptions of mite/predator relationships influenced his control selection. He used oil with occasional sprays of Plictran because of a) problems with resistance; b) oil helped control San Jose Scale as well; and c) it avoided problems with the predator/prey relationships.

7) Codling moth was not perceived by the growers as being much of a problem in their area.

8) The factors selected by the growers as being the most important in apple scab control were:

a) expected weather pattern
b) relative probability that control will prevent substantial damage
c) weather experienced to date in the season
d) experience in neighboring orchards
e) apple variety
f) costs of alternative controls
g) the amount of time needed to cover orchard with spray.

Prices, yields and toxic residues will not be regarded as being very influential. One grower stated that regardless of the price or effectiveness of difolatan he refused to use it since it caused discomfort for his workers and it was not worth the risk of labor problems.

Most of the growers commonly use a mix of protectant and eradicant programs. They may apple a protectant spray on one side, every other row and then eradicate as problems arise. Frequently mentioned chemicals used were polyram, cyprex, captan and benlate.

9) All the growers indicated that they routinely used traps but that this year there was a problem in the availability pheromone.

10) These growers had hired a consultant to help with the pest management so they indicated that they occasionally inspected their orchards with an "outside expert" as well as with extension personnel. Inspections were never done with chemical company/distributor representatives.

11) Resistance has been a problem experienced by all of the growers. One grower pointed out that when he had poor success with controlling a pest

with whatever he had used in the past or knew of someone who had better success with a new control, he switched without necessarily diagnosing a resistance problem.

Mite resistance was cited as a problem which has been addressed by rotating chemicals and by shifting to an oil/vydate (after bloom) schedule. Occasionally, chemicals may be combined to control resistant scab strains. Frequently this is accomplished indirectly by applying different chemicals in different stages of the season or as the weather pattern changes (i.e., pre-bloom use of cyprex or polyram and post-bloom use of captan and benlate--influenced by the weather).

RISK PREFERENCE RESULTS

Grower No.	Income Level		
	$0	$4000	$14,000
1	(.0000, -.0005	(-.0001, -.001)	(.0006, .0001)
2	(∞, .001)	(∞, .001)	(.0006, .0001)
3	(∞, .001)	(-.0001, -.001)	(-.0001, -.001)
4	(.001, .0003)	(.0006, .0001)	(.0000, -.0005)
5	(.0003, .0000)	(∞, .001)	(.0006, .0001)
6	(∞, .001)	(∞, .001)	(∞, .001)

In comparing the results of this small group of apple growers to studies on farmers of various enterprises the only real conclusion is that the preferences of both groups are hetergenous but their preference measures fall in about the same range. The fruit growers may appear slightly more conservative since they exhibit a smaller proportion of negative coefficients and a larger proportion of highly positive coefficients. It should be noted that the larger survey asked the respondents to make four pairwise comparisons while the fruit grower survey involved only three comparisons. This resulted in wider intervals for the shorter survey and explains why coefficients of $+\infty$ appear for the fruit growers but not in the Carman or Love surveys.

APPENDIX IV

LISTING OF PROGRAM

```
      SUBROUTINE SELECT (IGO,I)
      LOGICAL DEBUG,MOTH,MITE,SCAB,IWSCOUT,HSPRAY
      COMMON /DB/ DEBUG,MOTH,MITE,SCAB,IWSCOUT,HSPRAY,INTSCT
      COMMON /INT/ GPP,SCMPOP
      COMMON /DATE/ IDAY,JDAY,IYR,ISTRAT,JSTRAT,KSTRAT,IPART
      IF(I.EQ.2) GO TO 100
C SELECT WHICH MODELS ARE TO BE OPERATED
      SCAB=.FALSE.
      MITE=.TRUE.
      MOTH=.FALSE.
C SELECT WHETHER REVISED MITE DECISION WILL BE USED
      HSPRAY=.TRUE.
C SELECT WHETHER WEEKLY SCOUTING WILL BE USED
      IWSCOUT = .TRUE.
C SELECT THE SCOUTING INTERVAL
      INTSCT = 7
C SELECT INITIAL MOTH POP LEVEL (LOW-0.1, MED-1.0, HI -10.0)
      SCMPOP=1.0
C SELECT THE GROWER PROBLEM PERCEPTION FOR MITES
      GPP=9.0
C
C SELECT STRATEGY COMBINATIONS
100   CONTINUE
      IGO = 0
C     IF(ISTRAT.EQ.5.AND.KSTRAT.EQ.2.AND.JSTRAT.EQ.2) IGO = 1
C     IF(ISTRAT.EQ.5.AND.KSTRAT.EQ.2.AND.JSTRAT.EQ.1)IGO = 1
C     IF(ISTRAT.EQ.5.AND.KSTRAT.EQ.3.AND.JSTRAT.EQ.2) IGO=1
C     IF(ISTRAT.EQ.5.AND.KSTRAT.EQ.12.AND.JSTRAT.EQ.1)IGO = 1
C     IF(ISTRAT.EQ.5.AND.KSTRAT.EQ.12.AND.JSTRAT.EQ.13) IGO=1
CC    IF(KSTRAT.GT.0) IGO=1
CC    IF(JSTRAT.GT.3.AND.JSTRAT.LT.8) IGO=1
CC    IF(JSTRAT.GT.10.AND.JSTRAT.LT.15) IGO=1
C     IF(ISTRAT.EQ.5.AND.KSTRAT.EQ.13.AND.JSTRAT.EQ.1) IGO = 1
C     IF(ISTRAT.EQ.5.AND.KSTRAT.EQ.13.AND.JSTRAT.EQ.13)IGO = 1
C     IF(ISTRAT.EQ.7.AND.KSTRAT.EQ.2.AND.JSTRAT.EQ.1) IGO=1
C     IF(ISTRAT.EQ.7.AND.KSTRAT.EQ.2.AND.JSTRAT.EQ.2)IGO = 1
C     IF(ISTRAT.EQ.7.AND.KSTRAT.EQ.3.AND.JSTRAT.EQ.2) IGO=1
C     IF(ISTRAT.EQ.7.AND.KSTRAT.EQ.12.AND.JSTRAT.EQ.1)IGO = 1
C     IF(ISTRAT.EQ.7.AND.KSTRAT.EQ.12.AND.JSTRAT.EQ.13) IGO=1
C     IF(ISTRAT.EQ.7.AND.KSTRAT.EQ.13.AND.JSTRAT.EQ.1) IGO = 1
C     IF(ISTRAT.EQ.7.AND.KSTRAT.EQ.13.AND.JSTRAT.EQ.13)IGO = 1
C     IF(ISTRAT.EQ.8.AND.KSTRAT.EQ.2.AND.JSTRAT.EQ.2) IGO = 1
C     IF(ISTRAT.EQ.8.AND.KSTRAT.EQ.3.AND.JSTRAT.EQ.2)IGO = 1
C     IF(ISTRAT.EQ.8.AND.KSTRAT.EQ.2.AND.JSTRAT.EQ.1) IGO=1
C     IF(ISTRAT.EQ.8.AND.KSTRAT.EQ.12.AND.JSTRAT.EQ.1)IGO = 1
C     IF(ISTRAT.EQ.8.AND.KSTRAT.EQ.4.AND.JSTRAT.EQ.13) IGO=1
C     IF(ISTRAT.EQ.8.AND.KSTRAT.EQ.13.AND.JSTRAT.EQ.1) IGO = 1
C     IF(ISTRAT.EQ.8.AND.KSTRAT.EQ.13.AND.JSTRAT.EQ.13)IGO = 1
C     IF(ISTRAT.EQ.5.AND.JSTRAT.EQ.13) IGO=1
C     IF(ISTRAT.EQ.7.AND.JSTRAT.EQ.13) IGO=1
C     IF(ISTRAT.EQ.8.AND.JSTRAT.EQ.13) IGO=1
C     IF(ISTRAT.EQ.5.AND.JSTRAT.EQ.2) IGO=1
C     IF(ISTRAT.EQ.7.AND.JSTRAT.EQ.2) IGO=1
C     IF(ISTRAT.EQ.8.AND.JSTRAT.EQ.2) IGO=1
       IF(JSTRAT.EQ.2) IGO= 1
       IF(JSTRAT.GT.3.AND.JSTRAT.LT.15) IGO = 1
       IF(JSTRAT.EQ.6) IGO=0
        IF(JSTRAT.GT.7.AND.JSTRAT.LT.11) IGO=0
      RETURN
      END
```

```
      PROGRAM APPEST (TAPE1,OUTPUT,TAPE4)
C
C
C APPLE PEST MODEL
C  SIMULATES ACTION OF SCAB, MITE AND CODDLING MOTH
C  OVER 20-YEAR PERIOD FOR VARIOUS CONTROL STRATEGIES
C
C
C  SUBROUTINES:
C INITIALIZATIONS
C    GETWET   - GETS NATURE DATA
C    INIT     - INITIALIZES VARIABLES ANNUALLY
C TREES
C    STAGE    - DETERMINES STAGE OF GROWTH
C    FROST    - CALCULATES FROST DAMAGE FOR DAY
C SCAB
```

```
C     SCABINF - DETERMINES LEVEL OF SCAB INFECTION FOR DAY
C     APPLY   - IMPLEMENTS SPRAYING STRATEGY
C     SCABDAM - CALCULATES YIELD LOSSES AND APPLIES SPECIAL SPRAY (CALLS
C  RESULTS
C     ECON    - CALCULATES ANNUAL LOSS, COST, AND REVENUE
C     STATS   - CALCULATES MEANS AND SDS (CALLS CALC)
C
C  VARIABLE ISTAGE INDICATES GROWTH STAGE OF TREE:
C   1 = THROUGH GREEN TIP
C   2 = GREEN TIP TO 1/2" GREEN
C   3 = 1/2" GREEN TO TIGHT CLUSTER
C   4 = TIGHT CLUSTER TO PINK
C   5 = PINK TO BLOOM
C   6 = BLOOM TO PETAL FALL
C   7 = AFTER PETAL FALL
C
C  ARRAY IPRO INDICATES DAYS OF PROTECTION FOR:
C   (1) - FULL DIFOL
C   (2) - REDUCED DIFOL
C   (3) - HALF CAPTAN
C   (4) - FULL CAPTAN
C   (5) - BENLATE
C  (6)  - 1/3 STRENGTH PLICTRAN
C   (7) -   1/2 STRENGTH PLICTRAN
C   (8) - FULL STRENGTH PLICTRAN
C   (9) - FULL STRENGGTH CARZOL
C   (10) - PYRETHROID TREATMENT FOR CODLING MOTH
C  (11) - BENLATE IMPACTS ON MITES
C  (12) - GUTHION
C
C  ARRAYS INFLEV AND INFPER INDICATE INFECTION LEVEL
C   (O=NONE,1=LIGHT,2=MODERATE,3=HEAVY) AND INFECTION PERIOD
C   (O=NO,1=YES) RESPECTIVELY FOR:
C   (1) - TODAY
C   (2) - YESTERDAY
C   (3) - DAY BEFORE YESTERDAY
C
       LOGICAL DEBUG,MOTH,MITE,SCAB,IWSCOUT,HSPRAY
       COMMON /NATURE/ YIELD(20),FPRICE(20),PPRICE(20),PREC(168,20),
     + ATEMP(168,20),DDAYS,TODDAYS,SDDAYS(20),NETREV(20)
       COMMON /ACCUM/ STRATS(20),STRATSS(20),GRANDS(20),GRANDSS(20),
     + NSTRAT,NGRAND,NACCUM
       COMMON /TREE/ ISTAGE,FDFRUIT,SDFRUIT,CDFRUIT,DMFRUIT,TYIELD
       COMMON/CMSCOUT/ THEAT,MOTHKIL,MSPRAY,ECM1,ECM2,ECM3,
     +CMLEVEL,LUCK,CMLOSS,ITERAT,OLD,WORMAPL
       COMMON /SCABDAT/ INFLEV(3),INFPER(3),NINF
       COMMON /CHEMS/  BENLATE,CAPTAN,DIFOL
     + ,PLICTRN,CARZOL,GUTHION,PYRTHRD,IPRO(12),NSPRAY,MISSSP,NEXTSP
       COMMON /DATE/ IDAY,JDAY,IYR,ISTRAT,JSTRAT,KSTRAT,IPART
       COMMON /DB/ DEBUG,MOTH,MITE,SCAB,IWSCOUT,HSPRAY,INTSCT
       DATA NSTRAT,NGRAND /2*0/
       DATA NEXTSP /999/
       DATA NSCAB,NMITE,NMOTH /11,17,19/
       NACCUM = 20
       DO 10 I=1,NACCUM
       STRATS(I)=0.0
       STRATSS(I)=0.0
       GRANDS(I)=0.0
       GRANDSS(I)=0.0
 10    CONTINUE
       DEBUG=.FALSE.


       NYEAR=20
       MISSSP = 0
C      IF(DEBUG)NYEAR=10
       CALL SELECT (IGO,1)
       IF(.NOT.MOTH)NMOTH = 1
       IF(.NOT.SCAB)NSCAB = 1
       IF(.NOT.MITE)NMITE = 1
       IF(SCAB.OR.MITE.OR.MOTH)GO TO 20
       PRINT 900
       STOP
 20    CONTINUE
C
C   GET NATURE DATA
       CALL GETWET
C
C   BEGIN STRATEGY LOOP
  100 DO 500 ISTRAT = 1,NSCAB
       DO 500 JSTRAT = 1,NMITE
```

```
      DO 500 KSTRAT = 1,NMOTH
      CALL SELECT (IGO,2)
      IF(IGO.EQ.0)GO TO 500
C
C     IF(ISTRAT.NE.3.OR.JSTRAT.NE.7) GO TO 500
      CALL RANDOM
      IF(MITE) CALL MSTRAT
       IF(MOTH) CALL CMSTRAT
      PRINT 1000, ISTRAT,JSTRAT,KSTRAT
      PRINT 1200
      DEBUG=.FALSE.
C
C  BEGIN ANNUAL LOOP
      DO 400 IYR = 1,NYEAR
      CALL INIT
      TYIELD = YIELD(IYR)
       CALL CMINIT
      DDAYS=SDDAYS(IYR)
C
C  BEGIN DAILY LOOP
      DO 300 JDAY = 90,245
      IDAY = JDAY - 89
      DEBUG=.FALSE.
C     IF(IYR.EQ.1.AND.ISTRAT.EQ.1) DEBUG=.TRUE.
C     DEBUG=.TRUE.
C     IF(JDAY.GT.213) DEBUG=.FALSE.
C     IF(JDAY.GT.205) DEBUG=.FALSE.
      CALL DDAY
      CALL STAGE
C     CALL FROST
      IF(ISTAGE.EQ.8.AND.MOTH) CALL CODMOTH(ATEMP(IDAY,IYR),
     + TYIELD)
      IF(SCAB)CALL SCABINF
      CALL ATTEN
      IF(JDAY.LT.237.AND.SCAB)CALL APPLY
      IF(JDAY.LE.244.AND.MITE)CALL MITECON
      IF(SCAB) CALL SCABDAM
      IF(.NOT.MOTH.AND.JDAY.GT.244) GO TO 300
      IF(MITE.AND.IWSCOUT.OR.MOTH) CALL SCOUT(IDAY,JSTRAT)
      IF(IWSCOUT.AND.MITE) CALL MMORT
      IF(DEBUG)PRINT 9000,ISTRAT,IYR,JDAY,ATEMP(IDAY,IYR),
     + PREC(IDAY,IYR),DDAYS,ISTAGE,INFLEV,INFPER,IPRO,NEXTSP,NSPRAY,
     + SDFRUIT,FDFRUIT,BENLATE,CAPTAN,DIFOL
9000  FORMAT(" DAILY: ",I1,I2,I4,F4.1,F4.2,F4.0,21I3,5F8.2)
300   CONTINUE
C  END DAILY LOOP
C
       CALL ECON
400   CONTINUE
C  END ANNUAL LOOP
C
      CALL STATS(1)
C
      WRITE(4,5000) KSTRAT,NETREV
5000  FORMAT(2X,I2,20I6)
500   CONTINUE
C  END STRATEGY LOOP
C
      PRINT 1100


C
C FINAL STATS
      PRINT 1200
      CALL STATS(2)
C
C     IF(.NOT.SCAB) STOP "END OF DEBUG"
C     SCAB=.FALSE.
C     NSCAB=3
C     GO TO 100
900   FORMAT(1H1," ALL MODELS DISABLED. CHECK VALUES OF MITE,MOTH,SCAB")
1000  FORMAT(15H1SCAB STRATEGY ,I2 /
     + 15H MITE STRATEGY ,I2/
     + 15H MOTH STRATEGY ,I2 //)
1100  FORMAT(1H1," STATISTICS FOR ALL STRATEGIES COMBINED"//)
1200  FORMAT(53H  PREDICTED  FROST  SCAB   MOTH    NET   FRESH   PROC
     + 54H  MITE  TOTAL NUMBER BEN- CAP-       PLIC-  CAR- GUTH-
     + 27H  PYR-  CONTROL  PROD   NET /
     + 53H      YIELD  DAMAGE DAMAGE DAMAGE  YIELD  PRICE  PRICE
     + 54H DAMAGE REVENUE OF   LATE  TAN  DIFOL TRAN   ZOL   ION
     + 29H ETHROID  COSTS COSTS REVENUE /
```

```
     + 5H YEAR,5(7H (BU)  ),3(7H  ($)  ),6H  ($),6HSPRAYS,5H (OZ) ,
     + 6H (LB) ,6H (GL) ,4(6H (LB) ),1X,3(7H  ($)  ) /
     + 1H ,6H------,13(10H----------))
      END
```

CARD NR.	SEVERITY	DETAILS	DIAGNOSIS OF PROBLEM
94	I		CONTROL VARIABLE IN COMMON OR EQUIVALENCED, OPTIMIZATION MAY BE INHIBITED.
95	I		CONTROL VARIABLE IN COMMON OR EQUIVALENCED, OPTIMIZATION MAY BE INHIBITED.
96	I		CONTROL VARIABLE IN COMMON OR EQUIVALENCED, OPTIMIZATION MAY BE INHIBITED.
109	I		CONTROL VARIABLE IN COMMON OR EQUIVALENCED, OPTIMIZATION MAY BE INHIBITED.
116	I		CONTROL VARIABLE IN COMMON OR EQUIVALENCED, OPTIMIZATION MAY BE INHIBITED.

```
      SUBROUTINE GETWET
C
C READS IN WEATHER,YIELD, AND PRICE DATA
C CARD TYPE (IT) 1 = TEMP, 2 = PRECIPITATIN, 3 = YIELD,
C                  4 = FRESH PRICE, 5 = PROCESSED PRICE.
C
      LOGICAL DEBUG,MOTH,MITE,SCAB,IWSCOUT,HSPRAY
      COMMON /DB/ DEBUG,MOTH,MITE,SCAB,IWSCOUT,HSPRAY,INTSCT
      COMMON /NATURE/ YIELD(20),FPRICE(20),PPRICE(20),PREC(168,20),
     + ATEMP(168,20),DDAYS,TODDAYS,SDDAYS(20),NETREV(20)
      DIMENSION DAT(21)
      DATA ATEMP,PREC /6720*-99./
      DATA YIELD,FPRICE,PPRICE /60*-99./
C J = YEAR, K = FIRST DAY (JULIAN)
1     READ(1,1000)IT,J,K,DAT
1000  FORMAT(I1,2I3,21F5.0)
      IF(EOF(1))500,3
3     IF(IT.GE.1.AND.IT.LE.5)GO TO 5
      PRINT *," CARD TYPE OUT OF RANGE:  ",IT
      STOP
5     GO TO (10,20,30,40,50), IT
C TEMP DATA
C NOTE: ATEMP AND PREC ARE INDEXED SUCH THAT ATEMP(1,YR) IS 90TH DAY OF
10    CONTINUE
      DO 15 I=1,21
      L=I+K - 90
15    ATEMP(L,J)=DAT(I)
      GO TO 1
C PREC DATA
20    CONTINUE
      DO 25 I=1,21
      L=I+K - 90
25    PREC(L,J)=DAT(I)
      GO TO 1
C YIELD DATA
30    CONTINUE
      DO 35 I=1,20
35    YIELD(I)=DAT(I) + 0.0
      GO TO 1
C FRESH PRICE
40    CONTINUE
      DO 45 I=1,20
45    FPRICE(I)=DAT(I)
      GO TO 1
C PROCESSED PRICE
50    CONTINUE
      DO 55 I=1,20
55    PPRICE(I)=DAT(I)
      GO TO 1
C
C CALCULATE STARTING DDAYS (SDDAYS) FOR EACH YEAR
500   DO 75 I=1,20
      R1=RANF(-1)
      R2=RANF(-1)
      Z=((-2.*ALOG(R1))**.5)*COS(6.2832*R2)
      SDDAYS(I)=580. + 80.*Z
75    CONTINUE
C
C CHECK NATURE
      DO 100 I=1,168
      DO 100 J=1,20
      IF(ATEMP(I,J).EQ.-99.)GO TO 910
      IF(PREC(I,J).EQ.-99.)GO TO 920
100   CONTINUE
```

```
C CHECK OTHERS
      DO 200 I=1,20
      IF(YIELD(I).EQ.-99.)GO TO 930
C  SET THE YIELD EQUAL TO 500 SINCE FROST AND PEST DAMAGE ACCOUNT
C  FOR VARIANCE IN YIELD.
C     YIELD(I) =  500.
      IF(FPRICE(I).EQ.-99.)GO TO 940
      IF(PPRICE(I).EQ.-99.)GO TO 950
200   CONTINUE
C
C CALL MITE INIT
      IF(MITE)CALL INTMITE
      RETURN


C
C ERROR MESSAGES
910   PRINT *," INCOMPLETE TEMP DATA:  YEAR ",J,", DAY ",I
      STOP
920   PRINT *," INCOMPLETE PREC DATA:  YEAR ",J,", DAY ",I
      STOP
930   PRINT *," INCOMPLETE YIELD DATA"
      STOP
940   PRINT *," INCOMPLETE FPRICE DATA"
      STOP
950   PRINT *," INCOMPLETE PPRICE DATA"
      STOP
      END


      SUBROUTINE RANDOM
      COMMON /RANSEED/IRAN(5)
C
C SETS SEEDS FOR 4 RANDOM SERIES:
C (1) = SCAB INFECTION
C (2) = SCAB DAMAGE
C (3) = MITE PERCEPTION ERROR
C (4) = MITE MONITORING ERROR
      IRAN(1)=10HABCDEFGHIJ
      IRAN(2)=10HYZXWVUTSRQ
      IRAN(3)=10HAZBYCXDWEV
      IRAN(4)=10HZAYBXCWDVE
      IRAN(5)=10HMNOPQRSTUV
      RETURN
      END


      FUNCTION SRANF(I)
      COMMON /RANSEED/ IRAN(5)
C SETS SEED TO RANDOM SERIES I, GETS RANDOM NUMBER (SRANF),
C  AND SAVES NEW SEED
      CALL RANSET (IRAN(I))
      SRANF = RANF(-1)
      CALL RANGET (IRAN(I))
      RETURN
      END


      SUBROUTINE INIT
C
C  ANNUAL INITIALIZATIONS
C
      COMMON /NATURE/ YIELD(20),FPRICE(20),PPRICE(20),PREC(168,20),
     + ATEMP(168,20),DDAYS,TODDAYS,SDDAYS(20),NETREV(20)
      COMMON /TREE/ ISTAGE,FDFRUIT,SDFRUIT,CDFRUIT,DMFRUIT,TYIELD
      COMMON /SCABDAT/ INFLEV(3),INFPER(3),NINF
      COMMON /CHEMS/  BENLATE,CAPTAN,DIFOL
     + ,PLICTRN,CARZOL,GUTHION,PYRTHRD,IPRO(12),NSPRAY,MISSSP,NEXTSP
      COMMON/MITEDAT/SAER(20),SAAF(20),IAFD(20),IERD(20),
     + AER,AAF,EPY,AFFFR,YY,AFFCON,ERINJ(3),CON,
     + EMX,ELPDPO(10),ERI(10),AFI(10)
      COMMON/MITEDA2/IECTH1,IECTH2,X,NSCOUT,NX,KONN,
     + IPC,IERROR,KEMX,SCCOST
C
C
      ISTAGE = 1
C
      NINF = 0
      DO 20 I=1,3
      INFLEV(I)=0
20    INFPER(I)=0
```

```
C
      DO 30 I=1,12
30    IPRO(I) = 0
      NEXTSP = 999
      NSPRAY = 0
      SCCOST=0.0
C
      PLICTRN = 0.0
      CARZOL  = 0.0
      GUTHION = 0.0
      PYRTHRD = 0.0
      BENLATE = 0.0
      DIFOL   = 0.0
      CAPTAN  = 0.0
      SDFRUIT = 0.0
      FDFRUIT = 0.0
      CDFRUIT = 0.0
      DMFRUIT = 0.0
C
C
C MITE INITIALIZATIONS
      DO 1030 MY=1,3
      ERINJ(MY)=0.
 1030 CONTINUE
      YY=0.
      EMX=-1.
      AFFCON=0.0
      DO 1700 I=1,10
      ERI(I)=0.0
 1700 CONTINUE
      AER=0.
      AAF=0.
      CON=0.
      KONN=0
      NX=8
      EPY=0.0
      AFFFR=0.
      NSCOUT=0
      EPY=AER*1.107
       KEMX=0
      RETURN
      END

      SUBROUTINE ATTEN
C
C  REDUCES DAYS OF PROTECTION (IPRO) FOR ALL CHEMICALS DAILY
C
      COMMON /TREE/ ISTAGE,FDFRUIT,SDFRUIT,CDFRUIT,DMFRUIT,TYIELD
      COMMON /CHEMS/  BENLATE,CAPTAN,DIFOL
     + ,PLICTRN,CARZOL,GUTHION,PYRTHRD,IPRO(12),NSPRAY,MISSSP,NEXTSP
      DO 10 I=3,12
      IPRO(I) = IPRO(I) - 1
      IF(IPRO(I) .LT. 0) IPRO(I) = 0
10    CONTINUE
C
C FOR DIFOL, SPRAY IS ACTIVE UNTIL PINK FOR HALF AND PETAL FALL FOR FULL
      IF(ISTAGE.GE.5)IPRO(2)=0
      IF(ISTAGE.GE.7)IPRO(1)=0
      RETURN
      END

      SUBROUTINE DDAY
C
C ACCUMULATE DEGREE DAYS (BASE 43) USING AVG TEMP
C
      COMMON /NATURE/ YIELD(20),FPRICE(20),PPRICE(20),PREC(168,20),
     + ATEMP(168,20),DDAYS,TODDAYS,SDDAYS(20),NETREV(20)
      COMMON /DATE/ IDAY,JDAY,IYR,ISTRAT,JSTRAT,KSTRAT,IPART
      TODDAYS = ATEMP(IDAY,IYR)-43.
      IF(TODDAYS)10,10,20
10    RETURN
20    CONTINUE
      IF(TODDAYS.GT.43.)TODDAYS = 43
      DDAYS = DDAYS + TODDAYS
      RETURN
      END

      SUBROUTINE STAGE
```

```
C
C FINDS STAGE OF GROWTH OF TREE (ISTAGE) AS FUNCTION OF
C  DEGREE DAYS (DDAYS)
      COMMON /TREE/ ISTAGE,FDFRUIT,SDFRUIT,CDFRUIT,DMFRUIT,TYIELD
      COMMON /DATE/ IDAY,JDAY,IYR,ISTRAT,JSTRAT,KSTRAT,IPART
      COMMON /NATURE/ YIELD(20),FPRICE(20),PPRICE(20),PREC(168,20),
     + ATEMP(168,20),DDAYS,TODDAYS,SDDAYS(20),NETREV(20)
      IF(ISTAGE.GE.8) RETURN
      GO TO (10,20,30,40,50,60,70),ISTAGE
C ISTAGE = 1:  THROUGH GREEN TIP
10    IF(DDAYS.LT.700.)RETURN
C ISTAGE = 2:  GREEN TIP THROUGH 1/2" GREEN
      ISTAGE = 2
20    IF(DDAYS.LT.750.)RETURN
C ISTAGE = 3:  1/2" GREEN THROUGH TIGHT CLUSTER
      ISTAGE = 3
30    IF(DDAYS.LT.800.)RETURN
C ISTAGE = 4:  TIGHT CLUSTER THROUGH PINK
      ISTAGE = 4
40    IF(DDAYS.LT.900)RETURN
C ISTAGE = 5:  PINK THROUGH BLOOM
      ISTAGE = 5
50    IF(DDAYS.LT.1000)RETURN
C ISTAGE = 6:  BLOOM THROUGH PETAL FALL
      ISTAGE = 6
60    IF(DDAYS.LT.1100)RETURN
C ISTAGE = 7:  AFTER PETAL FALL
      ISTAGE = 7
      IPF=JDAY
      RETURN
70    CONTINUE
      IF((JDAY-IPF).GT.7)ISTAGE=8
      END
```

```
      SUBROUTINE FROST
C
C CALCULATES FROST DAMAGE DAILY AS FUNCTION OF TEMP AND STAGE
C  ASSUMES MINIMUM TEMP 10 DEGREES BELOW AVERAGE
C
      COMMON /NATURE/ YIELD(20),FPRICE(20),PPRICE(20),PREC(168,20),
     + ATEMP(168,20),DDAYS,TODDAYS,SDDAYS(20),NETREV(20)
      COMMON /TREE/ ISTAGE,FDFRUIT,SDFRUIT,CDFRUIT,DMFRUIT,TYIELD
      COMMON /DATE/ IDAY,JDAY,IYR,ISTRAT,JSTRAT,KSTRAT,IPART
      DIMENSION AI(6),BI(6)
      DATA AI /12.75,30907.,1.125E8,1.512E9,9.313E13,1.777E16/
      DATA BI /.306,.5744,1.25,1.14875,1.14875,1.31286/
C
      DATA TLOW /7.0/
C NO DAMAGE AFTER PETAL FALL
      IF(ISTAGE.GE.7)RETURN
      DAMPER = 1./(1.+AI(ISTAGE)*EXP(-BI(ISTAGE)
     + * (ATEMP(IDAY,IYR)-TLOW)))
      IF(DAMPER.GT..99)RETURN
      IF(DAMPER.LT..25) DAMPER=.25
      FD =  (1. - DAMPER) * TYIELD
      TYIELD = TYIELD - FD
      FDFRUIT = FDFRUIT + FD
      IF(TYIELD.LT.0.)TYIELD = 0.
      RETURN
      END
```

```
      SUBROUTINE SCABINF
C
C FINDS SCAB INFECTION LEVEL (INFLEV) AS FUNCTION OF PREC AND ATEMP
C      SCABINF=0 - NONE, 1 - LIGHT, 2 - MODERATE, 3 - HEAVY
C ALSO UPDATES INFPER (INFECTION PERIOD FLAG)
C
      COMMON /NATURE/ YIELD(20),FPRICE(20),PPRICE(20),PREC(168,20),
     + ATEMP(168,20),DDAYS,TODDAYS,SDDAYS(20),NETREV(20)
      COMMON /CHEMS/  BENLATE,CAPTAN,DIFOL
     + ,PLICTRN,CARZOL,GUTHION,PYRTHRD,IPRO(12),NSPRAY,MISSSP,NEXTSP
      COMMON /SCABDAT/ INFLEV(3),INFPER(3),NINF
      COMMON /DATE/ IDAY,JDAY,IYR,ISTRAT,JSTRAT,KSTRAT,IPART
      DIMENSION TLEV(3),PLEV(5),PROB(3,25,3)
      DATA TLEV /45.,55.,65./
      DATA PLEV /.01,.1,.3,.5,1.0/
      DATA ((PROB(I,J,1),I=1,3),J=1,25)/
     + 1.0,1.0,1.0,  1.0,1.0,1.0,  1.0,1.0,1.0,  1.0,1.0,1.0,
     +.938,1.0,1.00,  .911,.973,1.00,  .927,.958,.979,  .941,.971,1.00,
```

```
     +.821,.929,.964,  .861,.945,.945,  .845,.921,.979,  .875,.958,.958,
     +.750,.833,.833,  .791,.833,.875,  .750,.875,.979,  .833,.958,1.00,
     +.750,1.00,1.00,  .778,.917,.972,  .750,.778,.945,  .875,1.00,1.00,
     +.769,.846,.885,  .875,.875,.875,  .750,.844,.906,  .750,.833,.833,
     + 1.00,1.00,1.00/
      DATA ((PROB(I,J,2),I=1,3),J=1,25)/
     +  .806,.945,.973,  .778,.841,.936,  .810,.953,1.0,
     + .833,.958,.958,  .750,1.00,1.00,  .643,.668,.775,  .708,.833,.916
     +,.765,.883,1.00,  .286,.715,.858,  .444,.777,.777,  .385,.693,.924
     +,.500,.833,.833, 0.00,.333,.333,  .167,.333,.500, 0.00,.500,.917
     +,.333,.833,1.00, 0.00,1.00,1.00,  .111,.666,.888, 0.00,.111,.778
     +,.500,1.00,1.00,  .076,.384,.538,  .500,.500,.500, 0.00,.375,.625
     +,0.00,.333,.333,  .875,.875,.875/
      DATA ((PROB(I,J,3),I=1,3),J=1,25)/
     + 1.0,1.0,1.0,  1.0,1.0,1.0,  1.0,1.0,1.0,  1.0,1.0,1.0,
     +.875,1.00,1.00,  .820,.945,1.00,  .855,.917,.959,  .882,.941,1.00,
     +.643,.857,.929,  .723,.889,.889,  .689,.843,.959,  .750,.917,.917,
     +.500,.667,.667,  .583,.667,.750,  .500,.750,.959,  .667,.917,1.00,
     +.500,1.00,1.00,  .556,.833,.945,  .500,.555,.889,  .750,1.00,1.00,
     +.538,.692,.769,  .500,.500,.500,  .500,.687,.813,  .500,.667,.667,
     + 1.00,1.00,1.00/
C THE VARIABLE PROB IS THE PROBABILITY OF AN INFECTION - IT IS A THREE
C DIMENSIONAL ARRAY WITH THE FIRST DIMENSION THE INFECTION LEVEL, THE SE
C DIMENSION BEING THE WEATHER CATEGORY AND THE LAST DIMENSION IS THE PAR
C PART OF THE SEASON.
      IF(JDAY.GT.96) GOTO 5
      LEVEL=0
      ICAT=1
      GO TO 300
    5 ICAT=25
      R= SRANF(1)
      LEVEL=0
C FIND PART OF SEASON
          JDAY = IDAY + 89
      IPART = 1
      IF(JDAY.LT.121)GO TO 1
      IPART = 2
      IF(JDAY.LT.167)GO TO 1
      IPART = 3
      IF(JDAY.LT.213)GO TO 1
      IPART = 4
    1     CONTINUE
      IF(ATEMP(IDAY,IYR).LE.35.) GO TO 100
C FIND TEMP CATEGORY
      DO 10 IT=1,3
      IF(ATEMP(IDAY,IYR).LT.TLEV(IT)) GO TO 20
10    CONTINUE
      IT = 4
C FIND PREC CATEGORY
20    DO 30 IP=1,5
      IF(PREC(IDAY,IYR).LT.PLEV(IP)) GO TO 50
30    CONTINUE
      IP = 6
C FIND ICAT
50    ICAT=(IP - 1) * 4 + IT
      IF(ICAT.GE.1.AND.ICAT.LE.25)GO TO 100
      PRINT *," ICAT OUT OF RANGE:  ",ICAT,".   TEMP =  ",
     + ATEMP(IDAY,IYR),".   RAIN =  ",PREC(IDAY,IYR)
      STOP


C  CHECK SPRAY EFFECTS  ON INFECTION LEVEL
  100 IF(IPART.EQ.4.AND.NINF.LE.2)GO TO 300
      DO 101 I=1,5
      IF(IPRO(I).GT.0)GO TO 300
101     CONTINUE
C
C USE ICAT AND PROB TO FIND INFECTION   BASED ON RANDOM NUMBER, R
103   CONTINUE
      K=IPART
      IF(K.EQ.4)K=2
      DO 110 I=1,3
      IF(R.LT.PROB(I,ICAT,K)) GO TO 120
110   CONTINUE
      LEVEL = 3
      GO TO 300
120   LEVEL = I - 1
C
C  BRING INFLEV UP TO DATE
300   INFLEV(3) = INFLEV(2)
      INFLEV(2) = INFLEV(1)
```

```
      INFLEV(1) = LEVEL
C
C  UPDATE INFPER (= 1 IF TEMP GT 36 AND PREC GT .01, I.E., ICAT GT 4)
C
      CONTINUE
      INF=0
      IF(ICAT.GT.4.AND.ICAT.NE.25)INF=1
      INFPER(3) = INFPER(2)
      INFPER(2) = INFPER(1)
      INFPER(1) = INF
C
C SET THE INFECTION PERIOD PREDICTOR EQUAL TO 0 IF BENLATE ACTIVE
      DO 350 I=1,3
  350 IF(IPRO(5).GT.2) INFPER(I)=0
      RETURN
      END


      SUBROUTINE APPLY
C
C  IMPLEMENTS SPRAYING STRATEGY ACCORDING TO ISTRAT
C
      COMMON /NATURE/ YIELD(20),FPRICE(20),PPRICE(20),PREC(168,20),
     + ATEMP(168,20),DDAYS,TODDAYS,SDDAYS(20),NETREV(20)
      COMMON /TREE/ ISTAGE,FDFRUIT,SDFRUIT,CDFRUIT,DMFRUIT,TYIELD
      COMMON /SCABDAT/ INFLEV(3),INFPER(3),NINF
      COMMON /CHEMS/  BENLATE,CAPTAN,DIFOL
     + ,PLICTRN,CARZOL,GUTHION,PYRTHRD,IPRO(12),NSPRAY,MISSSP,NEXTSP
      COMMON /DATE/ IDAY,JDAY,IYR,ISTRAT,JSTRAT,KSTRAT,IPART
      DATA MIDDLE /166/
C
C  WHICH STRATEGY?
      IDAY = JDAY - 89
      GO TO (100,200,300,300,500,300,700,200,900, 900,1000) ISTRAT
************************************************************************
C  STRATEGY 1 - DO NOTHING
100   CONTINUE
      RETURN
************************************************************************
C  STRATEGY 2 - DIFOL AT GREEN TIP, THEN CAPTAN EVERY 14 DAYS AFTER PF
C  STRATEGY 8 - SAME, BUT LOWER DIFOL DOSE
200   CONTINUE
      IF(JDAY.GT.90)GO TO 201
      IDIFOL = 1
      NEXT = 9999
      IF(ISTAGE.GE.2)GO TO 225
201   CONTINUE
C CHECK SPECIAL SPRAY FLAGS
      IF(NEXTSP.EQ.999.AND.MISSSP.EQ.0)GO TO 210
      NEXT = JDAY + 7
      RETURN
210   CONTINUE
C CHECK INFECTION LEVEL
      IF(INFLEV(3).LE.0)GO TO 215
      NEXT = 999
      RETURN
215   CONTINUE
      IF(ISTAGE.LT.2.AND.JDAY.GE.99) GO TO 220
      IF(ISTAGE - 2)290,220,220
C
C  PAST GREEN TIP
220   CONTINUE
      IF(IDIFOL.EQ.0) GO TO 230
C SPRAY DIFOL IF NECESSARY
      IF(PREC(IDAY,IYR).GE..02)RETURN
225   IDIFOL = 0
      IF(ISTRAT.EQ.2)DIFOL = DIFOL + 5
      IF(ISTRAT.EQ.8)DIFOL = DIFOL + 3
      IF(ISTRAT.EQ.2)IPRO(1)=1
      IF(ISTRAT.EQ.8)IPRO(2)=1
      NSPRAY = NSPRAY + 1
      RETURN
230   CONTINUE
      IF(ISTRAT.EQ.8) GO TO 233
      IF(ISTAGE - 7)290,250,250
  233 IF(ISTAGE - 5)290,250,250
C
C  PAST PETAL FALL
250   CONTINUE
      IF(NEXT.EQ.9999)NEXT = JDAY
      IF(PREC(IDAY,IYR).GE..02)RETURN
```

```
      IF(JDAY.GT.219.AND.NINF.LT.2)RETURN
      IF(JDAY.LT.NEXT)RETURN
      ICOVER=3
       IF(ISTRAT.EQ.8) ICOVER=5
      NEXT=JDAY + 7
      IF(IPART.GT.2)NEXT= JDAY + 14
      IF(NSPRAY.GT.ICOVER) GO TO 265
      IPRO(4)=14
       IF(IPART.LT.3) IPRO(4)=7
      IF(IPART.LT.3)IPRO(4)=7
      CAPTAN=CAPTAN + 8.0
      INFLEV(2)=0
      GO TO 275
265   IPRO(3)=14


      IF(IPART.LT.3)IPRO(3)=5
      CAPTAN = CAPTAN + 4
  275 NSPRAY = NSPRAY + 1
      INFLEV(1) = 0
290   RETURN
*************************************************************************
C  STRATEGY 3 - CAP EVERY 7 DAYS TIL MIDSEASON; THEN EVERY 14 DAYS
C  STRATEGY 4 IS SAME, BUT HALF DOSE
C STRATEGY 6 IS BENLATE AND CAPTAN IN COMBO SAME TIME
300   CONTINUE
      IF(JDAY.GT.90 )GO TO 301
      NEXT = 100
301   CONTINUE
C CHECK SPECIAL SPRAY FLAGS
      IF(NEXTSP.EQ.999.AND.MISSSP.EQ.0)GO TO 310
      NEXT = JDAY + 7
      RETURN
310   CONTINUE
C CHECK INFECTION LEVEL
      IF(INFLEV(3).LE.0)GO TO 315
      NEXT = 999
      RETURN
315   CONTINUE
      IF(JDAY.LT.NEXT)RETURN
      IF(PREC(IDAY,IYR).GT..02)RETURN
      IF(JDAY.GT.219.AND.NINF.LT.2)RETURN
      IF(IPART.LT.3)NEXT = JDAY + 7
      IF(IPART.GE.3)NEXT = JDAY + 14
      IF(ISTRAT-4)360,350,370
  350 IPRO(3)=14
      IF(IPART.LT.3) IPRO(3)= 5
      CAPTAN=CAPTAN + 4
      GO TO 380
  360 IPRO(4)=14
      IF(IPART.LT.3) IPRO(4)=7
      CAPTAN=CAPTAN + 8
      INFLEV(2)=0
      GO TO 380
  370 IPRO(5)=14
      IF(IPART.LT.3)  IPRO(5)=7
      IPRO(11)=14
      BENLATE=BENLATE + 12
      CAPTAN = CAPTAN + 4
      INFLEV(2)=0
      INFLEV(3)=0
  380 NSPRAY=NSPRAY + 1
      INFLEV(1)=0
      RETURN
*************************************************************************
C  STRATEGY 5 - APPLY BENLATE WHEN INFPER, UNLESS SPRAYED YESTERDAY
500   CONTINUE
      IF(JDAY.GT.219.AND.NINF.LT.2) RETURN
      IF(JDAY.GT.90)GO TO 510
      NEXT = 999
      IYEST = 0
510   CONTINUE
      IF(NEXTSP.NE.999.OR.MISSSP.EQ.1)RETURN
      IF(NEXT.LT.JDAY)GO TO 524
      IF(IYEST.NE.1)GO TO 520
      IYEST = 0
      RETURN
520   IF(INFPER(2).NE.1.AND.INFPER(3).NE.1)RETURN
      IF(IPRO(5).GE.1)RETURN
  524 IF(IPRO(5).GE.1) RETURN
      IF(PREC(IDAY,IYR).LE..02)GO TO 525
```

```
      NEXT = JDAY
      RETURN
525   CONTINUE
C  INFPER  (INFECTION PERIOD) - SPRAY
      NEXT = 999
      IYEST = 1
      IPRO(5) = 14
      IF(IPART.LT.3) IPRO(5)= 7
      IPRO(11)=14
      BENLATE = BENLATE + 16
      DO 530 I=1,3
530   INFLEV(I) = 0

      NSPRAY = NSPRAY + 1
      RETURN
************************************************************************
C  STRATEGY 7 - CAPTAN EVERY 7 DAYS; HALF DOSE AFTER MIDSEASON
700   CONTINUE
      IF(JDAY.GT.90)GO TO 701
      NEXT = 100
701   CONTINUE
C CHECK SPECIAL SPRAY FLAGS
      IF(NEXTSP.EQ.999.AND.MISSSP.EQ.0)GO TO 710
      NEXT = JDAY + 7
      RETURN
710   CONTINUE
C CHECK INFECTION LEVEL
      IF(INFLEV(3).LE.0)GO TO 715
      NEXT = 999
      RETURN
715   CONTINUE
      IF(JDAY.LT.NEXT)RETURN
      IF(PREC(IDAY,IYR).GT..02)RETURN
      IF(JDAY.GT.219.AND.NINF.LT.2)RETURN
      NEXT = JDAY + 7
      IF(ISTAGE.GE.7)NEXT= JDAY + 14
      IF(IPART.LT.3.AND.ISTAGE.GE.7) NEXT = JDAY +10
      NSPRAY = NSPRAY + 1
      IF(ISTAGE.GE.7) GO TO 725
      IPRO(4)=14
      IF(IPART.LT.3) IPRO(4)=7
      CAPTAN=CAPTAN + 8
      INFLEV(2)=0
      GO TO 750
  725 IPRO(3)=14
      IF(IPART.LT.3)IPRO(3)=5
      CAPTAN=CAPTAN + 4
       IF(IPART.LT.3.AND.ISTAGE.GE.7) CAPTAN=CAPTAN + 2
       IF(IPART.LT.3.AND.ISTAGE.GE.7) IPRO(3)=7
C THE ABOVE STATEMENT CORRECTS THE APPLICATION AT 1ST COVER TO BE 6LBS/ACRE
  750 INFLEV(1)=0
      RETURN
************************************************************************
C  STRATEGY 9 - DIFOL AT GREEN TIP, BENLATE AT INFPER AFTER PETAL FALL
C  STRATEGY 10 - SAME, BUT BENLATE AFTER PINK, LOW DIFOL DOSE
900   CONTINUE
      IF(JDAY.GT.219.AND.NINF.LT.2)RETURN
      IF(JDAY.GT.90)GO TO 901
      IDIFOL = 1
C IYEST = 1 INDICATES SPRAYED YESTERDAY
      NEXT = 999
      IYEST = 0
      IF(ISTAGE.GE.2)GO TO 925
901   CONTINUE
      IF(NEXTSP.NE.999.OR.MISSSP.EQ.1)RETURN
      IF(ISTAGE.LT.2.AND.JDAY.GE.99) GO TO 920
      IF(ISTAGE - 2)990,920,920
C
C  PAST GREEN TIP
920   CONTINUE
      IF(IDIFOL.EQ.0) GO TO 930
C  SPRAY DIFOL
      IF(PREC(IDAY,IYR).GT..02)RETURN
925   IDIFOL = 0
      IF(ISTRAT.EQ.9) DIFOL = DIFOL + 5
      IF(ISTRAT.EQ.10)DIFOL = DIFOL + 3
      IF(ISTRAT.EQ.9)IPRO(1) = 1
      IF(ISTRAT.EQ.10)IPRO(2) = 1
      NSPRAY = NSPRAY + 1
      RETURN
```

```
930    CONTINUE
       IF(ISTRAT.EQ.10)GO TO 935
C  STRATEGY 9
       IF(ISTAGE - 7)990,950,950
C  STRATEGY 10
935    IF(ISTAGE - 5)990,950,950
C
C  PAST PETAL FALL (OR PINK, IF STRATEGY 10)
950    CONTINUE
       IF(IYEST.EQ.0) GO TO 960


       IYEST = 0
       RETURN
960    CONTINUE
C  INFPER?
       IF(NEXT.LT.JDAY)GO TO 964
       IF(INFPER(2).NE.1.AND.INFPER(3).NE.1)RETURN
       IF(IPRO(5).GE.1)RETURN
964    IF(PREC(IDAY,IYR).LE..02)GO TO 965
       NEXT = JDAY
       RETURN
965    CONTINUE
       IF(IPRO(5).GE.1)RETURN
       NEXT = 999
       IYEST = 1
       NSPRAY = NSPRAY + 1
       IPRO(5) = 14
       IF(IPART.LT.3)IPRO(5) = 7
       IPRO(11)=14
       BENLATE = BENLATE + 16
       DO 970 I=1,3
970    INFLEV(I)=0
990    RETURN
C*************************************************************
C  STRATEGY 11 -- ERADICATE WITH BENLATE (16 OZ/AC) WHEN THERE
C  IS AN INFECTION NOT WHEN CONDITIONS HAVE BEEN RIGHT FOR AN
C  INFECTION TO OCCUR. ASSUMES PERFECT KNOWLEDGE.
1000    CONTINUE
       IF(JDAY.GT.219.AND.NINF.LT.2) RETURN
       IF(JDAY.GT.90)GO TO 1010
       NEXT = 999
       IYEST = 0
1010    CONTINUE
       IF(NEXTSP.NE.999.OR.MISSSP.EQ.1)RETURN
       IF(NEXT.LT.JDAY)GO TO 1024
       IF(IYEST.NE.1)GO TO 1020
       IYEST = 0
       RETURN
1020    IF(INFLEV(2).EQ.0.AND.INFLEV(3).EQ.0)RETURN
       IF(IPRO(5).GE.1)RETURN
 1024   IF(IPRO(5).GE.1) RETURN
        IF(PREC(IDAY,IYR).LE..02)GO TO 1025
       NEXT = JDAY
       RETURN
1025    CONTINUE
C  INFPER  (INFECTION PERIOD) - SPRAY
       NEXT = 999
       IYEST = 1
       IPRO(5) = 14
       IF(IPART.LT.3) IPRO(5)=7
       IPRO(11)=14
       BENLATE = BENLATE + 16
       DO 1030 I=1,3
1030    INFLEV(I) = 0
       NSPRAY = NSPRAY + 1
       RETURN
       END

       SUBROUTINE SCABDAM
C
C  CALCULATES YIELD LOSSES DUE TO SCAB DAMAGE, IF ANY.  CALLS SPSPRAY
C  AS REQUIRED.
C
       COMMON /NATURE/ YIELD(20),FPRICE(20),PPRICE(20),PREC(168,20),
     + ATEMP(168,20),DDAYS,TODDAYS,SDDAYS(20),NETREV(20)
       COMMON /TREE/ ISTAGE,FDFRUIT,SDFRUIT,CDFRUIT,DMFRUIT,TYIELD
       COMMON /SCABDAT/ INFLEV(3),INFPER(3),NINF
       COMMON /CHEMS/  BENLATE,CAPTAN,DIFOL
     + ,FLICTRN,CARZOL,GUTHION,PYRTHRD,IPRO(12),NSPRAY,MISSSP,NEXTSP
```

```
      COMMON /DATE/ IDAY,JDAY,IYR,ISTRAT,JSTRAT,KSTRAT,IPART
      R=SRANF(2)
      IF(INFLEV(3).GE.2)NINF = NINF + 1
      IF(JDAY.GE.NEXTSP.OR.MISSSP.EQ.1) GO TO 100
      IF(INFLEV(3).EQ.0)RETURN
      IF(ISTRAT.NE.1) CALL SPSPRAY
      IF(INFLEV(3).EQ.0) RETURN
      IF(INFLEV(3).EQ.1)FACT = .05
      IF(INFLEV(3).EQ.2)FACT = .10 - R * .05
      IF(INFLEV(3).EQ.3)FACT = .75 - R * .70
      IF(INFLEV(3).EQ.3.AND.ISTAGE.LT.2)FACT=.20-R*.15
      IF(SDFRUIT.GT.0) GO TO 50
      IF(ISTAGE.LT.3) GO TO 50
      IF(ISTAGE.EQ.8)FACT=FACT*0.35
      IF(ISTAGE.EQ.7) FACT= FACT*0.45
      IF(ISTAGE.EQ.6) FACT=FACT*0.58
      IF(ISTAGE.EQ.5) FACT= FACT*0.7
      IF(ISTAGE.EQ.4) FACT= FACT*0.78
      IF(FACT.LT..05.AND.FACT.GT.0.0) FACT=.05
   50 SDFRUIT = SDFRUIT + FACT
      IF(SDFRUIT.GT.1.0)SDFRUIT=1.0
      IF(ISTRAT.EQ.1) RETURN
      NEXTSP = 999
      RETURN
  100 CALL SPSPRAY
      IF(INFLEV(3).EQ.0) RETURN
      IF(INFLEV(3).EQ.1)FACT = .05
      IF(INFLEV(3).EQ.2)FACT = .10 - R * .05
      IF(INFLEV(3).EQ.3)FACT = .75 - R * .70
      IF(INFLEV(3).EQ.3.AND.ISTAGE.LT.2)FACT=.20-R*.15
      IF(SDFRUIT.GT.0) GO TO 200
      IF(ISTAGE.LT.3) GO TO 200
      IF(ISTAGE.EQ.8)FACT=FACT*0.35
      IF(ISTAGE.EQ.7) FACT= FACT*0.45
      IF(ISTAGE.EQ.6) FACT=FACT*0.58
      IF(ISTAGE.EQ.5) FACT= FACT*0.7
      IF(ISTAGE.EQ.4) FACT= FACT*0.78
      IF(FACT.LT..05.AND.FACT.GT.0.0) FACT=.05
  200 SDFRUIT = SDFRUIT + FACT
      IF(SDFRUIT.GT.1.0) SDFRUIT= 1.0
      RETURN
      END

      SUBROUTINE SPSPRAY
C
C  APPLIES SPECIAL SPRAY WHEN SCAB DAMAGE OCCURS
C
      COMMON /NATURE/ YIELD(20),FPRICE(20),PPRICE(20),PREC(168,20),
     + ATEMP(168,20),DDAYS,TODDAYS,SDDAYS(20),NETREV(20)
      COMMON /TREE/ ISTAGE,FDFRUIT,SDFRUIT,CDFRUIT,DMFRUIT,TYIELD
      COMMON /DATE/ IDAY,JDAY,IYR,ISTRAT,JSTRAT,KSTRAT,IPART
      COMMON /SCABDAT/ INFLEV(3),INFPER(3),NINF
      COMMON /CHEMS/  BENLATE,CAPTAN,DIFOL
     + ,PLICTRN,CARZOL,GUTHION,PYRTHRD,IPRO(12),NSPRAY,MISSSP,NEXTSP
      IDAY = JDAY - 89
      IF(PREC(IDAY,IYR).GT..02)GO TO 30
      MISSSP = 0
C
      BENLATE = BENLATE + 16
      IPRO(5) = 14
      IF(IPART.LT.3) IPRO(5)=7
      IPRO(11)=14
      NSPRAY = NSPRAY + 1
      DO 10 I = 1,3
10    INFLEV(I) = 0
      IF(NEXTSP.EQ.999) GO TO 20
      NEXTSP = 999
      RETURN
20    NEXTSP = JDAY + 7
      RETURN
30    MISSSP = 1
      RETURN
      END

      SUBROUTINE ECON
C
C  CALCULATES COSTS, MATERIAL USE,NET REVENUE ON YEARLY BASIS
C
      COMMON /DATE/ IDAY,JDAY,IYR,ISTRAT,JSTRAT,KSTRAT,IPART
```

```
      COMMON /NATURE/ YIELD(20),FPRICE(20),PPRICE(20),PREC(168,20),
     + ATEMP(168,20),DDAYS,TODDAYS,SDDAYS(20),NETREV(20)
      COMMON /ACCUM/ STRATS(20),STRATSS(20),GRANDS(20),GRANDSS(20),
     + NSTRAT,NGRAND,NACCUM
      COMMON /TREE/ ISTAGE,FDFRUIT,SDFRUIT,CDFRUIT,DMFRUIT,TYIELD
      COMMON /SCABDAT/ INFLEV(3),INFPER(3),NINF
      COMMON/MITEDA2/IECTH1,IECTH2,X,NSCOUT,NX,KONN,
     + IPC,IERROR,KEMX,SCCOST
      COMMON/CMSCOUT/ THEAT,MOTHKIL,MSPRAY,ECM1,ECM2,ECM3,
     +CMLEVEL,LUCK,CMLOSS,ITERAT,OLD,WORMAPL
      COMMON /CHEMS/  BENLATE,CAPTAN,DIFOL
     + ,PLICTRN,CARZOL,GUTHION,PYRTHRD,IPRO(12),NSPRAY,MISSSP,NEXTSP
      LOGICAL MOTH,SCAB,MITE,IWSCOUT
      COMMON /DB/ DEBUG,MOTH,MITE,SCAB,IWSCOUT,HSPRAY,INTSCT
C
C
C DAMAGE
C MITES - MITEDAYS TO O
      IF(MITE)CALL ESMITES
C SCAB - PERCENT TO O
C
      SDFRUIT=0.0
      FSCA=0.0
      PSCA=0.0
      FSCA=SDFRUIT
      IF(SDFRUIT.LT..4) GOTO 60
      FSCA=.4
      PSCA=SDFRUIT-.4
   60 CONTINUE
      SDFRUIT = TYIELD * SDFRUIT
C MOTH
      CDFRUIT = CMLOSS*TYIELD
C
      FYIELD=TYIELD - CDFRUIT
C YIELD AND REVENUE
      TYIELD = TYIELD - SDFRUIT - CDFRUIT
      APRICE = .4 * FPRICE(IYR) + .6 * PPRICE(IYR)
      TOTREV=(FYIELD*(.4-FSCA)*FPRICE(IYR))+(FYIELD*(.6-PSCA)
C YIELD AND REVENUE
      TYIELD = TYIELD - SDFRUIT - CDFRUIT
      APRICE = .4 * FPRICE(IYR) + .6 * PPRICE(IYR)
      TOTREV=(FYIELD*(.4-FSCA)*FPRICE(IYR))+(FYIELD*(.6-PSCA)
     + *PPRICE(IYR)) + (SDFRUIT*PPRICE(IYR)*.725)
C SCAB
      CSDAM= (FYIELD*APRICE)  - TOTREV
C MOTH
      CCDAM = CDFRUIT * APRICE
C MITE (DMFRUIT IS FRACTION OF VALUE)
C   CALCULATED ABOVE (CMDAM)
C
C SPRAY COSTS
C SCAB
      SPCOSTS = BENLATE * .659 + DIFOL * 24.0 + CAPTAN * 1.85
      IF(.NOT.SCAB)SPCOSTS = 175.00
C THE DEFAULT COSTS FOR SCAB CONTROL ARE EQUAL TO COSTS OF
C SCAB STRATEGY OF 14 CAPTAN SPRAYS (7 FULL DOSE AND 7 HALF)
C THIS IS THE CONVENTIONAL SPRAY PROGRAM
C MOTH
      SPCOSTC =  MSPRAY*1.41 +GUTHION*10.50 +PYRTHRD*21.00 + 57.41
C      THE PRICE OF THE PYRTHROID IS ASSUMED TO BE 3/4 OF PRICE OF GUTHI
      IF(.NOT.MOTH)SPCOSTC = 71.76
C MITE
      SPCOSTM = PLICTRN * 27.75 + CARZOL * 33. + NSCOUT * .5
      IF(.NOT.MITE)SPCOSTM = 20.03
C GENERAL - .702/SPRAY LABOR, .698/SPRAY MACHINE
      NSPRAY = NSPRAY + MSPRAY
      IF(IWSCOUT)SCCOST=12.0
      SPCOST = NSPRAY * 1.4 + SPCOSTS + SPCOSTC + SPCOSTM + SCCOST
C
C CONTROL COST
      CCONTRL = SPCOST + CSDAM + CMDAM + CCDAM
C PRODUCTION COST
C 363.57 = OVERHEAD

C 1.01 = .80 VARIABLE PRODUCTION, .21 MARKETING
C 340.29 = OTHER MATERIAL COSTS
      PROCOST = 363.57 + 1.01 * FYIELD + SPCOST + 340.29
      REVNET  = TOTREV - PROCOST
      NETREV(IYR)=REVNET * 10
      PRINT 1000,IYR,YIELD(IYR),FDFRUIT,SDFRUIT,CDFRUIT,TYIELD,
     + FPRICE(IYR),PPRICE(IYR),CMDAM,TOTREV,NSPRAY,BENLATE,CAPTAN,
```

```
     + DIFOL,PLICTRN,CARZOL,GUTHION,PYRTHRD,CCONTRL,PROCOST,REVNET
1000  FORMAT(I3,5F7.1,3F7.2,F8.2,I4,7F6.1,1X,F7.2,2F8.2)
C
C  ACCUMULATE
      CALL TOTAL (YIELD(IYR),1)
      CALL TOTAL (FDFRUIT,2)
      CALL TOTAL (SDFRUIT,3)
      CALL TOTAL (CDFRUIT,4)
      CALL TOTAL (TYIELD,5)
      CALL TOTAL (FPRICE(IYR),6)
      CALL TOTAL (PPRICE(IYR),7)
      CALL TOTAL (CMDAM,8)
      CALL TOTAL (TOTREV,9)
      CALL TOTAL (FLOAT(NSPRAY),10)
      CALL TOTAL (BENLATE,11)
      CALL TOTAL (CAPTAN,12)
      CALL TOTAL (DIFOL,13)
      CALL TOTAL (PLICTRN,14)
      CALL TOTAL (CARZOL,15)
      CALL TOTAL (GUTHION,16)
      CALL TOTAL (PYRTHRD,17)
      CALL TOTAL (CCONTRL,18)
      CALL TOTAL (PROCOST,19)
      CALL TOTAL (REVNET,20)
      NSTRAT = NSTRAT + 1
      RETURN
      END

      SUBROUTINE TOTAL (Q,N)
C ACCUMULATES SUM AND SUM OF SQUARES OF Q IN NTH ELEMENTS OF
C  STRATS AND STRATSS
      COMMON /ACCUM/ STRATS(20),STRATSS(20),GRANDS(20),GRANDSS(20),
     + NSTRAT,NGRAND,NACCUM
      IF(N.LT.1.OR.N.GT.NACCUM)GO TO 900
      STRATS(N) = STRATS(N) + Q
      STRATSS(N) = STRATSS(N) + Q * Q
      RETURN
C
900   PRINT *," IMPROPER CALL OF SUBROUTINE TOTAL.  N = ",N
      STOP
      END

      SUBROUTINE STATS (IT)
C
C  COMPUTES MEANS AND SDS EITHER FOR END OF STRATEGY (IT = 1)
C  OR ALL STRATEGIES (IT = 2)
C
      COMMON /ACCUM/ STRATS(20),STRATSS(20),GRANDS(20),GRANDSS(20),
     + NSTRAT,NGRAND,NACCUM
      DIMENSION AVG(20),SD(20),VAR(20)
C
      IF(IT.EQ.2) GO TO 100
      CALL CALC (STRATS,STRATSS,NSTRAT,AVG,VAR,SD,NACCUM)
      PRINT 1100
1100  FORMAT("OSTATISTICS FOR ALL YEARS:")
C  ACCUMULATE GRAND TOTALS
      NGRAND = NGRAND + NSTRAT
      DO 10 I=1,NACCUM
      GRANDS(I) = GRANDS(I) + STRATS(I)
      GRANDSS(I) = GRANDSS(I) + STRATSS(I)
10    CONTINUE
      GO TO 200
C
C  IT = 2:  GRAND AVG, ETC
100   CALL CALC (GRANDS,GRANDSS,NGRAND,AVG,VAR,SD,NACCUM)
C
C     PRINT RESULTS
200   PRINT 2000,AVG,VAR,SD
C
2000  FORMAT(3H AV,8F7.1,F8.1,F4.0,7F6.1,1X,2F7.1,F8.1 /
     + 3H VR,8E7.1,E8.1,F4.1,7F6.0,2E7.1,E8.1, /
     + 3H SD,8F7.1,F8.1,F4.1,7F6.1,1X,2F7.1,F8.1)
C
C  IF STRAT  CALL, ZERO OUT  STRAT ACCUMS
      IF(IT.EQ.2)RETURN
      DO 500 I=1,NACCUM
      STRATS(I) = 0.0
      STRATSS(I) = 0.0
500   CONTINUE
```

```
      NSTRAT = 0
      RETURN
      END

      SUBROUTINE CALC (S,SS,N,A,V,SD,L)
      DIMENSION S(L),SS(L),A(L),V(L),SD(L)
C
C  CALCULATES AVERAGE (A), VARIANCE(V), STANDARD DEVIATION(SD) FOR EACH
C  OF L TOTALS (S), SUMS OF SQUARES (SS),  USING N FOR EACH
C
      IF(N.GE.2)GO TO 5
      PRINT *," N LT 2 FOR SD CALCULATION"
      RETURN
5     CONTINUE
      FN=N
      DO 10 I=1,L
      A(I)= S(I)/FN
      V(I) = (SS(I) - FN * A(I)**2) / (FN -1.)
      SD(I) = SQRT(V(I))
 10   CONTINUE
      RETURN
      END

      SUBROUTINE MSTRAT
      COMMON /DATE/ IDAY,JDAY,IYR,ISTRAT,JSTRAT,KSTRAT,IPART
      COMMON/TREE/ISTAGE,FDFRUIT,SDFRUIT,CDFRUIT,DMFRUIT,TYIELD
      COMMON/MITEDA2/IECTH1,IECTH2,X,NSCOUT,NX,KONN,
     + IPC,IERROR,KEMX,SCCOST
      COMMON/MITEDAT/SAER(20),SAAF(20),IAFD(20),IERD(20),
     + AER,AAF,EPY,AFFFR,YY,AFFCON,ERINJ(3),CON,
     + EMX,ELPDPO(10),ERI(10),AFI(10)
      COMMON/NATURE/YIELD(20),FPRICE(20),PPRICE(20),PREC(168,20),
     +ATEMP(168,20),DDAYS,TODDAYS,SDDAYS(20),NETREV(20)
      DIMENSION ICODE (4,17)
C 4 NUMBERS IN EACH SET ARE IECTH1,IECTH2,IPC, AND IERROR
      DATA ICODE /0,0,0,0, 0,0,4,0, 0,0,5,0, 15,15,4,0,
     + 28,22,4,0, 28,7,4,0, 35,25,4,0, 28,0,5,0,
     + 15,0,5,0, 35,0,5,0,  15,15,4,1, 28,22,4,1,
     + 28,7,4,1, 35,25,4,1, 28,0,5,1, 15,0,5,1,
     + 35,0,5,1 /
C IERROR=0  ZERO SAMPLING ERROR
C  IERROR=1  50 IN GROWER PERCEPTION; 50 IN MONITORING
C
C

C JSTRAT=1-BIO;2-CAL 4 6/15 & 8/15;3-CAL 5 6/15 & 8/15;4-IPM 15/15 4:
C 5-IPM 28/22 4; 6-IPM 28/7 4;7-IPM 35/25 4;8-IPM 28 5;9-IPM 15 5;
C 10-IPM 35 5
C 11-17 SAME AS 4-10 BUT WITH ERROR
      IECTH1 = ICODE(1,JSTRAT)
      IECTH2 = ICODE(2,JSTRAT)
      IPC = ICODE(3,JSTRAT)
      IERROR = ICODE(4,JSTRAT)
C
C
      RETURN
      END

      SUBROUTINE MITECON
C**********COMMON VARIABLES:ELPDPO(10),IPRO(12),JDAY,IERD(20),IYR,IAFD(2
C
C
C
C  THIS SUBROUTINE SECTION CALCULATES BIRTH RATES AND PREDATION RATE
C  AND ADJUSTS POPULATIONS FOR THEM
C
      LOGICAL DEBUG,MOTH,MITE,SCAB,IWSCOUT,HSPRAY
      COMMON /DATE/ IDAY,JDAY,IYR,ISTRAT,JSTRAT,KSTRAT,IPART
      COMMON/DB/DEBUG,MOTH,MITE,SCAB,IWSCOUT,HSPRAY,INTSCT
      COMMON/TREE/ISTAGE,FDFRUIT,SDFRUIT,CDFRUIT,DMFRUIT,TYIELD
      COMMON/CHEMS/BENLATE,CAPTAN,DIFOL,
     +PLICTRN,CARZOL,GUTHION,PYRTHRD,IPRO(12),NSPRAY,MISSSP,NEXTSP
      COMMON/MITEDA2/IECTH1,IECTH2,X,NSCOUT,NX,KONN,
     + IPC,IERROR,KEMX,SCCOST
      COMMON/MITEDAT/SAER(20),SAAF(20),IAFD(20),IERD(20),
     + AER,AAF,EPY,AFFFR,YY,AFFCON,ERINJ(3),CON,
     + EMX,ELPDPO(10),ERI(10),AFI(10)
      DATA ELPDPO/.6,.14,.08,.08,.02,.016,.016,.016,.016,.016/
C
```

```
C
      DO 1600 I=1,7
C     IF(DEBUG)PRINT 1650,ELPDPO(I),I,IPRO(I)
 1650 FORMAT(*  MITE:ELPDPO(I),I,IPRO(I)*,F10.3,2X,2I3)
 1600 CONTINUE
C
      IF(JSTRAT.LT.4)GO TO 190
      IF(IAFD(IYR).GT.JDAY.AND.IERD(IYR).GT.JDAY)RETURN
  190 CONTINUE
      IF(IAFD(IYR).EQ.JDAY)AAF=SAAF(IYR)
      IF(IERD(IYR).EQ.JDAY)AER=SAER(IYR)
      IF(IERD(IYR).EQ.JDAY)EPY=AER*1.107
      IF(IAFD(IYR).EQ.JDAY)AFFFR=AAF*.3477
      CALL PRED
      IF(JDAY.GE.IERD(IYR)) CALL ERPOP
      IF(JDAY.GE.IAFD(IYR)) CALL AFPOP
C
      IF(DEBUG)PRINT 1000,AAF,AER,AAF
      IF(IERD(IYR).GT.JDAY)GO TO 3504
C
C  THIS SECTION OF MITE CALCULATES THE NUMBER OF DAYS ABOVE THE INJURY
C  THRESHOLD (15 MITES PER LEAF), THE NEED FOR SPRAYS AND MITE MORTALITY
C DUE TO SPRAYS
C
      CALL MITEINJ(JY)
C
      IF(DEBUG)PRINT 5000,AER,ERINJ(JY),JDAY
 5000 FORMAT(*  MITEINJ:AER+*,F7.2,*  ERINJ=*,F7.2,
     &    *    JDAY=*,I5)
C
C    IF WEEKLY SCOUTING PROGRAM IS FOLLOWED, THE GROWER PERCEPTION
C   AND MMORTALITY SECTIONS ARE SKIPPED
 3504 IF(IWSCOUT)GO TO 600
C
C   THIS SECTION IDENTIFIES FOR IPM STRATEGIES WHEN A GROWER PERCEIVES
C  A MITE PROBLEM AND REQUESTS A PROFESSIONAL SCOUT. THERE IS A THREE
C  DAY DELAY BETWEEN THE REQUEST AND THE ARRIVAL OF THE SCOUT. THE
C  SCOUT VISITS THE ORCHARD TWICE -- THREE DAYS APART.
      IF(JSTRAT.EQ.1)GO TO 700
      IF(JSTRAT.GE.4)GO TO 3058
      IF(JSTRAT.GT.1.AND.JSTRAT.LT.4)CALL MSCOUT
C     IF(IERD(IYR).GT.JDAY) GO TO 700
      IF(JSTRAT.GT.1.AND.JSTRAT.LT.4) GO TO 2354
      CALL MSCOUT
      GO TO 2354
 3058 CONTINUE
      IF(KONN.EQ.1) GO TO 2175
      IF(IERROR.EQ.1)GO TO 2185
      IF(AER.GT.X)GO TO 2057
       GO TO 2175
2185  CALL RAN(AER,.25,C,RANAER)
      IF(RANAER.GT.X)GO TO 2057
      GO TO 2175
 2057 NX=7
C KONN IS USED TO INDICATE THAT MITE PROBLEM HAS BEEN PERCEIVED
      KONN=1
C  NX IS USED TO PERMIT 3 DAY DELAY BETWEEN MITE PROBLEM PERCEPTION


C  AND SCOUTING (AND BETWEEN SPRAY AND SECOND SCOUT)
C
C
 2175 IF(NX.EQ.8)GO TO 2354
       NX=NX - 1
C      IF (DEBUG) PRINT 2450,NX,X,AER,KONN
 2450 FORMAT(*   MITE:NX,X,AER,KONN*,10X,I3,10X,F10.2,10X,F10.2,I5)
       IF(NX.EQ.3)GO TO 2356
       IF(NX.EQ.O)GO TO 2352
       GO TO 2354
 2356 CALL MSCOUT
        NSCOUT=NSCOUT + 1
       GO TO 2354
 2352 CALL MSCOUT
       NX=8
       KONN=O
 2354 CONTINUE
C  THIS IS THE END OF THE GROWER PERCEPTION SECTION
C
C  THIS SECTION CALCULATES THE MORTALITY OF THE POPULATIONS
C DUE TO THE SPRAYS
      IF(DEBUG) PRINT 6001,IPC,CARZOL,PLICTRN,NSPRAY,NSCOUT
```

```
      CALL MMORT
C
C
600   CONTINUE
C
      IF(DEBUG) PRINT 6002
1000  FORMAT(*MITE.AAF=*.F8.3,*     AER=*.F8.3,
    &*       AAF=*,F10.3)
C
700   RETURN
C
6000  FORMAT(1X,*DEBUG 2: IPRO(ISTR)*,I3)
6001  FORMAT(1X,*DEBUG 1*,10X,*CHECK,I,C,P,NS,NSCOUT*,5X,I5,2F6.3,10X,
    + 2F10.3,I5)
6002  FORMAT(1X,*DEBUG 3*)
      END


C
C
C@@@#@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@
      SUBROUTINE INTMITE
C*************COMMON VARIABLE:  IAFD(20),IERD(20),SAAF(20),IYR,SAER(20)
C  THIS SUBROUTINE INTIALIZES VARIABLES PRIORTO MITE SUBROUTINE
C  VALUES CHOSEN FROMIER FOR RED MITE ANDIAF FOR AMBLYSEIUS FALLACIS
C
      LOGICAL DEBUG,MOTH,MITE,SCAB,IWSCOUT,HSPRAY
      COMMON/DB/DEBUG,MOTH,MITE,SCAB,IWSCOUT,HSPRAY,INTSCT
      COMMON /INT/ GPP,SCMPOP
      COMMON/MITEDA2/IECTH1,IECTH2,X,NSCOUT,NX,KONN,
    + IPC,IERROR,KEMX,SCCOST
      COMMON/MITEDAT/SAER(20),SAAF(20),IAFD(20),IERD(20),
    + AER,AAF,EPY,AFFFR,YY,AFFCON,ERINJ(3),CON,
    + EMX,ELPDPO(10),ERI(10),AFI(10)
C
      DIMENSION IAF(10),IER(20),POP(20)
      DATA IER/28,57,69,76,82,87,91,95,99,103,107,112,
    &117,122,127,133,140,147,157,169/
C
      DATA IAF/79,91,101,111,121,131,141,151,161,172/
C
      DATA POP/.024,.365,.502,.590,.664,.738,.810,.882,.956,
    &1.031,1.110,1.192,1.282,1.376,1.423,1.609,1.756,1.945,
    &2.207,2.636/
C
C
C
      DO 500 IYR=1,20
      DO 300 I=1,4
      RR=0.0
      R1=RANF(0)
      DO 100 J=1,20
      RR=RR +.05
      IF(R1.LT.RR) GO TO 150
100   CONTINUE
150   GO TO (1,2,3,4)I
   1  J=(J+1)/2
      IAFD(IYR)=IAF(J) + 74
C DATE OF PREDATOR EMERGENCE
C
      GO TO 200
C DATE OF PEST EMERGENCE
2     IERD(IYR)=IER(J) +74
C
C
      GO TO 200
C STARTING PREDATOR POPULATION
3     SAAF(IYR)=POP(J) *.1
C
      GO TO 200
C STARTING PEST POPULATION
C
4     SAER(IYR)=POP(J)
C
C
200   IF(DEBUG)PRINT 1000,I,J,RR
300   CONTINUE
      PRINT 2000,IYR,IAFD(IYR),IERD(IYR),SAAF(IYR),SAER(IYR)
500   CONTINUE
C
C SET THRESHOLD FOR MITE PROBLEM PERCEPTION
```

```
      X = GPP
C
1000  FORMAT(* INTMITE:I,J,RR*,2X,2I3,F6.2)
2000  FORMAT (* YEAR,IAFD,IERD,SAAF,SAER*,I3,2I6,2F10.2)
      RETURN
      END

C
C
C#################################################################
      SUBROUTINE PRED
C*********COMMON VARIABLES: ATEMP(168,20),IYR,JDAY,IDAY
C
C  THIS SUBROUTINE CALCULATES THE CONSUMPTION OF THE
C  ER POPULATION BY THE AF POPULATION IN TETRANYCHUS
C  UTRICAE EGG EQUIVALENTS (CON)
C
      LOGICAL DEBUG,MOTH,MITE,SCAB,IWSCOUT,HSPRAY
      COMMON/DB/DEBUG,MOTH,MITE,SCAB,IWSCOUT,HSPRAY,INTSCT
      COMMON /DATE/ IDAY,JDAY,IYR,ISTRAT,JSTRAT,KSTRAT,IPART
      COMMON/NATURE/YIELD(20),FPRICE(20),PPRICE(20),PREC(168,20),
     +ATEMP(168,20),DDAYS,TODDAYS,SDDAYS(20),NETREV(20)
      COMMON/MITEDA2/IECTH1,IECTH2,X,NSCOUT,NX,KONN,
     + IPC,IERROR,KEMX,SCCOST
      COMMON/MITEDAT/SAER(20),SAAF(20),IAFD(20),IERD(20),
     + AER,AAF,EPY,AFFFR,YY,AFFCON,ERINJ(3),CON,
     + EMX,ELPDPO(10),ERI(10),AFI(10)
C
C
C
      YY=.00271316*ATEMP(IDAY,IYR)**3 - .53852*ATEMP(IDAY,IYR)**2 +
     $35.6868 * ATEMP(IDAY,IYR) - 782.635
      B=.0002279*ATEMP(IDAY,IYR)**2 - .03443*ATEMP(IDAY,IYR) + 1.47288
C
      IF(DEBUG)PRINT 1200,AFFFR,YY,B
 1200 FORMAT(*   PRED:AFFFR,YY,B*,3F10.3)
      IF(AAF.GT.0.0) GO TO 100
      CON=0.0
      IF(DEBUG) PRINT 1300,AER,AAF,CON,EPY
 1300 FORMAT(*  PRED:AER,AAF,CON,EPY*,4F10.3)
      RETURN
  100 CON=-ALOG(EXP(-YY*B*AAF)-EXP(-B*EPY-B*YY*AAF) +EXP(-B*EPY))/B
      CON=(AFFFR/AAF)*CON
C
            IF(DEBUG)PRINT 1000,ATEMP(IDAY,IYR),CON,AAF,AER
1000  FORMAT(* PRED:AT,CON,AAF,AER*,4F6.2)
C
      RETURN
C
C
      END

C
C
C@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@
      SUBROUTINE ERPOP
C*****COMMON VARIABLES:EMX,IDAY,ELPDPO(10),ATEMP(168,20),IYR,JDAY,ERI(10
C
C  SUBROUTINE CALCULATES THE RED MITE (ER) POPULATION LOSS DUE TO
C  PREDATION AND SUBTRACTS IT FROM THE PRESENT POPULATION.  THEN THE
C  POPULATION INCREASE DUE TO REPRODUCTION IS CALCULATED AND ADDED TO
C  THE POPULATION
C
       LOGICAL DEBUG,MOTH,MITE,SCAB,IWSCOUT,HSPRAY
      COMMON /DATE/ IDAY,JDAY,IYR,ISTRAT,JSTRAT,KSTRAT,IPART
       COMMON/DB/DEBUG,MOTH,MITE,SCAB,IWSCOUT,HSPRAY,INTSCT
      COMMON/NATURE/YIELD(20),FPRICE(20),PPRICE(20),PREC(168,20),
     +ATEMP(168,20),DDAYS,TODDAYS,SDDAYS(20),NETREV(20)
      COMMON/MITEDAT/SAER(20),SAAF(20),IAFD(20),IERD(20),
     + AER,AAF,EPY,AFFFR,YY,AFFCON,ERINJ(3),CON,
     + EMX,ELPDPO(10),ERI(10),AFI(10)
      COMMON/MITEDA2/IECTH1,IECTH2,X,NSCOUT,NX,KONN,
     + IPC,IERROR,KEMX,SCCOST
      DIMENSION DR(10)
C
      IF(KEMX.GT.0.) GO TO 150
C
      DO 100 I=1,10
      ERI(I)=AER*ELPDPO(I)*2.5*.75
```

```
  100 CONTINUE
C
  150 EMX=.148*ATEMP(IDAY,IYR) - 7.57
C
      KEMX=KEMX + 1
      OVIP=EMX*(ERI(6)*.79+ERI(7)*.96+ERI(8)*.67+
     &  ERI(9)*.52+ERI(10)*.05)
      IF(OVIP.LT.0.0) OVIP=0.0
C
      IF(AER.GT.70)OVIP=0.0
      FCON=1.
      IF(EPY.GT.0.)FCON=(EPY-CON)/EPY
C
C
      IF(DEBUG) PRINT 1000,FCON,AER,OVIP,CON,ERI(10)
 1000 FORMAT(*ERPOP:FCON,AER,OVIP,CON,ERI(10)*,5F10.3)
C THIS SEQUENCE HANDLES AN ABSOLUTE REDUCTION (3) IN POP DUE TO STARVATI
C
C     IF(AER.LT.100) GO TO 425
C     AER=AER * .97
C     DO 450 I=2,10
C     ERI(I)=.97 * ERI(I)
C 450 CONTINUE
C     GO TO 400
C 425 CONTINUE
C
      DR(1)=1./(749.9*EXP(-.065*ATEMP(IDAY,IYR)))
      DR(2)=(2.9195-.3983*.75)*.001*EXP(.0745*ATEMP(IDAY,IYR))
      DR(3)=(2.7883-.2113*.75)*.001*EXP(.0745*ATEMP(IDAY,IYR))
      DR(4)=(2.4047-.1489*.75)*.001*EXP(.0745*ATEMP(IDAY,IYR))
      DR(5)=(2.97*.0001)*EXP(.1035*ATEMP(IDAY,IYR))
      DR(10)=DR(9)=DR(8)=DR(7)=DR(6)=5./(-.533*ATEMP(IDAY,IYR)+53.42)
C
      ERF=AER=0.
C
      DO 200 J=1,9
      I=11-J
      IF(DR(I).GT.1.0) DR(I)=1.0
      IF(DR(I).LT.0.0)DR(I)=0.0
      IF(DEBUG)PRINT*,"ERPOP;DR(I),ERI(I),I",DR(I),ERI(I),I
      Q=ERI(I)*(1.-DR(I))
      B=ERI(I-1)*DR(I-1)
      ERI(I)=(ERI(I)*(1.-DR(I))+ERI(I-1)*DR(I-1))*FCON
C     IF(DEBUG)PRINT*," ERPOP;DR(I),ERI(I),I",DR(I),ERI(I),I
      IF(DEBUG)PRINT*,"     ERI(",I,")=",Q,"+",B
C
      AER=AER+ERI(I)*1.33
      IF(I.LE.4) GOTO 200
      ERF=ERF+ERI(I)
  200 CONTINUE


C
      IF(AER.LT.35.) GO TO 600
      DO 500 I=2,10
      ERI(I)=ERI(I)*.97
  500 CONTINUE
  600 CONTINUE
C
      ERI(1)=ERI(1)*(1.-DR(1))+OVIP
      IF(AER.GT..2) GOTO 400
      POPINCR=0.
      IF(AER.GT.0.0)POPINCR=.2/AER
      ERF=0.
      IF(AER.EQ.0.0)GO TO 1200
      AER=.2
 1200 CONTINUE
      DO 300 I=2,10
      ERI(I)=ERI(I)*POPINCR
      IF(I.LE.4) GOTO 300
      ERF=ERI(I)+ERF
  300 CONTINUE
  400 CONTINUE
C
      EPY=1.33*ERI(2)*.6397+1.33*ERI(3)*.5878+
     $ (ERI(4)+.33*ERF)*1.383+ERF*1.959
C
      IF(DEBUG) PRINT 1400,AER,POPINCR,EPY,FCON,ERI(10)
 1400 FORMAT(*  ERPOP: AER,POPINCR,EPY,FCON,ERI(10)*,5F10.3)
      IF(DEBUG)PRINT*,"  ERPOP,ERI(1),ERF  ",ERI(1),ERF
C
```

```
      RETURN
      END

C
C@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@
      SUBROUTINE AFPOP
C************COMMON VARIABLES: AFFCON,AFI(10),IDAY,ELPDPO(10),ATEMP(168,2
C**************'JDAY,EMX
C
      LOGICAL DEBUG,MOTH,MITE,SCAB,IWSCOUT,HSPRAY
      COMMON/DB/DEBUG,MOTH,MITE,SCAB,IWSCOUT,HSPRAY,INTSCT
      COMMON /DATE/ IDAY,JDAY,IYR,ISTRAT,JSTRAT,KSTRAT,IPART
      COMMON/NATURE/YIELD(20),FPRICE(20),PPRICE(20),PREC(168,20),
     +ATEMP(168,20),DDAYS,TODDAYS,SDDAYS(20),NETREV(20)
      COMMON/MITEDAT/SAER(20),SAAF(20),IAFD(20),IERD(20),
     + AER,AAF,EPY,AFFFR,YY,AFFCON,ERINJ(3),CON,
     + EMX,ELPDPO(10),ERI(10),AFI(10)
      COMMON/MITEDA2/IECTH1,IECTH2,X,NSCOUT,NX,KONN,
     + IPC,IERROR,KEMX,SCCOST
      DIMENSION DR(10)
C
      IF(AFFCON.GT.0.) GO TO 150
      DO 100 I=1,10
      AFI(I)=AAF*ELPDPO(I)*2.5*.8
  100 CONTINUE
C
  150 A=-.0000598*ATEMP(IDAY,IYR)**2+.008555*ATEMP(IDAY,IYR)-.3114
      B=.00011768*ATEMP(IDAY,IYR)**3-.02381417*ATEMP(IDAY,IYR)**2
     & + 1.59869*ATEMP(IDAY,IYR) - 35.356
      C=-.00010882*ATEMP(IDAY,IYR)**3 + .021618*ATEMP(IDAY,IYR)**2
     & -1.4235*ATEMP(IDAY,IYR) + 30.92
      AFFCON=0.0
      IF(AFFFR.GT.0.0)AFFCON=CON/AFFFR
      EMX=A*AFFCON**2 + B*AFFCON + C
      OVIP=EMX*(AFI(6)*1.74+AFI(7)*1.57+AFI(8)*.9+AFI(9)
     & *.54 + AFI(10)*.4)
      IF(OVIP.LT.0.0) OVIP=0.0
C
      IF(DEBUG)PRINT*," AFPOP,AFFCON,EMX,OVIP   ",AFFCON,EMX,OVIP
      IF(DEBUG)PRINT*," AFPOP; YY   ",YY
      DR(1)=.02*ATEMP(IDAY,IYR) - 1.11
      DR(2)=.046*ATEMP(IDAY,IYR)-2.60
      DR(3)=.046*ATEMP(IDAY,IYR)-2.55
      DR(4)=.024*ATEMP(IDAY,IYR)-1.22
      DR(5)=.0357*ATEMP(IDAY,IYR)-1.90
      DR(10)=DR(9)=DR(8)=DR(7)=DR(6)=(.0018*ATEMP(IDAY,IYR)-.091)*5
C
      IF(AFFCON.GT.YY*.75) GOTO 180
      DO 160 I=5,10
      AFI(I)=AFI(I)*.95
  160 CONTINUE
      IF(AFFCON.GT.YY*.25) GOTO 180
      DO 170 I=2,10
      AFI(I)=AFI(I)*.8
  170 CONTINUE
  180 CONTINUE
C
      AAF=AFF=0.
      DO 200 J=1,9
      I=11-J
      IF(DR(I).GT.1.0) DR(I)=1.0
      IF(DEBUG)PRINT*," AFPOP;DR(I),AFI(I),I",DR(I),AFI(I),I
      Q=AFI(I)*(1-DR(I))
      B=AFI(I-1)*DR(I-1)
      AFI(I)=(AFI(I)*(1.-DR(I)) + AFI(I-1)*DR(I-1))
      IF(DEBUG)PRINT*," AFPOP;DR(I),AFI(I),I",DR(I),AFI(I),I
      IF(DEBUG)PRINT*,"    AFI(",I,")=",Q,"+",B
C
      AAF=AAF + AFI(I)*1.25
      IF(I.LE.4) GO TO 200
      AFF=AFF + AFI(I)
  200 CONTINUE
C
      AFI(1)=AFI(1)*(1-DR(1)) + OVIP
      IF(AAF.GT..02)GO TO 400
      POPINCR=0.0
      IF(AAF.GT.0.0)POPINCR=.02/AAF
      AFF=0.
      AAF=.02
      DO 300 I=2,10
```

```
      AFI(I)=AFI(I)*POPINCR
      IF(I.LE.4) GOTO 300
      AFF=AFI(I) + AFF
  300 CONTINUE
  400 CONTINUE
C
      AFFFR=(.1562*(AFI(2)*1.25) + .1999*((AFI(3)*1.25) +
     & AFI(4)*.25) + .2436*AFI(4) + .1749*AFF*.25 + AFF)
      IF(DEBUG)PRINT*," AFPOP,AFI(1),AFF   ",AFI(1),AFF
      RETURN
C
C
C
      END

C
C
C@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@
C
      SUBROUTINE MITEINJ(JY)
C********COMMON VARIABLES: JDAY
C
      COMMON /DATE/ IDAY,JDAY,IYR,ISTRAT,JSTRAT,KSTRAT,IPART
      COMMON/MITEDA2/IECTH1,IECTH2,X,NSCOUT,NX,KONN,
     + IPC,IERROR,KEMX,SCCOST
      COMMON/MITEDAT/SAER(20),SAAF(20),IAFD(20),IERD(20),
     + AER,AAF,EPY,AFFFR,YY,AFFCON,ERINJ(3),CON,
     + EMX,ELPDPO(10),ERI(10),AFI(10)
C  THIS SUBROUTINE DIVIDES THE GROWING SEASON INTO THREE PARTS: UP TO
C  JUNE 15; JUNE 16 THROUGH AUGUST 15; AND FROM AUGUST L6 ON.  THE
C  NUMBER OF MITES ABOVE THE THRESHOLD ON THIS DAY ARE ADDED TO THE
C  RUNNING SUM KEPT FOR EACH PART OF THE SEASON
C
C
      IF(JDAY.GT.166) GO TO 100
      JY=1
      GO TO 300
100   IF(JDAY.GT.227) GO TO 200
      JY=2
      GO TO 300
200   JY=3
  300 DAM=AER-15.
      IF(DAM.LT.O.)DAM=O.
      ERINJ(JY)=ERINJ(JY) + DAM
      RETURN
      END

C#######################################################################
C
      SUBROUTINE MSCOUT
C     C******KDAY,JX,INT
      LOGICAL DEBUG,MOTH,MITE,SCAB,IWSCOUT,HSPRAY
      COMMON /DATE/ IDAY,JDAY,IYR,ISTRAT,JSTRAT,KSTRAT,IPART
      COMMON/CHEMS/BENLATE,CAPTAN,DIFOL,
     +PLICTRN,CARZOL,GUTHION,PYRTHRD,IPRO(12),NSPRAY,MISSSP,NEXTSP
      COMMON/MITEDA2/IECTH1,IECTH2,X,NSCOUT,NX,KONN,
     + IPC,IERROR,KEMX,SCCOST
      COMMON/MITEDAT/SAER(20),SAAF(20),IAFD(2C),IERD(20),
     + AER,AAF,EPY,AFFFR,YY,AFFCON,ERINJ(3),CON,
     + EMX,ELPDPO(10),ERI(10),AFI(10)
      COMMON/DB/DEBUG,MOTH,MITE,SCAB,IWSCOUT,HSPRAY,INTSCT
C  THIS SUBROUTINE CHECKS THE ACTIVE AMBLYSIEUS FALLACIS (AAF)
C  AND THE ACTIVE EUROPEAN RED MITE (AER) POPULATIONS AND MAKES A
C  RECOMMENDATION: IPRO(1) FOR NO SPRAY, MCS(2) FOR 1/3 STRENGTH PLICTRA
C  IPRO(7) FOR 1/2 STRENGTH PLICTRAN
C  IPRO(8) FOR FULL STRENGTH PLICTRAN AND MCS(5) FOR FULL STRENGTH CARZO
C
      DATA ISDATE1/180/
      DATA ISDATE2/210/
      RANAER=O.
C
C     DEBUG=.TRUE.
      IF(JSTRAT.GT.1.AND.JSTRAT.LT.4) GO TO 500
C
      IF(IPC.EQ.5)GO TO 570
C
C THERE IS AN ERROR IN THE MONITORING BUT 95 OF TIME IT IS WITHIN
```

```
C   10  OF ACTUAL LEVEL
C
      IF(IERROR.EQ.1)GO TO 810
      IF(AER.LT.IECTH2)GO TO 400
      IF(PLICTRN.EQ.0.0.AND.HSPRAY) GOTO 100
      IF(AAF.LT..08)GO TO 200
      IF(AER.GT.IECTH1)GO TO 200
      TRP1=.099*AER -.3
      TRP2=.08267*AER - .34
      IF(AAF.GT.TRP1)GO TO 400
      IF(AAF.LT.TRP2)GO TO 100
      GO TO 110
810   CALL RAN(AER,.25,4,RANAER)
      IF(RANAER.LT.IECTH2) GO TO 400
      IF(PLICTRN.EQ.0.0.AND.HSPRAY) GO TO 100
       IF(AAF.LT..08) GO TO 200
      IF(RANAER.GT.IECTH1)GO TO 200
      TRP1=.099*AER - .3
      TRP2=.08267*AER - .34
      IF(AAF.GT.TRP1)GO TO 400
      IF(AAF.LT.TRP2)GO TO 100
C
  110 ISPRAY=6
      PLICTRN=PLICTRN + .333
      NSPRAY=NSPRAY + 1.
      GO TO 300
C
100   ISPRAY=7
      PLICTRN=PLICTRN + .5
      NSPRAY=NSPRAY + 1.
      GO TO 300
C
200   ISPRAY=IPC + 4
      IF(IPC.EQ.4)PLICTRN=PLICTRN + 1.
      IF(IPC.EQ.5)CARZOL=CARZOL + 1
      NSPRAY=NSPRAY + 1.
C
300   CONTINUE
      IPRO(ISPRAY)=14
      GO TO 600
400   CONTINUE
      IF(DEBUG)PRINT 6009,NSPRAY
 6009 FORMAT(*     MSCOUT:NSPRAY*,5X,I3)
      GO TO 580
500   CONTINUE
      IF(JDAY.EQ.ISDATE1)GO TO 560
      IF(JDAY.EQ.ISDATE2)GO TO 560


      GO TO 580
  560 ISPRAY=IPC + 4
      NSPRAY=NSPRAY + 1
      IPRO(ISPRAY)=14
      IF(JSTRAT.EQ.3)CARZOL=CARZOL + 1
      IF(JSTRAT.EQ.2)PLICTRN= PLICTRN + 1
      GO TO 600
  570 IF(IERROR.EQ.1)GOTO 574
      IF(AER.LT.IECTH1)GO TO 600
      ISPRAY=IPC + 4
      NSPRAY=NSPRAY + 1
      CARZOL =CARZOL + 1
      IPRO(ISPRAY)=14
      GO TO 600
574   CALL RAN(AER,.25,4,RANAER)
      IF(RANAER.LT.IECTH1) GO TO 600
      ISPRAY=IPC + 4
      NSPRAY=NSPRAY + 1
      CARZOL=CARZOL + 1
      IPRO(ISPRAY)=14
      GO TO 600
C
  580 IF(DEBUG) PRINT 6666,JDAY,NSPRAY
6666  FORMAT(* NO SPRAY ON JDAY *,I3,*  NSPRAY = *,I3)
C 600 DEBUG=.TRUE.
  600 CONTINUE
      IF(DEBUG)PRINT 1000,AER,AAF,IECTH1,IECTH2,RANAER,JDAY
 1000 FORMAT(*  MSCOUT:AER,AAF,IECTH12,RANAER,JM*,2F10.2,2I5,
     +F10.2,I5)
C     DEBUG=.FALSE.
      RETURN
      END
```

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C@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@
      SUBROUTINE MMORT
C******COMMON VARIABLES: IPRO(12),ERI(10),AFI(10),ELPDPO(10)
C
C  THIS SUBROUTINE CALCULATES THE MITE MORTALITY DUE TO THE PESTICIDES
C  RESIDUAL. I VALUES DETERMINE THE THE PESTICIDE: 1 FOR NO SPRAY, 2 + 1
C  IPRO(6)=1/3 PLICTRAN: IPRO(7)=1/2 PLICTRAN; IPRO(8)=PLICTRAN; IPRO(9)
C  CARZOL; IPRO(10)= PYRETHROID;
C  IPRO(11)=BENALATE
C
      LOGICAL DEBUG,MOTH,MITE,SCAB,IWSCOUT,HSPRAY
      COMMON/DB/DEBUG,MOTH,MITE,SCAB,IWSCOUT,HSPRAY,INTSCT
      COMMON/CHEMS/BENLATE,CAPTAN,DIFOL,
     +PLICTRN,CARZOL,GUTHION,PYRTHRD,IPRO(12),NSPRAY,MISSSP,NEXTSP
      COMMON/MITEDAT/SAER(20),SAAF(20),IAFD(20),IERD(20),
     + AER,AAF,EPY,AFFFR,YY,AFFCON,ERINJ(3),CON,
     + EMX,ELPDPO(10),ERI(10),AFI(10)
      DIMENSION BENM(15),SMAF(5),SMER(5)
C
      DATA BENM/ .02,.05,.14,.24,.35,.44,.48,.5,.5,.5,.48,.45,.38,
     &.22,.05/
      DATA SMAF/0.,.10,.70,.99,.99/
      DATA SMER/.70,.85,.99,.99,.10/
C
C
C     DEBUG=.TRUE.
      DO 600 ISTR=6,11
      KISTR=ISTR - 5
      IF(IPRO(ISTR).EQ.0) GO TO 200
      IF(ISTR.EQ.11) GO TO 100
C
      IF(DEBUG)PRINT*,"ISTR",ISTR
      IF(DEBUG)PRINT*,"MMORT,SMER(IS),",SMER(KISTR),SMAF(KISTR)
C
      AER=AER - AER*SMER(KISTR)*EXP(-.23*(14-IPRO(ISTR)))
      AAF=AAF-AAF*SMAF(KISTR)*EXP(-.23*(14-IPRO(ISTR)))
C
      IF(DEBUG)PRINT*,"MMORT, AER,AAF",AER,AAF
      IF(DEBUG)PRINT*,"EXP",EXP(-.23*(14-IPRO(ISTR)))
C
      GO TO 150
  100 AER=AER-AER*BENM(IPRO(ISTR))
C
      AAF=AAF-AAF*BENM(IPRO(ISTR))
C
  150 DO 175 I=2,10
      ERI(I)=AER*ELPDPO(I)*2.5*.75
      AFI(I)=AAF*ELPDPO(I)*2.5*.8
      IF(DEBUG) PRINT 2000, ERI(I),AFI(I),I
 2000 FORMAT(*   MMORT:   ERI,AFI,I*,10X,2F10.3,I3)
  175 CONTINUE
C
  200 CONTINUE
      IF(DEBUG)PRINT 4000,AAF,AER,ISTR,IPRO(ISTR)
 4000 FORMAT(*    MORT:,AAF,AER,ISTR,IPRO(ISTR)*,2F7.3,2I4)
600   CONTINUE
C     DEBUG=.FALSE.
      RETURN
      END

C
C@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@
C
      SUBROUTINE ESMITES
C*****COMMON VARIABLES:  DMFRUIT
C
C  THIS SUBROUTINE CALCULATES THE MONETARY LOSS IN DOLLARS PER ACRE DUE
C  TO MITE INJURY. FOR THE EARLY, MIDDLE AND LATE PARTS OF THE SEASON,
C  THE MAXIMUM LOSS/ACRE ARE 200.00,133.33,AND 57.20 DOLLARS
C  RESPECTIVELY. THE MAXIMUM IS REACHED AT 2000 MITE DAYS/LEAF. FOR
C  EACH OF THE THREE PARTS BETWEEN 0 AND 2000 THE FUNCTION INCREASES IN
C  A LOGISTIC LIKE FAISHION AND IS CONSTANT ABOVE 2000.
C
      LOGICAL DEBUG,MOTH,MITE,SCAB,IWSCOUT,HSPRAY
      COMMON/DB/DEBUG,MOTH,MITE,SCAB,IWSCOUT,HSPRAY,INTSCT
      COMMON/TREE/ISTAGE,FDFRUIT,SDFRUIT,CDFRUIT,DMFRUIT,TYIELD
      COMMON/MITEDAT/SAER(20),SAAF(20),IAFD(20),IERD(20),
```

```
     + AER,AAF,EPY,AFFFR,YY,AFFCON,ERINJ(3),CON,
     + EMX,ELPDPO(10),ERI(10),AFI(10)
      DIMENSION AERINJ(3)
C
      DMFRUIT=O.
      DATA AERINJ/.12,.08,.03432/
C
      DO 100 I=1,3
      IF(ERINJ(I).GT.2000) GO TO 50
      X=AERINJ(I)*(ERINJ(I)/2000)**2
      DMFRUIT=DMFRUIT + X +X*((AERINJ(I)-X)/AERINJ(I))
      IF(DEBUG)PRINT 1000,DMFRUIT
      GO TO 100
C
   50 DMFRUIT=DMFRUIT + AERINJ(I)
      IF(DEBUG)PRINT 1000,DMFRUIT
C
  100 CONTINUE
 1000 FORMAT(*   DMFRUIT=*,F6.2)
      RETURN
      END

C*************************************************
      SUBROUTINE SCOUT(IDAY,JSTRAT)
      LOGICAL DEBUG,MOTH,MITE,SCAB,IWSCOUT,HSPRAY
      COMMON/DB/DEBUG,MOTH,MITE,SCAB,IWSCOUT,HSPRAY,INTSCT
      COMMON /CMSCOUT/ THEAT,MOTHKIL,MSPRAY,ECM1,ECM2,ECM3,
     +CMLEVEL,LUCK,CMLOSS,ITERAT,OLD,WORMAPL
C ISDATEN = SCOUTING DATE (NUMBERED FROM DAY 90)
      DATA ISDATE1/91/
      DATA ISDATE2/121/
      IF(DEBUG) PRINT 200,IDAY
200   FORMAT(*SCOUT*,I5)
      IF(.NOT.IWSCOUT) RETURN
      IF(IDAY/INTSCT*INTSCT.EQ.IDAY)GO TO 100
      IF(JSTRAT.EQ.1) RETURN
      IF(JSTRAT.LT.4.AND.MITE) GO TO 40
      RETURN
  100 CONTINUE
      IF(MOTHKIL.NE.O) GOTO 50
      IF(MOTH) CALL CMSCOUT
      DEBUG=.FALSE.
   50 IF(.NOT.MITE) RETURN
      IF(JSTRAT.EQ.1) RETURN
      IF(JSTRAT.LT.4)GO TO 40
      CALL MSCOUT
      RETURN
   40 CONTINUE
      IF(IDAY.EQ.ISDATE1) CALL MSCOUT
      IF(IDAY.EQ.ISDATE2) CALL MSCOUT
      RETURN
      END

C********************************************************
      SUBROUTINE CODMOTH(AVTEMP,APPLES)
C******************************************************************
C
C       THIS SUBROUTINE MODELS CODLING MOTH POPULATION DYNAMICS.
C       OTHER SUBROUTINES CALLED EXCLUSIVELY FROM THIS SUBROUTINE
C       ARE  CMMORT, DGREDA2, AND DELAY.
C
C
C****************************************************************
      COMMON /CMSCOUT/ THEAT,MOTHKIL,MSPRAY,ECM1,ECM2,ECM3,
     +CMLEVEL,LUCK,CMLOSS,ITERAT,OLD,WORMAPL
      COMMON /MOTH/ DEL(5),DELP(5),IK(5),X(6),XIN(6),
     +R(25,5),STRG(5),PLR(5)
      COMMON /DATE/ IDAY,JDAY,IYR,ISTRAT,JSTRAT,KSTRAT,IPART
      INTEGER DEL,DELP
      DIMENSION OM(25)
      DATA DDD/2./
      DATA OM/O.,15.,22.5,15.,11.25,7.5,3.75,18*O./
C*
C*
C***************BEGIN MODEL.
      PLR(1)=.00103
      PLR(2)=.00140
      PLR(3)=.00023
      PLR(4)=O.
      PLR(5)=O.
```

```
C*
      IF(MOTHKIL.EQ.O) GOTO 100
         CALL CMMORT(R,XCMMORT,MOTHKIL)
100   CONTINUE
C
C*      CALCULATE TODAY"S DEGREE-DAYS (DHEAT) AND ADD TO
C*   ACCUMULATED HEAT (THEAT).
C*
110         DHEAT=AVTEMP-50.
120         THEAT=THEAT+DHEAT
C*
C*      CALCULATE NIT (NUMBER OF ITERATIONS) FOR TODAY.
C*
129         NIT=(DHEAT+OLD)/DDD+.00001
            OLD=DHEAT+OLD-NIT*DDD
            IF(NIT.LE.O) GOTO 170
C*
C*      INNER LOOP (140) CONTROLS ITERATIONS FOR TODAY.
C*
            DO 140 IT=1,NIT
C*
C*      LOOP 130 UPDATES MODEL BY ONE DDD.
C*
              DO 130 IB=1,5
                ISTG=6-IB
130             CALL DELAY(X(ISTG),X(ISTG+1),R(1,ISTG),PLR(ISTG),
     +           DEL(ISTG),DELP(ISTG),DDD,IK(ISTG))
C*
C*   LOOP 133 ADDS LARVAE TO THE CODLING MOTH POPULATION
C*   INTO THE ORCHARD FROM THE SUROUNDING AREA
              ITERAT=ITERAT+1
              IF(ITERAT*DDD.LT.900) GOTO 134
              IF(ITERAT*DDD.GT.1000) GOTO 134
                 ITERAT=1000
                 DO 133 J=6,15
C     PRINT*," LINE 2223.5"
133                 R(J,2)=R(J,2)+.002555*APPLES*.0022
C*
C*
C*      CALCULATE OVIPOSITION THIS DDD WHICH BECOMES X(1).
C*
134           OVIP=O.
              IB=IK(5)
              DO 135 J=1,IB
135             OVIP=OVIP+OM(J)*R(J,5)*.537
              X(1)=OVIP
C*
      IF(MOTHKIL.EQ.O) GOTO 139
C*      SPRAY MORTALITY TO NEWLY HATCHED LARVA
        IF(MOTHKIL.NE.O) R(1,2)=R(1,2)*(1-XCMMORT)
C*


C*      CALCULATE NUMBER OF APPLES WITH CODLING MOTH LARVAE
 139          WORMAPL=WORMAPL+R(1,2)*(APPLES-WORMAPL)/APPLES
        IF(WORMAPL.GT.APPLES) WORMAPL=APPLES
C*2365C*
140           CONTINUE
C*
C*      LOOP 160 CALCULATES STORAGE IN EACH STAGE. THIS REPRESENTS
C*   THE NUMBER OF INDIVIDUALS IN EACH STAGE AT THE END OF THE DAY.
C*
C*
          DO 160 I=1,5
              SUM=O.
              IB=IK(I)
              DO 150 J=1,IB
150             SUM=SUM+R(J,I)
160           STRG(I)=SUM*DEL(I)/IK(I)
      CMLEVEL=STRG(1)/APPLES
      STRG(5)=STRG(5)+STRG(4)
C
C THE MODEL ASSUMES THAT THERE ARE 100 TREES/ACRE; 100APPLES/BU
C APPLES IS TERMS OF APPLES/TREE WHILE TYIELD IS IN TERMS OF
C BU/ACRE SO TO CONVERT APPLES TO APPLES PER ACRE --
C APPLES=100APPLES * BU/ 100*TREES * ACRE;  CMLOSS IS PROPORTION
C OF TOTAL APPLES INFECTED.
      CMLOSS=WORMAPL/APPLES
C*
C*      OUTPUT MODEL STATE AT END OF THE DAY.
C*
```

```
C     PRINT 2000,JDAY,DHEAT,THEAT,STRG(1),STRG(2),STRG(3),STRG(5),OVIP
C*
170   RETURN
2000  FORMAT(1X,I7,6X,F5.2,4X,F6.1,5(3X,F7.2))
      END
```

```
C**************END   MODEL.
      SUBROUTINE CMINIT
C****************************************************************
C*                                                              *
C*      INITIALIZATION SUBROUTINE                               *
C*                                                              *
C****************************************************************
      COMMON /INT/ GPP,SCMPOP
      COMMON /CMSCOUT/ THEAT,MOTHKIL,MSPRAY,ECM1,ECM2,ECM3,
     +CMLEVEL,LUCK,CMLOSS,ITERAT,OLD,WORMAPL
      COMMON /MOTH/ DEL(5),DELP(5),IK(5),X(6),XIN(6),
     +R(25,5),STRG(5),PLR(5)
      INTEGER DEL,DELP
      DIMENSION IR(25,5)
      DATA DEL/145,587,265,50,175/
      DATA   IK/5*15/
      DATA IR/30*0,4,12,16,8,2,6,10,16,18,8,85*0/
      ITERAT=0
      OLD=200.
      CMLEVEL=0.0
      CMLOSS=THEAT=WORMAPL=0.
      MSPRAY=LUCK=MOTHKIL=0
      DO 75 I=1,5
         DELP(I)=DEL(I)
         STRG(I)=XIN(I)=0.
         IB=IK(I)
         FIK=FLOAT(IK(I))
             FDEL=FLOAT(DEL(I))
         DO 74 J=1,IB
             RJI=FLOAT(IR(J,I))
             R(J,I)=RJI*(FIK/FDEL)*(SCMPOP/100.)
74           STRG(I)=STRG(I)+IR(J,I)*(SCMPOP/100.)
75       X(I+1)=R(IB,I)
      XIN(6)=0.
      X(1)=R(IK(5),5)
      RETURN
      END
```

```
**************************************************************
      SUBROUTINE DELAY (VIN,VOUT,R,PLR,DEL,DELP,DT,K)
      DIMENSION R(1)
      INTEGER DEL,DELP
      FK=FLOAT(K)
      B=1.+(DEL-DELP)/(FK*DT)+PLR*DELP/FK
      IDT=1.+2.*DT*FK/DELP*AMAX1(B,0.)
      A=FK*DT/(DELP*FLOAT(IDT))
      DELP=DEL
      KM1=K-1
      DO 20 J=1,IDT
         DO 10 IC=1,KM1
             I=K-IC+1
10           R(I)=R(I)+A*(R(I-1)-B*R(I))
20       R(1)=R(1)+A*(VIN-B*R(1))
      VOUT=R(K)
      RETURN
      END
```

```
C**************************************************
C*
C            SUBROUTINE CMSCOUT
C*
C**************************************************
C*
C*  THIS SUBROUTINE DETERMINES THE SPRAY SCHEDULE
C*  USING EITHER  A CHALENDAR BASED SYSTEM STARTING
C*  AT FRUIT SET OR THE IPM ALGORITHM WHICH CALLS
C*  FOR SPRAYS WHEN CODLING MOTH POPS ARE OVER THE
C*  SET THRESHOLD
      LOGICAL DEBUG,MOTH,MITE,SCAB,IWSCOUT,HSPRAY
      COMMON/DB/DEBUG,MOTH,MITE,SCAB,IWSCOUT,HSPRAY,INTSCT
      COMMON /DATE/ IDAY,JDAY,IYR,ISTRAT,JSTRAT,KSTRAT,IPART
      COMMON /CMSCOUT/ THEAT,MOTHKIL,MSPRAY,ECM1,ECM2,ECM3,
```

```
     +CMLEVEL,LUCK,CMLOSS,ITERAT,OLD,WORMAPL
      COMMON/CHEMS/BENLATE,CAPTAN,DIFOL,
     +PLICTRN,CARZOL,GUTHION,PYRTHD,IPRO(12),NSPRAY,MISSSP,NEXTSP
      COMMON /TREE/ ISTAGE,FDFRUIT,SDFRUIT,CDFRUIT,DMFRUIT,TYIELD
C*
C MOTH STRATEGIES
C 1) DO NOTHING
C 2) CALENDAR - GUTHION
C 3) CALENDAR - PYRETHROID
C 4) IPM, NO ERROR - GUTHION .001,.005,.003
C 5) IPM, NO ERROR - PYRETHROID .001,.005,.003
C 6) IPM,NO ERROR - GUTHION .001,.001,.001
C 7) IPM, NO ERROR - PYRETHROID .001,.001,.001
C 8) IPM, NO ERROR - GUTHION .002,.01,.006
C 9) IPM, NOERROR - PYRETHROID .002,.01,.006
C 10) IPM, NO ERROR - GUTHION .0015,.0075,.0045
C 11) IPM, NO ERROR - PYRETHROID .0015,.0075,.0045
C 12) IPM, RANDOM ERROR - GUTHION .001,.005,.003
C 13) IPM, RANDOM ERROR - PYRETHROID .001,.005,.003
C 14) IPM,RANDOM ERROR - GUTHION .001,.001,.001
C 15) IPM, RANDOM ERROR - PYRETHROID .001,.001,.001
C 16) IPM, RANDOM ERROR - GUTHION .002,.01,.006
C 17) IPM, RANDOMERROR - PYRETHROID .002,.01,.006
C 18) IPM, RANDOM ERROR - GUTHION .0015,.0075,.0045
C 19) IPM, RANDOM ERROR - PYRETHROID .0015,.0075,.0045
C
C
C     PRINT*," IN CMSCOUT","   CMLEVEL=",CMLEVEL
      DEBUG=.FALSE.
      IF(KSTRAT.EQ.1)RETURN
      IF(KSTRAT.GT.3) GOTO 100
C*
C*   THIS SECTION CONTROLS CALENDAR SPRAYS
C*
      IF(DEBUG) PRINT 1100,KSTRAT,ECM1,ECM2,ECM3,CMLEVEL,CMLEV,
     + THEAT,ISTAGE,MSPRAY,LUCK,MOTHKIL,JDAY
1100  FORMAT(*KS,ECM123,CM2,THEAT,IS,MS,LU,MK,JD*,4I3,2F5.3,F6.1,
     + 5I4)
         IF(ISTAGE.LT.8) RETURN
            IF(THEAT.LT.1710.) GOTO 900
               RETURN
C*
C*
C*   THIS SECTION CONTROLS IPM SPRAYS
C*
100   CONTINUE
      CMLEV = CMLEVEL
      IF(DEBUG) PRINT 1100,KSTRAT,ECM1,ECM2,ECM3,CMLEVEL,CMLEV,
     + THEAT,ISTAGE,MSPRAY,LUCK,MOTHKIL,JDAY
      IF(KSTRAT.LT.12)GO TO 150
C SET CMLEV = TO PERCEIVED LEVEL (WITH ERROR)
      CALL RAN(CMLEVEL,.25,5,CMLEV)
150   CONTINUE
      IF(DEBUG) PRINT 1100,KSTRAT,ECM1,ECM2,ECM3,CMLEVEL,CMLEV,
     + THEAT,ISTAGE,MSPRAY,LUCK,MOTHKIL,JDAY
      GOTO(200,300,400,1000)MSPRAY+1
C*
200      IF(CMLEV.GT.ECM1) GOTO 900
            RETURN
C*
300      IF(THEAT.GT.800.) GOTO 400
      IF(DEBUG) PRINT 1100,KSTRAT,ECM1,ECM2,ECM3,CMLEVEL,CMLEV,

     + THEAT,ISTAGE,MSPRAY,LUCK,MOTHKIL,JDAY
            IF(CMLEV.GT.ECM2) GOTO 900
               RETURN
C*
400       IF(THEAT.LT.1200.) RETURN
      IF(DEBUG) PRINT 1100,KSTRAT,ECM1,ECM2,ECM3,CMLEVEL,CMLEV,
     + THEAT,ISTAGE,MSPRAY,LUCK,MOTHKIL,JDAY
              IF(LUCK.EQ.1) RETURN
                IF(CMLEV.GT.ECM3) GOTO 900
                   RETURN
C*
C*
900   MOTHKIL=14
      IF(DEBUG) PRINT 1100,KSTRAT,ECM1,ECM2,ECM3,CMLEVEL,CMLEV,
     + THEAT,ISTAGE,MSPRAY,LUCK,MOTHKIL,JDAY
      IF(KSTRAT.EQ.2.OR.KSTRAT.EQ.4.OR.KSTRAT.EQ.6)GO TO 910
      IF(KSTRAT.EQ.8.OR.KSTRAT.EQ.10.OR.KSTRAT.EQ.12) GO TO 910
```

```
      IF(KSTRAT.EQ.14.OR.KSTRAT.EQ.16.OR.KSTRAT.EQ.18) GO TO 910
      IPRO(12)=14
      PYRTHD = PYRTHD + 1.
      GO TO 920
  910 CONTINUE
      IPRO(10)=14
      GUTHION = GUTHION + 1.
  920 CONTINUE
      MSPRAY=MSPRAY+1
      IF(THEAT.GT.1000.) LUCK=1
C     PRINT*," START OF SPRAY"
C*
 1000 RETURN
      END

C*****************************************************
C*
                SUBROUTINE CMMORT(R,XCMMORT,MOTHKIL)
C*
C*****************************************************
C*
C*
      DIMENSION R(25,5)
C*
      CMMRT=.9*.67**((14-MOTHKIL)/2)
      XCMMORT=.9*.5**((14.000001-MOTHKIL)/14)
C     PRINT*,"  CMMRT=",CMMRT,"XCMMORT=",XCMMORT
C*
      DO 100 J=1,15
         R(J,1)=R(J,1)*(1.-CMMRT)
         R(J,5)=R(J,5)*(1.-CMMRT)
      IF(J.GT.12) GO TO 100
         R(J,4)=R(J,4)*(1.-CMMRT)
  100 CONTINUE
C*
      MOTHKIL=MOTHKIL-1
C*
      RETURN
      END

C@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@
      SUBROUTINE RAN(AMEAN,RANGE,NSERIES,RANVAR)
      LOGICAL DEBUG,MOTH,MITE,SCAB,IWSCOUT,HSPRAY
C THIS SUBROUTINE CALCULATES A NORMALLY RANDOM
C VARIABLE WITH A MEAN OF "MEAN" AND A STANDARD
C DEVIATION OF "SDEV". THE SDEV IS CALCULATED FROM INFORMATION
C ON THE DESIRED RANGE WHICH THE RANVAR SHOULD
C INTO 95 OF THE TIME. (ASSUMES THAT CI OF 95--
C MEAN + AND - 1.96*SDEV SO RANGE SHOULD BE 1/4
C THE WIDTH OF DESIRED CONFIDENCE INTERVAL.
C
      R1=SRANF(NSERIES)
      R2=SRANF(NSERIES)
      Z=((-2.*ALOG(R1))**.5)*COS(6.2832*R2)
      SDEV=AMEAN*RANGE
      RAER=SDEV*Z
      RANVAR= RAER + AMEAN
C     IF(DEBUG) PRINT 100,AMEAN,RANGE,Z,RAER,RANVAR
C100   FORMAT(*     RAN:AMEAN,RANGE,Z,RAER,RANVAR*,5F11.2)
      RETURN
      END

      SUBROUTINE CMSTRAT
      COMMON /DATE/ IDAY,JDAY,IYR,ISTRAT,JSTRAT,KSTRAT,IPART
      COMMON /CMSCOUT/ THEAT,MOTHKIL,MSPRAY,ECM1,ECM2,ECM3,
     +CMLEVEL,LUCK,CMLOSS,ITERAT,OLD,WORMAPL
      DIMENSION CODE(3,8)
      DATA CODE/.001,.005,.003, .001,.005,.003,
     + .001,.001,.001, .001,.001,.001,
     + .002,.01,.006, .002,.01,.006,
     + .0015,.0075,.0045,.0015,.0075,.0045/
      DATA ECM1/.001/
      DATA ECM2/.005/
      DATA ECM3/.003/
      IF(KSTRAT.LT.4) RETURN
      KKSTRAT=KSTPAT-3
      IF(KSTRAT.GT.11) KKSTRAT=KSTRAT-11
      ECM1=CODE(1,KKSTRAT)
```

```
      ECM3=CODE(2,KKSTRAT)
      ECM2=CODE(3,KKSTRAT)
      RETURN
20    END
```