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Eric Anthony Scorsone

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Stephen B. Harsh
Major professor

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Eric Anthony Scorsone

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ABSTRACT

EVALUATING ALTERNATIVE PLUM CURCULIO CONTROL STRATEGIES USING A BIOECONOMIC SIMULATION APPROACH

By

Eric Anthony Scorsone

Tart Cherry growers in Northern Michigan have begun adopting Integrated Pest Management (IPM) strategies. However, industry participants are uncertain about the economic performance of new IPM strategies. The cause for uncertainty relates to the price-static decision rule underlying the IPM strategy. A major source of uncertainty in the tart cherry industry is widely fluctuating price levels from season to season from 5 cents / lb. to 45 cents /lb. In some years, the price-static action threshold may perform poorly and expose growers to substnatial financial risk. A proposed price-flexible action threshold could supplement the price-static action threshold and improve economic performance. A bioeconomic simulation model was developed to test the economic performance of the two IPM strategies and non-IPM strategies. Results indicate that the proposed price-flexible action threshold could potentially improve economic performance over the price-static decision rule and non-IPM strategies.

This thesis is dedicated to my wife and best friend, Kendra Scorsone, for her patience and love through many tough times.

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1.1 Introduction

The fruit industry is an important part of Michigan agriculture. Three thousand farms representing one hundred fifty thousand acres are active in Michigan (Flore et al., 1992). The major fruit crops grown in Michigan are apples, tart cherries, sweet cherries, strawberries, grapes, nectarines, pears, plums, raspberries, apricots, and blueberries (Flore et al., 1992). In 1990, the market value of these crops was 186 million dollars.

Tart cherries are the second most important crop in the fruit industry. Michigan is the leading tart cherry producing state with 34,000 acres and a market value of 27 million dollars (Flore et al., 1992). A high percentage of tart cherries are grown in Northwest Michigan in and around the Leelaunau Peninsula region. In 1989-1990, Dr. Flore of Michigan State and others undertook a survey of fruit growers on their major concerns and behavior (Flore et al., 1992). The survey revealed that the key concern of fruit growers was their ability to obtain adequate price levels (Flore et al., 1992). This is especially important in the tart cherry industry where prices have varied widely and in a number of years have fallen below break-even levels. Due to varying and low price levels, growers believed that their ability to control costs would have a major influence on their financial sustainability in the future (Flore et al., 1992).

Pest control options and public attitude were the second most important concern among growers. Growers were concerned about negative public perceptions towards the use of pesticides and government pesticide regulations (Flore et al., 1992). Pesticides represent on average 17% of a fruit growers costs (Flore et al., 1992). Tart cherry growers may spend 270 dollars per acre on pest control costs (Scorsone and Swinton, 1995). Pesticide costs and environmental regulations combined with occasional below break-even price levels are forcing growers to look for ways to use agrochemicals efficiently and safely.

A number of possible pest control strategies can be used in tart cherry orchards. Growers may use a "fixed strategy" that does not use scouting information. A fixed strategy does not respond to changing market or biological conditions. Pesticides are applied based on when pests normally occur and which chemicals are the most effective. A fixed strategy can be thought of as a "standard operating procedure." Growers apply pesticides on relatively fixed dates to ensure complete pesticide protection of their orchards, regardless of actual pest population levels. Fixed strategies may incur unnecessary financial costs in low price seasons.

The alternative is a "flexible strategy" or IPM strategy which gathers information about the ecosystem and makes a decision based on that information. A flexible strategy does not automatically apply a pesticide to an orchard, but analyzes collected information. IPM systems are often based on the concept of collecting information about a field or orchard through pest sampling and using decision rules to recommend control decisions. These decision rules compare collected information to established pest thresholds. These thresholds represent the point where the value of pest damage exceeds control costs. If threshold levels are exceeded, a pesticide is applied. Flexible strategies can respond to changing biological conditions in the orchard. Flexible use of an input may improve economic performance for a grower. Fixed pest control strategies may apply pesticides when they are not needed or miss a needed application.

Integrated pest management (IPM) has become a possible solution to the pest control needs of tart cherry managers. Nationally, IPM has been recognized as an important strategy to contain pest control costs and address environmental and health concerns associated with pesticides. IPM is often defined as the use of biological, cultural, and chemical control combined with increased biological information to manage pests (Pedigo et al., 1986). IPM is associated with plans to achieve lower farm production costs and reductions in environmental impacts. This is achieved through reduced pesticide usage in many years with the use of IPM systems. Two comprehensive studies showed that under most conditions producers will use less chemicals for control under an IPM system compared to traditional pest control strategies (Osteen, Bradley, and Moffitt, 1981; Norton and Mullen, 1984). The Clinton Administration, as part of its food safety and pesticide reform action, proposed in 1993 a goal of 75% of U.S. cropland under IPM by 2000. Recently, the USDA and EPA announced plans to reach that goal. IPM appears to be an approach to agricultural management which can achieve the twin goals of economic and environmental sustainability. However, many growers have concerns about the risks of IPM and its use has been constrained.

The Michigan Fruit Industry Survey revealed that Michigan fruit producers are adopting IPM practices. Results indicate that 59% of growers are using pest monitoring, pest thresholds and/or biological control (Flore et al, 1992.). Over 60% surveyed indicated they would decrease pesticide use through IPM or organic practices (Flore et al., 1992). To build upon the success of current IPM programs, new methods and technologies need to be developed to assist growers in making the transition to information intensive agriculture.

There is an increasing need for pest scouts and consultants in the tart cherry industry of Northwest Michigan (Laubach, 1995). More growers are willing to adopt and use IPM techniques. Recently, Jim Laubach and Jim Johnson of Michigan State University produced a tart cherry insect scouting manual (Johnson and Laubach, 1995). This manual was designed to facilitate adoption of IPM tools by growers and consultants.

In this manual, a scouting protocol and action threshold are presented for the plum curculio insect (Johnson and Laubach, 1995). The plum curculio is identified as a major insect pest of tart cherry orchards (Johnson and Laubach, 1995). The plum curculio causes damage during the early growing season. The curculio lays its eggs in the young fruit and causes the fruit to drop off the tree and reduces yield (Johnson and Laubach, 1995). The manual presents a scouting and control strategy for the plum curculio during the early growing season. The strategy involves visually scouting for the insect and use of an action threshold.

The Michigan tart cherry industry has adopted the use of a number of IPM techniques. Michigan extension agents have divided IPM users into extensive and intensive IPM (Nugent and Thorton, 1995). Extensive IPM can be defined as the use of code-a-phone, pest alert bulletins, and other information from Extension offices. The code-a-phone system tells growers what pests have been spotted or what disease conditions may exist. Pest alert bulletins are put out by extension offices to alert growers about pest problems in their region. This type of IPM strategy uses regional pest information. Growers who use the system usually do not scout themselves, but rely on scouting reports from other orchards. Users of extensive IPM may change strategies based on regional conditions.

Intensive IPM is the use of scouting information to determine the appropriate action for the control of pests. Information about the biological system is considered the foundation of any intensive IPM system. Information usually refers to sampling to estimate the status of pests and crops. This information is used to determine if and when to control pest populations. Traditional pest control does not rely on scouting or site-specific field information. IPM is usually defined as the use of intensive IPM methods. Biological information allows the grower to use a flexible strategy that responds to conditions that exist in the orchard.

In the context of IPM strategies, flexible use of an input means the implementation of an economic injury level and action threshold. The theory of economic injury levels and action thresholds has been established in a number of articles (Pedigo et al., 1986; Pedigo et al., 1989; Stern et al., 1959; Headley, 1972; Onstad, 1987). Some inputs, such as a fertilizer, produce financial gains and increase output. Increased output (e.g. yield per acre) is multiplied by price to derive increased revenue. If this revenue increase exceeds the cost of purchasing and applying the fertilizer, a financial gain is achieved. Crop protection involves the use of inputs, such as pesticides, to avoid or reduce the damage caused by a pest. A pest will cause a certain amount of damage that reduces yield or quality. The objective of applying a pesticide is to reduce loss of yield or decline in quality caused by a pest. The damage that is affected by the application of a pesticide depends on the effectiveness of the material. Preventable damage is that part of total pest damage that can be affected by a pesticide application and is the relevant factor for decision making.

Preventable future damage is the main factor measured through the IPM scouting process. The pest population numbers from the scouting report serve as an index to expected preventable damage of the period between scouting reports. The scouting report measures past damage, but its real purpose is to estimate future damage which can be prevented by the application of a pesticide. The scouting report represents the key piece of biological information for the grower.

Tart cherry scouting and pest control decisions are made on a weekly basis. The most common IPM decision rules are the economic injury level and economic or action threshold. The economic injury level (EIL) is defined as the pest population level at which the benefits of controlling the pest exceeds the costs of control (Pedigo et al., 1986). The EIL is found by multiplying crop price, total damage caused by pest population (such as a percentage of yield lost), and the effectiveness of the control tactic (amount of pests killed) (Pedigo et al., 1986). The EIL is the actual point where benefits and costs are equal. The EIL is based on the assumptions of no control delays and constant daily scouting reports. However, the decision maker using IPM decision rules must base their actions on estimated benefits and costs rather than actual figures. Scouting only occurs once a week and therefore information gaps exist. The grower will not have real time information after the scouting is completed. The scouting report serves to estimate future pest activity until the next scouting session. The action threshold is based on the same components as the EIL, but takes into account the fact that scouting does not occur constantly and that other operational delays may exist. The action threshold is the point where the estimated future value of preventable damage exceeds the cost of control. If a sampled population meets or exceeds the EIL, it will be too late to stop the population from causing economic loss to the grower due to the delay in applying a control tactic. Therefore, the action threshold is used as an estimate of a pest population which has the potential to reach the EIL point between the current and next scouting period. The scouting report estimates are used to calculate whether or not the action threshold has been reached and a control tactic should be applied.

1.2 Research Objectives

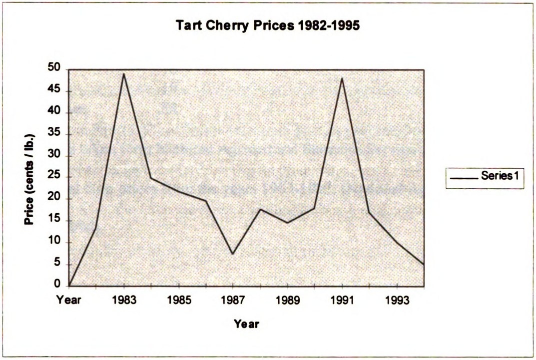
If growers are to adopt IPM management systems or flexible strategies, they must be convinced that IPM generated strategies will lead to improved economic performance. Growers want to ensure that their crop is adequately protected, but also that they do not misuse or overuse pesticides. The purpose of this study is to illustrate the improved economic performance growers may achieve by adopting IPM systems. It is hypothesized that the flexible pest management control strategies have better performance than fixed strategies. Performance is defined as the net return of applying(yield loss saved-cost) or not applying(yield loss-cost saved) a pesticide. The first hypothesis is that the Laubach-Johnson action threshold, developed in the tart cherry scouting manual, will prove to be more profitable than a fixed calendar-based spraying system (Johnson and Laubach, 1995).

To use flexible strategies, biological information must be gathered from the farm in the form of pest scouting. This pest monitoring, is the most important input for traditional IPM systems. It was believed by developers of Integrated Pest Management that increased biological information and fairly simple decision rules could improve farm pest management (Stern et al., 1959). In a USDA study on adoption of IPM by U.S. farmers, IPM users are distinguished from non-IPM users by the practice of pest monitoring (Vandeman et al., 1994). Pedigo in a recent book on sampling methods for arthropods defines the basis for IPM and ecology as "sampling populations to determine kinds and numbers of living species" (Pedigo et al., 1994). In an evaluation of Extension IPM programs, pest monitoring and thresholds are the basic components for any IPM system (Virginia Cooperative Extension Service, 1987). Clearly, pest information is the driving force behind the use of current IPM systems. However, the Extension Evaluation defines IPM as "the increased use of information to make better pest management decisions" (Virginia Cooperative Extension Service, 1987). This definition leaves room for an expansion of the meaning of information. An expanded definition of IPM may allow for the use of other types of information to improve decision making. A major goal of this project is to show that other types of information can be utilized along with pest information in the control decision.

This study proposes to use price forecasting information as well as biological information to determine pest control actions. Traditional IPM systems have treated price information as a parameter which is fairly constant or given. Price is one component of the economic injury level and action threshold equations. The value of expected loss from pest damage is a function of pest numbers, damage per pest, and product price. Past studies have used either past price, an average of past prices, or commodity futures prices to estimate an action threshold or economic injury level. The standard action threshold rule is A.T. = D*K*P/ C (where D = damage per pest, K = control tactic efficiency, P = market price, C = control cost) (Pedigo et al., 1986). The threshold decision rule requires either explicit or implicit calculations for the price parameter (P).

Tart cherry prices have been very volatile in the past. A review of tart cherry data found that the tart cherry market exhibits wide price swings between seasons and this causes great volatility in the expected value of lost crop (Chart 1). Interest has been expressed by entomologists and pest consultants on how to account for price volatility in control decisions. A simple rule that uses last years price as the expected price for the current year will often produce inaccurate estimates in tart cherries. Futures market prices are not available for tart cherries. Pest control decisions using action thresholds require valuations of the crop. Valuation is achieved through the crop price. A need exists to predict within a certain range the price of the crop to assist decision makers. An important question is to what degree can decision making improve with the use of a price prediction model. If growers can improve economic performance with a biologically-flexible strategy, they may be able to improve performance even more with a price and biologically flexible system. The second hypothesis states that growers will improve economic performance by using an action threshold which incorporates price predictions for early season control over a calendar-based control strategy or the Laubach action threshold. This study will address the impact of including an explicit price prediction model for pest control strategies. Pest control strategies that take into account early season price forecasts will be compared to strategies which do not take into account price forecasting information, such as fixed calendar-based spray strategies or price static action thresholds.

Figure 1: Tart Cherry Prices 1982-1995



Price forecasting information has not been used in previous IPM economic studies. Part of the reason is the stability of crop prices such as corn or wheat whose prices trade in a fairly narrow range. Growers and researchers simply used past price averages or futures market prices for the price parameter in threshold calculations (Johnson, 1995). Tart cherry prices exhibit a very wide range of fluctuation. A comparison of coefficient of variation between field crops, such as corn, soybeans, and wheat, reveals the difference in price level fluctuations. The coefficient of variation was calculated for corn, soybeans, wheat, and tart cherries between the1983-1993 crop years. As figure 1 shows, tart cherry prices have exhibited large fluctuations.

Table 1: Comparison of Crop Coefficient of Variation

Crop	Coefficient of Var.
Wheat	.15
Corn	.16
Soybeans	.19
Tart cherries	.58

Note: Data taken form National Agricultural Statistics Service Internet gopher Database for national crop prices from the years 1983-1993, (National Agricultural Statistics Service, 1996).

This research project involves two objectives related to the tart cherry training manual and the plum curculio action threshold (Johnson and Laubach, 1995). The first objective involves the study hypotheses and the economic evaluation of different action threshold strategies. The Laubach action threshold will be evaluated in comparison to a price-flexible threshold and a fixed calendar strategy. Financial performance, including a mean and dispersion measure, of the various strategies will be compared with to determine which one provides better economic performance. The second objective is a short discussion of how growers or scouts could use the prototype price-flexible action threshold if it is shown to have better economic performance.

1.3 Report Organization

Chapter two presents a literature review that covers two areas. The first section reviews the various definitions of the economic threshold, action threshold, and economic injury level. The second section discusses optimization studies and non-optimizing simulation techniques as used in earlier studies. Chapter three explains the methodology used by this study to develop the analytical model and evaluate various pest control strategies. Chapter four provides details on the structure of the simulation model. Model components and relationships are explained. Chapter five presents the results of simulating and testing action threshold and non-threshold pest control strategies. Chapter six discusses future research and industry needs and possible changes and extensions to the simulation model.

Ch.2: Literature Review

2.1 Introduction

Before addressing the problem identified in the prior chapter, a literature review was undertaken to examine previous research efforts and identify gaps and missing research elements. The goal of this research project is to build on previous studies and attempt to introduce new analysis elements that have been previously ignored. The first section of the review covers various definitions and specifications used in IPM analysis. The literature discusses three related decision rules: economic threshold (ET), economic injury level (EIL), and action threshold (AT). This review will mostly be limited to insect control studies in the economic and entomology literature.

The second section covers various studies that have attempted to estimate actual thresholds or compare various pest control strategies involving the use of thresholds. Studies reviewed here can be divided into several categories. The first category contains optimization studies. The main objectives of these studies was to select the optimal economic threshold strategy for a given pest-crop ecosystem. The second category of studies are those which estimate pest action thresholds. These studies did not attempt to find the optimal strategy, but rather focused on calculating the action threshold level. The third category of studies compared IPM action threshold strategies and non-IPM control strategies through simulation models of the ecosystem. The goal was not to find the optimal strategy, but to compare various predefined pest control actions.

2.2 Defining the Economic Injury Level, Economic Threshold, and Action Threshold

A review of the literature reveals a number of different definitions and models concerning the economic threshold, action threshold, and economic injury level. Economists, entomologists, and extension and field workers have not consistently interpreted these concepts. Also, the theoretical concepts and actual field use of injury levels and thresholds are often very different. For the purposes of model specification and development, a review was conducted to determine the theory and previous use of the EIL and ET or AT.

Integrated Pest Management (IPM) has a long history of development and use in the United States. Entomologists and other pest scientists were the first to develop IPM concepts and management practices. The 1920's and 1930's saw Isley, a pest scientist, using trap crops, thresholds, scouting and other forms of ecological pest management for control of boll weevil in cotton (Virginia Cooperative Extension Service, 1987). Pierce, another pest scientist in the 1930's, asked if all insect damage be considered in the decision to use a pest control method (Pedigo et al., 1986). Questions like this and concerns of overuse of pesticides and insect resistance to chemicals led to the formal development of IPM.

Many terms and concepts have become associated with integrated pest management. Stern et al.(1959) are credited with first developing the concept of the economic injury level, damage boundary, and economic threshold. These concepts were later refined by Pedigo, Norton, Onstad and other entomologists and economists.

In 1959, Stern and others published what is considered the key article establishing the formal definition and relationships involved in the use of IPM systems (Pedigo et al., 1986). Stern et al.(1959) called IPM "applied pest control which combines and integrates biological and chemical control." They also developed the economic injury level concept which is considered one of the fundamental concepts of IPM. The EIL was established as the "lowest population density that will cause economic damage"(Stern et al., 1959). Economic damage was defined as "the amount of injury that justifies the cost of control" (Stern et al., 1959). This concept related to Pierce's question of when an insect population became a threat to the crop. The economic threshold became the point at which control should be initiated to prevent a population from reaching the economic injury level (Stern et al., 1959). Given delays in applying a pest control measure, a manager who waited for a pest population to reach the economic injury level could risk economic damage and financial loss. However, Stern's definition lacked a detailed explanation of how to calculate or use the concept of economic damage. No mathematical description was given for the analysis of economic damage. Despite these weaknesses, the Stern article initiated a period of rapid development and expansion of IPM development and use (Pedigo et al., 1986).

In the early 1970's, Stern reviewed the progress and development of economic thresholds and economic injury levels for pest management (Stern, 1973). He stated that the EIL-ET decision rule should balance benefits and costs. Very few thresholds had been developed at the time of the article. Stern blamed this on lack of basic ecological knowledge, including density-damage relationships. The density-damage relationship correlates the amount of damage done by different pest population levels (Stern, 1973).

For development of thresholds, he recommended identifying key pests and measuring a damage-density relationship.

In the early 1970's, economists began to develop a rigorous and quantitative basis for the economic threshold. The economists J.C. Headley and G.A. Norton were the first to describe the economic injury level and economic threshold in mathematical terms. Headley redefined the economic injury level as the economic threshold. Before Headley, the economic threshold was defined as "the level at which damage can no longer be tolerated and, therefore, the level at or before which it is desirable to initiate deliberate control actions" (National Research Council, 1969). Headley's conception of the term was quite different from the one used by Stern, the National Research Council, and other pest scientists. The economic threshold became the optimal pest population level which maximized returns. With this threshold, managers should apply a control measure to reduce the population level to the optimal level. The optimal quantity and timing of application of a pesticide is the result of models based on this economic threshold. This combination maintains the optimal population level. Some economists have continued to use this definition in pest control studies (Talpaz and Borosh, 1974; Regev et al., 1976; Talpaz et al., 1978). However, the economic threshold definition of Stern and others remains the most popular among agricultural biologists and economists, such as L.J. Moffitt, D. Hall, and others.

Norton is considered the first economist to lay the mathematical foundation for the economic injury level as commonly used by entomologists and other pest scientists. The equation's general form is:

(1) $EIL = C/ (P*D*E)$

The model contains four variables including pesticide or control costs (C), price of the crop(P), damage per pest(D), and pesticide efficiency(E). The result of this calculation is a pest level which if allowed to continue may cause economic damage and financial loss. This figure is used in conjunction with the scouting report levels. The decision rule states that if the scouting report level is above the economic injury level then a control measure should be applied. This decision rule is static and does not consider interseasonal dynamics or carryover effects. It remained for others to describe the relationship between the EIL and ET or AT.

Pedigo, following Stern, and Norton, calls the economic injury level the point at which the current value of crop damaged by a pest matches or exceeds the costs of control. The Pedigo economic injury level is a variation of the Norton model and has four basic variables. The Pedigo EIL general equation is:

(2) $EIL = C/ (P*D*K)$

(Pedigo et al., 1986). The crop value is multiplied by the damage per pest, total number of pests, and control efficiency. The economic variables are the price of the crop (P) and the cost of control or management costs (C) (Pedigo et al., 1986). The biological variable (D) is a function of two components. The first component is the amount of injury caused by a single pest. *Injury* is defined by Pedigo as "effect of a pest on host physiology that is usually deleterious"(Pedigo et al, 1986). Pedigo then goes on to define *damage* as "measurable loss of host utility, most often yield or quality"(Pedigo et al., 1986). Injury is the starting point for damage, but a pest's activities will not automatically lead to damage. The idea that some injury will not cause damage is fundamental to IPM programs. For example, a single pest may injure (x) amount of cherries on a tree. However, injury does not necessarily lead to damage so the second component is the translation of injury into actual yield loss expressed as a percent of total yield or an actual tonnage or bushel figure. This injury (x) translates into a yield loss of (y) lb. from a single tree. For this model to work, a linear relationship between these two components must be accepted. The last variable is control tactic efficiency (K). Current pest numbers are determined through scouting analysis of pest numbers in the field or orchard. The EIL decision rule assumes that the control tactic can be applied right at the moment that the injury level is reached. Also, an assumption is made that scouting is done on a daily basis or nearly all the time.

A number of terms accompany the Pedigo economic injury level including the damage boundary and action threshold. The point at which damage begins to occur is the *damage boundary*. The EIL will never be below the damage boundary because injury below this point does not cause any actual yield loss. The EIL will be somewhere above the damage boundary based on the value of the EIL parameters.

The action threshold is defined by Pedigo as "the level of pest damage corresponding to the latest date for which a given control tactic could be applied to prevent an increasing pest population from reaching the economic injury level"(Pedigo et al., 1986). The Pedigo economic threshold is defined as a pre-application population whose estimated crop damage will exceed control costs. The Headley economic threshold was defined as a post-application population which requires calculating a pesticide dosage level and timing schedule. Economists and entomologists have often been using different concepts concerning thresholds. The Laubach-Johnson plum curculio-tart cherry action threshold under evaluation here uses the term action threshold to refer to the Pedigo definition. For this study, the term action threshold will refer to the Pedigo-style threshold and the economic threshold will refer to the Headley-style threshold

The action threshold is the practical rule which can be used by growers and consultants to time control actions. The AT is based on the same variables as the EIL, but must take into account a number of other factors. The action threshold takes into account the fact that scouting is not done on a daily basis, but perhaps a weekly or bi-weekly basis. The action threshold also takes into account the time delays associated with various control tactics (Pedigo, 1989). One major difficulty in using the economic threshold is that future population growth and injury growth rates must be estimated (Pedigo, 1989). If scouting occurs on a weekly basis, the sample estimates must be used to predict the following week pest activity levels and expected damage rates. If the value of the estimated future crop damage exceeds the cost of control, a control tactic should be applied. This can be translated into the decision rule. If the EIL is expected to be reached in the period between scouting times, then a control should be applied.

A number of different action thresholds are identified by Pedigo. The *nominal threshold* is based on the subjective experience of a grower or pest scout and has no underlying economic injury level (Pedigo, 1989). The *nominal threshold* is not based on research or experimental procedures. Usually, an experienced extension agent or pest scout will give their best estimates of potential damage, key time periods for activity, and a threshold level.

A *simple threshold* is based on subjective estimates for the EIL and ET variables. Unlike the *nominal threshold*, an explicit EIL is used in the calculation of the *simple threshold*. This type of threshold is fairly static and may not be able to respond to changes, such as new crop varieties or changes in pest activities.

Objective action thresholds are based on an underlying economic injury level. In this case, an explicit EIL is calculated and estimates are made to determine if the pest population will reach the EIL. An *objective fixed action threshold* is "based on a fixed percentage of the economic injury level (e.g. 50% or 75%)" (Pedigo, 1989). The *objective descriptive action threshold* is based on a population growth function and the expected future growth of injury units. An estimate is made when and if a population will reach the economic injury level. If the population estimates reach the EIL, then a control method is utilized.

Pedigo lists five limitations of the EIL and AT (Pedigo, 1989). First, no mathematical relationship between the EIL and the AT exists. A number of definitions and estimates exist, but none of these are widely supported. Second, many thresholds in use are nominal thresholds and are not based on an explicit EIL. Third, it is very difficult to estimate population growth rates for many pests. This makes it very difficult to estimate preventable damage. Fourth, many EIL and AT economic variables are difficult to predict for certain crops, such as market value. Fifth, there have been few attempts to incorporate externality effects into economic injury level or economic threshold calculations. The key difference between the EIL and AT is that the EIL is based on current pest activity whereas the AT uses future projections of pest activity.

Onstad also explores the theory of the EIL and AT (Onstad, 1987). Onstad claims that the basis for decision making with the AT is a "comparison of the expected preventable injury and damage with the cost of control"(Onstad, 1987). Again, the emphasis is placed on expected or future projections of damage in using the AT decision rule. The Onstad action threshold compares damage with and without implementing a control measure. The value of the damage after control is subtracted with the value of damaged crop with no control. Control is initiated when the subtracted damage value equals or exceeds the cost of control. Onstad also examines situations where the pest density-damage relationship is not linear. A clear distinction is made between the action threshold and economic injury level. A general model for calculating the action threshold relative to the economic injury level is given. The Onstad AT model accounts for control tactic implementation delays and time between scouting periods.

A number of University and government researchers have also attempted to define the EIL and AT. The Virginia Tech IPM evaluation study (1987) defined the economic injury level as dependent on a pest density-damage relationship, control cost, crop value, the cost of failure to control the pest. The President's Council on Environmental Quality (1979) declared action thresholds to vary with pest density and damage, crop value, human risk factors, cost of control, and ecological concerns. An FAO Plant Protection Division paper defines the action threshold as "the minimum population where a control action is warranted" (Reichelderfer, 1984). The AT was defined as varying with crop value, a damage function, cost of control, and control method kill function. This is another case where the EIL is called the AT.

2.3 Previous Pest Control Economic Studies

Pest control optimization studies evaluate alternative strategies given specified forms of biological and economic equations describing the system of interest. They attempt to find a strategy that optimizes a criterion of interest, which is usually profit. An exhaustive search of all possible strategies is performed to determine which produces the optimal results. Several studies of this nature have attempted to find optimal action and economic thresholds.

Three different objectives have been attempted among optimization studies. One has been to compute the optimal dose, timing, and post-application population of a pesticide control. This is analogous to the Headley-type economic threshold. Talpaz and Borosh (1974) estimated the optimal timing and dosage of pesticide applications for cotton in Texas. The unique contribution of this study was the incorporation of multiple treatments. Previously, pest control studies had optimized a profit function based on a single pesticide application. A numerical optimization method was used to solve the profit maximization problem. A subsequent Talpaz et al. study (1978) estimated timing and dosage of a pesticide application for the boll weevil in cotton. The major conclusions were that timing was insensitive to changes in parameters, but dosage level changed with price.

A second type of optimization study has estimates an entomology-style action threshold. These studies calculate optimal pre-application population levels and dosage. The economic threshold is based on profit maximization, whereas the action threshold falls short of this performance due to its comparatively fixed nature (Moffitt et al., 1985). However, decision makers clearly prefer the simpler and easier to use action threshold over the economic threshold (Moffitt et al., 1984; Moffitt and Farnsworth, 1987). Field use of the economic threshold requires dosage computation for every possible combination of infestation levels, prices, input costs, and so forth. Two studies have shown that the difference in profit under the two strategies is minor (Moffitt et al., 1984; Moffitt and Farnsworth, 1987).

A third study type is the optimization of multiple control methods. This often involves biological, cultural, and chemical control methods. The optimal levels and timing of various control methods are estimated by these studies. Shoemaker and Onstad (1984) develop a dynamic programming model to calculate optimal levels of biological, chemical, and cultural control of alfalfa weevil in New York. The optimal policies were most sensitive to changes in weather and weevil density. Insecticide applications were never chosen as the optimal strategy across a wide variety of options. Zacharias and Grube (1986) also used dynamic programming to compute optimal strategies for two soybean insect pests (corn rootworm and cyst nematode). This was one of the first attempts to incorporate multiple pests into the evaluation of optimal strategies. Illinois Extension Service pest decision rules are based on single pest action thresholds and price rules without regard for multiple pest interactions (Zacharias and Grube, 1986). A price rule was established by the Illinois Extension service. Below a certain price, pest susceptible cultivars should be planted (Zacharias and Grube, 1986). Above the price level, resistant cultivars or pesticides should be used (Zacharias and Grube, 1986). These decision rules are based solely on consideration of the soybean cyst nematode (Zacharias and Grube, 1986). The major conclusion was that the extension recommendations and optimal decision rules were very close (Zacharias and Grube, 1986). However, this relationship failed when some of the parameters were varied. It was observed that single pest management strategies may be suboptimal. Changes in price and yield parameters resulted in a shift in optimal combinations of crop control measures that were different than Illinois Extension Service guidelines.

Simulation models have been used by various authors to compare pest control strategies. An important difference between simulation and optimization studies is the use of predefined strategies by simulation models. The authors decide which strategies to test under the various biological-economic combinations and record performance results. Combinations of climate, pest levels, and economic conditions are run with thousands of different possible values. All the previous authors have used profit as their performance criterion.

Various techniques are used to measure and compare different strategies under simulation studies. Reichelderfer used benefit-cost analysis to compare eleven different pest control strategies for soybeans (Reichelderfer and Bender, 1978). A number of other studies have used stochastic dominance to compare the profit probability distributions of various strategies. Greene et al. (1985) used stochastic dominance to compare the profitability of IPM strategies with conventional prophylactic control. Boggess et al. (1985) used stochastic dominance to compare forty different scouting strategies. Another method has been the use of simple comparisons of expected profit and pesticide use under different strategies (Hall and Moffitt, 1985).

A weakness of simulation models is possibility of overlooking a strategy which is potentially better. Since strategies are predefined at the beginning of the analysis, some strategic alternatives may be overlooked. The power of optimization studies lies in their ability to test all possible strategies as defined by the model. In this way, no superior strategies are overlooked. However, some optimization tools (e.g. dynamic programming) cannot handle a large number of decision variables. A large number of decision variables can lead to an extremely large and unsolvable search space.

Price information has rarely been explicitly considered in pest control economic studies. It has been assumed that growers and researchers will not have a problem in deciding which price level to use when calculating threshold levels. Most studies have focused on the estimation of the biological variables as described by Pedigo especially the injury and damage relationship. In prior economic studies, past average price or current prices are used to calculate profitability or net returns for pest control strategies. Many studies have simply used a fixed number as the price parameter (Moffitt and Farnsworth, 1987; Moffitt et al, 1984; Hall and Moffitt, 1985; Greene et al., 1985; Reichelderfer and Bender, 1979; Szmedra et al., 1990; Rossing et al., 1994; Boggess et al., 1985; Talpaz et al., 1978). For decision support systems, product price is usually a data input parameter which must be supplied by the user in decision support systems (Wilkerson and Mishoe, 1990; Capineria et al., 1983; Mann et al., 1986). Some authors have attempted to predict the price needed for their model based on some external price submodel. One optimization study utilized future prices, in the form of Chicago Board of Trade quotes, for pest control decisions (Zacharias and Grube, 1986). However, they did not examine the impact of fluctuating prices (Shoemaker and Onstad, 1983; Zacharias and Grube, 1986). Previous studies have not studied the impact of fluctuating prices. Usually, price information has been considered a simple, fixed parameter .

Ch. 3: Methodology

3.1 Introduction

This chapter will be divided into two sections. The first section will describe the context for which the simulation was designed. The decision environment for this system includes the orchard ecosystem, pest life cycle and behavior, pest control manager activities, and tart cherry industry conditions. The second section discusses the methods and tools used to develop the various procedures which comprise the PLUMSIM simulation model.

3.2 Tart Cherry-Plum Curculio Ecosystem

A tart cherry orchard is a complex ecosystem with many insects, fungi, plants, and other forms of life interacting with the tart cherry tree. Some of these interactions are positive and assist the cherry tree, while others prevent growth or damage the tree or its constituent parts. One goal of the cherry orchard manager is to produce a high yield of quality fruit on the tree. To accomplish this goal, the manager must prevent harmful organisms from damaging the tree or fruit and enhancing positive biological interaction.

The tart cherry production season begins in early to mid-May and ends in mid to late July. A bearing tart cherry tree begins its growth at the green tip stage and ends at the harvest stage, generally 10 or 11 weeks in duration. The 8 or 9 weeks from green tip to pre harvest is the period where a number of key pest control decisions must be made. Diseases are a problem throughout this period. Cherry leaf spot is a major disease concern that can weaken and eventually destroy cherry trees (Johnson, 1995; Laubach, 1995). The disease causes premature defoliation which weakens the trees and may not allow them to survive winter months and causes low quality fruit. Leaf spot occurs as a middle and late season problem. Brown rot is the other disease of concern that causes direct fruit damage, reducing yield and fruit quality. Brown rot is a problem in the early and late season (Johnson, 1995; Laubach, 1995).

A number of insects cause problems in tart cherry orchards. The key pests are the plum curculio and cherry fruit fly. In some years, the green fruitworm may also be a problem. The cherry fruit fly is the most important insect in the tart cherry system due to Food and Drug Administration (FDA) regulations (Johnson, 1995; Nugent and Thorton, 1995). These standards do not allow any larvae of cherry fruit fly in cherries at the point of processing. The cherry fruit fly only emerges late in the production season, a few weeks before harvest. Any larvae found by inspectors, called harvest infestation, will lead to rejection of the growers delivery. Inspectors do not treat plum curculio larvae as being different from cherry fruit fly larvae (Johnson, 1995; Nugent and Thorton, 1995). Therefore, growers must implement a very careful and thorough spray program near the end of the season for both pests. Growers treat the plum curculio and cherry fruit fly as identical during the end of season control program. A major question was whether or not successful IPM techniques could be developed within the current restrictions on harvest infestation..

The plum curculio (PC) is another major pest of tart cherry trees in the eastern United States. It can be a problem throughout the growing season, but generally late May through June is the period of greatest concern for cherry growers. The plum curculio is a weather sensitive pest. It is not a strong flier and will avoid areas or conditions of strong wind (McGiffen and Meyer, 1986). The insect does not disperse evenly through a tart cherry tree (Nugent and Thorton, 1995). Most studies have found that PC reside in trees with dense foliage cover to protect themselves (LaFleur and Hill, 1987). It will generally avoid the upper one third of the tree and may cause damage only along a number of branches on a tree (Nugent and Thorton, 1995). The entire tree may be free of damage except for one local area where damage will have occurred along entire branches (Nugent and Thorton, 1995). The plum curculio is mostly active at night, although it can be seen moving during the day (Racette et al., 1991). Most activity, such as feeding and egg-laying, are done in the early evening hours (Racette et al., 1991).

The major damage caused by plum curculio is laying eggs in the fruit (Laubach, 1995a). Typically, the plum curculio insect overwinters outside the orchard under soil in nearby tree lots or abandoned orchards and begins to migrate into the orchard during spring (Laubach, 1995). The movement appears to based on air temperature and humidity levels (McGiffen and Meyer, 1986). It is still uncertain as to the exact conditions which cause plum curculio migration. Once in the orchard, the female insect begins to lay eggs. The female insect chews a hole in the fruit and lays eggs in the hole (Nugent and Thorton, 1995). She then chews another crescent shaped hole near the first hole. This is done to prevent the fruit scar tissue from crushing the eggs and larvae (Nugent and Thorton, 1995). The larvae emerge and chew around the fruit down to the pit. At this point, the fruit becomes very soft and loses structure. Later, the pupae emerge form the fruit and fall to the ground to bury themselves either within or outside the orchard. After a number of weeks, the adult insect emerges from the ground and may feed on the trees until migrating out of the orchard for the winter (Johnson, 1995).

3.3 Plum Curculio Integrated Control Strategy

Previously, growers used a calendar-based approach and sprayed whenever the curculio was considered a threat in the system. Normally, three or four sprays would be directed against the early season plum curculio populations. Control of plum curculio was considered essential because if the harvested fruit was infected, the entire crop would be rejected. This fixed strategy did not rely on scouting or site-specific information to assess plum curculio populations.

A new approach has been developed by Jim Laubach, owner of the agricultural consulting firm, Hort Systems. Recently, Jim Johnson, an MSU entomologist, and Jim Laubach released a tart cherry insect scouting manual (Johnson and Laubach, 1995). Part of this manual is devoted to integrated control for the plum curculio that involves three elements. The first element of the system is to divide the tart cherry season into a pest harvest infestation period and non-harvest infestation period. The second element is a scouting protocol to determine insect inspection methods. The third element is an action threshold to determine when a plum curculio population is threatening economic loss and should be controlled.

It was known by some experts and growers that damage by the plum curculio in the early season caused tart cherries to fall off the tree and not cause infestation problems at harvest (Laubach, 1995; Thorton, 1995). A major concern was the development of a method to determine at what point in the season plum curculio eggs would cause infestation at harvest. The first element of the Laubach -Johnson system was to divide the growing system into yield loss and harvest infestation periods. Recent research by Laubach demonstrated a growing degree day model for dividing the season into yield loss and harvest infestation periods (Laubach, 1995). 375 degree days base 50 (GDD = 50) is considered the point where plum curculio egg-laying damage becomes a harvest infestation threat (Laubach and Johnson, 1995). Before the 375 degree days, plum curculio damage causes yield loss, known as June drop, but will not cause harvest infestation (Laubach and Johnson, 1995). With this development, IPM techniques which tolerate some damage, could be used to manage plum curculio control decisions in early and mid season. Laubach was able to show that before the threat of harvest infestation, plum curculio damage reduces crop yield as damaged fruit fall to the ground during June, (Laubach, 1995). The Tart cherry scouting manual details how new scouts can use the Laubach-Johnson system.

The point between June drop and harvest infestation is the first element of the current Laubach-Johnson action threshold system. The second element of the Laubach-Johnson system is the scouting protocol. Typically, scouts measure insect numbers with a sampling protocol. While it is possible to count plum curculio insects, there is no industry accepted trapping measure for the plum curculio. Two possible scouting methods are identified in the tart cherry insect training manual: tree beating and visual damage counting. The only available method for counting pests is the tree beating method. This method involves the use of a large net and beating stick and is recommended for the period from full bloom to shuck split. During this period, the pest is scouted by attempting to strike trees and knock insects off into a net surrounding the trunk of the tree. 50 trees per acre are sampled striking one branch of each tree. From full bloom to shuck split, the danger from plum curculio is crop reduction. Fruit injured will fall off the trees and not be present at harvest. The tree is struck and net catches are counted for plum curculio. However, further interviews have established that the tree beating method is very difficult to use and requires a well-trained scout. The plum curculio is a very excitable pest and will play dead if any loud noises occur near it (Johnson, 1995). Scouts must be very quiet when using the tree beating method.

The second scouting method is a visual count of damage or stings on fruit. Damage is measured as a sting on the fruit caused by the female beetle. During ovisposition, the female chews a hole in the fruit and lays the eggs inside and then chews another oval shaped scar near the egg-laying hole. The training manual recommends the visual method for the period from shuck split to 375 growing degree days (base 50) after full bloom. Orchards are examined on a weekly to bi-weekly basis. Scanning is the process where scouts go through the orchard and observe how many stings are present. Twenty trees per acre for three minutes each are sampled during this period.

The third element of the Laubach-Johnson system is the action threshold. The action threshold is the point where control should be initiated because the estimated benefits of control exceed the costs. As stated in the literature review section, the action threshold and economic threshold are treated here as synonymous. The action threshold developed by Johnson and Laubach divides the season into a period of pre-harvest fruit drop and a period of larval infestation at harvest. Action thresholds can be used during the pre-375 degree day period. The threshold rule for the tree beating method is if 5 insects per acre are observed, then a control is initiated. The action threshold for the visual method is if 20 stings per acre are present in the sample then a control should be initiated. The action threshold is based on the best estimates of pest scouts and entomologists with safety factors built in.

A decision to use a pesticide should be based on the ability of that control tactic to prevent future damage for the period of effective residue. An insecticide applied today will be effective for a period of 7 to 10 days depending on the material used. Scouting measures the damage already caused by the plum curculio. This damage is a sunk cost, it has already occurred and cannot be controlled. Prior damage should not be a factor in whether or not to use a pesticide. Samples obtained by scouting may be used to estimate future pest activity and potential damage. As discussed in chapter two, the action threshold is based on projections of expected future pest damage. The decision to spray is predicated on weighing the benefits and costs of preventing expected future pest activity. Future, not present, damage is the relevant factor in whether or not to use a pesticide.

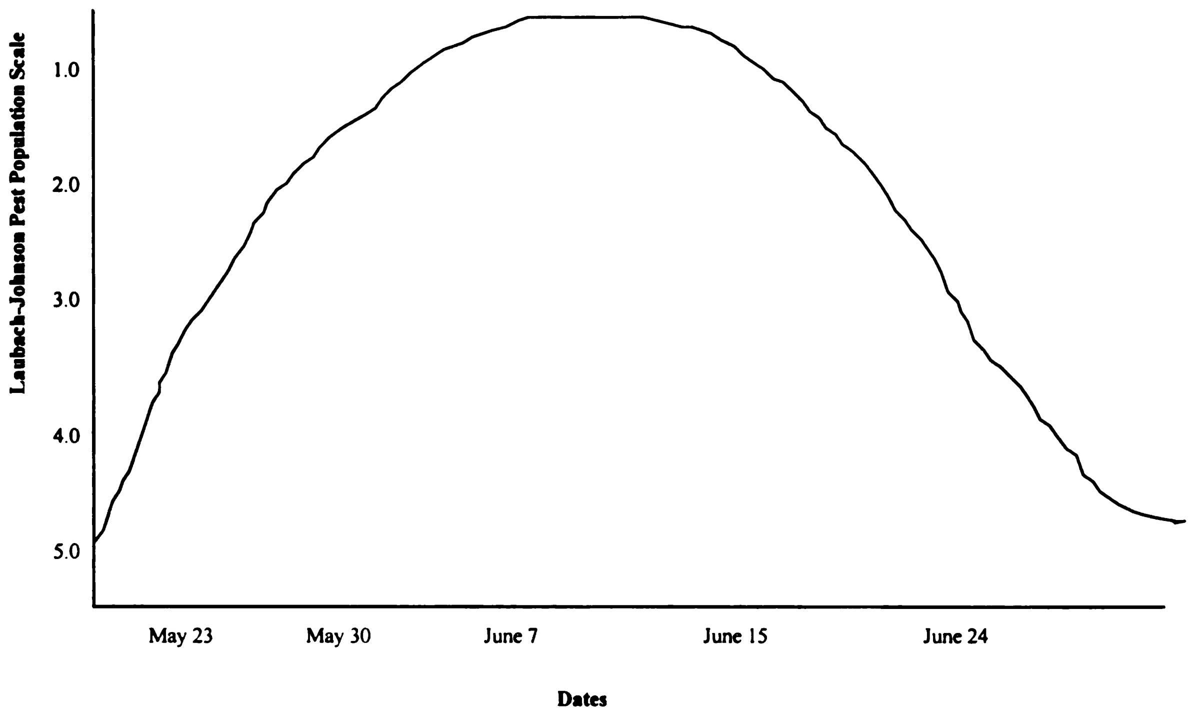
The action threshold system relies on measuring current population and estimating future pest population activity. Initially, it appeared there would be no method available for measuring future population activity levels. Scouts, such as Jim Laubach, only implicitly measure future population activity levels. No explicit formula existed for relating current and future plum curculio population activity levels. The training manual expresses action thresholds in terms of sting counts. Finally, sting counts appeared to be the measure which could relate current population activity and estimate future population activity and total damage estimates.

The training manual was designed for new scouts or growers who have limited experience. Experienced scouts often do not use the same methods and have learned rules of thumb and other shortcuts to minimize their time in any one orchard. The economics of the scouting business is based on the ability of practitioners to minimize their time in the orchard and maximize the total acres they can scout in a given time period while still collecting useful information. Laubach and his scouts do not count stings during acre sweeps. The scout walks through the orchard and determines a rough estimate of plum curculio activity which is ranked on the Laubach population activity scale.

The current Laubach system uses a one to five rating system for pest population assessment. Based on scouting reports, the population is ranked on the 1-5 interval, 5 being the lowest population level. Each acre is assessed and given a ranking on the scale. This study utilized the Laubach system as a method of representing present and future plum curculio populations in an orchard.

To develop estimates of future population activity, Jim Laubach was asked a number of questions to establish a range of plum curculio behavior.

Figure 2: Plum Curculio Population Activity Curve



The dates are based on average tart cherry tree activity and expected scouting times. In total, four decision periods where a decision to control or not control has been identified. The first two decision periods, between May 23-May 30 and June 6-June 13, represent a higher upside risk of pest activity. During these decision periods, the pest population may potentially accelerate its future damaging behavior at a fairly high rate. For example, a population could increase from level 3.7 to 1.7 or somewhere between that range, 2 scale points, but no lower or higher. As shown in Table 2, future pest behavior may expand two levels from current scouting reports between May 23 and June 6. Between June 7 and June 20, the future pest behavior upside risk declines to a one level expansion. The downside risk, or potential future decline in population activity, is defined at one level for all decision periods. For example, a level 3.5 population level could fall to a 4.5 level but no lower in this model. The downside reduction is lower than the upside increase because once a population is established it is unlikely that activity will fall off unless the weather is extremely unfavorable (Laubach, 1995).

With this general framework, triangular distribution was used to represent the combination of current and future pest activity levels. Each possible current pest level (1.0 - 5.0) can be related to three possible future values on the triangular distribution. The expected value, optimistic value, and pessimistic value are three possible future pest states that may occur from the current pest level. The most likely value is the one with the highest probability of occurrence. The optimistic and pessimistic values represent the two extreme values which the current population activity could attain in the future. These future levels of pest activity can in turn be translated into potential damage estimates. These damage estimates, along with crop value and pesticide efficiency, form the basis for one side of the action threshold equation.

The damage-density relationship or crop loss assessment is a key parameter of an action threshold. It expresses damage, often in terms of yield loss, that different levels of pest populations may potentially inflict on a orchard or field. For example, a ten percent infestation of an orchard by a certain pest may lead to a 30% loss of yield. This relationship forms the basis for the control decision. There are two broad categories of crop loss assessment, subjective and objective. An objective measure is based on scientific field studies where all other variables are held constant and trials are replicated. In field trials, insect injury is observed or artificially created and yield loss is measured (Poston et al.,1983). These observations can be analyzed as regression equations which relate pest levels with yield loss (Teng, 1987).

The plum curculio damage-density relationship is poorly understood at this time. No objective measure of crop loss by plum curculio is widely accepted by entomologists. Up to this point, no studies have correlated yield loss with plum curculio population levels. Part of the problem is the inability of pest scientists to estimate population levels based on sampling numbers due to lack of knowledge concerning curculio reproductive and migratory behavior. Another problem is the fact that Laubach and his scouts do not use random sampling. No mathematical or statistical analysis can be used in this situation to estimate population parameters based on sample numbers (Johnson, 1995).

If statistical analysis cannot be used to convert current pest samples to future population estimates, the question must be asked as to what value are the data from samples. Subjective measures of crop loss are based on expert or grower experience and an understanding of the pest-crop ecosystem. Laubach and his scouts use their experience to interpret their samples and estimate population activity levels and damage. The Laubach interval scale represents their method of assessing current and future populations. Embedded in the interval scale are damage estimates caused by different plum curculio activity levels.

Given the current state of plum curculio knowledge, a subjective measure of crop loss is used in PLUMSIM. Using the interval scale and past experience, Jim Laubach was asked to assess the potential damage inflicted by different levels of plum curculio. These subjective assessments formed the basis of the density-damage relationship for the PLUMSIM model. A regression equation was calculated from the damage-density relationship. This equation is used to estimate damage based on observed plum curculio levels.

(3) $croploss1 = [12.409245 + (value1 * -2.47039394)] ^\wedge (1 / .43)$

where

value1 = potential future plum curculio population

croploss1 = yield loss in pounds per acre to potential p.c. population

Damage estimates were expressed in yield (lb. of cherries) lost per acre due to plum curculio egg laying activity. The best functional fit was a power function (R^2 = 98%). This equation is used in the simulation to correlate potential damage with pest population levels.

3.4 Pest Control Strategies Tested

Three plum curculio control strategies were chosen to be analyzed in this study. These strategies represent what many growers are actually using for plum curculio management. They were developed with the assistance of expert opinion and published documents (Nugent, 1995; Laubach, 1995; Michigan Agricultural Statistics Service, 1995; Flore et al., 1992). The first strategy is the traditional calendar-based spray schedule. Growers base their spray decisions on predetermined dates when keys pests are suspected to be a problem. It has been estimated that 10-15% of growers are currently using this strategy (Laubach, 1995; Nugent, 1995). This strategy involves the use of some biological information. A good example of this strategy in practice is the MSU Fruit Spray Calendar developed by pest scientists at MSU. This calendar gives dates when pests in different fruit crops are expected to be a problem. Growers spray when key pests are expected to be in the orchard and vulnerable. This is a fixed strategy and does not utilize site-specific biological information, but rather expected pest conditions based on average regional conditions. Future expected prices are ignored in the fixed calendar system.

The calendar strategy is expected to perform best under high price conditions. In this scenario, the correct financial decision is to often spray the trees on a regular and fairly heavy basis. This is because the yield is more financially valuable and even a small amount of damage will equal or exceed the cost of control. A grower who does not spray and experiences moderate to high pest populations may lose a large amount of valuable yield. Under high prices, the value of a good decision and the cost of a mistake increases. This means that a decision to spray has the potential to save large amounts of crop generated profits. As price increases, the value of yield saved increases as does the potential to lose large amounts of money when a spray is missed. The calendar strategy is expected to perform favorably relative to other strategies in high price conditions. With low prices, growers could potentially not need to spray frequently and a calendar strategy may lead to overspraying and financial loss on pesticide applications, especially when pest populations are low.

The strength of the fixed strategy is that it does not expose the orchard to the risk of financial loss from plum curculio damage. This strategy is very conservative with almost constant pesticide residue on the trees. This ensures that if a large population emerges it will be controlled and damage prevented. Plum curculio populations are kept at low levels throughout the season. The initial decision period is the only point where a large population could exist. After that period, the grower simply applies an alternate row spray on a seven to ten day basis. The strategy is simple to implement and does not require scouting. The disadvantage of the strategy is that it overapplies pesticides in almost every case. Unless the pest population and cherry prices are at exceptionally high levels, pesticides do not need to be applied every week for the length of the season. In many cases, the application of pesticides in this strategy are not financially justified by the amount of damage prevented.

The second strategy is a biologically-flexible strategy based on an action threshold. Biological information, in the form of pest scouting reports and site-specific biological information, is used. Information from the orchard is combined with weather station information to make control decisions (Laubach, 1995). This is the current strategy used by many growers and consultants in the Northwest Michigan tart cherry belt (Laubach, 1995; Nugent, 1995). The Laubach-Johnson action threshold is set at level 2.5 {based on the Laubach 5-point interval scale). This corresponds to approximately 70.5 pounds of plum curculio damage in an acre. The Laubach-Johnson action threshold was not set with an explicit economic injury level computation, but rather estimated using the knowledge of Jim Laubach and other tart cherry pest control experts (Laubach, 1995). This threshold could be characterized as a nominal threshold (see Ch. 2). Price information is only implicitly used in the Laubach threshold. Setting a fixed threshold places an implicit value on the tart cherry crop. The fixed crop price comes out to approximately 13 cents per pound, and the threshold cannot respond to changing price conditions.

The Laubach-Johnson fixed action threshold was expected to perform best under low price conditions with performance declining as prices rose. With the 13 cents / pound threshold, it is biased towards the low to middle range of tart cherry prices. Often, the pest population will be below the Laubach-Johnson threshold and a no-spray decision will be recommended. If a crop has a low value, a strategy to spray only under fairly heavy pest conditions will perform well. In a low price season, even with heavy pest damage, it is desirable not to spray as the benefits of control will often not exceed the costs of control. On the other hand, high crop prices lead to a situation where frequent spraying becomes financially viable. A fixed action threshold may be unable to respond to changing conditions. Pesticide applications which were financially justified may be missed and lead to potential losses. With a fixed threshold, growers could be exposed to large financial losses under a high price situation. In some cases with high prices, growers may come out ahead if the pest population remains low. However, the potential risk of large financial losses exists.

A third strategy is a price and biologically-flexible strategy that uses several types of information for decision making. The Laubach strategy only used biological information and static price information to make decisions. The third strategy, called a price-flexible action threshold, proposes to use explicit price forecasting information, as well as scouting reports, to make control decisions. The proposed price-flexible action threshold is based on the definitions and concepts found in Norton, Onstad, and Pedigo (Pedigo, 1989; Onstad, 1987). The price-flexible strategy is a variation of the objective descriptive action threshold described by Pedigo (Pedigo, 1989). Many elements of the price-flexible action threshold are based on subjective grower experience rather than objective scientific testing. However, the strategy does have a calculated economic injury level as its foundation. The price-flexible action threshold is a hybrid between a nominal threshold and an objective descriptive action threshold. To successfully use the price-flexible action threshold, it is necessary to forecast tart cherry prices in the beginning of the growing season.

Tart cherry crop prediction can be a very challenging process. Tart cherry crop estimates are provided by the USDA on June 15. These estimates are too late for pest control decisions in late May and early June which is often when plum curculio is a problem. The Michigan Frozen Food Association also sponsors a yearly guesstimate of tart cherry crop estimates in mid to late June. These figures can be used to cross check early estimates, but again are often to late for decision making. To use a price-flexible action threshold, a new crop estimate is needed as of May 15-June 1 period. Previously, the tart cherry marketing board which administered the marketing order for cherries in the mid-1980's often estimated new crop numbers at their meetings (Ricks, 1995). Currently, a price forecasting model exists for tart cherries but only predicts prices near the end of the growing season (Ricks and Hanson, 1992). A new marketing order will be voted on later this year and would provide another forum for new crop estimates (Ricks, 1995).

The price forecasting model was developed using economic variables to forecast a price for the current year tart cherry crop. Price is an important parameter in calculating an action threshold. Tart cherry price variability raises concerns about the economic viability of a price static threshold. Ricks and Hanson developed a price forecasting model for tart cherries (Ricks and Hanson, 1994). The original linear regression model was developed to predict price of frozen tart cherries based on crop size, previous years average frozen cherry price, frozen cherry carryover stocks, consumer price index, and disposable personal income. For the years 1960-1991, these independent variables were regressed with the dependent variable, frozen tart cherry price, to estimate a linear multiple regression model.

The estimated Ricks-Hanson model is as follows:

(4) **P** = 8.14863 - 1.33150 **S** - .06350 **Ca** + .485887 **LP** - 1.98113 **CPI** + 1.58977 **DI**

(9.05) (-8.93) (-.81) (4.11) (-1.96) (2.20)

P = Marketing year average price of frozen tart cherries (cents / lb.)

S = Total U.S. new crop of tart cherries for processing (mil lb.)

Ca = Carryover stocks (July 1) of frozen tart cherries (mil lb.)

CPI = Consumer Price Index (1967 = 100)

DPI = Disposable Personal Income (bil. pounds)

significance level t-statistic(95% level) = 1.71

significance level F-statistic (95% level) = 2.76

R-squared = .92

The numbers in quotes below the equation are t-statistics. For the Ricks-Hanson equation, the significance level for t-statistic based on a confidence level of 95% (alpha = .05) is 1.71. Theses numbers indicate that all variables are statistically significant except for carryover stocks. The model estimates indicate the percentage change in tart cherry prices due to a change in a price causing factor.

Managers need to make pest control spray decisions in May-July. Tart cherries are harvested in mid to late July and the Ricks-Hanson model uses actual new crop production values, as of late July, to estimate price. These estimates are too late to be of use to managers. The price prediction model must be able to estimate price based on available data as of mid to late May. A set of interviews were used to develop an early-season price forecasting system. This early season price predictor is a variation of the Ricks-Hanson model. The predictor uses estimated U.S. crop levels, as of June 1, rather than actual new crop numbers to estimate price. The predictor also uses grower prices rather than frozen cherry prices at the processing level. Dr. Ricks was queried to draw upon his knowledge of previous U.S. crop estimates as of June 1 for the 1976-1993 period. These figures were used with disposable personal income, consumer price index, May 1 carryover stocks, and the previous year's price for the years 1976-1993 to estimate a linear multiple regression equation.

(5) **P** = 39.7986 - .14207 **S** - .21749 **Ca** + .087962 **LP** - .11702 **CPI** + .002846 **DI**

(.69) (-3.96226) (-.1.73) (.49) (-.37) (.42)

where:

P = Marketing year average price of frozen tart cherries (cents / lb.)

S = estimated new U.S. crop production levels in millions of lb.

Ca = Carryover stocks (July 1) of frozen tart cherries (mil lb.)

CPI = Consumer Price Index (1967 = 100)

DPI = Disposable Personal Income (bil. dollars)

R-squared = .76

significance level t-statistic(95% level) = 1.71

significance level F-statistic (95% level) = 2.76

This estimated equation became the price predictor, called *price forecaster*. Variables in the model were tested for significance using a t-test. For the *price forecaster* equation, the relevant t-statistic is 1.71. Three of the variables, disposable personal income, last years price, and consumer price index were found to be insignificant by the fact that there coefficients did not differ significantly from zero. The variables new crop level (S) and carryover stocks (C) as of May 1 are statistically significant based on the t-test. The F-statistic for the *price forecaster* equation means that the entire regression model is considered statistically significant at the alpha = .05 level. The final *price forecaster* equation predicts price of tart cherries per pound based on the value of carryover stocks (May 1) and the forecasted level of U.S. crop size as of May 15. The R^2 for this equation was .80 with a standard error of .07 cents/ per pound.

To use this price prediction model in an action threshold strategy, the model is run and mean or expected price is computed for the season. *Price forecaster* calculates the expected price based on two pieces of information, May 15 estimates of U.S. tart cherry production and May 1 carryover stocks. Entering this information into the price forecasting equation, an estimated price level is calculated for the year. This price becomes the basis for calculating the value of preventable damage. The forecasted price is multiplied with potential preventable damage and pesticide efficacy rating to determine the value of preventable damage. The preventable damage figure is calculated by taking the expected value of the triangular distribution for the decision period and calling the computer *croploss* function to estimate potential damage. At that point, preventable damage is compared to control costs. If the benefits of control exceed the costs, a pesticide application is recommended.

It is expected that the price-flex strategy should outperform the other strategies under most price scenarios. The price-flexible strategy can respond to varying price conditions by setting the action threshold higher or lower. With high prices, the action threshold will fall and control actions will be undertaken more frequently to prevent crop loss. The threshold will rise with under low prices and spraying will be less frequent. A fixed threshold will not be able to respond to price changes and will perform poorly under price conditions other than those implicitly calculated in the threshold. A calendar-based strategy will perform poorly in low price conditions due to the overapplication of unnecessary pesticides in most cases.

3.5 Price Scenarios

As stated in chapter one, the first study hypothesis was that the Laubach-Johnson threshold would provide better economic performance than the calendar strategy and a price-flexible action threshold would provide better economic performance than the Laubach-Johnson threshold or the calendar strategy. In order to test these hypotheses, three price scenarios have been developed. These scenarios reflect an average, high, and low national tart cherry crop year. As shown in the previous section, the main factor in tart cherry price determination is the current year supply. Price is inversely related to supply, so in a low supply year prices will tend to be high. The three price scenarios are 1)average (average yield), 2)high(low yield), and 3)low(high yield). These figures were calculated by dividing the U.S. actual crop size for the years 1982-1993 into quintiles. The first and last quintile were thrown out to avoid extreme years. Representative values were taken from the second, third, and fourth quintiles and used to forecast price in the *price forecaster* equation. The mean high price came out as 40.0 cents per pound, mean low price as 13.0 cents per pound, and the mean average price was 22.0 cents per pound. The high, average, and low forecasted price values are used by decision makers in the price-flexible action threshold strategy to calculate an explicit threshold level. The threshold level is compared to the scouting report number and a decision to spray or not is made. However, the price that actually occurs at the end of the season may be higher or lower than the forecasted price.

The three control strategies financial performance must be compared using the actual year end price. Price is a component of the financial result of utilizing or not utilizing a pesticide during a certain decision period and reflects a strategy's financial performance. To compute actual price, the standard deviation around the price forecaster equation mean estimated prices was used. These distributions (average, high, low price estimates) were randomly drawn from to return the actual price which may be higher, lower or the same as the mean estimated price. This actual season price was then used to compute the financial results for each strategy.

The question addressed in this research was whether or not economic performance could be improved through the use of increased price information. Current IPM methods or calendar based pest control strategies use minimal price or economic information to make decisions. The Laubach action threshold is price insensitive and fixed regardless of crop value. The study examines the use of price information, specifically a price forecasting system, to determine if economic performance can be improved over current pest control methods.

Ch. 4: Model description

4.1 Introduction

The model description chapter documents the factors considered by the PLUMSIM bioeconomic model. This model was developed to test and compare the financial results of the three plum curculio control strategies under three different price scenarios. The first part of this section describes the programming environment and logic in developing the PLUMSIM bioeconomic model. The second part of this section describes the flow of the PLUMSIM bioeconomic model. The results of the tests and comparisons are presented in the next chapter.

4.2 PLUMSIM Model Structure and Specification

4.2.1 Programming Environment

PLUMSIM is divided into a number of forms, objects, and procedures. The model is written in Microsoft Visual Basic 3.0 with some converted procedures from FORTRAN. Forms are the windows observed when running a program in the Microsoft Windows operating system. Objects are items which appear on the form, such as command buttons, text boxes, or pulldown menus. Each object on a form may contain code to tell the object how to respond to a user event such as a mouse click.

The Visual Basic syntax is similar to Microsoft Qbasic for DOS. However, Visual Basic is a partially object-oriented language. Unlike modular programming where a program begins at a specified point and ends at another point, object-oriented program flow responds to user events. Only the most likely program flow can be specified by the programmer, as exact flow will depend on the options selected by the user.

All code in Visual Basic is contained in a procedure. Procedures can be divided into sub procedures and function procedures. Sub procedures perform a task, but do not return a value to a calling procedure or program. Function procedures also perform a task and do return a value to the calling procedure or program. Some code may be contained in a code module which is a part of the program that does not respond to user events, but is called by forms or objects when needed. Objects, forms, and procedures may be reused in other Visual Basic applications.

4.2.2 PLUMSIM Structure

Three forms make up the PLUMSIM model. The first two forms start the program and obtain information needed to run the simulation and test a pest control strategy. The start form (START.FRM) initiates the PLUMSIM model and prepares the program for use. The strategy form (STRATEGY.FRM) collects information from the user concerning the pest control strategy to be analyzed. The third form (BEGIN.FRM) starts the simulation process and computes a distribution of returns for a given strategy over simulated conditions.

The strategy form utilizes information from the user concerning the strategy they wish to simulate and test. The action threshold level, strat, is defined during this process. The control tactic efficiency, effec, is also defined as a percentage of pest population killed with the use of a pesticide or other control tactic. Tactic efficiency is the users best estimate of the ability of a control tactic to kill a targeted pest. It should be expressed as a percentage of pest killed by application (0-100%). For plum curculio, the current organophosphates will often provide 80-90% kill (Laubach, 1995; Nugent and Thorton, 1995). For PLUMSIM, the assumed level of control tactic efficiency is 85%. The cost of control is represented by the variable *cost.* The organophosphate Guthion is assumed to the pesticide used in all of the potential IPM and non-IPM strategies. The cost for an alternate row spray of Guthion is $8.00/acre. All of this information is passed to the main PLUMSIM procedure (*PLUMBEHAVIOR).*

Table 2: User Defined Model Variables

Name	Description	Acceptable Values	Assumed Values
Strat	action threshold level	1-5	Laubach- 2.5, calendar- 5.0, price-flex - calculated each time
Effec	Pesticide kill efficiency	0-100%	85%
cost	cost of pesticide material	any positive number	$8.00 / acre (Guthion)

PLUMBEHAVIOR is activated from the form, BEGIN.FRM, which has two command buttons. One command button initiates the simulation process, while the other button stops the program and returns to the main menu. The simulation places calls to function procedures (arer, arel, fractn, price1, log10 croploss(1-4)) during run-time to retrieve several values for use in the main program. The main procedure P*LUMBEHAVIOR* is the engine which simulates controlled and uncontrolled plum curculio populations. This procedure is initiated by the pressing of the command button start on the begin form. The main procedure can be divided into a main loop process and four decision periods within the main loop. The main loop was run 5000 times to represent 5000 early tart cherry seasons. This implies that each pest control strategy was tested with 5000 possible plum curculio early season activity combinations. Each run of the main loop is considered a pest scenario where a pest population develops and changes throughout the season based on human and natural factors.

The four decision periods within the main loop represent the periods where control decisions are made during each season. They are identical in program structure but vary based on the population activity curve discussed in chapter 3 (figure 1). The four decision periods are represented by a four step process which will be discussed later. Each decision period represents a week as portrayed on the Laubach population activity curve (see figure 1). This week includes the scouting day plus subsequent pest population activity which occurs until the beginning of the next decision period. The decision period dates are as follows: first decision period, May 23 to May 30; second decision period, June 1 to June 7; third decision period, June 8 to June 15; fourth decision period June 16 to June 23. The four decision periods operate together to simulate an entire early tart cherry season.

A pest scenario is a single run of the main loop process. Each pest scenario begins with the drawing of a random number to represent the initial pest population as of May 23. The main loop begins by computing a floating point between 1.0 and 5.0. The numbers 1 - 5.0 represent the Laubach interval scale and the initial levels a pest scouting report may reveal during the first decision making period. The equation:

(4) $actual0 = (\text{Rnd} * 4) + 1$

is used to compute the random value. *Rnd* is a Basic keyword that generates a uniform random value between 0 and 1 using the computer clock. The value (1.0-5.0..) is stored in the variable *actual0* and represents the initial scouting report estimate on May 23.

The first decision period begins after drawing the initial pest scouting level. The first step is to create a triangular distribution based on the value of the current scouting report , (*actual0)*. This triangle is created based on Laubach-Johnson's population activity curve (figure 1). Optimistic, pessimistic, and most likely values are calculated to portray the triangle. This triangular distribution values represent all potential pest activity levels which could emerge during the week. Decision period one calculates the pessimistic value taking into account the upside risk of potential plum curculio activity as discussed in chapter three.

Table 3:PLUMSIM Growth parameters for plum curculio, Decision period 1 and 2

Pest population level scenarios

Current reported population	Optimistic	Expected	Pessimistic
actual < 3	*actual* + 1	(*optm* + *pessm*) / 2.5	set to level 1
actual > 3 and < 4	*actual* + 1	(*optm* + *pessm*) / 2.3	*actual* - 1.2
actual > 4	set to level 5	(*optm* + *pessm*) /1.2	*actual* - 1.2

Table 4: PLUMSIM growth parameters for plum curculio, Decision period 3 and 4

Pest population level scenarios

Current reported population	Optimistic	Expected	Pessimistic
actual < 3	*actual* + 1	(*optm* + *pessm*) / 1.7	set to level 1
actual > 3 and < 4	*actual* + 1	(*optm* + *pessm*) / 1.8	*actual* - 1.2
actual > 4	set to level 5	(*optm* + *pessm*) / 2.0	*actual* - 1.2

In Tables 2 and 3, the variables and constants reflect the Laubach plum curculio interval scale. The current reported population is the plum curculio population which is reported by scouts in the beginning of the decision period. The plum curculio population level scenarios represents the possible plum curculio level of growth during the week of the decision period following the scouting report. The equations in these tables are used in PLUMSIM to determine the optimistic, pessimistic, and expected pest population growth levels during the week between the current scouting results and the next scouting report. In four cases, the potential growth level is set to a specific number rather than being calculated. This is because of the range of the Laubach scale (1-5) and the need to keep the results within that numerical range.

In the second step, a random number using a Monte Carlo process is drawn from the triangular distribution previously created. This number, *value1,* represents the potential population level at the beginning of the next decision period. This potential population will become the actual population which emerges in the next decision period if no pesticide is applied. If a control is applied, this variable will be altered. The functions *fract*, *arear*, and *arel* are called during step two as part of the Monte Carlo process. *Arear* and *Areal* are functions that compute the left and right sides of the triangular distribution.

The third step involves testing to see what action the current decision rule will take and calculating the financial results of that decision. At this point, the population activity level calculated in step two which will emerge during the week (*value1*), is unknown to the decision maker. The decision maker must base the decision to spray or not spray on the scouting report estimates depicted as the value of the variable *actual0*. The variable *actual0* represents the biological information the decision maker has available. The variable *control* represents the control action recommended. For IPM strategies, the current threshold level, *strat*, is compared to the scouting report number, *actual0*. If the scouting report (*actual0*) exceeds the threshold (*strat*), control is initiated. *Control* with a value of one means that a control measure has been recommended. If the threshold is not exceeded, a control measure is not recommended and *control* is set to zero.

The financial results of a control or no control decision are then computed. The cost of control and value of preventable damage are compared to calculate a positive or negative net return. First, total damage is calculated from the croploss function. The *croploss* function uses a regression function (discussed in chapter three) to calculate total potential pest damage, *croploss1*, based on the population which emerged during the week drawn from the triangular distribution. Preventable damage is defined as the product of pesticide efficiency (*effec)* and total damage. It refers to the potential damage which could be prevented if a pesticide was applied. The equation for preventable damage is:

(6) $prevdam1 = croploss1 * effec$

where

prevdam = preventable damage in terms of cherry pounds lost

croploss1 = stage1 ^ (1 / .43)

{stage1 = 12.409245 + (value1 * -2.47039394)}

effec = pesticide efficiency

To compute the value of preventable damage, price is multiplied with preventable damage with the equation:

(7) *yieloss1* = *prevdam1* * price

where

yieloss1 = financial value of preventable damage

prevdam1 = preventable damage from equation above

price = actual end of season tart cherry price (cents per lb.)

If a pesticide was applied, preventable damage refers to the expected damage which the pesticide presumably averted. If no pesticide was applied, preventable damage refers to the expected damage which was incurred but could have been prevented.

Tart cherry price is calculated for each run of the main loop which represents a single tart cherry growing season. The price that actually occurs for the season is used to compute the value of preventable damage. Another Monte Carlo process is used to draw a number from a normal distribution created with mean zero and standard deviation of one. This Monte Carlo process takes a random number from zero to one and computes a standard deviation. The computed standard deviation figure is added to the defined high, low, or average price scenario to return the price for that season. The equation is:

(8) price = p + (stddev * .071)

where

price = actual end of season tart cherry price

p = model forecasted price for high, average, or low price scenario

stddev = standard deviation estimate

This price is put into the equation (*prevdam1* * *price*) to compute the value of preventable damage and serves as the basis for the net return equation. The price drawn from the distribution is different for each run of the main loop.

PLUMSIM measures the benefits and costs of a pesticide application by subtracting pesticide cost from the financial value of preventable damage. This calculation is made whether or not a pesticide was applied. The net return scale can take on values from -8 dollars to +80 dollars for each of the four decision periods. The -8 represents a decision period where a control was applied, but no damage actually occurred. The +80 represents a decision period where a control was applied and the population activity level was equal to one on the Laubach scale resulting in prevention of the maximum damage of 200 pounds multiplied by the maximum price allowed in the model 50 cents per pound. For a period where a pesticide was applied, the equation is:

(9) finloss1 = yieloss1 - cost

where

finloss1 = financial value of decision to spray

yieloss1 = value of preventable damage

cost = cost of pesticide

Again, the *yieloss* variable depicts the financial value of preventable damage. A positive figure implies that the cost of the pesticide material was more than offset by the benefits of preventing yield reduction and the decision was financially successful. A negative figure indicates that the cost of the pesticide application was not offset by preventing yield loss and the decision was financially unsuccessful. For a period where a pesticide was not applied, the equation is:

(10) finloss1 = *-yieloss1+ cost.*

where

finloss1 = financial value of decision not to spray

yieloss1 = negative value of preventable damage

cost = cost of pesticide

A positive figure means the value of preventable damage was less than control cost and decision was financially correct. A negative figure means that value of preventable damage exceeded the cost of control and a control should have been applied.

Step four of decision period one is to determine the impact of the control or no control decision on the current and migratory curculio population. The impact of a decision to control or not control affects the pest population, current and migratory, for the week represented by decision period one. *Value1* is the variable which represents the population which emerges during the week. If a control measure is applied, the variable *value1* is transformed to represent the population which exists in the orchard in the next decision period. The equation:

(11) *actual1*= (5 - *value1*) **effec* + *value1.*

where

actual1 = plum curculio population which exists at the beginning of decision period two

value1 = potential plum curculio population in decision period two

effec = pesticide efficiency

The potential population, *value1*, is modified due to the application of a pesticide. The distance between level 5.0 (meaning complete destruction of a population) and the potential population which may exists and will emerge during the week is considered 100% destroyed. This distance is multiplied by the actual control efficiency to give the population which will exist in the orchard during the week of decision period one. This accounts for the destruction of the current population and destruction of migratory beetles from outside the orchard. *Actual1* will then represent the controlled curculio population in decision period two. If no control is applied, the potential future population, the variable *value1*, becomes the actual population or *actual1*.

Results from this decision period are used to determine the population in decision period two. The controlled or uncontrolled population becomes the new population in the following decision period and is stored in the variable *actual1*. The variable *actual1(one)* depicts the population which will be observed in decision period two. This variable carryover portrays the controlled or uncontrolled population as it moves through the season.

The other decision periods sequentially proceed directly from decision period one in order. Decision period two is identical to decision period one in structure and parameter specification. The value of the *actual1* variable is used to create the three values for the next triangular distribution. A random number is drawn and the strategy is tested and financial results are computed. Decision period three and four continue the process using values from the previous decision period (the *actual2* and *actual3* variable carryover) as scouting reports estimates and record financial results. A parameter difference exists for decision period three and four due to somewhat different values for the most likely, pessimistic, and optimistic population levels. This is due to the reduced risk of increasing population activity levels in these periods based on the Laubach population curve.

Each decision period calculates a positive or negative net return value for the strategy under testing. Net return figures for the four decision periods are then combined to give a total net return value for that specific pest scenario-strategy combination. At the end of the main loop, this combined net return value is divided by ten. This converts the results into ten dollar increments. Another equation transforms the ten dollar increment figure into an integer which is then stored in an array. Each time an element of the array, represented as ten dollar increments, is called a one is added to that particular array elements. This method allows the net return results to be presented as a frequency distribution using $10.00 increments.

Ch.5: Results and Discussion

5.1 Introduction

This chapter presents the results of the strategies evaluated with the PLUMSIM model. The different control strategies were tested under three different price scenarios. The strategies were analyzed with five thousand pest scenarios and net return distributions generated for each of the three price scenarios. These distributions serve as the basis for evaluating and comparing the pest control strategies.

5.2 Methods of Analysis

Two forms of analysis were used to examine output from the PLUMSIM model. The two forms of analysis are both used in conjunction to attempt to address the objectives of this study. The hypothesis that a price-flexible strategy can outperform the Laubach-Johnson fixed economic threshold and the traditional calendar-based spray strategy was tested with the PLUMSIM model.

The first form of analysis was the mean or expected value of each price scenario distribution. The mean value is the average value that occurred during the simulation run. Again a simulation run was the combination of a price scenario (e.g., low, average, high) with several thousand possible plum curculio population scenarios. The mean value is the basis for part of the study's objectives concerning which strategy is preferable. To determine which strategy a risk neutral decision maker may prefer, the mean value is calculated for each strategy under the three different price scenarios. Risk neutral decision makers will choose the strategy that has the highest mean. The means of different strategies are compared in each of the price scenarios to determine which strategy is superior for a risk neutral decision maker.

The second form of analysis is stochastic dominance. Stochastic dominance is a method that allows the comparison of different strategies based on cumulative probability functions of possible net incomes of each strategy. These comparisons can help point out which strategies would be preferred by different classes of decision makers when considering their risk attitudes. Risk plays an important role in pesticide decisions (Moffitt et al., 1986; Feder, 1979).

The decision to spray is dependent on the cost of control. Pest control costs are determined by the cost of materials, pesticides, and the cost of machinery and labor used. In the case of tart cherries and the plum curculio, growers will be spraying for diseases at the same time. Therefore, the cost of machinery and labor is not included in the comparisons of plum curculio control strategies.

Before examining model results, various analysis options and possible outcomes will be reviewed. One possibility is the decision to withhold a spray during any given decision period. The maximum positive net return that is possible by not spraying a pesticide, in this case the organophosphate Guthion, is $8.00. This occurs when no plum curculio damage occurs and the material pesticide cost was not incurred. This limits the positive net returns that are possible by not applying a pesticide. Regardless of the price scenario being analyzed, the amount of positive net return in any simulated season is limited to this level.

In low price scenarios, the value of preventable damage is limited to approximately $20.00 per decision period. Control costs will are often financially unjustified in these scenarios. The best net return in the low price scenario is possible by either not spraying or minimal use of sprays. On the other hand, crop protection value can exceed $72.00 in reduced crop damage less $8.00 control costs an acre for each of the decision periods. The highest positive net returns are recorded in the high price scenario by controlling a potentially high level of plum curculio damage. The best high price strategy is one that can properly time control actions to knock down populations, but at the same time avoiding excess sprays. Excess sprays erode the positive net returns made through properly timed pesticide applications.

One additional aspect of the net return results is the cost of scouting which is incurred under the IPM strategies. In this study, the Laubach-Johnson action threshold and the price-flexible action threshold require scouting information to be used. Therefore, the net return associated with either strategy must be modified by the cost of scouting. Normally, scouting fees are on a per acre basis for one growing season. The scout does not collect information for one particular pest, such as the plum curculio, but will collect information on many insects, diseases, weeds, and general field conditions. It is necessary to associate part of the scouting cost to the plum curculio integrated control program. For tart cherries in Michigan, scouting costs may run from 18-30 dollars an acre. For this study, we will assume scouting costs of 20 dollars an acre. Of that total cost, ten percent will be associated with the plum curculio program. The total plum curculio scouting cost is then 2 dollars per acre per season. This figure is subtracted from the net return results for the IPM strategy. Other pests scouted for in tart cherry orchards are the green fruitworm, cherry fruit fly, leafspot and brown rot diseases, and general orchard conditions

5.3 Low Price Scenario Results

Model results for the low price scenario (price = 13 cents / lb. of cherries) were similar to the expected results discussed above. Under low prices, the price-flex strategy had the highest mean net return outcome, $23.62 per acre. The following table presents results for the low, average, and high price scenarios.

Table 5: Mean Net Return Results for Pest Control Strategies Under Various Price Scenarios

	Price-Flex	Laubach	Calendar
Price = .4	35.95	8.06	15.41
Price = .2	26.32	13.63	3.71
Price = .1	23.62	15.92	-18.44

The effective of calculated action threshold for this scenario was 80 pounds of tart cherries or approximately level 2.0 on the Laubach scale. This means that the price-flex strategy is expected to return over 23 dollars / acre to growers under low prices. In general, the price-flex strategy applied one spray per season in the first or second decision period. This appeared to be the best timing to keep the pest population at the lowest level for the early season with limited spraying. The single, occasional second application, was sufficient to maintain acceptably low levels of population and expected damage. Thresholds were high enough to prevent excessive applications with very low

As expected, the Laubach strategy also performed well under low prices. The Laubach strategy returned an average $15.92 per acre under the low price scenario (see Appendix 3). The Laubach strategy action threshold (Laubach interval scale: 2.5) was only slightly higher than the price-flex strategy and results were similar for the two control methods. The strategy only applied a pesticide when the population was causing significant damage. On average, one spray was applied per season to control plum curculio. This control usually came at the first period and reduced the population level. In most cases, the population did not recover to the action threshold level. The range for this strategy under low prices was larger than the price-flexible strategy, but still fairly narrow (see figure). In general, both the price-flex and Laubach strategies were profitable for growers under low prices.

The calendar strategy performed poorly returning an expected - $18.00 per acre in the low price scenario (see Appendix 3). The fixed strategy oversprayed and incurred negative net returns especially in decision periods three and four when pest population levels and expected damage was very low. Positive net returns were limited due to the low prices. These two factors led to a large overall expected loss. The calendar strategy has a very narrow range of values under low price conditions. The losses due to overspraying were limited to the material cost of the insecticide. In any given decision period, the maximum loss a grower could sustain would be in a situation where no damage occurred and a pesticide was applied. In this situation, the losses would be approximately -$8.00 an acre. Occasionally, a very high pest population would be controlled by the calendar system leading to some net return at the end of the early season period. However, it was more common that the strategy oversprayed in the first period and continued to overspray leading to an accumulation of negative net returns.

5.4 Average Price Scenario Results

Under the average price scenario (price = 22 cents per pound of cherries), the price-flex and calendar strategy improved performance and the Laubach threshold had lower performance. The price-flex strategy had the best performance with a mean value of $26.32 per acre. The range of values was quite small varying between - $10 to $30 an acre. Under average prices, the price-flexible action threshold level was around 36 1/2 lb. of tart cherries or Laubach interval level. The Laubach strategy had a mean value of $13.63 and a much wider range of values from the -$70 to $60 an acre. This range was large because the value for preventable damage increased. The potential value of preventable damage became much higher as prices rose. The cost of mistakes, such as damage that should have been controlled to prevent negative net returns but was not, increased in financial terms. The calendar strategy mean was $3.71 an acre. The rise in prices meant the value of controlled damage became more valuable and tended to offset the excessive control applications that followed. Excessive applications were not offset at all under the low price scenario. The range of this strategy was quite wide and skewed towards negative net return outcomes.

5.5 High Price Scenario Results

Performance trends continued in the high price scenario (price = 40 cents). The price-flex and calendar strategy improved performance and the Laubach strategy lost performance. The price-flex strategy was the leading strategy under high prices with a mean value of $35.95 per acre. The effective action threshold became approximately 20 lb. of tart cherries. This corresponds to level 3.5 on the Laubach interval scale. Typically, the strategy applied a control during the first and/or third decision period. The timing of the price-flex threshold was very close to hitting the population at the right moment. Damage was allowed but was prevented from reaching financial loss levels. The Laubach threshold allowed excessive damage to occur and the calendar strategy did not allow minor damage to occur. Nearly every season had at least one control action applied. The very low threshold made control likely to occur on a regular basis. However, at the same time, the price-flex strategy never applied more than two pesticide applications in any season. This appears to be the key difference between the price-flex threshold results and the Laubach threshold results. Compared to the Laubach threshold, the price flex threshold was set much lower under high prices. The implies that control will be applied much quicker or more frequently than the Laubach threshold. The number of sprays rose under high prices from an average of one alternate row spray per season to two alternate row sprays per season. The increasing cost and number of sprays were more than offset by the increased value of protection achieved.

With high prices, the Laubach decision rule turned in the lowest performance. The strength of the Laubach strategy under low prices became its weakness under high prices. In many cases, the pest population was fairly high and caused some damage, but not high enough to meet threshold levels. With low prices, the strategy avoided spraying unnecessarily. However with a high valued crop, underspraying became the key to low performance of the Laubach strategy. Mid-level pest populations caused enough damage of the high value crop to incur negative net returns. In some cases, these negative returns became quite large. The threshold allowed some financial loss to be incurred. As stated earlier, the risk of loss is greater with no pesticide in a decision period than when a pesticide is applied. This factor leads to lower risk for fixed pesticide application strategies over flexible strategies that avoid a spray and hope that the worst case pest population scenarios do not turn out to be true.

The calendar strategy under high prices produced positive net returns. The mean value for the calendar strategy was $15.41 per acre. The fixed strategy makes sense where high valued crops need to be protected. The value of preventable damage often exceeded the cost of control as discussed earlier. The calendar strategy mean was much lower than the price-flexible strategy because it has a built in tendency to overspray which reduces the season long value of net returns. The positive net returns in one period are offset by losses due to overspraying in subsequent periods. Some occurrences of negative net return outcomes occurred when an unneeded control was applied.

5.6 Risk Analysis

In choosing between strategies, risk plays an important role for orchard managers. Pesticides have often been called an "insurance" input. This is because they prevent or minimize the chances of a possible negative event or activity from occurring (Feder, 1979; Antle, 1987; Greene et al., 1987). A pesticide application does not increase the output of a grower but avoids incurring a loss or drop of yield or quality that may occur. Pesticides are a major cost component for orchard growers. However, the cost of a pesticide may be insignificant compared to the value of the crop that may be lost, especially in high price years. Growers may feel the benefits far outweigh the costs and decide to spray or even overspray to ensure adequate protection.

Risk analysis is based on the fact that a decision maker, such as a cherry grower, focuses on the range of possible outcomes as well as the expected outcomes. A particular strategy may on average be very profitable, but also entail a wide possible range of values with the possibility of very high negative occurrences. Another possible strategy may offer a lower expected value, but a much tighter or narrower range of values. The decision maker may prefer a strategy that has lower expected outcomes, but offers the assurance of protection from very low or negative outcomes. These decision makers are defined as being risk adverse. Risk adverse people are willing to give up some additional income to achieve peace of mind. Insurance strategies, such as a fixed calendar-based pest control, may offer assurance of avoiding disasters.

Stochastic dominance is a method for comparing activities that have stochastic or random outcomes (Moffitt et al., 1985). For this study, each pest control strategy has a series of outcomes that are based on random functions. Therefore, the final outcomes for the control strategies are random. A method of risk analysis was needed to compare the outcomes of the different strategies. Mean or expected values do not account for the risk associated with the use of a strategy. Stochastic dominance can be used to determine how different groups of decision makers would rank strategies based on risk.

Some types of analysis require the specification of a specific form of the utility or preference function. Stochastic dominance does not require utility function specification. It applies to different classes of decision makers and their preference for a certain activity or strategy (Moffitt et al., 1985). First degree stochastic dominance applies to all decision makers who have upward sloping utility functions (Moffitt et al., 1985). In this case, upward sloping utility functions imply that utility or farmer welfare increases with pest mortality. Second degree stochastic dominance applies to a smaller group of decision makers. This group is all decision makers who are risk averse (Moffitt et al., 1985). Risk averse decision makers place greater weight on negative outcomes versus positive outcomes and are willing to engage in activities which reduce their exposure to risk.

To use stochastic dominance, probability distributions of outcomes for different activities must be compared (Moffitt et al., 1985). Cumulative distribution functions are created and plotted on the same chart for comparison. First degree stochastic dominance requires a distribution to completely dominant another distribution (Moffitt et al., 1985). This can be observed as a distribution that is entirely to the right of another distribution. First degree dominance implies second degree dominance. Second degree dominance occurs when the portion of a distribution to the left of another distribution exceeds that portion which is to the right of the other distribution (Moffitt et al., 1985).

In the case of plum curculio control strategies, risk is presented as the stochastic outcome from the bioeconomic model in the form of positive or negative net returns due to using a particular strategy. The price-flex strategy is first degree dominant over the Laubach and calendar strategies under low prices based on chart . The Laubach strategy is first degree dominant over the calendar strategy. Decision makers would prefer the price-flexible strategy over the other strategies based on risk attitudes. The Laubach strategy would be preferred by all decision makers over the calendar strategy. These results help verify our hypothesis that a price-flexible strategy would produce superior results compared to either a fixed action threshold or fixed strategy.

The average price scenario has the price-flex strategy as the first degree dominant strategy over the other possible strategies. Again, all decision makers would prefer this strategy over the others. There is no first or second degree dominant strategy among the Laubach strategy and the calendar strategy. The Laubach strategy is clearly superior through most of the distribution except at the left hand tail where the two distributions cross. The left hand side of the table is the point where poor financial outcome occur. Poor or negative outcomes weigh heavily on the decision making of risk averse growers. Because the calendar strategy crosses at this point, it cannot be claimed that risk averse decision makers would prefer the Laubach strategy under average price years. Therefore, the Laubach strategy is neither first or second degree dominant over the calendar strategy.

Under low price conditions, the price-flex strategy is still the first degree dominant strategy. The Laubach strategy and calendar strategy dominant each other on different parts of the distribution, neither the Laubach nor the calendar strategy dominant one another in the high price scenario.

The results from stochastic dominance analysis tend to confirm the hypotheses of this study. The price-flexible has the potential to perform better than the current recommendations in the Cherry Insect Training Manual or a traditional calendar based strategy (Johnson and Laubach, 1995). There is also some evidence that the Laubach fixed action threshold performs better than the calendar based strategy under most conditions. Similar results have been appeared in other studies. Greene et al. (1987) showed that Integrated Pest Management strategies, using economic thresholds, were first degree dominant over traditional, non-scouted, strategies. This analysis was restricted to fixed or simple economic thresholds. Richardson (1994) was also able to show with a simulation model that IPM decision rules outperformed the traditional fixed calendar strategies. A study by Szmedra (1994) provided results with the opposite conclusion.

They showed that a strategy which applied a pesticide on a fixed date was first degree dominant over a strategy that used a simple economic threshold based on extension recommendations.

Ch.6: Conclusion

6.1 Introduction

The last chapter is divided into three sections. The first section describes the verification and validation process for the PLUMSIM model. Also in this section, shortcomings of the PLUMSIM approach are detailed. The second section summarizes the key results from the study and guidelines are discussed for integrated control programs related to the plum curculio in cherry orchards. The third section discusses the future of integrated pest management for plum curculio and other cherry insects in general and the role of information technology.

6.2 Verification and Validation

Model results are only reliable if the underlying model parameters, relationships, and assumptions are valid. Two different methods are recognized for determining the reliability and usefulness of a model. Validation is the process of checking the model results versus the results of the real system (Baker and Curry, 1976). Verification concerns the "truthfulness" of the internal logic and reliability of the model (Baker and Curry, 1976). In this case, the results are the different profit figures for various pest control strategies. Components of the model can be tested for comparisons with real system results. The PLUMSIM model cannot be tested against real system results. Growers do not track the profitability of their pest control strategies, but rather track the profitability for their entire operation. Embedded in this performance measure are many different components of orchard management that makes the comparison with PLUMSIM output impossible. Growers or consultants do not track the damage caused by different levels of plum curculio populations. At this time, it is not possible to compare

PLUMSIM's crop loss assessment with real world data as none are available from producers or the research community.

For PLUMSIM, verification was achieved through expert acknowledgment that the model results and components seem reasonable with their experiences and knowledge (Laubach, 1995; Johnson, 1995). The model components were developed with the help of Jim Laubach and Jim Johnson. Most tart cherry industry and university officials consider these individuals to be the most knowledgeable experts concerning plum curculio-tart cherry interactions. With the help of Johnson and Laubach, the PLUMSIM model structure was configured and specified. Therefore, model verification must rely on expert knowledge due to the lack of well-established data sets or research or grower records.

Validation is the process of establishing the "usefulness" of the model (Baker and Curry, 1995). Usefulness refers to the people who will actively operate and use the model. An important question is if the model will be used by the intended audience. It is possible that the PLUMSIM model could be adapted to create a price-flexible action threshold system. First, the user would need to obtain information on estimated new tart cherry crop size and May stock carryover numbers. Second, this information would be used to forecast a season price. Third, the forecasted price and control costs would be used in the action threshold equation to estimate the threshold. The threshold is a plum curculio damage level expressed as pounds per acre of tart cherries. Fourth, the pounds per acre figure is then converted into a Laubach interval number and can be used by scouts to recommend control actions. Other growers or scouts could develop their own damage estimates and use the price information to estimate an action threshold. The

PLUMSIM model could be adapted to represent a system for calculating a price-flexible action threshold as opposed to the current price-fixed action threshold.

The current use of PLUMSIM involves testing new pest control strategies based on profitability and potential risk. This is only one step in the long process of growers actually adopting a new strategy. The PLUMSIM model could be transformed into a crop protection decision support system. The price-flexible action threshold could be implemented using the PLUMSIM model as discussed above. However, the PLUMSIM model could be used to evaluate any type of plum curculio strategy, including the Laubach fixed action threshold. The PLUMSIM model has demonstrated the potential economic benefits of adopting some type of Integrated Pest Management strategy.

A number of weaknesses can be identified with the PLUMSIM approach. In its current form, the PLUMSIM model is not an optimization model. The PLUMSIM model was designed to test a number of pest control strategies to determine which one provided the best economic performance. It does not search and identify the optimal plum curculio pest control strategy. As presented in the literature review section, some pest control studies identified the optimal timing and amount of pesticide applications. Other studies identified the optimal combination of pest control methods, including timing and amount. In PLUMSIM, the user must specify beforehand the type of pest control strategy they wish to test. This means that an optimal strategy may be overlooked in the research process.

A second weakness or limitation of the model is the data or specifications upon which the model structure relies. A model is only as good as the foundation of data and structure that it is built on. A lack of biological knowledge concerning the plum curculio forced us to use subjective estimates of plum curculio damage and population activity. Most simulation studies are built on a foundation of objective scientific knowledge such as repeated field or lab trials or other methods. Economists are able to adapt these biological models to an economical setting for various research purposes. In this case, knowledge acquisition techniques were used. Experts were asked to develop their best estimates on biological activity. These estimates then served as the foundation for PLUMSIM. This can be considered a weakness of the PLUMSIM model. Parts of the model structure may be incorrectly specified. However, real world decision makers, such as scouts or growers, must currently base their decisions on this subjective knowledge base. PLUMSIM does represent the best subjective knowledge base on plum curculio activity in tart cherry trees.

A third weakness of the PLUMSIM approach is that it does not consider other forms of integrated control such as biological or cultural control. The PLUMSIM model currently only considers chemical control methods. However, nonchemical control methods could be introduced depending on the type of procedures and schedule used. At this time, there is very little knowledge about what kinds of nonchemical control methods may be used to control plum curculio. One possibility is the use of ground feeding birds that was suggested by Chouinard (1993) and has been tested in apple orchards at the Kellogg Biological Station outside Kalamazoo, MI.

A weakness should be pointed out concerning the price prediction model used in the price-flex threshold. The price prediction model is a simple multiple regression model. Shifts in demand or structural changes in the tart cherry industry could invalidate the *price forecaster* model. Growers, scouts or others who would potentially use the price-flex threshold need to be aware of limitations of *price forecaster* and its proper use. The model results rely heavily on the subjective estimates of others concerning the expected new tart cherry U.S. crop size. A number of experts should be consulted before settling on the size of the forthcoming crop. These experts include the head of the Cherry Marketing Institute and experts at the Michigan Agricultural Cooperative Marketing Association.

6.3 Summary

The tart cherry industry has been at the forefront of adopting IPM practices. Already, many growers are using scouting, action thresholds, weather forecasting for disease control, and other practices. One important lesson discovered here is that in many cases only one or two insecticides are needed to adequately control early season plum curculio damage. Growers should be willing to tolerate some damage from the plum curculio in the period from petal fall to 375 growing degree days. Scouting can help boost the economic performance of many growers. Under low or average prices, the Laubach style action threshold provides superior economic performance to the calendar based strategy. Risk averse decision makers should also be willing to adopt Laubach style action thresholds under many price scenarios. The results under high prices are somewhat mixed. It is unclear which strategy decision makers would choose in this case. Overall however, the weight of evidence appears to be in the favor of the Laubach fixed action threshold over a fixed calendar pest control strategy.

The evidence seems to support accepting the study's second hypothesis. The second hypothesis stated that a price-flexible action threshold could potentially provide better economic performance over a simple action threshold or a fixed calendar-based strategy. In all three price scenarios, the price-flex action threshold was superior. Decision makers, regardless of risk attitudes, will potentially prefer the price-flex threshold over the other types of pest control strategies. Potentially, the price-flexible action threshold could supplement or replace the Laubach fixed action threshold.

The tart cherry industry is facing very difficult economic times. Extraordinarily low prices made the 1995-1996 marketing year one of the most disastrous periods for the industry in quite awhile. With large carryover stocks and record yields, the expected price is around 05 cents a pound. Prices and economic conditions may not improve for a number of years yet. With large amounts of tree planted in the early 1980's, production could potentially remain at high levels. For many growers, survival has become an important question. In this economic environment, growers need to use pesticides carefully. It appear that the Laubach action threshold can be supplemented with a price-flexible action threshold for plum curculio control. Furthermore, the price-flex threshold could be extended to the green fruitworm with some additional work. While the decision to spray pesticides is complex, results from this study show growers are potentially better off using IPM action thresholds. Risk averse growers should also potentially prefer the action threshold approach to a calendar or fixed strategy to pest control. Extensive IPM users, such as those who use regional pest information instead of orchard specific information, were not represented in this study (see chapter one). It is difficult to characterize were exactly their pest control methods fall. Extensive IPM growers do not use threshold or scouting, but do obtain other forms of information and adjust pesticide application based on this information. This approach may improve economic performance for growers over a calendar-intensive approach. It is difficult to assess comparisons to intensive IPM methods. One major consideration is if growers using extensive IPM strategies alter pest control based on price conditions or only based on regional biological information. Lack of knowledge concerning extensive IPM users practices constrained us to consider only calendar-based pest control and intensive IPM practices.

APPENDICES

Appendix A: Glossary of Terms Used

Action Threshold (Pedigo, 1989): population density at which control action should be initiated to prevent an increasing pest population from reaching the economic injury level

Action Threshold (Stern, 1959): decision level chosen such that there is little likelihood that the real management system might inadvertently permit the pest population to exceed the economic injury level

Control Tactic (Onstad, 1987): material, equipment and method used to remove, repel, or kill a pest population

Damage (Pedigo, 1986): measurable loss of host utility, most often including yield, quality, or aesthetics

Damage Boundary (Pedigo, 1989): lowest level of injury at which damage can be measured

Density / Damage function (Onstad, 1987): relates the density of one or more life stages of a pest to the economic loss in crop or livestock yield and quality

Degree Day: biological process of interest, such as insect growth and development, will not begin until a temperature threshold is reached

Economic Damage (Stern, 1959): amount of injury that will justify the cost of artificial control measures

Economic Damage(Southwood and Norton, 1973): Economic damage is the point where cost of control equals value of yield damaged by pest. C(a) = Y[s(a)] * P[s(a)] -Y(s) * P(s), where: y = yield, p = price per unit of yield, s = level of pest injury, s(a) = level of injury as modified by the control action, a = control action, c = cost of control

Economic Injury Level(Stern, 1959): lowest population density that will cause economic damage

Economic Injury Level (Southwood and Norton, 1973): density at which the cost of control equals the economic loss prevented by implementing the control tactic

Equivalent (Pedigo, 1986): total injury equivalents for a pest population at a given time

Injury (Pedigo, 1986): effect of the pest activities on host physiology that is usually damaging

Injury Equivalent (Pedigo, 1989): total injury produced by a single pest over an average lifetime

Nominal (subjective) Threshold: based on practitioner or scouts experience, not based on a calculated E.I.L.

Objective Threshold: Based on a calculated E.I.L. and change with variations in E.I.L. components.

A. Fixed E.T.: the economic threshold is set a fixed rate or percentage from the E.I.L.

B. Descriptive E.T.: population description, including expected rate of population growth and injury levels, is done. These estimates are used to base control actions.

Appendix B: Net Return Results

Table 6: Mean Net Return Results for Pest Control Strategies Under Various Price Scenarios

	Price-Flex	Laubach	Calendar
Price = .4	35.95	8.06	15.41
Price = .2	26.32	13.63	3.71
Price = .1	23.53	15.92	-18.44

Table 7: Stochastic Dominance Results

(Symbols in boxes represent which strategies are dominated by the strategy in the above column; FDD represents first degree stochastic dominance, SDD represents second degree stoachastic dominance; C = calendar, P = price-flex, L = Laubach)

	Price-Flex	Laubach	Calendar
Price = .4 FDD	L, C		
Price = .2 FDD	L, C		
Price = .1 FDD	L, C	C	
Price = .4 SDD	L, C		
Price = .2 SDD	L, C		
Price = .1 SDD	L, C	C	

Appendix C: Frequency Distribution charts for Net Return Results

Figure 3: Price-flex price=.13 mean=23.53

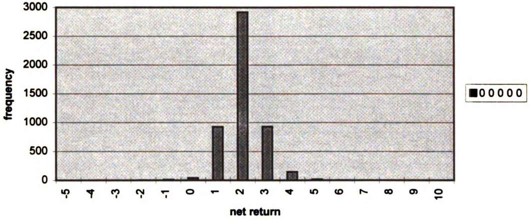


Figure 4: Laubach price=.13 mean=15.93

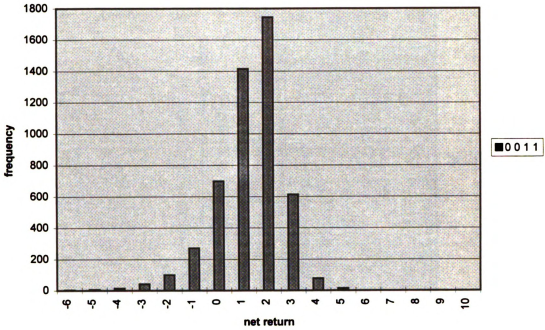


Figure 5: Calendar price = .13 mean = -18.44

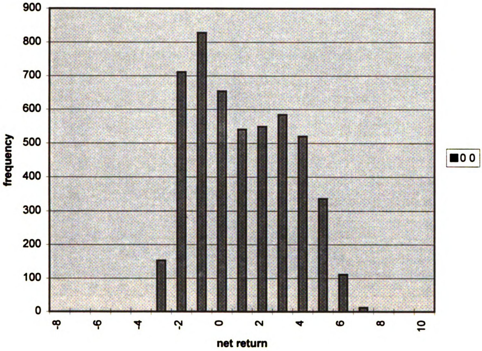


Figure 6: Price-flex price=.22 mean=26.32

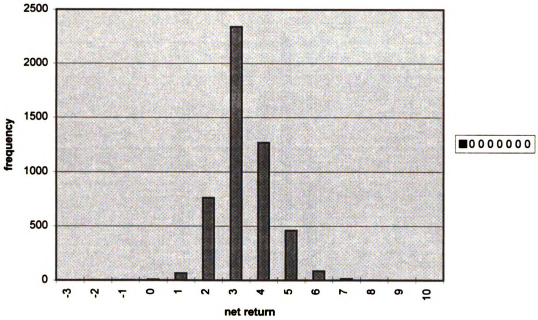


Figure 7: Laubach price=.22 mean=13.63

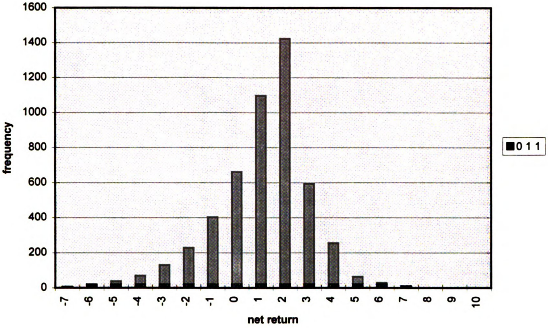


Figure 8: Calendar price=.22 mean=3.71

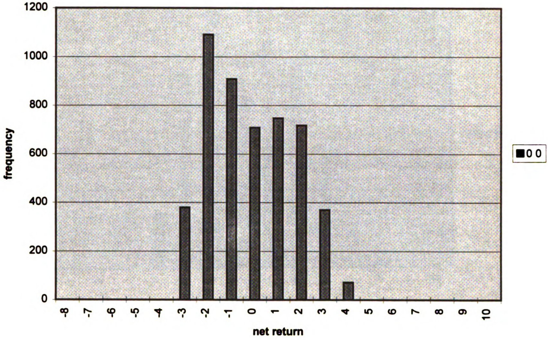


Figure 9: price -flex price = .4 mean = 35.95

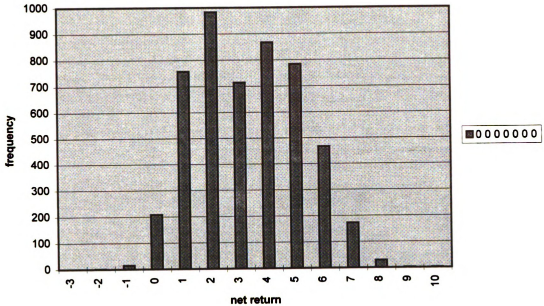


Figure 10: Laubach price=.4 mean=8.06

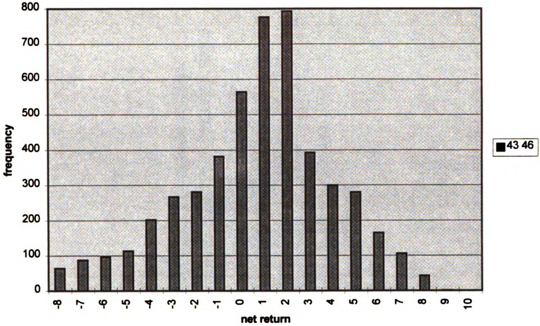


Figure 11: Calendar price=.4 mean= 15.40

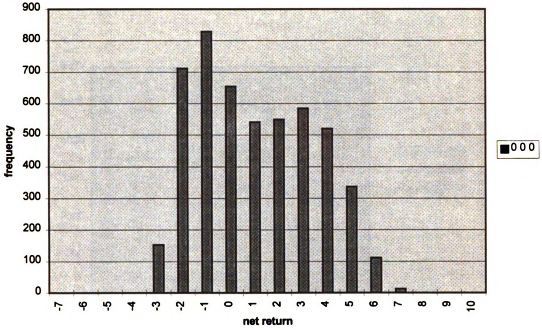


Figure 12: Stochastic Dominance price=.40

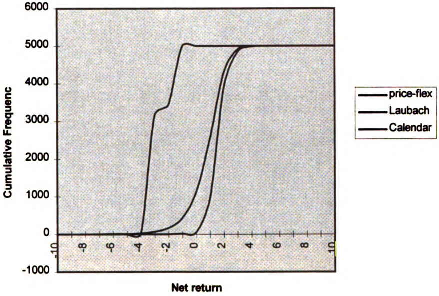


Figure 13: Stochastic dominance price = .22

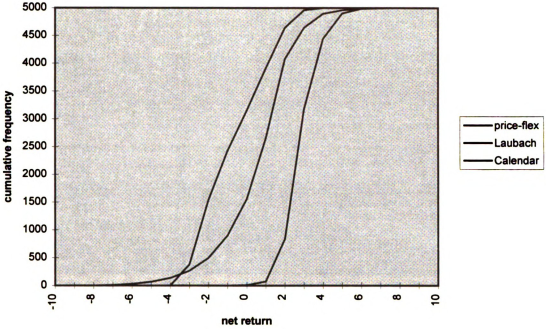
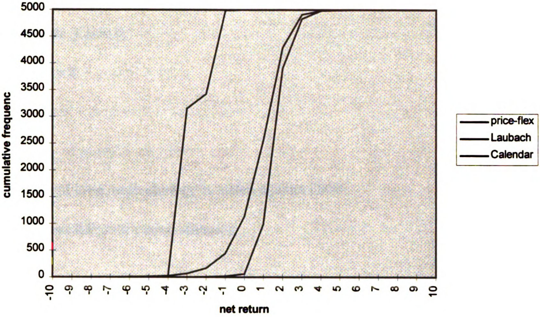


Figure 14: Stochastic dominance price = .13



Appendix D: PLUMSIM program routine

```
Sub Simulate_Click ()
 Const cost = 8

sum = 0
'begin general loop, each strategy is tested against 2000
'runs of a four decision period situation.

J = 0
Call price1(p)
Do Until J = 500
'generate random number between
'1.0 and 4.999...this is the first scouting period
actual1 = (Rnd * 4) + 1

   'the triangular distribution draws a figure to represent the potential future
   'population that may emerge from the current population.
   If actual1 > 4 Then
      optm1 = 5
      pessm1 = actual1 - 1.2
      expct1 = (optm1 + pessm1) / 2.3
```

```
ElseIf actual1 >= 3 Then
  optm1 = actual1 + 1
  pessm1 = actual1 - 1.2
  expct1 = (optm1 + pessm1) / 2.3
      If pessm1 < 1 Then
      pessm1 = 1
      End If

ElseIf actual1 < 3 Then
  optm1 = actual1 + 1
  pessm1 = 1#
  expct1 = (optm1 + pessm1) / 2.5
End If

'A population figure is drawn from the
'triangular distribution which becomes the potential
'future(7-10 days from current decision period) population

If frctn() < arer1() Then
  value1 = pessm1 + ((expct1 - pessm1) * (Sqr(frctn() / arer1())))
```

```
   Else
   value1 = optm1 - ((optm1 - expct1) * (Sqr((1 - frctn()) / arel1())))

End If

'First, check to see if the threshold(strat) currently under testing is higher or lower than
'current scouting numbers(actual). Second, assign value to variable control.
'third step is to calculate value of preventable damage and compare to control cost
'for profitability of simulation run at hand.
   stage1 = 12.409245 + (value1 * -2.47039394)
   croplos1 = stage1 ^ (1 / .43)
   prevent1 = croplos1 * effec
   threshold = prevent1 * p
   If threshold > cost Then
      control1 = 1
      prevdam1 = croploss1() * effec
      yieloss1 = prevdam1 * price
      finloss1 = yieloss1 - cost

   ElseIf threshold < cost Then
   control1 = 0
```

```
    prevdam1 = croploss1() * effec
    yieloss1 = prevdam1 * price
    finloss1 = -yieloss1 + cost
End If

'evaluate decision to control population
'based on comparing potential preventable damage
'to control cost

'using control variable value, a new population figure is calculated based on
'whether or not a spray was used.

If control1 = 1 Then
    actual0 = (5 - value1)
    actual2 = (actual0 * effec) + value1
    ElseIf control1 = 0 Then
    actual2 = value1
End If

'transition to period two
```

```
If actual2 > 4 Then
   optm2 = 5
   pessm2 = actual2 - 1.2
   expct2 = (optm2 + pessm2) / 2.3

   ElseIf actual2 >= 3 Then
      optm2 = actual2 + 1
      pessm2 = actual2 - 1.2
      expct2 = (optm2 + pessm2) / 2.3
            If pessm2 < 1 Then
            pessm2 = 1
            End If

   ElseIf actual2 < 3 Then
      optm2 = actual2 + 1
      pessm2 = 1#
      expct2 = (optm2 + pessm2) / 2.5
End If

'A population figure is drawn from the
'triangular distribution which becomes the potential
```

```
'future(7-10 days from current decision period) population

If frctn() < arer2() Then
   value2 = pessm2 + ((expct2 - pessm2) * (Sqr(frctn() / arer2())))

   Else
   value2 = optm2 - ((optm2 - expct2) * (Sqr((1 - frctn()) / arel2())))

End If

'First, check to see if the threshold(strat) currently under testing is higher or lower than
'current scouting numbers(actual). Second, assign value to variable control.
'third step is to calculate value of preventable damage and compare to control cost
'for profitability of simulation run at hand.
   stage2 = 12.409245 + (value2 * -2.47039394)
   croplos2 = stage2 ^ (1 / .43)
   prevent2 = croplos2 * effec
   threshold = prevent2 * p
   If threshold > cost Then
      control2 = 1
      prevdam2 = croploss2() * effec
```

```
        yieloss2 = prevdam2 * price

        finloss2 = yieloss2 - cost


    ElseIf threshold < cost Then

    control2 = 0

    prevdam2 = croploss2() * effec

    yieloss2 = prevdam2 * price

    finloss2 = -yieloss2 + cost

End If


'evaluate decision to control population

'based on comparing potential preventable damage

'to control cost




'using control variable value, a new population figure is calculated based on

'whether or not a spray was used.

If control2 = 1 Then

    actual0 = (5 - value2)

    actual3 = (actual0 * effec) + value2

    ElseIf control2 = 0 Then
```

```
    actual3 = value2


End If


'the triangular distribution draws a figure to represent the potential future
'population that may emerge from the current population.
If actual3 > 4 Then
    optm3 = 5
    pessm3 = actual3 - 1.2
    expct3 = (optm3 + pessm3) / 2

    ElseIf actual3 >= 3 Then
        optm3 = actual3 + 1
        pessm3 = actual3 - 1.2
        expct3 = (optm3 + pessm3) / 1.8
            If pessm3 < 1 Then
            pessm3 = 1
            End If

    ElseIf actual3 < 3 Then
        optm3 = actual3 + 1
        pessm3 = 1#
```

```
    expct3 = (optm3 + pessm3) / 1.7
End If


'A population figure is drawn from the
'triangular distribution which becomes the potential
'future(7-10 days from current decision period) population
If frctn() < arer3() Then
   value3 = pessm3 + ((expct3 - pessm3) * (Sqr(frctn() / arer3())))

   Else
   value3 = optm3 - ((optm3 - expct3) * (Sqr((1 - frctn()) / arel3())))

End If


'First, check to see if the threshold(strat) currently under testing is higher or lower than
'current scouting numbers(actual). Second, assign value to variable control.
'third step is to calculate value of preventable damage and compare to control cost
'for profitability of simulation run at hand.

   stage3 = 12.409245 + (value3 * -2.47039394)
   croplos3 = stage3 ^ (1 / .43)
   prevent3 = croplos3 * effec
```

```
  threshold = prevent3 * p
  If threshold > cost Then
     control3 = 1
     prevdam3 = croploss3() * effec
     yieloss3 = prevdam3 * price
     finloss3 = yieloss3 - cost

  ElseIf threshold < cost Then
  control3 = 0
  prevdam3 = croploss3() * effec
  yieloss3 = prevdam3 * price
  finloss3 = -yieloss3 + cost
End If

'evaluate decision to control population
'based on comparing potential preventable damage
'to control cost



'using control variable value, a new population figure is calculated based on
'whether or not a spray was used.
```

```
If control3 = 1 Then
   actual0 = (5 - value3)
   actual4 = (actual0 * effec) + value3

   ElseIf control3 = 0 Then
   actual4 = value3

End If



'the triangular distribution draws a figure to represent the potential future
'population that may emerge from the current population.
If actual4 > 4 Then
   optm4 = 5
   pessm4 = actual4 - 1.2
   expct4 = (optm4 + pessm4) / 2

   ElseIf actual4 >= 3 Then
      optm4 = actual4 + 1
      pessm4 = actual4 - 1.2
      expct4 = (optm4 + pessm4) / 1.8
```

```
            If pessm4 < 1 Then

            pessm4 = 1

            End If


     ElseIf actual4 < 3 Then

       optm4 = actual4 + 1

       pessm4 = 1#

       expct4 = (optm4 + pessm4) / 1.7

   End If


   'A population figure is drawn from the

   'triangular distribution which becomes the potential

   'future(7-10 days from current decision period) population

   If frctn() < arer4() Then

     value4 = pessm4 + ((expct4 - pessm4) * (Sqr(frctn() / arer4())))


     Else

     value4 = optm4 - ((optm4 - expct4) * (Sqr((1 - frctn()) / arel4())))


   End If


   'First, check to see if the threshold(strat) currently under testing is higher or lower than
```

```
'current scouting numbers(actual). Second, assign value to variable control.
'third step is to calculate value of preventable damage and compare to control cost
'for profitability of simulation run at hand.
  stage4 = 12.409245 + (value4 * -2.47039394)
  croplos4 = stage4 ^ (1 / .43)
  prevent4 = croplos4 * effec
  threshold = prevent4 * p
  If threshold > cost Then
    control4 = 1
    prevdam4 = croploss4() * effec
    yieloss4 = prevdam4 * price
    finloss4 = yieloss4 - cost


  ElseIf threshold < cost Then
  control4 = 0
  prevdam4 = croploss4() * effec
  yieloss4 = prevdam4 * price
  finloss4 = -yieloss4 + cost
  End If

'evaluate decision to control population
```

```
'based on comparing potential preventable damage
'to control cost
 'using control variable value, a new population figure is calculated based on
'whether or not a spray was used.
If control4 = 1 Then
   actual0 = (5 - value4)
   actual5 = (actual0 * effec) + value4

   ElseIf control4 = 0 Then
   actual5 = value4

End If

totalfin = finloss1 + finloss2 + finloss3 + finloss4
index = Int(totalfin / 10)
profit(index) = profit(index) + 1

J = J + 1
sum = totalfin + sum
mean = sum / 5000
```

```
Loop

Print mean, p, control1, control2, control3, control4

End Sub
```

Appendix E: PLUMSIM Variable List

actual1 = value of population that exists in decision period one

actual2 = value of population that exists in decision period two

actual3 = value of population that exists in decision period three

actual4 = value of population that exists in decision period four

arel1 = left side of decision period one triangular distribution

arel2 = left side of decision period two triangular distribution

arel3 = left side of decision period three triangular distribution

arel4 = left side of decision period four triangular distribution

arer1 = right side of decision period one in triangular distribution

arer2 = right side of decision period two in triangular distribution

arer3 = right side of decision period three in triangular distribution

arer4 = right side of decision period four in triangular distribution

control1 = binary variable indicating status of pesticide application (0=no control, 1 = control) in decision period one

control2 = binary variable indicating status of pesticide application (0=no control, 1 = control) in decision period two

control3 = binary variable indicating status of pesticide application (0=no control, 1 = control) in decision period three

control4 = binary variable indicating status of pesticide application (0=no control, 1 = control) in decision period four

croplos1 = expected crop loss value calculated by price-flex threshold for d. p. one

croplos2 = expected crop loss value calculated by price-flex threshold for d. p. two

croplos3 = expected crop loss value calculated by price-flex threshold for d. p. three

croplos4 = expected crop loss value calculated by price-flex threshold for d. p. four

cost = cost of control

effec = pesticide efficiency rating, percentage kill of pest for a given application period

expct1 = expected value of triangular distribution d.p. one

expct2 = expected value of triangular distribution d.p. two

expct3 = expected value of triangular distribution d.p. three

expct4 = expected value of triangular distribution d.p. four

finloss1 = financial evaluation of decision(control/no control) in d.p. one

finloss2 = financial evaluation of decision(control/no control) in d.p. two

finloss3 = financial evaluation of decision(control/no control) in d.p. three

finloss4 = financial evaluation of decision(control/no control) in d.p. four

height1 = height of triangular distribution in d.p. one

height2 = height of triangular distribution in d.p. two

height3 = height of triangular distribution in d.p. three

height4 = height of triangular distribution in d.p. four

optm1 = optimistic value for population activity used in triangular distribution for d.p. one

optm2 = optimistic value for population activity used in triangular distribution for d.p. two

optm3 = optimistic value for population activity used in triangular distribution for d.p. three

optm4 = optimistic value for population activity used in triangular distribution for d.p. four

pessm1 = pessimistic value for population activity used in triangular distribution for d.p. one

pessm2 = pessimistic value for population activity used in triangular distribution for d.p. two

pessm3 = pessimistic value for population activity used in triangular distribution for d.p. three

pessm4 = pessimistic value for population activity used in triangular distribution for d.p. four

p = expected price based on estimated crop size for high, average, low price scenario

price = price that emerges at end of season for high, average, low price scenarios

prevdam1 = damage that could potentially be prevented with a pesticide in d.p. one

prevdam2 = damage that could potentially be prevented with a pesticide in d.p. two

prevdam3 = damage that could potentially be prevented with a pesticide in d.p. three

prevdam4 = damage that could potentially be prevented with a pesticide in d.p. four

stage1 = intermediate step in calculating actual yield loss in d.p. one

stage2 = intermediate step in calculating actual yield loss in d.p. two

stage3 = intermediate step in calculating actual yield loss in d.p. three

stage4 = intermediate step in calculating actual yield loss in d.p. four

strat = action threshold level set for Laubach threshold strategy

value1 = population activity level that actually emerges from potential activity in triangular distribution in d.p. one

value2 = population activity level that actually emerges from potential activity in triangular distribution in d.p. two

value3 = population activity level that actually emerges from potential activity in triangular distribution in d.p. three

value4 = population activity level that actually emerges from potential activity in triangular distribution in d.p. four

yieloss1 = damage caused by population activity that occurs in d.p. one

yieloss2 = damage caused by population activity that occurs in d.p. two

yieloss3 = damage caused by population activity that occurs in d.p. three

yieloss4 = damage caused by population activity that occurs in d.p. four

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