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By

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ABSTRACT

AN ECONOMIC ANALYSIS OF PEST MANAGEMENT INFORMATION
SYSTEMS WITH APPLICATION TO ALFALFA WEEVIL CONTROL

By

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Pest management decisions are made under conditions of imperfect knowledge. Pest management programs are information systems developed to aid in the pest management decisions making process.

Any pest management program involves: 1) design, 2) implementation and 3) evaluation. Pest control guidelines are developed in the design phase. Usually, implementation of the guidelines requires field specific information. Evaluation means determining the value of the information made available through the pest management program.

A systematic way of evaluating alternative pest control guidelines is developed in the study. First, a probability distribution for possible outcomes for each alternative pest management practice is determined. The use of mathematical models to generate a distribution is discussed. The distributions are then compared using methods developed for selecting among risky alternatives. The value of information is calculated by comparing the outcomes of decisions made with the information to the outcomes made without the information.

The evaluation method developed is applied to control crop loss of alfalfa due to alfalfa weevil. Seven alternative control strategies are considered. Four of the strategies involve the use of pesticides. One uses a single routine spray and another uses two routine sprays per

season. The third uses a static threshold and the fourth uses a dynamic threshold for deciding on the timing of a spray application.

Two of the control guidelines use early harvesting to control weevils. One of these uses accumulated degree days to schedule the first harvest. The other uses the pest population and accumulated degree days to set the harvest date. The last alternative is to use a routine harvest date and no sprays.

The outcomes for each control strategy are simulated using a mathematical model of the alfalfa-alfalfa weevil agroecosystem. The model simulates single field for a single year. Fifteen years of weather data for Gull Lake Michigan are used to generate a probability distribution for each management strategy.

The strategies are compared using several methods for comparison of decisions made under uncertainty. In all cases the early cutting schedules are preferred to the spray rules and the no control strategy. The effects of altering the intensity of monitoring on the outcomes for these alternatives involving monitoring are also evaluated. Sampling intensity did not affect the results.

to Peggy

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CHAPTER I

INTRODUCTION

1.1 Problem Statement

Our chemically-oriented, high-energy technology has increased agriculture's productivity. It has also created perplexing problems concerning the quality and safety of the environment and food supply. Some of the chemical inputs that the farmer finds profitable to use are considered toxic substances in a broader context. A market economy allows farmers to ignore unpriced externalities arising from pesticide use. Externalities that cannot be associated with direct monetary costs are not taken into account in his "to use, or not to use" decision. In recognition of this dilemma, regulations have been introduced by the public sector to modify pest control practices.

However, regulation of pesticide use in order to reduce environmental damage and related health hazards need not mean a reduction of the quality and quantity of agricultural products. As a result of rising energy costs and decreasing effectiveness of pesticides, chemical controls by themselves may no longer be as econmically viable as they were once perceived to be.

An alternative approach to crop protection based on the eradication of pests is the management of agro-ecosystems based on maintaining pest populations at tolerable low levels. The latter approach called integrated pest management (IPM), relies on ecological principles for the development of pest control strategies.

The objectives of IPM are often assumed to include a reduction in pesticide use. This is not quite accurate. Limiting pesticide use is not part of the design of pest management programs. Theoretically, IPM could increase the use of pesticides. In practice, however, growers employing IPM strategies have reduced their use of pesticides on average. Thus, pesticide reduction has been a consequence but not a requirement of IPM.

It is clear that the success of pest management is contingent upon implementation at the grower level. Pest management programs must be incorporated into farm management practices. However, there are numerous obstacles to the adoption of IPM.

While IPM may reduce expenditure for pesticides it may also increase demands on management. The decision-making process incorporating IPM is typically more complex than adherence to routine spray schedules. Monitoring of fields for stages of crop development and pest population levels are typically required. In contrast, routine spray schedules simplify overall planning on the farm. In addition, growers may want the maximum protection afforded by routine spraying. They may be willing to spend more on spray materials to guarantee maximum yield and reduce risk of crop loss.

Where aerial sprays are used, IPM creates other management problems. It is probable that when one person is given a spray recommendation from an IPM program so will his neighbor. Where spray equipment is hired, all fields requiring treatment may not be sprayed in time. If a routine spray schedule is followed, on the other hand, a contract can be set up with the spray operator at the beginning of the season to guarantee services.

Growers frequently apply several pesticides for the control of numerous pests in one spray. They may be unwilling to apply each pesticide at a different time. Further complications arise when pest management programs are available for one pest but not others. If a grower is following a routine spray schedule for one pest, he is likely to throw in an "insurance" application for others.

Ideally, reliable pest control guidelines should be developed for each cropping system and each region of the country individually. This goal has not been reached and indeed may never be. IPM involves multiple pests, parasites, predators, crops and control techniques. While this is appealing on a theoretical level, it may be unmanageable in an applied sense. Even looking at a single crop, understanding the relationships among pests, controls, yield and weather is not a minor task.

Some problems involved in adoption of pest management practices have been outlined. In order to facilitate implementation of IPM at the grower level the expected returns to alternative pest management programs must be established. With this objective in mind, a framework for the analysis of pest management programs will be put forth.

Any pest management program involves three phases: 1) design; 2) implementation; and 3) evaluation. Each phase involves the acquisition and analysis of information to generate decisions. What is meant by a pest management program is sometimes ambiguous because IPM programs exist at both the research/extension level and the grower level.

At the research/extension level, guidelines for pest control are developed in the design phase along with a means for providing information to growers. First, the problem to be solved must be clearly defined. The design process also involves the acquisition and analysis of information. The end product is the development of control guidelines and a practical means of applying the guidelines. Monitoring may or may not be included in the program.

Implementation at the research/extension level is the transmission of information to decision makers at the firm level. Once the program is being executed, its performance should be evaluated and the program design modified if necessary. No matter how eloquent its design a pest management program in this context is not successful unless the information it provides is utilized in production decisions.

At the grower level, the design of a pest management program is the choice among alternative pest management programs and control guidelines developed at the research/extension level. The precursor of this decision is recognizing the problem at hand. Application of the control guidelines usually involves acquisition of field specific information. Setting up a procedure for collecting the information required by the control guidelines is also part of the design process.

Implementation at the grower level means using the problem specific information and control guidleines to generate the recommendation of a control practice or technique. Execution of the control practice is also part of the implementation stage. The performance of the system in response to the control practice employed should be evaluated in the context of crop loss and feedback given to the manager and research/extension personnel.

To avoid ambiguity, the term pest management program will be used throughout to refer to programs at the research/extension level. The term pest management strategy will be used in reference to the grower level.

Information is needed at the research/extension level and the grower level and at each phase. Detailed information encompassing several locations and several years is analyzed at the research extension level to develop control guidelines. Growers need information to choose among guidelines. In order to operationalize a set of guidelines, growers must have information regarding their specific situation. Information collected at the grower level can be used to develop and refine guidelines at the research/extension level. Thus, information flows from the grower to research and extension as well as from research and extension to the grower.

IPM depends upon information about the current state of the pest-crop ecosystem to predict future states based upon a priori information. From these predictions control recommendations are made. The need is not simply for a monitoring program, but for an information acquisition/delivery system capable of collecting, interpreting and transmitting data in a timely and efficient manner. This involves development and implementation of regional monitoring programs, data analysis technologies and capabilities, and information delivery systems.

Each dimension can be designed and administered in a number of different ways. Pest management programs may be coordinated by Cooperative Extension, chemical fieldmen, private consultants, grower-owned cooperatives or individual growers. The information provided may be either field specific or regional.

Monitoring may be administered by any of these institutions. Monitoring also varies in terms of how often samples are taken and the number of points sampled as well as the size of the geographic area covered. Information from several regions can be utilized to predict emergence and movement of pests. Regional coordination is particularly important for control of pests that are not problems every year (e.g., army worm).

If data are processed at a central location, information must be interpreted and transmitted back to the field quickly in a usable form. Information can be disseminated by radio announcements, recorded telephone messages, printed pest alerts sent by mail, personal contact or any combination of these. Computer terminals in Cooperative Extension offices are used to establish effective communication networks to meet these needs in a number of states.

Control recommendations depend on timely information describing the state of the agroecosystem such as accumulated degree days, pest population levels or stage of plant development. While information need not be quantitative, in practice it is presented as a cardinal or ordinal measure. Ordinal measures involve a rating system. For example, the abundance of insects can be described by the following: 1) none; 2) few; 3) common; 4) abundant; and 5) extreme. In contrast, a cardinal measure is the number of insects collected in 20 sweeps of a field.

Data in either format is subject to error for at least two reasons. Sampling errors are attributable to uneven distribution in the field, wind velocity, rainfall, the skill of the scout and other reasons. Errors in sampling procedure take place when measurements made in a small area are extrapolated to a larger area.

Even when measurements are accurate, the population to be estimated may differ from one location to another location or from one time period to another. In other words, the mean and variance of the sample taken, regardless of measurement error, may be correct for one location or time period but not another. These errors arise from a poor design of the sampling procedure.

It follows that frequent sampling in numerous locations reduces error. However, it is not feasible to monitor all locations at all times for all pests. There is a tradeoff between accuracy in information and the cost of information.

Pest management programs can be viewed as information systems. As such, expected returns to a pest management program are equivalent to returns to the information provided by the program. Therefore, by assessing the value of information afforded by alternative designs of pest management programs, the performance of the programs can be evaluated and compared. This will aid in the design, implementation and modification of IPM programs.

1.2 Objectives

Pest management programs are information acquisition/delivery sytems. The information generated is utilized in the pest management decision making process for selection of pest control strategies.

This study serves two purposes. First it proposes to develop a means for evaluating IPM programs and strategies. There are countless possibilities for the format and content of the information presented through pest management programs. Even when programs and strategies have been developed and used for specific pest-crop problems, there needs to be a systematic way of evaluating them.

The evaluation process can be used to choose among pest management programs and to improve the design of a particular pest management program. The procedure followed in this study is applicable to any pest crop situation.

Second, the study provides information for the control of alfalfa weevil and the design of monitoring programs for alfalfa weevil control in alfalfa. The results are appropriate at least for the Great Lakes States and the northeastern United States where fall-laid eggs of alfalfa weevil adults do not survive the winter. This means there is no larval feeding in the spring as there is in warmer climates.

There are several known methods for control of alfalfa weevil in alfalfa. Some of these methods involve the proper timing of implementation which in turn means monitoring of the pest and crop conditions during the growing season. This study identifies alternative pest control strategies and compares their effectiveness in controlling alfalfa weevil during a single season. In order to accomplish this, a model was developed to simulate the alfalfa-alfalfa weevil agro-ecosystem and the impact of alternative management strategies on weevil population and ultimately on alfalfa yield and quality. The model was run for 15 years of weather data from Gull Lake Michigan and seven different management strategies. Multiple years were used to establish a probability distribution of income for each strategy.

Several evaluation methods were used in order to compare the income distributions generated by each management strategy. The results from each method were compared. The effects of altering the intensity and accuracy of monitoring on the probability distributions were also evaluated.

1.3 Dissertation Organization

In this chapter the concept of IPM has been introduced. Pest management programs have been described as information systems used to make pest control decisions. The objectives of the study have been discussed.

Chapters II, III, and IV present the background necessary for evaluation of pest management programs. In each of these chapters topics are discussed under the general rubric of pest management and then applied to the alfalfa weevil control problem. Each of these chapters provide the building blocks needed to design and execute an evaluation of pest management programs.

Chapter II discusses the pest management concept in detail. Several models for development of pest control guidelines are presented. Pest management strategies for alfalfa weevil control are described in the context of the ideas developed.

Chapter III is divided into three major sections and an introduction. The first section explores the design of an information system and the role of information in pest management decision making. Decision making is discussed under conditions of imperfect information. The process of incorporating new information into the decision making process is described and then formalized. Several methods for comparing the income flows resulting from alternative information systems are presented. Application is made to the alfalfa weevil problem.

In the second section of Chapter III, the public and private goods nature of information is discussed. Examples of alternative institutional arrangements for pest management programs are sketched.

In the last section several approaches to measuring the value of information are presented. Empirical studies are discussed.

Chapter IV discusses the use of mathematical models in the design and analysis of pest management programs. An alfalfa-alfalfa weevil simulation model is described in detail. The model is used in the analysis of Chapter VI. Validation and limitations of the model attributable to the abstractions from reality required by the modeling process are presented.

Chapter V draws upon the foundation built in the previous chapters to develop a method for analysis of the value of real time information for various alfalfa weevil control strategies. A management model is linked to the alfalfa-alfalfa weevil model to simulate alfalfa production for each control strategy and under conditions of different information flows. Chapter VI presents the results of the simulation runs and analysis of the results.

The final chapter, Chapter VII, summarizes the study and implications of the results of the design and evaluation of pest management programs in general and for alfalfa weevil control in particular.

CHAPTER II

PEST MANAGEMENT

2.1 Introduction

The term "pest" has no biological meaning. An organism becomes a pest to crop production only in an economic context. A pest alters the condition of a crop in such a way that the value of production is reduced for a given set of inputs and economic conditions. Each year substantial crop damage occurs due to insects, weeds, pathogens, nematodes and other pests. The reduction in potential crop production for the U.S. in 1974 has been valued at $55 billion (Pimental 1976).

Pest control is a broad term encompassing all procedures used to reduce the detrimental effects of organisms on yield or quality in agricultural production. Pesticides are the most common method of pest control in the U.S.

Damage occurs despite extensive use of pesticides and other means of pest control. Total sales of pesticides have averaged more than 1 billion pounds per year since 1970. In 1980, 846 million pounds were used for crop protection, almost twice the amount used 10 years earlier and 2 1/2 times the amount used in 1966 (USDA, 1981).

As the volume of pesticide use has grown, so has the number of species that have developed resistance to pesticides (Figure 2.1). Other unfavorable consequences of pesticide use include resurgence of target pest populations and outbreaks of secondary pests. These negative consequences are the result of ignoring the adaptive capabilities of the environment and the interrelationship between agro-ecosystems and the total ecosystem. It is not surprising then,

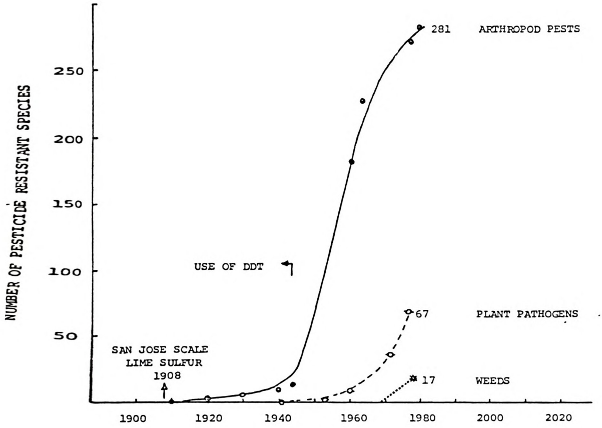

Figure 2.1 The Development of Pesticide Resistant Species of Arthropod, Pathogen, and Weed Pests Since 1908.

Source: B. Croft, "Potentials for research and implementation of integrated pest management on deciduous tree-fruits," pages 101-115 in E. Smith and D. Pimental (eds.). Pest Control Strategies, 1978.

that use of chemical pesticides has also created a hazard for fish, wildlife and man.

The purpose of this chapter is to provide some background in the theoretical basis of pest management. In the second section the historical development of the philosophy of pest control is outlined. The definition of pest control in its current usage is broken down into several major concepts. Each of these concepts is explored. It is apparent from this exercise that the "best" management strategy depends upon the objectives of the decision maker and the performance criteria used to evaluate the strategy employed.

In the third section several theoretical models are presented which act to develop further the concept of pest management. They help identify the type of information which is necessary for developing pest control guidelines. Difficulties encountered in these simple models illuminate the complexity of practical application of the ideas presented in the first section.

The fourth section outlines the methods available for control of the alfalfa weevil based on the IPM philosophy. The use of biological information to develop pest control strategies is demonstrated.

2.2 The IPM Concept

Integrated pest management (IPM) is an approach to crop protection based on ecological principles. Management strategies are developed in the context of an agro-ecosystem. These strategies include an integration of well-timed chemical applications, biological controls, resistant plant varieties and cultural practices.

The methods used in IPM are not new. Cultural control practices are the earliest form of crop protection used by man. The concept of biological control dates from the late 19th century and the conscious development of pest-resistant plant varieties began around 1900. The use of chemical compounds for crop protection also has a long history. During the 18th century various combinations of tobacco, animal manures, soot, dry ashes, sea water, urine, soap, turpentine and alcohol were recommended for insect and/or disease control.

Because of the immense success of chemical controls following World War II, the emphasis in research shifted away from resistant varieties and other forms of control. The chemical approach dominated applied entomology from the 1920s through the 1960s with some notable exceptions. In the past 15 years, recognition of the negative consequences of dependence on chemical controls revived interest in other control methods.

The idea of integrating control strategies also has a historic base. The term integrated control was originally applied in the 1950s to control insects using both biological and chemical control (Smith and Allen, 1954; Stern et al., 1959). The fundamental idea is to attack pest populations at their peak while leaving parasite populations intact. It was later broadened to include all control methods (Smith and Reynolds, 1965). Later the term "pest management" replaced "integrated control" (Geier, 1970). The concept of pest management has been broadened to include all classes of pests (diseases, insects, nematodes and weeds). Pest management and IPM are now used interchangeably.

IPM implies an integration of disciplines (entomology, plant pathology, agronomy, and economics) as well as an integration of control methods. The development of the IPM concept has been described by Smith, Apple and Botrell (1976).

> The evolution of the concept and its terminology spans a period of several decades and has been influenced greatly by changing technologies and societal values. Some crop protection specialists continue to discredit the concept as representing only new jargon applied to long established crop protection practices. We acknowledge that IPM is not a disjunct development in crop protection - it is an evolutionary stage in pest control strategy - but it represents a new conceptual approach that sets crop protection in a new context within a crop production system.

As defined by the Office of Technological Assessment, IPM is a "comprehensive approach to the use of various control methods that takes into account the role of all kinds of pests in their environment, possible interrelationships among pests, and other factors".

The FAO panel of experts on integrated pest control (1967) defined integrated pest management as:

> ... a pest management system that in the context of the associated environment and the population dynamics of the pest species, utilizes all suitable techniques and methods in as compatable a manner as posible and maintains the pest populations at levels below those causing economic injury.

Both definitions advocate pest management as a systems approach to pest control based on ecological principles not only focused on satisfying the short run needs of an individual firm. The full advantages and limitations of any control method cannot be identified for a single firm during one season. The pest management approach is designed to recognize the benefits and losses, experienced by all members of society over time, associated with pest control practices.

By taking a broad perspective, the list of control strategies available is increased but so is the complexity of choosing a control strategy. Choosing a control strategy requires knowledge of the effects implementation of each available strategy will have on the pest and the environment and an evaluation of these effects. In other words, the overall impact of each strategy must be predicted from our understanding of the system being managed and compared using some performance criteria. In order to accomplish this, the characteristics of the system to be analyzed must be identified.

Any definition of pest management is purposefully general and thus vague as to what characteristics should be considered in selecting a pest control strategy and how to evaluate those factors. However, the definitions do serve as general guidelines. Components of the FAO definition of IPM quoted above will be addressed individually to elaborate the ideas presented in the definition.

ASSOCIATED ENVIRONMENT

Pest management decisions are made based on the characteristics of the environment that effect crop loss attributable to pests. The most critical environmental factor is weather. Temperature, precipitation, solar radiation and wind influence the status of the plant, pest and natural enemies directly or indirectly. For example, the emergence of pests and overwintering behavior are determined by temperature.

The pest problems in a particular field are also related to the physical characteristics of the field and the area surrounding the field. The slope of the land, drainage, elevation and proximity to drainage ditches and natural waterways affect pest levels as well as the entry of any pesticides into the food chain. Wooded areas provide overwintering sites for pests. Weeds bordering a field harbor pests throughout the year.

The hazards posed by pest control (primarily pesticide use) to humans, domestic animals and wildlife are usually referred to as social costs. Social costs are rarely if ever included in the calculation of costs and benefits of pest control strategies at the firm level. The term associated environment has a broader interpretation when social costs are being considered than when they are not.

POPULATION DYNAMICS OF PEST SPECIES

Pests compete with members of their own species and other species for food. Some insect species will feed at a constant rate until a crop is destroyed while others will adjust their feeding rate to the population density. When a pest population is reduced, this will make food available for another species. The problem of a secondary outbreak occurs when an increase in the population of a second species is attributable to control of the target pest.

Pest populations also interact with predators, parasites and pathogens. Enemies of the pest may compete with each other.

TECHNIQUES AND METHODS OF CONTROL

Pesticides provide an immediate reduction of pest populations and remain an important tool for pest management. However, pesticides need not be applied as a prophylactic. The proper timing of pesticides based on the level of pest infestation and plant status can reduce the number of applications and improve control. Pesticides are often injurious to natural enemies of the pest. This negative effect can also be diminished by careful timing of applications. Although pesticide use is now the most common method of pest control, several other methods exist including biological controls, resistant plant varieties, and cultural practices.

Biological control is provided by predators, parasites or pathogens that are natural enemies of the pest. These organisms may be propagated in the laboratory and released into the environment. Because so many pests are not native to the areas they infest, the natural enemies of the pest must often be imported. The release of a predatory lady beetle and a fly imported from Australia in 1888 to control cottony cushion scale on citrus in California is probably the earliest U.S. example of biological control introduced by man. These two predators eliminated the scale as an economic pest within a year. Biocontrol agents are very specific and are less likely to produce undesirable side effects than is conventional pesticide use.

Several other more recently developed techniques show potential for insect control. Insect pheromones are a means of direct control by trapping. They can also be released to inhibit mating as can sterilized males. Juvenile hormones introduced to the environment work by interfering with the maturation of insects.

The use of resistant plants has been effective in the control of certain nematodes, plant pathogens and a few insects. Damage is reduced due to some physical characteristics of the plant. Some plants contain chemicals that are toxic to insects feeding on them. Others avoid damage by maturing rapidly. This allows for early harvesting before extensive damage from pests occurs. Still others do not avoid damage but regenerate lost plant materials quickly.

Cultural or physical practices regulate pests by changing their environment. Cultural control practices were the earliest form of crop protection instituted by man developed mostly by trial and error.

Control methods now include removal of crop stubble (sanitation) to reduce overwinter survival, tillage to destroy overwintering pests, removal of alternative hosts, rotation of crops to limit the build up of pest populations and the timing of planting and harvesting. Other physical practices include pruning, defoliation, isolation from other crops, the use of trap crops, and the management of water and fertilizer.

Crop rotation can be used to control insects, weeds, diseases and nematodes. Crops should not be followed by similar crops (e.g. grains followed by grains) to benefit from crop rotation. Some weed problems can be controlled in one crop better than in another. In this case, crop rotation does not directly control weeds but makes it possible for other technologies to provide control.

The increase in narrow row spacing, broadcast seeding, and no-tillage has meant a decrease in using mechancial weed control after planting and an increased reliance on herbicides. Although no-till results in a lower percentage of weed germination, no-till requires greater use of chemicals than conventional tillage.

Public actions are usually not included in a list of pest management tactics. However, they play a critical role in pest management. Regulations restrain, encourage or require the utilization of certain pest control methods. Government regulations take many forms. Most are directed at pesticide use. Restrictions on pesticide use affect farmers' pest control choices.

Legislation - The first federal law designed to control pesticides was the Federal Insecticide Act of 1910 which pertained to only insecticides and fungicides. Its main purpose was to protect farmers

against poor quality or fraudulent products. The 1938 amendment of the Pure Food Law of 1906 set tolerances for certain pesticide residuals in foods. The Federal Insecticide, Fungicide and Rodenticide Act (FIFRA) was signed into law in 1947. It required that any of these products be registered with USDA before they could be marketed in interstate commerce. The main purpose of the law was to make pesticides safe to the user. This was accomplished by requiring complete and useful labeling by the manufacturer and further requiring that the label instructions for application be followed by the user.

FIFRA was administered by the Pesticide Regulation Division of USDA until 1970 when responsibility was transferred to the newly established Environmental Protection Agency (EPA). In 1972 FIFRA was amended to include the classification of pesticides, the registration of applicators and identify EPA as the responsible agency. A more detailed description of the current legislation follows.

The procedure for registration begins with a statement filed with EPA by the applicant which includes a statement of all claims to be made for the pesticide, the complete formula for the pesticide, a copy of the labeling of the pesticide, and any directions for its use. The applicant must furnish any information required by EPA for registration. Registration will be approved if the pesticide is found to meet the claims made for it and "when considered with any restrictions imposed [under FIFRA] it will perform its intended function without unreasonable adverse effects on the environment; and when used in accordance with widespread and commonly recognized practice it will not generally cause unreasonable adverse effects on the environment."

As part of the registration of a pesticide it is classified for general use or restricted use. A pesticide is classified for restricted use if it is determined that "without additional regulatory restrictions [the pesticide may cause] unreasonable adverse effects on the environment, including injury to the applicator." Certifications require passing a written exam administered at the state level. Applicators are given either private or commercial status. Private applicators are limited to use of pesticides on property owned or rented by themselves or their employer.

The most important source of information to the layman for pesticide use is the label on the container. Labeling of all registered pesticides is required under FIFRA. Highly toxic pesticides must carry the words "Danger-Poison" on the label, moderately toxic pesticides the word "Warning" and slightly toxic pesticides the word "Caution". Other information required on the label includes:

1. Product name
2. Company name and address
3. Ingredients
4. Precautionary statements including hazards to humans and domestic animals, environmental hazards and physical or chemical hazards
5. Classification of pesticide (restricted or general use)
6. Category of applicator
7. Storage and disposal directions
8. Directions for use on each crop for which the pesticide is registered including application rates.

Knowledge of IPM techniques cannot be required for certification. However, the legislation requires federal standards and state plans for certification to provide information concerning integrated pest management to potential users upon request. In other words, it must be possible for growers to put IPM into practice.

A major part of the registration process is the Rebuttable Presumption Against Registration Process (RPAR). The RPAR activity is a review process for selected registered pesticides which allows for public participation. There were about 45 chemicals or groups of chemicals involved in the RPAR process in 1980. As of 1980, the registration for 6 pesticides had been cancelled or suspended by EPA and 15 pesticides had been voluntarily cancelled by the registrants.

Federal grades and quality standards set maximum tolerable levels for pest damage to food and insect parts in food. Although some standards are set for health purposes, quite often they reflect a demand for attractive fruit and vegetables. Pesticides have been used extensively for cosmetic purposes. It would be expected that a downward revision of grades and standards would reduce pesticide use while an upward revision would invite increased use (Carlson and Castle, 1972).

Taxes and subsidies can be used to alter pesticide use. Taxes on pesticide use increase the cost of this means of control. Theoretically they can be adjusted upward or downward until the 'optimal' level of aggregate pesticide use is attained.

Subsidies can be used to make one form of pest control more attractive than another. Subsidies to agricultural chemical companies to develop narrow-spectrum pesticides that kill only a few species make them more profitable to produce. Subsidies to public or private agencies such as The Federal Crop Insurance Corporation encourage the substitution of crop insurance for pesticide application.

Shifting production to areas where pests are not problematic reduces the need for artificial controls. Acreage shifts can also be used to isolate pollution producing activities from other activities or locate pollution producing activities in areas where the absorptive capacity of the environment is greatest. Spatial shifts can be encouraged by changes in market prices, taxes, subsidies or acreage allotments.

Other examples of regulations include the certification of disease free seeds and plants and guaranteeing the removal of abandoned orchards. Connecticut and Massachusetts recently passed laws to erradicate the barberry, an alternative host for the stem rust of wheat.

Societal values concerning pest control methods are expressed through the scope and form of regulation. Pest management techniques are chosen at the farm level within the constraints of regulation. The selection process of an individual grower must be consistant with the results of the regulatory process.

ECONOMIC INJURY

The FAO definition of IPM states that a pest management system should "maintain pest populations below those causing economic injury." The term economic injury was developed by entomologists to determine when pest control is appropriate. The economic injury level is defined as "the lowest population density that will cause economic damage" (Stern et al. 1959). Economic damage is the amount of injury that will justify the cost of artificial control measures. The implication is crop damage should be tolerated when the trade-off between damage and control costs is recognized.

Usually there is a lag between recognition of the need for control and the initiation of control and a second lag before the control takes effect. For this reason it may be necessary to implement controls before the injury level is reached. To capture this distinction, another term, economic threshold, was introduced by Vernon Stern in his pioneer article "Economic Thresholds" (1959). Based on the definitions of economic injury level and economic damage, economic threshold is defined as "the density at which control measures should be applied to prevent an increasing pest population from reaching the economic injury level." The economic threshold is always lower than the economic injury level to allow time for the control to take effect.

Edward and Heath (1964) defined the economic threshold as the population large enough to cause damages valued at the cost of practical control. The Subcommittee on Insect Pests of the Committee on Plant and Animal Pests established by the National Research Council (National Academy of Sciences, 1969) defined the economic threshold 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 activities."

To summarize, the FAO definition of IPM can be interpreted as a list of characteristics a pest control system should have in order to be consistent with the IPM philosophy. The control system should utilize methods and techniques that are environmentally sound. The methods and techniques should not work against each other in the long run (e.g. use of pesticides may reduce the effectiveness of biological controls over time). A pest management system should be based on ecological principles and draw from control mechanisms found in nature. Finally, the control system should be compatible with producer and user objectives. Thus, it should not tolerate economic damage, but neither should it include control measures that are not economically warranted.

The performance objectives of IPM are often assumed to include a reduction in pesticide use. This is not quite accurate. Limiting pesticide use is not part of the design of pest management programs. Theoretically, IPM could increase the use of pesticides. In practice, however, growers employing IPM strategies have reduced their use of pesticides on average. Thus, pesticide reduction has been a consequence, but not a requirement of IPM.

Even when the important biological relationships are understood for a particular pest management problem, the definitions of IPM are ambiguous. They provide no insights into several factors which are critical in operationalizing the IPM concept. The specific context in which decisions are made indicates what appropriate control methods are available. What is possible and favorable in one context may not be in another. The following dimensions must be clearly delineated before IPM can be put into practice.

Time Frame - The planning horizon determines what factors are fixed and what factors can be controlled by the manager. For example, once a cropping system and machinery are chosen the grower is locked in and has fewer control options. In a one year planning scheme, crop rotation is not an option. Most social costs are not realized in a single year. Pesticides move through the food chain over time.

Spatial Unit - The spatial unit to which the IPM concept is applied must be designated. Pest management can be oriented to a field, a farm or a region. The factors over which the decision maker has some control are different for each of these units. Similarly, the objectives of pest management vary for a farm, a region, the agricultural sector and society. The consequences of the actions of one producer are rarely independent of the actions of other producers. Consequently, the optimal management scheme for a region will differ from the aggregate of the management schemes of the producers in the region developed from the same information base. The same is true when actions are not independent among time periods.

Numerous combinations of spatial and temporal units are feasible for pest management design. For example, most biological control methods require regional management over several years.

In order to take a whole farm approach to pest management, the potential conflict in implementing control strategies and other farm activities should be recognized. For example, application of pesticides for protection of one crop may be prescribed at the same time as the harvesting or planting of another. If pest management is applied in a whole farm context, then the grower's entire decision agenda must be considered.

Institutional Structure - The structure of an economy determines the conduct of individual actors within that economy. Structure refers to all the factors which constrain the available lines of action open to an individual. The opportunity set for each individual is established by the structure.

A distinction can be made between natural factors and institutional factors that compose the structure of an economy. Institutional characteristics refer to social relations as opposed to natural phenomena. In the words of John R. Commons (1950), "An institution is collective action in control, liberation and expansion of individual action." Or according to A. Allan Schmid (1978) "interacting opportunity sets are what is meant by the institutional structure and can be distinguished from nature, technology, knowledge, tastes and other aspects of personality." These authors[1] use the terms institutions, property rights and rules more or less interchangeably.

Other authors[2], define institutions as business entities including individuals which perform economic activities (Kohls and Downey, 1972). In this context, the most important institution in a market economy is the firm. A broader definition includes business entities, rules, laws, customs and conventions involved in economic activity (Breimyer, 1976). Further, the business entities may be either public or private.

Adapting the broadened definition land grant colleges, the Extension Service, chemical firm fieldmen, regulations, crop insurance, input supplers and marketing orders are all institutions that affect pest management. Pest management decisions are made within the existing institutional structure. A strategy which is possible or feasible in one context may not be in another. Institutional change modifies the opportunity set of growers and ultimately their choice of pest control tactics.

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[1] These examples are drawn from the public expenditure literature.
[2] The following definitions are taken from the marketing literature.

Risk and Uncertainty[3] - Pest management decisions are made without perfect knowledge of the outcomes associated with alternative strategies. Risk and uncertainty enter the pest management decision making process in several ways, through (1) the agricultural biology, (2) technology and (3) institutions. All three are interrelated. New methods of control, including new pesticides, are continuously introduced, changing the technology available for production. Changing regulation of pest controls contributes to the variation in technology. Organization of the delivery of pest control information is changing rapidly. Economic events change prices. With price changes the value of crop loss and the cost of control vary.

The primary source of variation in crop production is weather. Stochastic factors in agriculture include spatial and temporal variation in pest types and population levels and variation in damage (both yield and quality) per pest. Susceptibility of pests to controls also varies as the genetic characteristics of the pest change over time. The effect of controls on other crops and the quality of crops is not known with certainty.

Uncertainty in pest management suggests the potential for using a decision framework incorporating risk. Decisions made with imperfect knowledge can be characterized by a probability distribution function for all possible outcomes. This distribution can be used to choose a control strategy once an individual's attitude toward risk (willingness to gamble) is known. An individual's attitude toward risk will affect

[3]The terms risk and uncertainty will be used interchangeably. A more rigorous approach to this topic is presented in section 3.2.

the selection of a control strategy, all other factors held equal. Given that individuals' preferences for risk vary, it is not possible to determine a unique optimal control strategy that will maximize utility for individuals with different risk preferences. However, by categorizing individuals as risk averse, risk neutral or risk preferers, it is possible to rank control strategies.

2.3 Operationalizing the Economic Threshold

As a science of resource allocation, economic theory can be applied to deciding 1) which combination of available pest management inputs to use, 2) what quantities of each input to use and 3) when to apply those inputs.

For certain control programs the decision process includes the number of applications or an amount of material to be applied. Other strategies are either implemented or they are not implemented. It is not really meaningful to ask what proportion of a field to plant in a resistant variety, or what percentage to harvest early. Similarly, for some strategies the timing of application is not a major concern. For example, a grower is concerned with whether or not it pays to construct a deer fence but not when to build it. For these reasons, although the definition of economic threshold refers to all pest control techniques, the threshold concept has been applied primarily to insecticide applications.

Any resource allocation problem consists of a description of the production process and a decision criterion for selecting inputs into that production process. Various theortical approaches to operationalizing the economic threshold will be presented below. They vary in the complexity of the description of the production process, the possible control strategies, and the decision criteria for choosing among the control strategies.

The earliest attempt at a systematic approach to determining the economic threshold based on economic theory was developed by Headley (1972). Headley used marginal analysis to derive a rigorous definition for the economic threshold from a simple pest control model. The model developed by Headley has four components.

1) Pest population growth function

$$P_t = P_{t-n}(1+r)^n \qquad (2\text{-}1)$$

2) Crop production function

$$y = N - cD_t \qquad (2\text{-}2)$$

3) Pest damage function

$$D_t = bP_t^2 - A \qquad (2\text{-}3)$$

4) Pest control cost function

$$0 = \frac{L}{P_{t-n}} \qquad (2\text{-}4)$$

where:

P_t	=	the pest population at time t
P_{t-n}	=	the population at time t-n
r	=	growth rate of the population per time period
$(1+r)^n$	=	compound growth factor
y	=	product yield
N	=	maximum possible yield
c	=	a constant parameter measuring incremental yield effects
D_t	=	pest damage in time t

b = constant parameter which enters into the incremental damage resulting from P_t

A = constant to define the damage tolerance level

0 = total control cost

L = a constant parameter influencing incremental costs

The equation for P_t (2-1) can be substituted into the damage function (2-3) to derive D_t as a function of P_{t-n}.

$$D_t = b[P_{t-n}(1+r)^n]^2 - A \qquad (2\text{-}5)$$

From this equation pest damage attributable to various pest levels at time t-n can be determined. Substituting (2-5) into (2-2) a production function can also be expressed in terms of P_{t-n}.

$$y = N - c\{b[P_{t-n}(1+r)^n]^2 - A\} \qquad (2\text{-}6)$$

This equation presents the relationship between pest population at time t-n and yield at time t.

Headley uses profit maximization as the decision criteria. Assuming that the producer is a price taker, the marginal revenue with respect to P_{t-n} is:

$$MR = \frac{dy}{dP_{t-n}} = -2cb(1+r)^{2n} P_{t-n} \qquad (2\text{-}7)$$

and the marginal cost of control is:

$$MC = \frac{dO}{dP_{t-n}} = - \frac{L}{P_{t-n}^2} \qquad (2\text{-}8)$$

Assuming profit maximization is the objective of the manager, the optimal pest level P_{t-n} to which the pest population should be reduced in period t-n is obtained by equating marginal revenue to marginal cost.

$$P_{t-n} = [\frac{L}{2cb(1+r)^{2n}}]^{\frac{1}{3}} \qquad (2\text{-}9)$$

This value of P_{t-n} is the economic threshold defined as the population level where the marginal cost of reducing the pest population by one increment is equal to the marginal increase in the value of production that results.

Headley interprets the definition of economic threshold to pertain to a single producer considering a single pest for a single season. The Headley model is essentially static. It provides no information on the optimal timing of applications during the season. He implicitly assumes that the optimal period for pest control (from time t-n to t) is "entomologically determined." The amount of damage realized before time t-n does not enter into the computations. Improvements in the Headley model have been made by a number of authors including Hall and Norgaard (1973), Talpaz and Borosh (1974), Heuth and Regev (1974) Shoemaker (1977) and Feder (1979).

Hall and Norgaard (1973) refine the Headley model to allow the time and dosage of pesticide application to vary. The simplifying assumption is made that there is a single optimal time of application which is determined simultaneously with the optimal quantity of pesticide applied. A "kill function" is added to Headley's model which determines the number of pests killed by a pesticide application as a function of the pesticide dosage and the time of pesticide application. A more complex pest population growth function is used which determines population as a function of the time of pesticide application and the kill function.

Unlike the Headley model, the pest population is calculated from the beginning of the season and not from the time of pesticide application. Damage occurring before the pesticide treatment is used in determining the economic threshold. The cost of control is determined by the quantity of pesticides used and not the number of pests killed. The damage and yield functions have the same form as in the Headley model. The optimum time and quantity of pesticide application are found by maximizing profit with respect to these two inputs simultaneously.

While the Hall and Norgaard model is an important extension of Headley's work, it is not rigorous enough for application to a specific problem. In the words of the authors "...We never meant for our model to be 'applied.' Our paper was a basic exploration of the definition of the [economic] threshold ...In our conclusion we stated that our model 'provides rigor to the definition of the concept of economic threshold but is too simple for practical application.'"

Talpaz and Borosh (1974) refine Headley's basic model by allowing for multiple treatments within a season. A setup cost for each application is added to the cost function. An explicit kill function is used so that numerical computations can be carried out for a specific pest and crop.

The control parameters are the quantity of pesticides applied for each treatment, and the number of applications. The timing of the applications is not a control parameter. If n is the optimal number of applications, the timing of applications is determined by dividing the growing period for the crop into n+1 equivalent periods. Sprays should be applied at the end of the first n periods and the harvest made at the end of period n+1.

Heuth and Regev (1974) also use a single crop, single pest, single year model and relax the assumption of a single chemical application. They make an important contribution by including long run impacts of pest control in their analysis to consider what they call "the dynamic properties of the economic threshold." Specifically, they include increasing pest resistance over time by characterizing pest susceptibility to chemical control as an exhaustible resource. User costs[4] associated with pest resistance are included in the analysis in addition to monetary costs of control to capture the effects of pest resistance. The user costs considered are "increased future costs of controlling the pest as a result of a decision to apply chemicals today" resulting from the depletion of the stock of susceptible pests (i.e. increasing pest resistance).

The economic threshold is determined as follows: "If the marginal value of insecticides in plant growth and pest growth is less than the marginal unit cost of insecticides plus the marginal cost of their use in reducing the stock of susceptibility, none will be used. If any insecticides are used, the level of use will be such that the marginal benefit equals the marginal cost."

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[4]The term 'user cost' was coined by Keynes and is used extensively in resource economics. As defined by Scott (1967) user cost is "The present value of the future profit foregone by a decision to produce a unit of output today."

Following this analysis, profit maximization that ignores user costs of pesticides results in nonoptimal behavior. However, the activities of an individual grower have essentially no impact on pest resistance. The solution presented is a regional solution for several growers with a multi-year planning horizon that maximizes regional profit. Some institutional change is necessary before user cost of reducing the stock of susceptibility will be included in the decision making process. The authors suggest "....appropriate Pigouvian taxes and subsidies may be defined for the region to achieve the centralized solution with decentralized decision making and thus maximize regional profits." Of course, this is only one of several possibilities.

Heuth and Regev's study is important for at least two reasons. First, they showed that the definition of economic threshold can include future effects of pest management beyond the current season. Second, if interdependencies between growers and time periods are to be considered in developing pest management strategies, profit maximization for a single firm is not an adequate decision rule.

All but the last of the studies discussed assumed that pest control decisions are independent of the pest population in subsequent time periods or seasons. When populations are not independent from year to year, combining the optimal strategies for each year independently will not result in an optimal strategy over the entire period. Headley (1975) illustrated this point with a hypothetical management system consisting of three available control methods and a two year planning horizon. The costs and percent mortality vary for each control method.

The functions implicit in Headley's example are:

1. Pest population function

$$P(t+1) = 3(1-M_i)P(t) \tag{2-10}$$

2. Value of crop production

$$Y_i(t) = 200\ D_i(t) \tag{2-11}$$

3. Pest damage function

$$D_i(t) = (1-M_i)P(t) \tag{2-12}$$

4. Cost of control

$C_1 = 0$

$C_2 = 10$

$C_3 = 30$

where:

$P(t+1)$	=	pest population in period t+1.
$P(t)$	=	pest population in period t.
M_i	=	mortality rate for control measure i in any single period.
$Y_i(t)$	=	value of crop production using control i in period t.
$D_i(t)$	=	value of crop loss attributable to pest population in period t using control i.
C_i	=	cost of control i for a single period.

The three control methods considered are 1) no control; 2) a combination of biological and chemical controls; and 3) chemical control. Costs and mortality for each are summarized below.

Control Method	% Mortality	Cost/Acre
1 - no control	0	\$ 0
2 - combination	75	\$ 10
3 - chemical	90	\$ 30

Headley shows through this simple example that maximization of net income, for each time period separately will not lead to the same selection of methods as will maximization of net income over several time periods. Further, the total incomes will not be equivalent. Letting $I_i(t)$ be the net income in period t using control i, the objective function can be represented as:

$$\max_i (I_i(t) + I_i(t+1)) \qquad (2\text{-}14)$$

where:

$$I_i(t) = Y_i(t) - C_i(t) \qquad i = 1, 2, 3$$

The problem of maximization over two time periods can be solved by constructing a decision tree for each possible combination of controls and finding the maximum net income by inspection (Figure 2.2).

An initial population of 100 is assumed. Maximization for each period individually leads to using method 2, a mix of biological and chemical controls, in each period. The total income for the two periods is \$336.25. Optimization over the two periods leads to using method 3, chemical control, in period 1, and method 2 in period 2. The total income in this case is \$342.50.

Shoemaker (1977) establishes a "multi-dimensional economic threshold" as a function of several variables including pest population density, natural enemy population density, plant vigor and maturity and

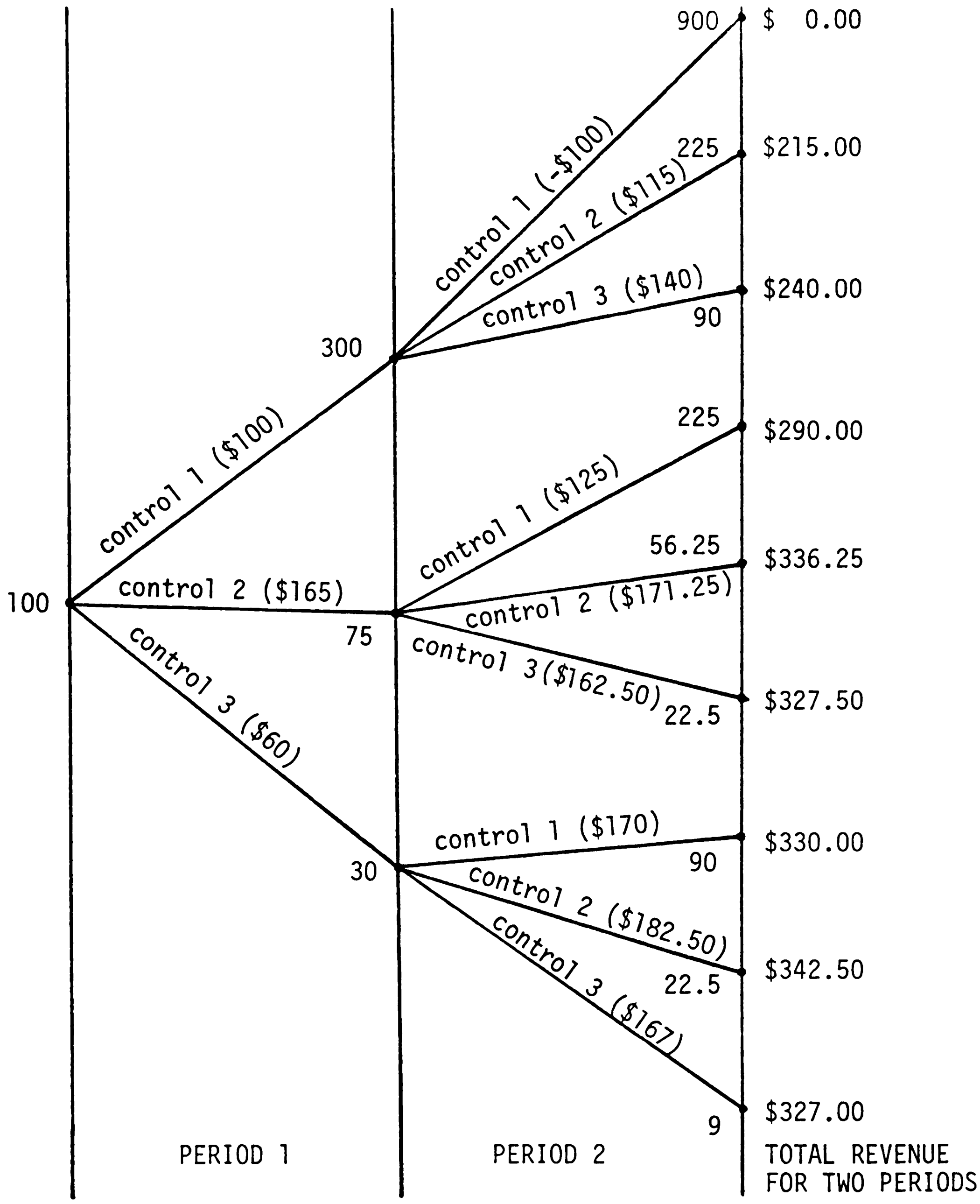

Figure 2.2 The nine possible outcomes for a hypothetical two-period pest control problem with an initial population level of 100 and three alternative control strategies. The numbers in parentheses are net incomes for each period. The numbers to the left of each branch are the initial population levels at the beginning of each period.

weather. She discusses the use of dynamic programming and a multiple-season objective function to develop pest management guidelines. Using this approach, the best combination of chemical, cultural and biological methods of control can be estimated. The ecosystem model utilized by Shoemaker can easily be described in the framework developed by Headley.

1. Population model

$$P_1(t+1) = G_1(P_1(t), P_2(t), Z(t), h(t), v(t)) \quad (2\text{-}15)$$

$$P_2(t+1) = G_2(P_1(t), P_2(t), Z(t), h(t), v(t)) \quad (2\text{-}16)$$

2. Crop production function

$$Y(t) = G_3(Z(t), h(t)) \quad (2\text{-}17)$$

3. Pest damage function

$$D(t) = G_4(P_1(t), P_2(t), Z(t), h(t), v(t)) \quad (2\text{-}18)$$

4. Cost of control

$$C(t) = G_5(v(t)) \quad (2\text{-}19)$$

where:

$P_1(t+1)$ = pest population in the spring of year t+1.

$P_1(t)$ = pest population in the spring of year t.

$P_2(t+1)$ = parasite population in the spring of year t+1.

$P_2(t)$ = parasite population in the spring of year t.

$Z(t)$ = weather pattern for year t.

$h(t)$ = time of harvest for year t.

$v(t)$ = amount of insecticide applied after harvest.

$Y(t)$ = yield expected in the absence of pest damage in year t.

$D(t)$ = amount of yield lost to pest feeding in year t.

$C(t)$ = cost of insecticide treatment.

The objective function used is profit maximization over several years. The best management policies are assumed to be those which maximize the present value of net income. Formulating the maximization problem as a dynamic programming problem results in the following:

$$\max_{\substack{h(i),\, v(i) \\ i=1,\, T}} \left[\sum_{i=1}^{T} \frac{1}{(1+r)^i} \left[P_i \; Y(t) - C(t)\right] \right. \qquad (2\text{-}20)$$

where:

r = discount rate

P_i = price of alfalfa in year i

subject to the constraints of equations (2-15)-(2-19).

The optimal management strategy has two components, the time of harvesting and the amount of insecticide applied. The population of natural enemies is considered in determining the control methods by describing the pest population as a function of the natural enemy population and the natural enemy population as a function of the control methods in the model.

Only the general form of the model is presented here. In application, each component of the model may be expressed by a series of equations to include greater detail in the model than is possible in a single equation.

The optimization procedure utilized by Shoemaker is dynamic programming. The procedure eliminates the need for estimating results for each possible combination of control strategies and initial populations.

One of the major limitations of dynamic programming is that the process must be Markovian. That is, the value of a variable at time t can depend on values at time t-1 but not on t-2, t-3, etc. A second problem with dynamic programming is that the number of state variables must be small for the optimization to be computationally feasible.

These problems are circumvented by defining the objective function in terms of three variables (the initial pest population, P_1, initial population of natural enemies, P_2, and the weather pattern Z). The complicated relationships among weather, pest populations, yield, timing of harvest, etc. are all incorporated into the functions G_1, G_2, G_3 and G_4, which are calculated outside the dynamic programming problem. Each of these functions can be described in an ecosystem model by a series of equations and solved numerically to determine C and Y from P_1, P_2 and Z. These values, in turn, are used to solve the dynamic programming problem. The ecosystem model can then include numerous variables without making the dynamic programming problem impossible. At the same time, the detail of the ecosystem model is not sacrificed.

The work reviewed so far has assumed that reasonably accurate ecosystem models are available and the outcomes of alternative control practices are known with certainty. However, in most pest management situations, each control alternative has a number of possible outcomes, some being more probable than others.

Feder (1979) introduces stochastic variables into a simple pest management model. Three sources of uncertainty are identified: 1) the rate of damage (b); 2) the pest population density (N); and 3) the effectiveness of pesticides (k). The analysis considers the effect of allowing each of these factors to be random while the other two are assumed to be nonrandom. Clearly, this simplifies the computational requirements. However, it is not obvious that the same results would be obtained if all three factors were assumed to be stochastic simultaneously.

The model is applicable to a single firm decision making process. In the words of the author "The optimal amount of pesticides implied...is 'private', not social because the farmer ignores the damage inflicted on wildlife and humans by pesticide drifts and residues and because of the other externalities related to pesticides used."

The model can be described as follows:

1. Pest population function

$$N^* = (1-k)N \qquad (2\text{-}21)$$

2. Crop production function

$$Y = Y^*(1-D) \qquad (2\text{-}22)$$

3. Damage function

$$D = bN \qquad (2\text{-}23)$$

4. Kill function

$$k = k(x) \qquad (2\text{-}24)$$

5. Cost of control

$$C = p_x x + F \qquad (2\text{-}25)$$

where:

N^* = pest population level after control is implemented.

k = proportion by which pest population is reduced by pesticides.

N = pest population level before control is implemented.

Y = crop yield.

Y^* = crop yield in the absence of pests.

D = crop loss to pests.

b = damage caused by a single pest.

x = amount of pesticides applied.

C = cost of control.

P_x = price of pesticides.

F = fixed costs of control.

The cost of management techniques other than pesticides is assumed to be fixed. The only control variable in this system is the amount of pesticides to be applied. Feder assumes risk averting behavior and consequently the objective function is maximization of expected utility as follows:

$$\underset{x}{\text{Max}}\ E\ [U(P_y Y - bN^*[1-k(x)] - p_x x-F)] \tag{2-26}$$

The first order conditions for an optimum are given by:

$$\frac{\partial E(U)}{\partial x} = E\ [U'(bNk'-Px)]<0 \tag{2-27}$$

and

$$x\ \frac{\partial E(U)}{\partial x} = 0 \tag{2-28}$$

While some of the variability in b is caused by random factors, the mean ($\bar{b}$) may be decreased by pest resistant varieties, timing of fertilizer and water application or other techniques. Farmers can be charged a fixed cost for information about these technologies because they increase the farmer's expected utility. A farmer will pay for information up until the point his expected utility is unchanged.

Uncertainty regarding N can be reduced by monitoring of fields. The cost of monitoring is on a per acre basis. In this case, growers should also be willing to pay for information. The result of information is a reduction in the frequency and quantity of pesticide use.

Feder looks at two alternative specifications of uncertainty in the kill function; (1) the variation in pest response to the pesticide declines for higher dosages; and (2) the variance increases with the dosage. In the first case pesticides are a risk reducing input. With a more effective pesticide, less is needed to maintain the pest population below a certain level and pesticide use will decrease. Growers will be willing to increase costs for a better quality chemical or information that will increase the effectiveness of current pesticides.

In the second case, pesticides are not a risk reducing input. With larger amounts of pesticides the variance of the utility function increases. A decrease in uncertainty regarding pesticide effectiveness will cause an increase in the amount and frequency of pesticides applied by lowering the economic threshold. Consequently, growers will pay for information to improve the efficacy of the pesticides and increase pesticide use.

The major contribution to the literature by Feder is the recognition that uncertainty affects pest management decisions. Most attempts to develop pest management programs have relied on the assumption that growers are risk neutral. Consequently, the objective function has been to optimize expected profit. Optimization implies control over pest management variables and perfect knowledge of the relationship between pest management variables and crop loss. In practice, the grower does not know with certainty either the amount of damage that will occur if a pest control strategy is not implemented or the outcome if a pest control strategy is implemented.

If the variability in pest damage is different for alternative pest management strategies, then growers with differing risk preferences may choose different pest control methods. Put another way, it may not be possible to identify a pest management program acceptable to a group of rational decision makers operating under uncertainty if their risk preferences differ. In fact, risk averse growers may prefer routine spray schedules if they reduce the variability in crop loss.

Decision making under uncertainty will be discussed in 3.2.4. Empirical studies of the relationship between risk preference and pest management decisions are discussed in 3.2.6.

2.4 Pest Management of the Alfalfa Weevil

The alfalfa weevil *Hypera postica* (Gyllenhal) is a European species that was first discovered in Michigan in 1966 (Dowdy, 1966) and has since spread and increased to damaging numbers over the lower peninsula (Ruppel and Guyer, 1972). It is now the most serious pest of alfalfa, threatening roughly half of the alfalfa acreage throughout the state.

The adult weevils are gray to brown beetles, one-quarter inch long. A broad dark band extends to the middle of their wings. The larvae have black heads and green bodies when fully grown with a white stripe down their backs. They are less than three-eights of an inch long.

Adult weevils overwinter in protected areas and become active in early spring. During this time, they feed on the leaves of the alfalfa and lay eggs inside the hollow stems of the plants.

The larvae hatch from the eggs beginning in late April and feed on the alfalfa leaves for three to four weeks. When full grown, they spin silken cocoons on the plant and enter a pupal stage. After one or two weeks, adults emerge from these cocoons from mid-June to mid-July. They feed for about a week and then move out of the alfalfa fields to protected areas.

Most adults remain in a resting period until the following spring. Although some become active and lay eggs in the fall, these eggs do not survive the winter in northern climates.

The alfalfa weevil became well-established in the New World, in part, due to the absence of natural enemies (parasites, predators, and diseases) that suppress its numbers in Europe. One method of control involves the introduction of biological control agents. Parasitic wasps have been introduced throughout Michigan for this purpose. The wasps lay their eggs in either the eggs or larvae of the alfalfa weevil.

Insecticides applied during the growing season have been the most widely used method of control. Proper timing of a spray is critical because of the short residual activity of the insecticides used. A spray applied too early will leave the crop unprotected, while a late spray may not avoid economic loss.

When the weevil was first discovered, it was feared insecticides would be the only means of avoiding economic losses. However, field observations indicated damage was not extensive until the alfalfa was flowering and, therefore, early cutting could be used to avoid loss and reduce the need for the use of insecticides. Montana investigators (Hastings and Pepper, 1951) proposed this strategy in 1950 but their recommendation was not accepted by the growers because they believed the value of the yield loss incurred by the early cutting more than offset the cost of chemical application. Hamlin et al. (1949) observed high larval and pupal mortality following cutting in Utah. Casagrande and

Stehr (1973) reported between 60 and 80 percent of the larvae present killed by harvesting.

Early harvest can also reduce loss since much of the damage attributable to the weevil occurs after the plants reach the late bud stage. While the early cutting reduces yield in the absence of pest populations, it improves the quality of the hay. Early harvest of the first cutting is now considered a viable alternative to insecticide application (Tesar, 1968).

Several guidelines for the timing of spray application and first cutting exist. They include advising growers to take the first cutting at the late bud stage for growers using a three-cut-per-season system (Tesar, 1968); apply insecticide when 25 to 50 percent of the alfalfa tips show damage (Janes and Ruppel, 1969); and spray if 25 percent of the tips show damage and will not be cut for a week or more (Ruppel et al. 1976). The underlying hypothesis is that crop yield and quality will be reduced if the recommendations are not followed. However, these criteria, while useful as rules of thumb, are not based on experimental data or controlled field trials. Developing rigorous guidelines for the timing and implementation of alfalfa weevil control strategies requires knowledge of the impact of alfalfa weevil feeding on the yield and quality of alfalfa for a particular region.

To summarize, at least three methods of control are available for control of alfalfa weevil. They are biological control, early harvesting and insecticide application. The latter two involve proper timing of implementation.

CHAPTER III

INFORMATION AND PEST MANAGEMENT

3.1 Introduction

In the preceeding chapter the fundamental ideas of pest management were discussed. A distinction was made between pest control guidelines and pest management programs. Pest control guidelines are decision rules for allocating resources to pest control.

Site specific information is necessary for applying the pest control guidelines to a particular situation. Pest management programs are information systems that make available pest control guidelines and the information necessary for utilizing the guidelines and ultimately making pest control decisions.

Information is an input into the managerial process from which decisions are the output. In this sense, information is a commodity for which there is a supply, demand and a market value. Information derives its value by improving decisions concerning the allocation of other resources.

The ultimate objective of this chapter is to develop a method for evaluating pest management programs. Pest management programs can be distinguished by the information they make available. It follows that pest management programs can be evaluated by looking at the impact of the information provided for management decisions.

Various topics in the study of information will be explored. The remainder of this chapter is divided into three sections.

The next section looks at the role of information in the decision making process. The implications of perfect and costless information for resource allocation are explored briefly. The restriction of perfect knowledge is then relaxed and decision making under uncertainty is discussed in the remainder of the section.

The third section looks at the characteristics of information as a commodity. These characteristics determine the supply and demand for information. The public goods nature of information and its implications are discussed. The theory presented is not appropriate for assigning a dollar value to information but provides insight into the difficulties of determining what information should be provided and whether or not the information should be provided by the public or private sectors or some combination of the two. Some alternative institutional arrangements for the provision of pest management information are presented.

The fourth section presents several quantitative approaches to computing the value of information provided by alternative information systems.

3.2 The Role of Information in Decision Making

This section is divided into six subsections. The first subsection describes the relationship between information and resource allocation.

The second subsection presents an information system paradigm and the components of our information system are discussed. The paradigm is useful in identifying some major ideas to be considered in evaluating information systems. The integral role played by the decision maker in the design of an information system is emphasized.

The point is made that the problem to be solved impacts the design of the information system. Perhaps the most important implication of the paradigm is that information only gains market value as an input into the decision making process. The paradigm is applied to pest management in the third subsection.

The information system paradigm points out the role of the decision maker in the design of an information system and the existence of a relationship between the generation of information and problem solving.

The fourth subsection attempts to describe the decision making process and the impact of information on problem solving. The concept of subjective probabilities for possible states of nature is introduced. Several decision criteria and algorithms for selecting among risky ventures are presented. The impact of the decision maker's attitude toward risk on resource allocation is also discussed.

The fifth subsection uses these ideas and looks at the role of learning in decision making. Bayes rule for revising subjective probabilities is defined.

In the sixth subsection empirical results of studies looking at attitudes toward risk and the impact on pest management decisions are presented.

3.2.1 Information and Resource Allocation

The fundamental activity of an economic actor is to allocate resources based on available information.[1] The performance of a market economy can be viewed as the result of decisions made in the process of allocating resources. Goods and services are rationed among consumers. The factors of production are allocated among producers.

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[1] Throughout this chapter the terms knowledge and information will be used interchangeably.

The following discussion will focus on the production side of the economy and in particular on pest control as an input to agricultural production. The business firm will be viewed as the principal organization for production activities.

The firm must make several decisions regarding production. The firm must choose the level of output for each product and how to produce the output. The firm must also determine what prices to charge for its outputs and pay for its inputs. Of course, the set of attainable combinations of activity and price levels is bounded. In making production decisions the firm faces three kinds of constraints: 1) technical; 2) government; and 3) market.[2]

Technological constraints define the production possibilities of a firm. That is, they describe all patterns of inputs and outputs that are feasible. These constraints stem from the physical laws of nature, the actions of others, and the current state of technology.

The basis of technological constraints is incompatible use of finite resources. For a physical factor allowing several uses, the resource must be allocated among these uses. The set of possible uses changes with changes in technology.

The output and factor utilization of others limits the opportunity set of a firm. In the simplest case, if A uses a resource then it is not available for use by B. Also, unless a firm supplies all of its own inputs, it is dependent on the production of inputs by other firms. The activities of other firms may entail the production of byproducts which

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[2]Technical and market constraints are suggested by Varian (1978) as constraints faced by a firm in determining a profit maximizing policy. The constraints may also be interpreted as three categories of externalities following the approach taken by Schmid (1978).

become unplanned inputs into the firm's own production function. Fruit production provides pollen for the honey producer. Smoke produced by one firm may necessitate the installation of air filters by another.

Government constraints are those constraints that influence the production activities of the firm through public action, i.e. property rights and rules that affect the opportunities of the firm. Government constraints can be viewed as costs imposed and benefits conferred on individuals by collective action.

Political action alters price and output levels. In so doing, cost of production is increased for some and revenue is increased for others. Government constraints are really market constraints or technical constraints created through the legal system.

While government constraints are the result of collective action, market constraints concern the impact of the independent actions of individuals on the opportunity set of the firm. The consumption patterns of consumers and the demand for inputs by other producers affect the price levels of the inputs and outputs of a firm. Prices act as signals transmitting market values for the allocation of resources. Government constraints are also signals transmitting information concerning nonmarket or social values. Thus, what is produced, how it is produced, and in what quantity is a function not only of market values but of nonmarket values.

The three categories of constraints facing a firm are by no means independent. Private sector markets, public sector decisions, and adoption of technology are all causally related. The technical constraints determine what can be produced and the available methods of production. Changes in technology alter the value of resources in production. Market constraints provide prices which determine the allocation of resources to produce various outputs and the choice of input mix. Government constraints alter the production possibilities and exchange values of inputs and outputs of production.

One of the ideal conditions often assumed in the analysis of a market economy is that producers and consumers possess perfect knowledge of all constraints facing them. Several consequences follow. On the production side, all firms have access to the same technology and all market prices are known with certainty. Firms can control the quantity and quality of their output. On the consumer side, consumers know what goods are available and the quality and price of the goods.

Under these conditions, it follows that no buyers will pay above the market price for any product. No producers will be able to price their products above the market price or be willing to accept less than the market price. Under the assumption of perfect knowledge there is a single price, markets clear, all individuals and firms are price takers, all products are produced with the least cost combination of inputs and a static equilibrium is reached. However, when imperfect information prevails, none of these conclusions necessarily holds.

The assumption of perfect and costless knowledge does not allow a market for information. When the assumption is relaxed, the activities of seeking information and supplying information become questions of resource allocation. Application of this approach to pest management views an agricultural producer as a consumer of pest control information and a pest management program as a commodity consisting of information.

Ideally pest management programs provide at least three categories of information: 1) information describing the relationship of crop loss to biological and environmental factors; 2) timely information about pest population levels, crop stage, and weather and 3) pest control guidelines.

The categories of information are interdependent. The first category of information constitutes a general knowledge of the agro-ecosystem being managed and is encompassed in pest control guidelines developed from past experience and observations. The second category is specific to the particular decision maker and is necessary for operationalizing the guidelines.

Pest control guidelines are a synthesis of the technical, market and government constraints cogent to the control decision. A control strategy will not be recommended if the expected cost is greater than the expected return given current prices. A pesticide that is not currently registered for use on a particular crop will not be recommended. Hence, as market and government constraints change, pest control guidelines must also change.

In practice pest management programs may not provide explicit information concerning technical, market or government constraints. However, this information is implicit in the pest control guidelines.

3.2.2. An Information System Paradigm[3]

In the preceding subsection the assumption of costless knowledge was relaxed. Information was described as a critical input into the

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[3]The term paradigm is used here to mean a model or structure. It does not refer to a self-contained theory, science or discipline.

management process for which decisions are the output. It follows that information only has economic value in the context of decision making under uncertainty. Relaxing the assumption of perfect and costless knowledge leads to the study of information systems responsible for the production of information. In this spirit Bonnen (1975) developed a paradigm to describe the inherent structure of any information system.

The paradigm develops a vocabulary for the components of an information system. A distinction is made between data and information. Data systems and information sytems are then placed in a decision making framework. The information system paradigm is a theoretical framework for studying the process of producing information for use in decision making. The paradigm is a useful tool for evaluating an existing or proposed information system by identifying the necessary components. The paradigm is presented here in some detail and applied to pest management in the next subsection (Figure 3.1).

DATA AND INFORMATION SYSTEMS

Data are an attempt to represent reality through measurement or counting. Data are usually numerical but data need not be in quantitative terms. For example, pest infestations can be described as extreme, moderate, or low. Of course, qualitative terms can be translated into ordinal measures (e.g. low = 1, extreme = 10). In any case data can be presented in several forms including tables, graphs and charts. The discussion will focus on statistical data although the ideas presented are equally applicable to qualitative data.

Data can be narrowly defined as the quantification of ideas or concepts that describe the world. Therefore, the production of data

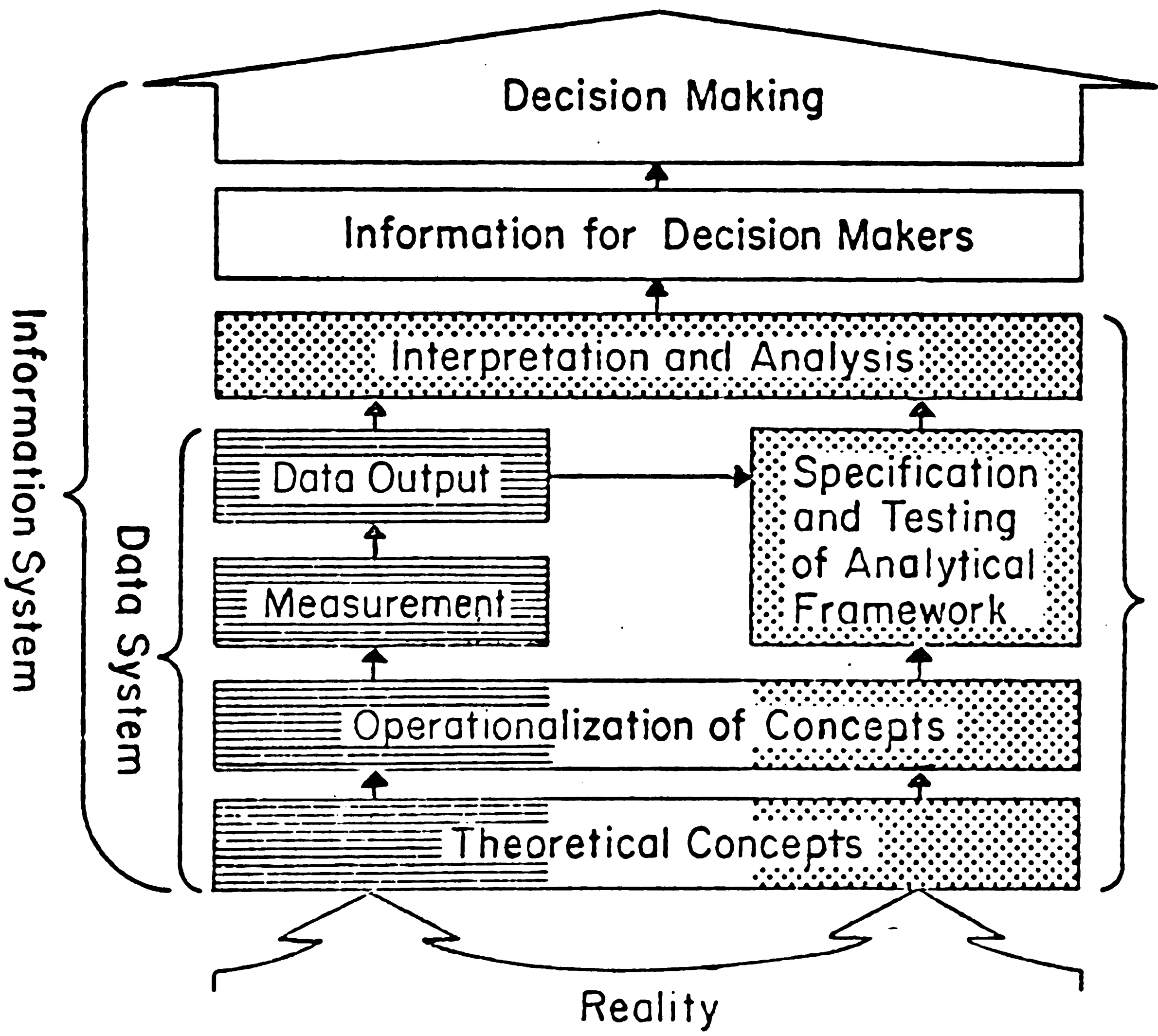

Figure 3.1 The elements of an information system

Source: Bonnen 1977

requires a conceptualization of the world that simplifies and categorizes reality in such a way as to allow quantification.

The concepts are operationalized by selecting and defining variables from the real world that are highly correlated with the categories of empirical phenomena established in the conceptual statement of a problem. Once the variables are defined, a technique for measurement must be developed and carried out. Thus, the production of data involves three steps: 1) conceptualizaton; 2) operationalization of the concepts; and 3) measurement. In the language of the systems scientist, the production of data can be viewed as a data system. The three phases then become; 1) problem definition; 2) selecting and defining variables; and 3) observation.

In this context the reliability of data has several different meanings, all of which are important. First, the reliability of the conceptual framework raises the question of whether or not the abstract concepts selected provide an adequate and pertinent representation of reality in the context of the decision being made. The accuracy of the measurement technique has nothing to do with whether or not you are measuring the right thing. Second, the reliabiity of the operationalization of a concept refers to the ability of the selected variables to reflect variation in the phenomena they were designed to measure. Finally, reliabiity of measurement technique is what is usually meant by statistical reliability. It is independent of conceptual or operational reliability.

Clearly, no amount of statistical sophistication can compensate for errors in the first two stages of data production. The example used by Bonnen is the concept of 'parity price.' He states that parity price "no matter how well measured, is a poor representation today of farmer welfare."

The demand for data is generated by the need to make decisions. Thus the conceptual framework must be based upon the objective of the inquiry. Otherwise, the resulting set of data may not be adequate or appropriate for the decision being made. Data that are relevant in one decision making context may be superfluous in another, depending upon the question to be answered and the beliefs of the decision maker.

Recognition of a decision making problem uncovers the need for data. The corresponding conceptual framework establishes what needs to be measured. But decision makers rarely use the raw product of data collection. Some level of analysis or interpretation is necessary to give the data meaning in a decision making context. The act of interpreting data transforms data into information. An information system, then, contains a data system as a subcomponent. The analysis and interpretation of the data produces information relevant to the decision making problem. In Bonnen's formulation the decision maker is endogenous to the information system and performs the function of a user as well as implicit designer of the system (Bonnen 1977).

The distinction between data and information is recognized by several authors (Eisgruber, 1967; Dunn, 1974; Davis, 1963). Davis points out that despite an abundance of data, in many cases the available data is insufficient for decision making. He defines data as groups of nonrandom symbols that represent quantities, actions, things, goals, etc. Data is only useful for decision purposes when processed and transformed into information.

Although it is clear that decision makers rarely use raw data, it is also clear that analysts rarely use raw data in the production of information (Rossmiller et al., 1977). The formatting of data is the most rudimentary form of interpretation. Nonetheless, it provides an important function in giving meaning to data. It facilitates communication among the producers of data, analysts and decision makers.

Most data is highly processed before an analyst or decision maker sees it. Data can be reformatted, combined with other data, aggregated, or described in word form. Clearly, a sharp distinction between data and information does not exist. A more accurate description is a continuous processing of data to get narrower and more decision specific information. While at an applied information system level the distinction between data and information is important, it is also crucial to note that at an epistemological level there is no difference. This follows from the fact that all inductive products have deductive priors, and vice versa (Chalmers, 1976).

In practice, data and analysis reduce uncertainty but never eliminate it. Thus, in reality there is no such thing as perfect information. Data and analysis, when utilized becomes information and gains value. The value of information depends upon the value of the decision in which it is used and the extent to which it effectively reduces uncertainty and the related decision error.

Perhaps a working definition of information is data that has been converted into a form useful to the decision maker. The 'conversion' may be a simple tabulation or a sophisticated statistical analysis. In any case, information identifies relationships among datum related to a problem.

One other point which will be referred to as the data overload problem deserves mention (Shaffer, 1978). It is possible to render information useless to the decision maker simply by providing too much. There is a point after which the decision maker is unable to incorporate more information into the decision making process or integrate the information available. An information system must function not only to process data into information but also to select information and synthesize it into a form compatible with the decision maker's needs.

ROLE OF DECISION MAKER IN AN INFORMATION SYSTEM

Ultimately, the purpose of the information system is to provide information for problem solving. The decision maker has the clearest insight into the definition of the problem.

The decision maker is part of the information system because the goals of the decision maker are essential to the design of the information system. However, the decision maker is rarely the designer of the information system. Also, there may not be a direct loop from the decision maker back to data collection.

It is tempting to look at the information system as producing a supply of information and the decision maker as generating the demand for information. But the demand generated by the decision maker is often reflected to the supplier through the analyst depending upon the specific organization of the system.

It is important to recognize that the information system paradigm and supply and demand analyses are designed to answer completely different questions. The information system paradigm does not outline production stages. Rather it is an epistomological statement attempting to map the logic of how you know what you can say you know. The paradigm identifies the dimensions of an information system and can act as a set of guidelines for analyzing and improving a system.

This is not to say that information cannot be correctly interpreted as a commodity. The important point is that "information only becomes an economically valuable commodity in the context of decision making" (Riemenschneider and Bonnen, 1979).

Like any valuable commodity, the characteristics of information influence its production and use within the economy. The factors that affect the supply and demand for information will be addressed in section 3.3.

UNDERLYING CONCEPTUAL FRAMEWORK

One of the key aspects of the paradigm is the recognition of a conceptual framework underlying all data production. Observations are not independent of theory. This point is emphasized by A.F. Chalmers in his treatise What Is This Thing Called Science? (1976). He states: "Theory of some kind must preceed all observation statements and observation statements are as fallible as the theories they presuppose. Observation statements must be made in the language of some theory, however vague." Chalmers emphasizes the need to develop an appropriate conceptual framework to produce reliable data. He later states,

> Observation statements...are always made in the language of some theory and will be as precise as the theoretical or conceptual framework as they utilize is precise... Precise, clearly formulated theories are a prerequisite for precise observation statements. In this sense theories preceed observation.

The discussion to this point has focused on the production of information for decision making from the analysis of data. It is also possible to derive information directly from laws and theories. This kind of reasoning is called deductive reasoning and does not involve measurement or observation.

Deductive reasoning constitutes the discipline of logic. Logic and deduction cannot establish the truth of predictions or explanations of physical phenomena. Deduction does establish the logical validity of an argument. That is, for a valid argument, if the premise is true, then the conclusion must be true. Whether or not the premises are true cannot be proved by an appeal to logic.

Bonnen, adopting Churchman's terminology, refers to the deductive process as an inquiry system. Ideally, in an information system, the data system and the inquiry system utilized in a specific decision making process will be based upon the same set of theoretical concepts. Further, the definitions of variables that operationalize those concepts should also be identical. Unless there is a common conceptual ground and definition of variables, data cannot be used to validate theory. Empirical testing of hypotheses necessitates data which are designed around the same conceptual grounds as the hypotheses themselves. Some examples related to pest management follow to illustrate the ideas presented.

3.2.3. Application of the Information System Paradigm

MEASUREMENT OF BIOLOGICAL TIME

One of the most critical factors affecting biological processes is ambient temperature. Maximum and minimum daily temperatures are collected in numerous weather stations in every state and published monthly by the National Oceanic and Atmospheric Administration in a volume entitled Climotological Data.

In a very short period of time the daily maximum and minimum temperatures become too much data to easily interpret. Further, temperature data in and of itself says nothing about pest emergence or population growth. Some understanding of the relationship between temperature and population dynamics is necessary. Two concepts, temperature threshold and heat accumulation, are often introduced to solve these problems.

For a given biological process there exists a temperature threshold below which no activity occurs. Heat accumulation above the appropriate threshold aggregates daily temperature data into a single measure. The effect of temperature on the process can be described or predicted using the measure of heat accumulation over the threshold.

The measure most commonly employed is degree days. However, there are several methods available for calculating degree days. All methods begin calculation of heat accumulation on a specified day, usually January 1. Degree days above the specified threshold are calculated daily and added to the previous days' total to provide a measure of accumulated degree days for the year.

The simplest method of calculating degree days for any one day uses maximum and minimum daily temperatures. Daily degree days are calculated as the difference between the simple average of the day's high and low temperatures and the threshold as follows:

$$DD(t) = [(TH(t) + TL(t))/2]-B \qquad \text{for } (TH(t) + TL(t))/2>B$$

$$DD(t) = 0 \qquad \text{otherwise}$$

Where:

DD(t) = Daily degree days for day t;

TH(t) = Daily high temperature;

TL(t) = Daily low temperature; and

B = Lower threshold.

While this method is straightforward and easy to calculate, it may not be sufficiently precise. Take, for example, the case where the threshold is 50°F, the high temperature for the day is 54°F and the low temperature is 44°F. The average is then 49°F and no degree days are accumulated for that day. But the temperature was above 50°F for at least some period of time. Therefore, some activity took place but is not reflected in the degree day measure.

A second method for calculating degree days estimates heat accumulation as the area under a diurnal temperature curve was developed by Arnold (1960) and refined by Baskerville and Emin (1969) to include both an upper and lower threshold. The principal assumption of the method is that when temperature is plotted over the period of one day the area under the resulting curve is similar to the trigonometric sine curve constructed with the amplitude equal to the difference between the maximum and minimum temperature and is a good estimate of daily degree days (Figure 3.2).

Two interpretations of an upper threshold are possible. If the process is arrested by temperatures above the upper threshold (K2) then no heat units accumulate during the period in which K2 is exceeded. The resulting degree day calculation is the sum of areas A and C. If, on the other hand, temperatures above K2 retard but do not arrest the process then it is assumed that heat is accumulated at a constant rate

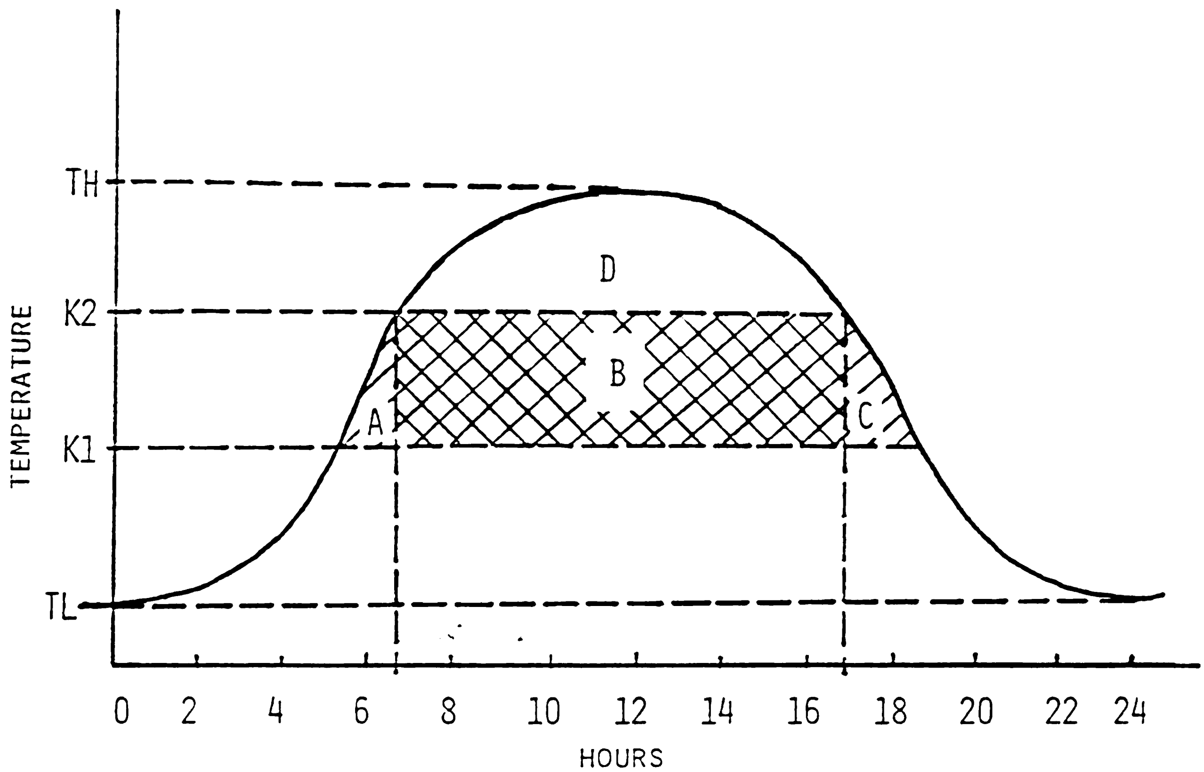

Figure 3.2 B-E method for calculating daily degree days by means of a sine curve. K1 is the lower threshold, K2 is the upper threshold, TH is the high temperature for the day, and TL is the daily low temperature.

for that period. In this case the degree day measure is the sum of areas A, B and C. Of course, if no upper threshold is imposed, the degree day measure is areas A, B, C and D.

The calculation of degree days is a good example of interpreting raw data to produce information. Using the same conceptual framework two methods of analysis were presented. The method used reflects, in part, needs of the decision maker.

Quite often degree day measures are used to predict the emergence of a population and stages of development. Unfortunately, the method used to calculate degree days is usually not made explicit in the literature. If an upper threshold is reported, the interpretation is usually excluded. When the underlying methodology is unclear the usefulness of the information is diminished.

MEASUREMENT OF PEST POPULATION

A second basic measurement in pest management is pest population. Obviously it is not plausible to count the total number of pests in a field. Some subsample must be used as a proxy. Several alternatives are used in practice. Using alfalfa weevil larvae as an example, common measures include the number of larvae per thirty stem sample, the number of larvae per twenty sweep sample and the number of larvae per square meter. Desirable characteristics of any sampling technique include the ability to repeat similar samples from the same sampling universe and ease in use.

A thirty stem sample requires selecting thirty stems of alfalfa at random, shaking the larvae from the alfalfa and counting the number of larvae. The larvae may or may not be sorted into instars[4] depending upon the data needs of the decision maker. It is difficult for a scout to select a truly random sample. There also may be great variability within a field. It is difficult for two individuals to get similar counts within the same field. A thirty stem sample has the advantage of recovering each age class of larvae with equal probability. That is, it is not more likely to detect one instar than another.

The use of the sweep net as a sampling tool allows a scout to cover a large area relatively quickly. Several problems arise with the use of sweep nets, however. A study by Cothran and Summers (1972) described differences in the ability to collect larvae of different age classes with a sweep net. In a later study, Cothran, Summers and Franti (1974) made a comparison of two standard sweep net techniques, the 180° sweep and the pendulum (P) sweep. They determined the average ratio of the mean of the 180° to that of the P sweep was about 1.76:1 when counts were low and about 1.8:1 otherwise. They found the two methods to be equally reliable but recommend the 180° sweep for low populations because it is more likely to recover larvae.

The study also looked at variation in counts among individuals using each tool. Significant differences in counts resulted among some of the individuals. The authors conclude that the results of sweep net sampling are not precise enough to use as the only basis for insecticide recommendations.

The number of larvae per square meter is a concept used only in mathematical models. It is not feasible for field work simply because

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[4]Instars are the stages of an insect between successive molts. A molt in insects and other anthropods is the shedding of the exoskeleton.

it is unthinkably labor intensive. If an average number of stems per square meter is estimated and an average number of larvae per thirty stem sample is known, it is a simple matter to estimate the average number of larvae per square meter. It should be emphasized that alfalfa stands are uneven within a field and the number of stems per M^2 varies with variety and age of the stand. Nonetheless, the results of field trials using a thirty stem sample are comparable to the results of simulation models based on an M^2 measure, if an assumption is made about the number of stems per M^2. No such conversion is possible between sweep net samples and larvae per thirty stem sample without research (similar to the Cothran study) devised specifically to compare the two techniques.

The use of different sampling techniques and units of measure makes synthesis of data in the literature difficult, if not impossible. In particular, the effect of larval population on alfalfa yield estimated in various studies cannot be compared when population is estimated using different methods. Sweep net data are usually presented without mention of sampling method again leaving comparison of results potentially inaccurate. This is a perfect example of a situation where the underlying concepts are consistent across research but the definitions of variables are not. Variables are often defined for compatibility with measurement techniques available.

The economic threshold is a fundamental concept in pest management (see 2.3). It is the population level beyond which the value of pest damage will exceed the cost of control. The economic threshold provides growers with information about expected loss to aid in pest control decision making.

In its simplest form, the economic threshold is a population level. Therefore, it can be presented in at least all of the ways described above for presenting pest populations. A single population level says nothing about dynamics throughout the system. A specified population level at the beginning of the season is not differentiated from the same population level at the middle or end of the season. Based on that single piece of information it is impossible to know whether pest populations are expected to increase or decrease in the immediate future.

To circumvent this problem the economic threshold is often described in terms of peak population density. Of course, in practice, it is impossible to identify the occurence of the peak population level until after it has passed. This information, while useful to researchers for discovering the relationship between pest population and crop loss, cannot be used for pest control decisions unless peak population can be predicted with some level of accuracy.

The expected time of the population peak can be estimated from past experience and is typically expressed in terms of degree days (e.g. peak population always occurs before 950 degree days base 48°F). It can also be predicted using mathematical models.

The economic threshold need not be a single measure at a single point in time. The term 'dynamic threshold' refers to a threshold that changes over time. For example, a dynamic threshold may be expressed as a series of pest populations coupled with degree day measures. Alternatively, it may be expressed as a series of pest populations coupled with some measure of plant development (e.g. plant height or plant stage).

In order to test any hypothesis about the effect of alfalfa weevil feeding on quality and yield, some unit of measure of pest population over time has to be selected. Several alternatives exist for measuring pest population. Quite often population at peak infestation is used as a gauge to compare infestations in different years. However, this measure does not capture the distribution of the population throughout the season. Further, peak population cannot be used for control recommendations unless it can be accurately predicted from prior observations of population level. Procedures are not presently available to satisfactorily predict the date and magnitude of the larvae peak.

One method used to circumvent these problems is to construct a variable to measure pest populations over time. For each sample date the number of larvae is plotted against the degree days accumulated from January 1 above the base temperature of 48°F (8.9°C) (Litsinger and Apple, 1973), the threshold for larvae development. The area under the curve obtained by connecting the data points corresponds to the measure of larvae degree days accumulated during the season (Figure 3.3). An estimate of the larval peak is not needed to calculate larvae degree days. Further, using growing degree days allows for comparison of data from different seasons and locations. The measure is also appropriate for a variety of sampling regimes. It requires only that samples be taken using a uniform population measure (e.g., number of larvae per 20 sweeps, number of larvae per stem).

The most commonly encountered means of presenting an economic threshold have been outlined above. The list of alternative specifications is endless. The point is, that starting with the

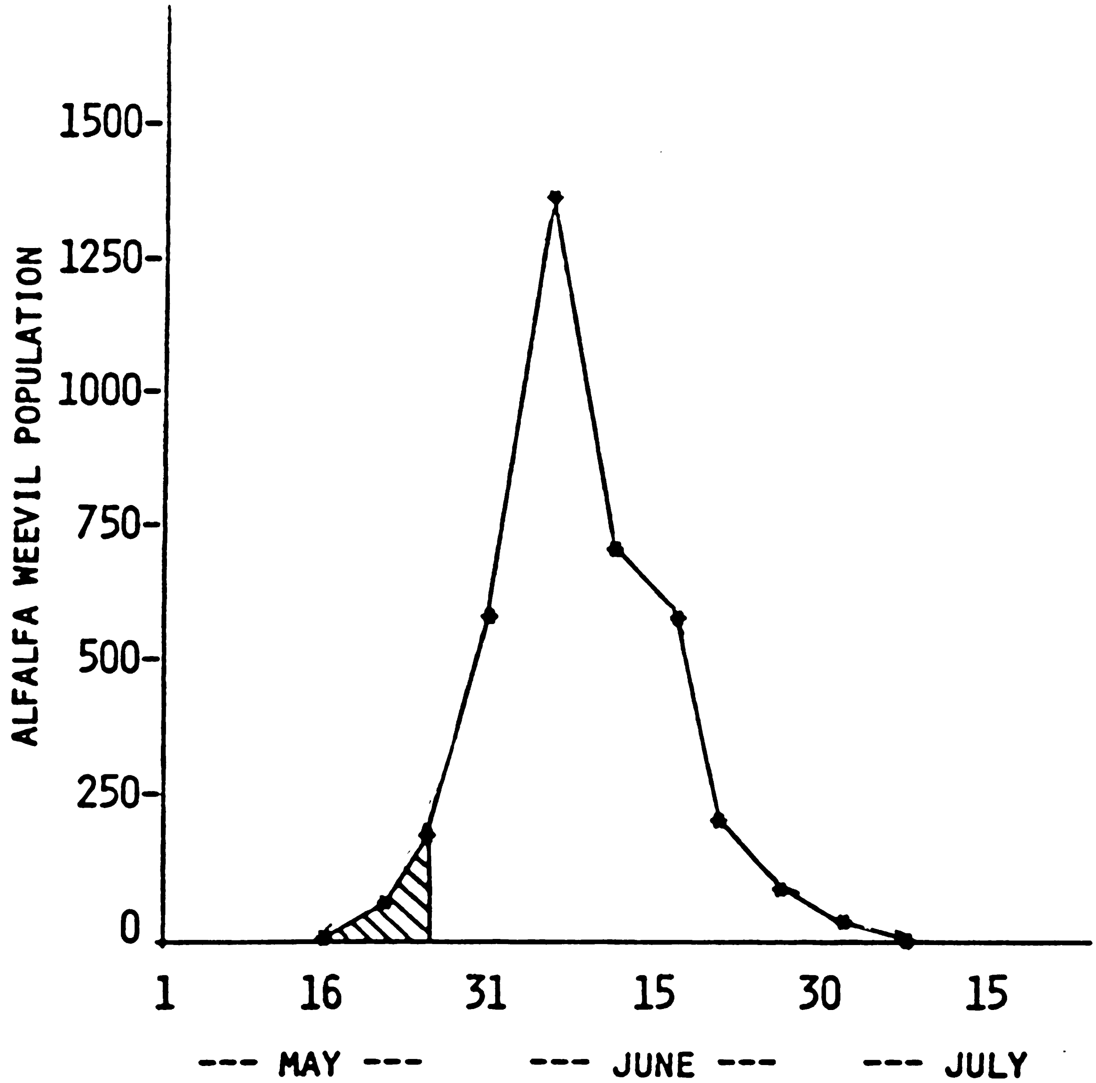

Figure 3.3 Calculation of larvae degree days

theoretical concept of an economic threshold, information provided to growers will vary depending upon the definiton of variables, measurement techniques, and format used for presentation.

3.2.4 Decision Making Under Risk and Uncertainty

An individual makes decisions in an evironment characterized by uncertainty whenever there is imperfect information regarding the problem to be solved. In this subsection the decision making process under conditions of imperfect knowledge will be given some rigor. The discussion can be interpreted as an elaboration of the final element of Bonnen's information system - "Decision Making" (Figure 3.1).

Risk and uncertainty affect production and consumption decisions when the outcome of an action is not known with certainty at the time the action is chosen. Frank Knight (1921) made the classic distinction between risk and uncertainty. He defined risk as a condition in which the possible outcomes of an action choice can be assigned a probability and uncertainty as a condition in which information about the relative chances of the different outcomes is not available.

While certain aspects of a decision reoccur over time for many decisions, repeated trials are not possible to discover the frequency with which outcomes occur. This does not mean that decisions are made ad hoc. Rather, people make decisions based upon their own ideas of probability (Ramsey, 1931; Savage, 1964; and Raiffa, 1968). These subjective probabilities are derived from objective evidence, personal experience and other sources. By assuming that for each decision there is a known set of possible outcomes with an associated subjective probability distribution the distinction between risk and uncertainty collapses and the terms can be used interchangeably for all intents and purposes.

The choice of a production strategy can be represented in a decision theory framework using a decision matrix (Table 3.1). There are n action choices (A_j, j = 1, 2, ...n) and m possible states of nature (N_i, i = 1, 2, ...m) with a probability (P_i) assigned to each state of nature. For each combination of action choice and state of nature there is an associated outcome (O_{ij}).

The simplest way to select among the action choices is to express each outcome in terms of a monetary value and maximize expected returns.[5] The maximizing principle can be expressed mathematically as:

$$\underset{j}{\text{Max}}:E(O_j) = \sum_{i=1}^{m} P_i \, O_{ij} \qquad (3\text{-}1)$$

and

$$\sum_{i=1}^{m} P_i = 1 \qquad (3\text{-}2)$$

Behavior under uncertainty is often explored using game theory. Games that cost their expected value to play are called fair games. In the eighteenth century the mathematician Daniel Bernoulli rigorously investigated the observation that in many situations people will refuse to play fair games. He illustrated this point with the famous "St. Petersburg Paradox".

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[5]For example, the outcome of an agricultural production decision (action choice) can be expressed as 3 tons per acre or $300 dollars per acre (assuming each ton of production is valued at $100).

Table 3.1

Decision Matrix for Decision Making Under Uncertainty

States of Nature	Probabilities of States	Action Choices				
		A_1	A_2	A_3	.....	A_n
N_1	P_1	0_{11}	0_{12}	0_{13}	.....	0_{1n}
N_2	P_2	0_{21}	0_{22}	0_{23}	.....	0_{2n}
N_3	P_3	0_{31}	0_{32}	0_{33}	.....	0_{3n}
.	.	.	.	.	.....	.
.	.	.	.	.	.....	.
.	.	.	.	.	.....	.
N_m	P_m	0_{m1}	0_{m2}	0_{m3}	.....	0_{mn}

Bernouillian decision theory offers an alternative to the maximize expected returns rule. The underlying hypothesis is that the relationship between income and utility is not necessarily linear. If the preferences of an individual are consistent with certain behavioral axioms and if an individual's utility function is known, it can be used to predict his choice among risky action choices (for which the probabilities of possible outcomes are known). Bernoulli developed an approach known as the expected utility hypothesis. The steps involved are the following:

1. Identify the possible action choices.
2. Identify the possible outcomes for each of the action choices.
3. Identify a probability density function for the outcomes.
4. Derive utility measures for the outcomes.
5. Determine the expected utility for each action choice by summing the utility measures for the outcomes which are weighted by the associated probability that each outcome will occur.
6. Select the action choice which produces the highest expected utility.

This procedure for implementing the Expected Utility Hypothesis can be expressed mathematically as:

$$\max_{j}: E[U(O_j)] = U[E(O_j)] = U[\sum_{i=1}^{n} P_i(O_{ij})] = \sum_{i=1}^{n} P_i U(O_{ij}) \qquad (3\text{-}3)$$

$$\text{and} \quad \sum_{i=1}^{n} P_i = 1 \qquad (3\text{-}4)$$

where:

$U(O_{ij})$ is the utility function for the decision maker and

$\sum_{i=1}^{m} P_i U(O_{ij})$ is the expected utility of action choice j.

In 1944 the expected utility hypothesis (EUH) was derived by von Newmann and Morgenstern from a set of axioms for "rational" behavior. Alternative sets of axioms can be used to deduce the EUH. Important questions have been raised about the axioms and no universally agreed upon set has been developed. Most proofs of the EUH require at least the following properties:

1. Orderability - An individual's preferences are transitive. For any three probability distributions, h_1, h_2, and h_3, if a person prefers h_1 to h_2 and h_2 to h_3 then he necessarily prefers h_1 to h_3.

2. Continuity - There is a continuous complete ordering of preferences.

3. Independence - If h_1 is preferred to h_2 and h_3 is some other probability distribution, then a lottery with h_1 and h_3 as prizes will be preferred to a lottery with h_2 and h_3 as prizes.

If decision makers have preferences consistent with the above axioms then an ordinal utility function can be drived which reveals his preference ranking of possible outcomes. The utility function is unique up to a linear transformation. If in addition, the decision maker has a subjective probability distribution associated with the set of outcomes for any action choice, then the expected utility of each action can be calculated. Further, the expected utilities can be used to rank or order the action choices according to the decision makers' preferences.

Bernoullian decision theory separates decision making under uncertainty into two components, utility and probability. Following this approach, prescriptions can be made for a decision maker as to which action choice should be selected based on an individual's subjective probability function and utility function.

In practice, it is difficult to ascertain both an individual's utility function and a probability distribution of the outcomes. Further, while the expected utility hypothesis is appealing because it allows for a complete ordering of stochastic events, it lacks generality. A utility function unique to an individual cannot be used to predict someone else's behavior. Utility functions must be defined for each individual in order to apply the EUH.

It can further be argued that utility functions must be defined for each individual and each problem to be solved. That is, an individual may derive more utility from $100 gained from choosing a better seed variety then $100 gained in a wager (even after the costs of making the decision or placing the wager are considered). It follows that a single utility function cannot be derived for an individual to predict behavior in a variety of uncertain situations. In order to apply the EUH it may be necessary to derive a utility function for each individual and each decision situation.

Various attempts have been made to establish general properties of utility functions and to construct decision rules based on these properties. The fundamental approach has been to categorize utility functions by the shape of the function without specifying the function precisely. Each category corresponds to an attitude toward uncertainty.

Decision rules are then developed for each attitude which can be used to predict behavior.[6]

The question remains as to whether or not it is meaningful to categorize an individual as having a particular attitude toward risk regardless of the problem to be solved. This does not make it impossible to make statements about behavior without specifying the utility function. It does mean that an individual may not follow the same decision rule in every situation.

In the following discussion decision makers are described as risk-averse, risk-neutral or showing risk preference, depending on the shape of their utility functions. Precise meaning is given to these terms.

It is possible that an individual will be risk-averse in one situation and risk seeking in another. The theory presented below was developed under the simplifying assumption that an individual's utility function does not vary from one situation to another.

However, the theory developed is appropriate to the more general case if the reader keeps in mind that one individual can display different behavior at different times, i.e. have more than one utility function. While the theory is intended to categorize groups of individuals according to their attitude toward risk, it may only be appropriate for categorizing utility functions.

All decision makers are expected to have positive marginal utility for additional wealth. That is, an increase in wealth is always assumed

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[6] Any decision rule is also a means of predicting behavior when a decision maker is rational. For example, the EUH can be interpreted as a decision rule for selecting among action choices or as a way of predicting an individual's action.

to be desirable. If it is also assumed that the utility function is differentiable, then:

$$U'(X) > 0 \tag{3-5}$$

If the second derivative, U" (X) exists, then it is the rate of change of marginal utility with respect to wealth. If U" (X) > 0, the marginal utility of wealth, U'(X), is strictly decreasing as wealth, X, increases and the decision maker is characterized as a risk averter. If U"(X) = 0, then U'(X) is constant as X changes and risk neutrality is demonstrated. If U"(X) > 0 then U'(X) increases as X increases and the decision maker shows a preference for risk.

It appears that the marginal utility (U'(X)) and the rate of change of marginal utility (U"(X)) are meaningful measures for comparison of the risk preferences of individuals. But a utility fuction is unique only up to linear transformation. This means that for a utility function U(X), adding a constant to U(X) or multiplying the function by a positive constant does not change the resulting preference ordering. Adding a constant to U(X) does not change the values of U'(X) or U"(X). However, multiplying U(X) by a positive constant also multiplies U' and U" by the same constant. Therefore, comparing the first or second derivatives of two individual's utility functions is meaningless.

Two measures of attitudes toward risk that are invariant under linear transformation of the utility function have been suggested by Arrow (1965) and Pratt (1964). They are:

1. Coefficient of absolute risk aversion $R_A(X) = - U''(X)/U'(X)$
2. Coefficient of relative risk aversion $R_R(X) = - XU''(X)/U'(X)$

Arrow and Pratt give two different but consistent interpretations of the coefficients. Both assumed that any individual is predominantly risk averse.

Arrow considers a lottery that involves a specified prize, h, with probability p of winning and probability 1-p of losing. The willingness of an individual to play will depend on the value of p and his present wealth, X. Absolute risk aversion measures the individual's insistence for more than fair odds. (A risk averter will refuse to play if $p<1/2$). If the prize is measured in proportion to his present wealth (i.e. $h = nX$) a similar interpretation can be made for relative risk aversion.

Pratt's interpretation is based on the concept of an insurance premium. An individual is offered the choice between a random income with mean, u, and variance, σ^2 and a certain income of X*. The difference between the expected income and the certain income (u-X*) can be interpreted as an insurance premium. In particular, there exists an income level X** such that the individual is indifferent between the certain income and the random income. This quantity is referred to as the certainty equivalent.

The absolute risk aversion and relative risk aversion coefficients measure the absolute and relative size of the corresponding insurance premium, respectively. A more risk-averse person would be willing to pay a higher insurance premium to avoid the risky income.

An interesting variation on this approach is presented by Magnusson (1969). Here the utility function has two arguments, the mean and variance of a random income. The certainty equivalent is then that income X** such that:

$$U = U(u, \sigma^2) = U\ (X^{**}, 0) \qquad (3\text{-}6)$$

Holding utility at a constant level (i.e. dU = 0) and differentiating the utility function:

$$U_1 du + U_2 d\sigma^2 = 0$$

U_1 and U_2 stand for the partial derivatives of the utility function with respect to the first and second arguments, respectively. Then assuming that $U_1 > 0$, the marginal rate of substitution between u and σ^2 can be found from (3-6) as:

$$\frac{du}{d\sigma 2} = - \frac{U_2}{U_1} \quad \frac{du}{d\sigma 2} = - \frac{U_2}{U_1} \qquad (3\text{-}7)$$

The ratio of differentials can be interpreted as the marginal rate of substitution between expected income and the variance of the income. If the variance is interpreted as a measure of risk, then the ratio is the marginal rate of substitution between expected income and risk. Any other measure of risk could be used to obtain the same result. The author goes on to say that if the ratio is positive ($U_2 < 0$) there is a risk-aversion, if it is zero ($U_2 = 0$) risk-neutrality and if it is negative ($U_2 > 0$) risk-preference.

The classification of a decision maker as risk-averse, risk-neutral or a risk-taker can be used to predict his preferences among action choices without deriving his utility function. Ideally, the action choice that would maximize expected utility for all decision makers regardless of their risk preferences could be identified simply from the distribution of the outcomes. Although it is possible to construct a set of action choices and related outcomes such that one action choice would be preferred by all decision makers, for an arbitrary opportunity set, such a universal utility maximizing action choice does not necessarily exist. A less ambitious but more fruitful venture is to identify a subset of the action choices in such a way that the utility maximizing action choice is necessarily contained in that subset for a large number of decision makers.

Valuation procedures that make use of a classification of utility functions and the distribution functions of outcomes to reduce the number of desirable action choices are referred to as efficiency criterion. Efficiency criteria have a tendency toward Type II error (Robison 1977). That is, the null hypothesis that a decision maker will be indifferent between two action choices may be accepted when it is false.

EFFICIENCY CRITERIA IN DECISION MAKING

Several efficiency criteria have been devised which make specific assumptions about attitudes toward risk but do not require specification of a single value utility function. Some examples follow.

The first, which has been described above, is to choose the action alternative with the largest expected value.

$$\text{Max:}E(0_{ij}) = \sum_{i=1}^{n} P_i(0_{ij}) \tag{3-8}$$

This criterion is identical to utility maximization of $U(0_{ij}) = 0_{ij}$, that is, the decision maker is indifferent towards risk. In this case, the marginal utility of wealth is neither increasing or decreasing.

A safety first criterion is another possibility for explaining the behavior of decision makers. This formulation of the decision function assumes that the grower maximizes expected value discounted by some measure of risk.

$$\underset{j}{\text{Max}}:[E(0_j) - a^{1/2}\, S_j) \tag{3-9}$$

The standard deviation of the value of outcomes for action choice O_j is denoted by S_j and a is the critical probability level. By setting a=0 we get the trivial case of risk neutrality. As the absolute value of a increases, the decision maker attributes a higher cost to variability of income and demonstrates increasing risk aversion. The criteria does not allow for a preference for risk.

Safety first is consistent with the expectation-variance criteria (E-V criteria). Using the E-V criteria, decision makers faced with two sets of outcomes with the same expected values and different variances will prefer the set with the smaller variance.

The maximim criteria represents extreme risk aversion. The decision maker assumes the worst will happen and compares the worst possible outcomes for each action choice. He then selects the action for which the worst possible outcome has the greatest value regardless of probability. The decision function is:

$$\underset{j}{\text{Max}}:(\underset{i}{\text{min}}:\ O_{ij}) \qquad (3\text{-}10)$$

Other examples are first degree stochastic dominance, second degree stochastic dominance and Meyer's stochastic dominance with respect to a function. These criteria are rigorous procedures utilizing the cumulative probability functions of outcomes related to action choices. The criteria differ in the underlying assumptions about the risk preferences of decision makers. Less restrictive assumptions allow the results to be more general but at the same time make it more difficult to reduce the number of action choices in the opportunity set. The probability of Type II error is increased.

FIRST DEGREE STOCHASTIC DOMINANCE

First degree stochastic dominance assumes only that the marginal utility for wealth is positive over the relevant income range (i.e. $U'(X) > 0$). Then $-\infty \leq R_A = -\frac{U''}{U'} \leq \infty$. The procedure for comparison of action choices is as follows. Suppose X and Y are stochastic income variables associated with action choices A_1 and A_2 with cumulative distribtution functions F and G, respectively. F and G may be either continuous or discrete functions. Let r be any income level. Then let:

$$F(r) \geq G(r) \text{ for all } r \tag{3-11}$$

and

$$F(r) > G(r) \text{ for some } r \tag{3-12}$$

It follows that $U(Y) > U(X)$ for all U such that $U' > 0$ and A_1 is preferred to A_2. F is said to be the dominant distribution. If $G(r) \geq F(r)$ for all r and $G(r) > F(r)$ for some r then $U(Y) > U(X)$. In this case G is dominant and A_2 is preferred to A_1 for all positive utility functions. If neither distribution is dominant, the action choices cannot be ordered by this criteria. Figure 3.4a and 3.4b illustrate first degree stochastic dominance for continuous and discrete distribution functions.

For two discrete income distributions with the same numbers of observations, an equivalent specification of FSD exists. Let X_i and Y_i be ordered sets of n income observations (i.e., $Y_i \leq Y_{i+1}$, $X_i \leq X_{i+1}$; $1 \leq i \leq n-1$) for action choices A_1 and A_2 respectively. Let X_0 and Y_0 equal 0 and X_{n+1} and Y_{n+1} equal infinity. Then cumulative probability functions can be constructed for the income observations as follows:

$$F(X) = \frac{i}{n} \text{ for } X_i \leq X < X_{i+1} \quad i = 0,1,2,\ldots n \tag{3-13}$$

$$G(Y) = \frac{i}{n} \text{ for } Y_i \leq Y < Y_{i+1} \quad i = 0,1,2,\ldots n \tag{3-14}$$

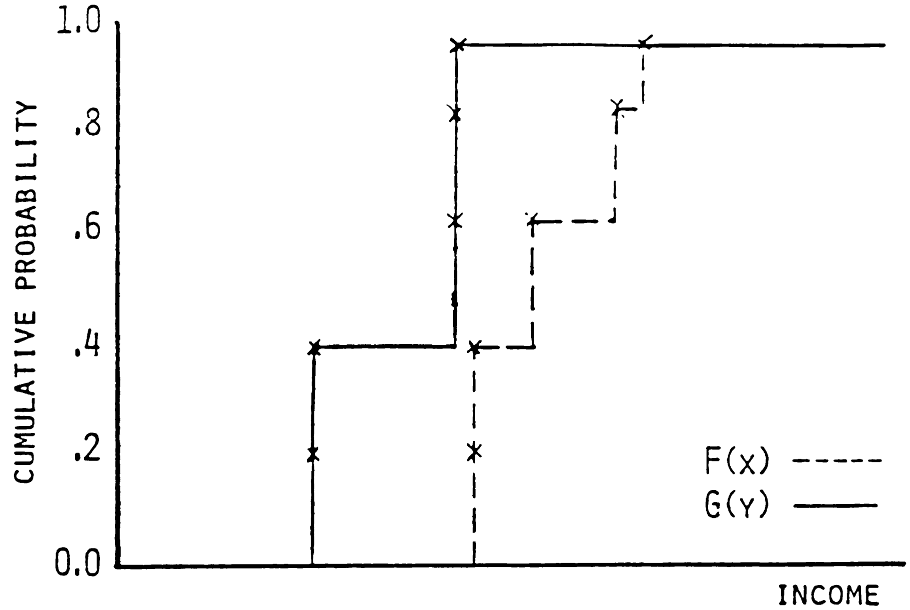

Figure 3.4A. First degree stochastic dominance (FSD)--F(X) and G(Y) are discrete probability distributions.

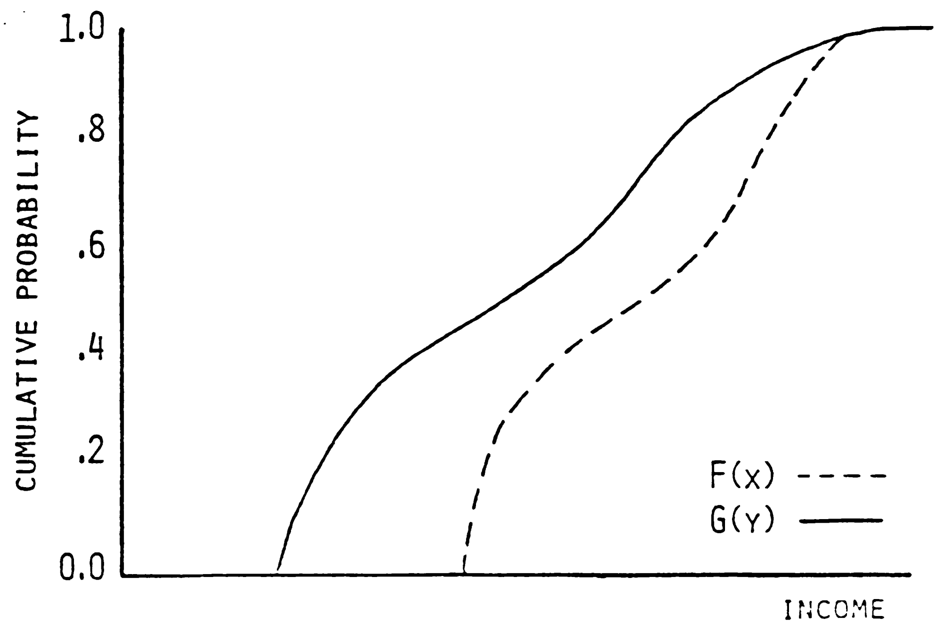

Figure 3.4B. First degree stochastic dominance (FSD)--F(X) and G(Y) are continuous probability distributions.

The distributions constructed in this way assure that each observation is equally likely. If we let r represent income level then distribution F dominates G and action choice A_1 is preferred to action choice A_2 if and only if:

$G(r) - F(r) \geq 0$ for all $r \geq 0$ (3-15)

and $G(r) - F(r) > 0$ for some $r \geq 0$ (3-16)

This procedure is illustrated in Table 3.2b. The values of $F(X_i)$ and $G(Y_i)$ are constructed following (3-13) and (3-14). In this example condition (3-15) is satisfied but (3-16) is not. F and G cannot be ordered and the decision maker is indifferent between A_1 and A_2.

An alternative and consistent test for first degree stochastic dominance can be performed by comparing the values of X_i and Y_i for each i. The distribution of X dominates the distribution of Y if and only if X_i is greater than or equal to Y_i for all i and a strict inequality holds for some i. F dominates G and action choice A_1 is preferred to action choice A_2.

Mathematically: $X_i - Y_i \geq 0$ for all i (3-15)*

$X_i - Y_i > 0$ for some i (3-16)*

where: $F(X_i) = G(Y_i)$ for all i and (3-17)

$U'(r) >$ (3-18)

An example is given in Table 3.2a. Notice that both procedures failed to order the action choices by FSD. The difference between the conditions in (3-15) and (3-16) and those in (3-15)* and (3-16)* is simply that in the former case the probability levels for each distribution are being compared for given income levels while in the latter case the income levels for given probability levels are being compared. Similarly, if Y_i is greater than or equal to X_i for all i and

Table 3.2a Hypothetical income data for 2 action choices, corresponding cummulative distribution functions, and tests for FSD and SSD.

i	X_i	$F(X_i)$	Y_i	$G(Y_i)$	$X_i - Y_i$	$\Sigma X_i - Y_i$
1	200	.2	100	.2	100	100
2	400	.4	100	.4	300	400
3	400	.6	500	.6	-100	300
4	550	.8	550	.8	0	300
5	600	1.0	550	1.0	50	350

Table 3.2b Alternative tests for first and second degree stochastic dominance using data from Table 3.2a.

Income (r)	F(r)	G(r)	G(r)-F(r)	ΣG(r)-F(r)
100	0.0	.4	.4	.4
200	.2	.4	.2	.6
300	.2	.4	.2	.8
400	.6	.4	-.2	.6
500	.6	.6	.0	.6
550	.8	1.0	.2	.8
600	1.0	1.0	.0	.8

strictly greater for at least one i then G is preferred to F. If neither set of conditions holds then first degree stochastic dominance fails to produce an ordering.

SECOND DEGREE STOCHASTIC DOMINANCE

Second degree stochastic dominance (SSD) makes an additional assumption about the character of the utility function. The marginal utility of wealth is assumed to be increasing (as with FSD) but at a decreasing rate. This implies that $U''(X) < 0$ and $R_A(X)$ ranges from 0 to positive infinity. The further restriction of the utility function means that SSD results are applicable to a smaller group of decision makers than are FSD results. SSD has the advantage that it can order action choices that are determined to have identical utility under FSD.

The second degree stochastic dominance criteria works as follows: Let F(X) and F(Y) be continuous cumulative distribtuion functions for the outcomes of actions A_1 and A_2, respectively. Then F(X) dominates G(X) if and only if:

$$\int_0^R [G(r) - F(r)]\, dr \geq 0 \text{ for all } R \tag{3-19}$$

and

$$\int_0^R [G(r) - F(r)]\, dr > 0 \text{ for some } R \tag{3-20}$$

$U(Y) < U(X)$ for all U such that $0 \leq R_A(r) \leq \infty$. In this case F is preferred to G (Figure 3.5a). Intuitively, A_1 reduces the probability of a low income in comparison to A_2. On the other hand A_2 has a higher probability of a very high income. However, if the decision maker is risk-averse, that is, his marginal utility for wealth is decreasing,

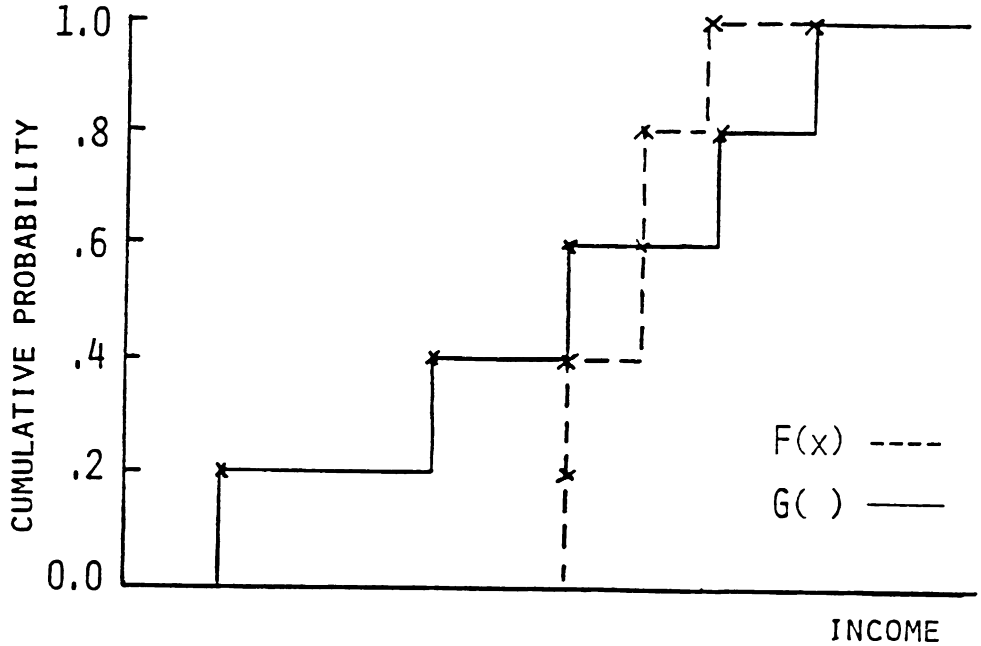

Figure 3.5A. Second degree stochastic dominance (SSD)--F(X) and G(Y) are discrete probability distributions.

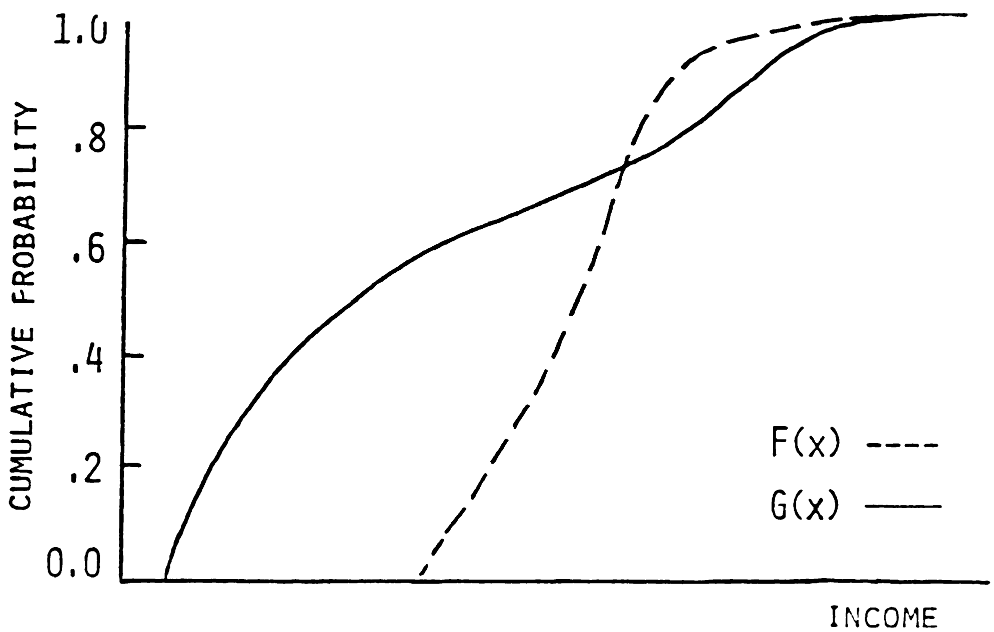

Figure 3.5B. Second degree stochastic dominance (SSD)--F(X) and G(Y) are continuous probability distributions.

then the utility gained by avoiding low incomes will more than offset the utility lost by decreasing the probability of very large incomes.

If F and G are interchanged in (3-19) and (3-20) then G is preferred to F for the appropriate utility functions. If strict equality holds in (3-19) and condition (3-20) is not met, then the action choices cannot be ordered by SSD.

The conditions for discrete cumulative distribution functions are:

$$\sum_{i=1}^{n} [G(r_i) - F(r_i)] > \text{ for all } n \qquad (3\text{-}21)$$

and

$$\sum_{i=1}^{n} [G(r_i) - F(r_i)] > 0 \text{ for some } n \qquad (3\text{-}22)$$

where:

$$0 \leq R_A(r) \leq \infty.$$

Here F is preferred to G (Figure 3.5b). If X_i and Y_i are ordered sets of n observations then F(x) and G(x) can be constructed as in (3-13) and (3-14).

An equivalent set of conditions for SSD is:

$$\sum_{i=0}^{n+1} (X_i - Y_i) \geq 0 \text{ for all } n \qquad (3\text{-}23)$$

and

$$\sum_{i=1}^{n+1} (X_i - Y_i) > 0 \text{ for some } n \qquad (3\text{-}24)$$

where:

$$F(X_i) = G(Y_i) \qquad (3\text{-}25)$$

$$X_0 = Y_0 = 0 \qquad (3\text{-}26)$$

$$0 \leq X_{n+1} = Y_{n+1} \leq \infty \qquad (3\text{-}27)$$

$$0 \leq R_A(r) \leq \infty \qquad (3\text{-}28)$$

Then U(X) is greater than U(Y) and F is preferred to G. Notice that in the examples illustrated in Figures 3.5a and 3.5b the FSD criteria fails to order the action choices while SSD ranks F preferred to G. It must be emphasized that the latter result is only relevant for risk-averse decision makers.

A distribution function may be first degree dominant over some range of income but not dominant over a larger range. In Figure 3.4b F dominates G over the entire income range. In Figure 3.5b F is first degree stochastic dominant over part of the income range but not the entire range. However, F is second degree stochastic dominant over the entire income range.

The second degree stochastic dominance criteria applies to a class of decision makers that includes those who are risk neutral and those who show any degree of risk aversion. The resulting preference ordering is dominated by the values of distributions at very low incomes. A distribution F(X) cannot dominate G(X) unless F(X) > G(X) for the lowest observed value of X. This problem is often referred to as the left-hand tail problem.

A second problem with SSD arises concerning decision makers with Friedman-Savage utility functions. That is, decision makers who are risk-averse over a broad range of incomes but are risk preferers at very high incomes. This form of a utility function was developed to explain participation in lotteries. SSD fails to account for different preferences at different income levels.

STOCHASTIC DOMINANCE WITH RESPECT TO A FUNCTION

Stochastic dominance with respect to a function is a criterion for ordering uncertain choices developed by Meyer (1977) in response to these difficulties. The criterion relaxes the restrictions on the value of the risk-aversion coefficient required by first and second degree stochastic dominance but at the same time does not require the derivation of a single valued utility function.

The criterion requires establishing upper and lower bounds on the risk-aversion coefficients U_r and L_r for all feasible income levels. The bounds are functions of income. Mathematically,

$$U_r = r_1(y)$$
$$L_r = r_2(y)$$

In practice, upper and lower bounds are established for intervals of income levels. The solution procedure developed by Meyer requires identifying a utility function, u(y), which minimizes,

$$\int_0^1 [G(y) - F(y)]\ u'(y)\ dy^7 \qquad (3\text{-}29)$$

subject to the constraint,

$$r_1(y) \leq -u''(y)/u'(y) \leq r_2(y),\ \text{for all } y \qquad (3\text{-}30)$$

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[7]The range of system outputs is normalized so that all values of y fall on the bounded interval [0, 1].

It can be shown that equation (3-29) is equal to the difference between the expected utilities of outcome distributions F(y) and G(y).[8] For decision makers whose utility functions satisfy the above constraint (3-30), if the minimum value of this difference is positive then the expected utility of F(y) is always greater than the expected utility of G(y). Consequently, F(y) is preferred to G(y) for the appropriate class of decision makers.

If the minimum is less than or equal to zero, the decision makers do not unanimously prefer F(y) to G(y). Neither can it be said that G(y) is preferred to F(y). If the minimum is negative, then a second equation

$$\int_0^1 [F(y) - G(y)]\, u'(y)\, dy \qquad (3\text{-}31)$$

must be minimized subject to the constraint (3-30). In this case, if the minimum value is positive than G(y) is preferred to F(y). If the results of minimizing (3-29) and (3-31) are both negative then the criterion fails to order the distributions. Put another way, neither distribution is unanimously preferred by the class of decision makers included.

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[8]This can be demonstrated in the following manner. Let f(y) and g(y) be the probability density functions associated with F(y) and G(y)

$$\int_0^1 f(y)u(y)dy - \int_0^1 g(y)u(y)dy = \int_0^1 [f(y)-g(y)]u(y)dy$$

is the difference between the expected utilities associated with the two distributions. Integrating by parts,

$$\int_0^1 [f(y)-g(y)]u(y)dy = [F(y)-G(y)]u(y)\Big|_0^1 - \int_0^1 [F(y)-G(y)]u'(y)dy = \int_0^1 [G(y)-F(y)]u'(y)dy$$

since [F(0)-G(0)] and [F(1)-G(1)] are both equal to zero.

It should be mentioned that first and second degree stochastic dominance are special cases of stochastic dominance with respect to a function. For FSD, $U_r = \infty$ and $L_r = -\infty$, for all y. For SSD, $U_r = \infty$ and $L_r = 0$, for all y.

3.2.5 Information Learning and Decision Making

From the discussion in 3.2.2, management can be conceived as a process for which information is an input and decisions are an output. In this light information only has value in the context of a decision.

The manager must define the problem, collect information, analyze the information and make a decision. These steps involve identifying 1) the action choices available, 2) information needed to choose among the action choices, 3) a procedure for analyzing the information and 4) a decision rule for selecting the best of the known action choices.

These steps are not necessarily carried out in any order. The gathering of information might reveal additional action choices and reformulation of the problem. The analysis procedure might require gathering additional information, and so forth.

A producer typically requires a broad range of information for making a production decision. The three categories of constraints facing a firm that were discussed in Section 3.2.1 can be interpreted as categories of information. They are: 1) technical, 2) market and 3) government.

A pesticide use decision requires information about the performance of the pesticide in controlling pest populations. The price of the pesticide and the value of the crop loss is also information required for the decision. Regulatory information about each pesticide considered for use is also necessary. This framework was formalized in the Headley model presented in 2.3. The mix of information required to solve the problem is imbedded in the equations of the model.

Each type of information has a temporal dimension. Information about the past and present is used to form expectations about the future. In addition each category of information has both a positive and normative dimension. (Johnson et al., 1961).[9] Normative information includes market and nonmarket values about the past, present and future. While positive information is used to predict the physical consequences of an action choice, normative information is used to predict the goodness and badness of the consequences.

The set of consequences to be considered is determined in the problem definition stage. In the Headley model (Sec. 2.3) the problem is defined for a single field and a single year. The impact of a control decision on pest populations in subsequent years or an adjoining field are not included in the analysis. Consequently, these impacts are not part of the weighing of "goods" and "bads". Further, no information about the probable impact on other fields or future pest populations is required. These consequences will not be part of the decision making process, regardless of the decision rule used, because they have not been specified for inclusion in the analysis. Thus, the values of the decision maker are imbedded in the outcome by design of the problem.

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[9]Johnson identifies three broad categories of information as institutional, technological and human. The third category includes both market and nonmarket values.

Once the problem is clearly defined, the Type I and Type II[10] errors that are acceptable to the decision maker must be specified. From this specification the cost and value of additional information can be calculated. The decision maker then must determine not only what form of information is necessary, but also what level of precision.

The riskiness of a decision depends on the reliability of all of the information used in all stages of the decision process. The reliability of the decision rule is only one source of uncertainty.

In pest management there is a trade-off between uncertainty in modeling and uncertainty in monitoring. The more accurately predictions about future states can be made from current information (models) the less accurately present states need to be measured (monitored). Conversely, an accurate measurement of the present state may compensate for a less accurate predictive model. The information contained in a pest management model used to predict future states of an agro-ecosystem is a synthesis of prior knowledge. Sample observations are collected by monitoring to estimate the current state of the system.

Bayes Rule or Bayes Theorem is a formal procedure for combining estimates from sample observations with prior knowledge so that both can be used in the decision making process. Prior knowledge may be the result of observation, purely subjective, or a combination of both. Bayes Theorem can be interpreted as a means of updating probability distributions derived before present information had become available. Alternatively, it can be viewed as a means of combining information from

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[10] A Type I error is accepting a hypothesis when it is false. A Type II error is rejecting a hypothesis when it is true.

two different sources. The fundamental theorem will be presented below.[11]

Suppose that an event, A, can occur only if events B_1 or B_2 occur. Further either B_1 or B_2 must happen but both B_1 and B_2 cannot occur simultaneously. The occurrence of B_1 or B_2 does not depend on the occurrence of A. However, either B_1 or B_2 must occur in order for A to occur. B_1 and B_2 can be viewed as alternative hypotheses and A as a sample observation.

The probabilities of the compound events AB_1 can be written as

$$P(AB_1) = P(B_1)\, P(A|B_1) \tag{3-32}$$

or

$$P(AB_1) = P(A)\, P(B_1|A) \tag{3-33}$$

where $P(A|B_1)$ and $P(B_1|A)$ are conditional probabilities. The objective of Bayes formula is to infer from the occurrence of A which hypothesis, B_1 or B_2, to accept. Solving the equations for $P(B_1|A)$,

$$P(B_1|A) = \frac{P(B_1)\, P(A|B_1)}{P(A)} \tag{3-34}$$

Quite often it is difficult to assess the probability of A. But since A can only occur when B_1 or B_2 occur,

$$P(A) = P(B_1)\, P(A|B_1) + P(B_2)\, P(A|B_2) \tag{3-35}$$

To put Bayes Rule in the context of information systems and decision theory, B_1 and B_2 can be interpreted as hypotheses about a future state of nature. $P(B_1)$ encapsulates a prior knowledge about the likelihood of a particular state of nature. It may be the result of

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[11]The discussion presented follows the presentation of Bayesian analysis in K.J. Cohen and R.M. Cyert, <u>Theory of the Firm,</u> Englewood Cliffs:Prentice Hall, Inc., 1975, p. 459-460.

repeated sampling, sequential sampling, subjective probabilities or any combination of these.

A is an observation of the current state of nature. In pest management A would be the result of biological and/or environmental monitoring. Then the posterior probability, $P(B_1|A)$ is the likelihood that B_1 will occur based on previous knowledge and current information about the status of the system.

The anlaysis can easily be extended to consider n possible states of nature B_1, B_2,...B_n. It follows that the probabilities used to maximize utility are a function of the information system utilized.

In Bayesian statistics, information is summarized in a prior probability function. The prior probabilities are revised as new information becomes available. This process is called sequential sampling (Wald, 1947).

In classical statistical theory, hypotheses are tested by repeated sampling. Given a data set and a choice between two hypotheses the analyst will either: 1) accept the null hypothesis; or 2) reject the null hypothesis. The only information utilized is the data set generated from the repeated sampling procedure. Using sequential sampling, an analyst may fail to accept or reject the null hypothesis, and choose to gather more information before making a choice.

The sequential sampling procedure is compatible with the mathematical approach to learning developed in the psychology literature (Bush and Mosteller, 1955). Learning is defined as any systematic change in behavior.

In a probabilistic view of behavior, an individual has a probability, p, of making a particular response. Learning is measured by the change in the individual's probability of making the response. Learning has ended when there is no longer a change in the probability of a particular response.

The definition of learning is meaningful in a decision theory context if learning is interpreted as a change in the decision maker's subjective probability function for the possible states of nature. The decision maker starts with a prior probability function. He gathers additional information and then revises that probability function. In turn, the change in probabilities corresponds to a change in the selection of an action choice.

Uncertainty about the states of nature are expressed in the probability function. Any change in the probability function is learning.

Glenn Johnson (1961) has identified five knowledge situations under which decisions are made. In the case of subjective certainty, knowledge is so complete that the decision maker can act without protection from possible mistakes. In essence, the future state of nature is known with certainty and the variance of the probability function is 0.

The remaining four cases are examples of subjective uncertainty. As stated above, specifications for choices must be set. In particular, the probabilities of Type I and Type II errors that will be tolerated must be specified. The marginal cost (MC) and marginal utility (MU) of additional information can be determined from this specification.

Learning is the situation where no decision can be made (MC < MU) and the decision maker continues to gather information. In the forced action situation learning is terminated prematurely even though the decision maker would like more information. For example, poor weather or a court order can terminate the learning process. Inaction occurs when the marginal utility of more information is so low you are not in a learning situation but you do have uncertainty. The specifications for a choice cannot be met but the cost of obtaining additional information exceeds the value of that information (MC > MU). Finally, involuntary learning or forced learning takes place when a decision is made under the constraint of an administrative action.

Learning is the internalization of knowledge. New information and past experiences are synthesized to improve decisions made under uncertainty. Learning implies improvements in the prediction of future states of nature. Attitudes toward risk reflect what degree of uncertainty is acceptable with respect to these predictions. Therefore, learning will continue only when this acceptable level is not met.

3.2.6 Risk Preferences and Pest Management Decision Making - Empirical Results

Several studies have looked into the question of attitude toward risk with regard to pest management decisions and the demand for information. The results of two studies are presented here.

Hanemann and Farnsworth (1980) address the question of adoption of IPM versus conventional control related to risk considerations. They analyzed data collected in the San Joaquin Valley from 44 cotton growers over the period 1970-1974. 28 of these growers used IPM and 16 used conventional chemical controls during the interview period.

Several hypotheses were tested.

1) There exists a difference in risk preference between growers who use IPM and those who employ conventional control.

2) The expected returns from IPM are different than for conventional control.

3) The variance of profits under the two strategies is not the same.

4) The subjective probability distributions of returns from IPM and conventional control are different for the two groups of growers.

Utility functions for 44 growers were generated using lotteries. The growers were classified according to their risk preferences. Five growers had nonuniform preferences (i.e. risk-prone then risk-averse or risk-averse then risk-prone as income increases). Of the remaining 39 growers, 20 were risk-prone to some degree, six were risk-neutral and 13 were risk-averse to some degree. The results showed no difference in attitude toward risk of growers choosing IPM and those using conventional control. Therefore, the hypothesis that growers using conventional control are risk-averse was rejected. Based on the data set, the expected profits and variance of profits were not significantly different for the two strategies. Combining these results, adoption of IPM could not be explained by risk preference or the difference in risk associated with IPM versus conventional control.

The subjective probability distributions of cotton yields, insecticide expenditures and pest damage under both IPM and conventional control strategies were constructed based on the interviews (Table 3.2). The subjective probability distributions matched the actual historic data quite well for yields but not for insecticide expenditures. The means of the subjective distributions for insecticides exceeded those of the actual distributions. The authors suggest that this discrepancy may

Table 3.3

Summary of Paired Comparison Tests of Means and Variances of Actual and Subjective Probability Distributions

Group	Yields	Insecticide Expenditure	Partial Profits[1/]
-----Actual Probability Distributions-----			
Both Groups	μ_{IPM}[2/] $= \mu_{CC}$ $\sigma_{IPM} < \mu_{CC}$	$\mu_{IPM} < \mu_{CC}$ $\sigma_{IPM} < \sigma_{CC}$	$\mu_{IPM} = \mu_{CC}$ $\sigma_{IPM} = \sigma_{CC}$
-----Subjective Probability Distributions-----			
IPM Growers	$\mu_{IPM}^{IPM} = \mu_{IPM}$ $\sigma_{IPM}^{IPM} \geq \sigma_{IPM}$	$\mu_{IPM}^{IPM} \geq \mu_{IPM}$ $\sigma_{IPM}^{IPM} \geq \sigma_{IPM}$	
CC Growers	$\mu_{CC}^{CC} = \mu_{CC}$ $\sigma_{CC}^{CC} = \sigma_{CC}$	$\mu_{CC}^{CC} \geq \mu_{CC}$ $\sigma_{CC}^{CC} = \sigma_{CC}$	
IPM Growers	$\mu_{IPM}^{IPM} > \mu_{CC}^{IPM}$ $\sigma_{IPM}^{IPM} < \sigma_{CC}^{IPM}$	$\mu_{IPM}^{IPM} < \mu_{CC}^{IPM}$ 3/ $\sigma_{IPM}^{IPM} < \sigma_{CC}^{IPM}$	$\mu_{IPM}^{IPM} > \mu_{CC}^{IPM}$ 3/ $\sigma_{IPM}^{IPM} = \sigma_{CC}^{IPM}$
CC Growers	$\mu_{IPM}^{CC} < \mu_{CC}^{CC}$ $\sigma_{IPM}^{CC} > \sigma_{CC}^{CC}$	$\mu_{IPM}^{CC} > \mu_{CC}^{CC}$ $\sigma_{IPM}^{CC} = \sigma_{CC}^{CC}$	$\mu_{IPM}^{CC} < \mu_{IPM}^{CC}$ $\sigma_{IPM}^{CC} > \sigma_{IPM}^{CC}$

[1]Partial profit - yield x actual price in 1976 - all insecticide expenses. Cotton prices and noninsecticide expenses are assumed to be the same for both groups.

[2]μ is the mean and σ is the variance of the probability distribution. The subscript denotes the group to which the distribution pertains. The superscript denotes a groups subjective distribution. Where no superscript is used, the distribution is the actual distribution. For example μ_{CC} is the actual mean for conventional control.

[3]The result holds at the .10 level but not at the .05 level. All other cases hold at the .05 level.

Adapted from Wm. Hanemann and R.L. Farnsworth, "Risk Preferences and Perceptions in the Use of IPM," paper presented at the annual meetings of AAEA, Champaign - Urbana, Illinois, 27-30 July, 1980.

be a reflection of expected insecticide price increases on the part of the growers.

The more interesting results are in the comparison of growers subjective probability distributions for the strategy they employ and the alternative strategy. Each group judged its strategy to have a higher expected profit than the alternative strategy because each underestimated the yields for the alternative strategy. Further, each group perceived the variance in the yields to be lower than for the other group. Hence, each group also perceived the variance in profits to be lower for their group than for the other group.

The obvious conclusion is that it is the subjective perceptions of outcomes rather than risk preferences that explains the choice of control method. A particular attitude toward risk does not make a grower a good or bad candidate for pest management services.

The findings of this study are consistent with the work of Savage (1964) who argued that people act as though they make decisions based on their own judgmental probability of outcomes which may or may not be consistent with actual probabilities. These subjective probabilities are developed based on evidence from formal and informal information sources.

In the study, the conventional control growers obtained information from chemical salesmen and the IPM growers from pest management consultants. The very act of requesting advice, or, in the case of IPM growers, paying for advice, indicates that growers seek information to revise their subjective probability distributions. The implication is that provision of information would increase the adoption of pest management.

In another study of attitude toward risk and adoption of IPM, Webster (1979) used Bernoullian decision theory to analyze the problem of whether or not to spray against Septoria, a fungal disease of wheat. The study relies on the theory presented above in 3.2.4. Risky decision making was divided into two components, utility and probability.

Application of fungicides was the only management strategy considered. The probability distribution of yield for sprayed fields were obtained from a plant pathologist for all possible combinations of field characteristics. The characteristics considered were:

1. the stage of growth of the crop (flag leaf or flowering)
2. the observation of infection in the crop, or not
3. the forecast of an infection period in the next seven days, or not
4. the topography of the crop site-whether favorable to the disease, or not
5. the susceptibility of the variety or not

For each stage of growth, there are 2 x 2 x 2 x 2 = 16 sets of characteristics. For each set, the likelihoods of several yield levels were estimated. From this subjective probability distribution, the expected yield for each set of characteristics was determined.

A study of 29 wheat growers in England was conducted in order to look at the range of attitudes toward risk in wheat production. From the preliminary study, seven growers representing the range of responses were chosen for further study. For each of the seven farmers utility functions were derived. It is important to note that the utility functions estimated are intended to pertain only to wheat production and not a general attitude towards risk. In the authors words, "The spraying decision is made for a particular crop at a particular time. So [the grower's] utility function for yield is estimated in relation to that crop and has significance only for it. Another year and another crop would imply another utility function". It is reasonable to assume that attitude toward risk varies by crop, region, soil, etc.

For each of the seven growers the utility maximizing recommendation of spray or don't spray was calculated for each of the 16 sets of field characteristics. In addition, the decisions were made for the hypothetical case of indifference to risk. In every case except one, the recommendations for each set of field characteristics are the same for the range of attitudes toward risk represented by the seven growers. In other words, if the recommendation to spray or not spray had been based solely on the assumption of risk-neutrality in only one of the 112 cases (16 sets of field conditions x 7 growers) would the spray recommendation have been different than the utiltiy - maximizing decision.

While the utility functions derived for the growers demonstrate differing attitudes toward risk, the differences were not strong enough to effect the control recommendation. It appears that risk-neutrality is an appropriate simplification for developing control guidelines.

Attitude toward risk of the farmers' tests appeared to be considerably less significant in the derivation of utility maximizing control recommendations than the specification of the probability distribution of yield under alternative sets of conditions. The analysis relied on the assumption that growers' subjective probabilities are identical to the plant pathologists. This means that the grower fully accepts the experts' opinion and that he has continuous access to that opinion.

If the growers' subjective probability function closely resembles that of the plant pathologist and risk-neutrality is assumed, utility maximizing control guidelines can be developed based on expected yield under various sets of field conditions. However, given the results of the Hanemann and Farnsworth study, it is heroic to assume that growers' subjective probabilities are identical.

3.2.7 Application to Alfalfa Weevil Pest Management

The stages of the decision making process have been identified above. They are: 1) problem definition, 2) information gathering, 3) interpretation of the information and 4) making the decision.

Problem definition involves identification of possible action choices. The decision making process is synonymous with selecting an action choice.

The probabilities of outcomes for each action choice and possible states of nature are derived through collection of information and analysis. Ideally, information gathering and analysis will continue until the marginal cost of additional information exceeds the additional value of that information.

Some normative common denominator is needed to assign values to each outcome. A decision rule must be selected for comparing the values of each outcome. An action choice is selected based upon application of the decision rule.

The alfalfa weevil pest management problem can be defined as reducing crop loss in alfalfa production attributable to alfalfa weevil feeding using all known techniques. The action choices available are: 1) harvest early, 2) spray, or 3) continue with conventional harvest schedules and don't spray (Sec. 2.4). The third choice may be viewed as the do nothing approach.

For the first two alternatives an infinite number of decision algorithms is possible for selecting the timing of implementation and deciding whether or not to implement control at all. A decision algorithm is a control guideline that specifies under what conditions a particular control method should be initiated. Usually a decision algorithm consists of a threshold and a control technique that should be implemented once the threshold is reached.

An example is spray if there are more than 400 larvae per square meter. A routine spray also falls under the definition. The algorithm can be defined as spray on June 1. Loosely speaking, June 1 is the threshold.

The information required for choosing a decision algorithm includes knowledge of 1) pest population dynamics, 2) plant growth and 3) the interaction of the two. In addition, the efficacy of alternative management practices must be studied.

Implementation of each algorithm requires certain information. The information required for applying an algorithm may include the pest population, plant height, parasite population, high and low daily temperatures, or the value of alfalfa as feed. Each of these measurements may be required on an hourly basis or once a season.

The identification of alternative decision algorithms involves the subdecision of choosing a monitoring scheme. The cost and value of additional information for each algorithm can be evaluated. From these results, the monitoring scheme that leads to the best results for each algorithm can be selected. Any comparison of decision algorithms should be based on the best monitoring scheme.

A rule for preference ordering of decision algorithms must be selected. Several methods for selecting among risky alternatives were presented in Section 3.2.4.

In order to use any of the efficiency criteria described some value must be asigned to the outcome associated with each algorithm. In Michigan, alfalfa hay is usually fed to animals raised by the same unit producing the hay. Only small quantities of hay are bought and sold. Therefore, market price is not a good measure of the value of the hay produced. The value of alfalfa hay as feed will be calculated in Section 4.5.

There are really two levels of decision making. The first is the selection of a decision algorithm and the second is the application of the algorithm to make a specific control decision. In many cases once a decision algorithm has been selected implementation of a control strategy becomes a skill rather than decision making.

3.3 The Public Goods Nature of Information

To capsulize the framework presented, an information system is comprised of three activities: 1) data collection; 2) interpretation of the data and 3) provision of the results of the interpretation to decision makers. Before appropriate information can be produced for

decision makers, the following must be established: 1) data needs and a method for measurement; 2) methodology for analyzing the data; and 3) a means for disseminating the information to decision makers in a timely and relevant form. This is the design aspect of an information system. Once the information system is designed, the implementation of the program involves operationalizing the same three activities.

When a pest management program is viewed as an information system, the discussion is further complicated by making a distinction between defining and operationalizing the economic threshold. Researchers collect data, analyze the data and produce information in the form of economic threshold. This is the design phase. Data collection will continue only to test and refine the definition of the economic threshold.

A second data system must be developed to operationalize the economic threshold for each growing season and on a regional or grower level. The information requirements for the implementation phase are determined in the design phase but need not be identical to the information requirements of the design phase.

Once data has been collected in the implementation phase it is interpreted using information generated in the definition phase. In other words, current field conditions are used to predict economic loss based on information already developed. A critical aspect of the design phase is establishing which individual, group or organization will carry out each activity. In particular, should information be produced by the public or private sector or some blend of the two?

Before addressing this question a more general question must be asked: Which goods and services (if any) should be provided by the public sector and which goods and services (if any) should be provided by the private sector? The nature of public goods will be discussed below in the context of market failure. In the next section the ideas will be applied to the provision of information for pest management.

3.3.1 Private vs. Pubic Goods

First a distinction must be made between public and private goods.[11] In the polar cases, private goods are those for which consumption by one person precludes consumption by another. Public goods, on the other hand, do not have this characteristic. Consumption by one individual does not deplete the supply of the good. This phenomena is referred to as joint supply or joint impact. Public goods, then, are distinguished from private goods by the intrinsic characteristics of the goods and not by the structure of the market sytem.

A further distinction can be made between joint impact goods for which consumption can be avoided and those for which it cannot. An example of the former is broadcast television, an example of the latter is national defense. The issue is whether or not consumers can exclude themselves from consumption.

A parallel consideration is the ability of producers to exclude consumers. For private goods market price acts as a mechanism for

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[11]Public goods are also referred to as collective, nonrival or social goods in the public expenditure literature. The term public good is unfortunate because it falsely imples that public goods should necessarily be provided by the public sector. It is used here out of convention.

excluding those who do not pay from consuming the goods. However, for joint impact goods, it may or may not be feasible to exclude those who do not pay. For example, a concert is a joint impact good for which the cost of exclusion is low. Fireworks, on the other hand, have the characteristic of jointness and high costs for exclusion.

Certain goods have high exclusion costs but are not joint impact goods. These goods are often referred to as common property resources. Examples include water and air. When clean air is used for waste disposal by one industry the supply is reduced. At the same time, it is difficult to establish ownership rights and to exclude those who do not pay.

Some public goods have the simultaneous characteristics of high exclusion costs and nonoptimal avoidance by the consumer. For these goods it is at the same time impossible for the producer of the good to exclude individuals from consuming the good and impossible for individuals to exclude themselves from consuming the good.

Four categories of public goods exist: 1) joint impact-avoidance optional, high exclusion cost; 2) joint impact-avoidance optional, low exclusion cost; 3) joint impact-avoidance nonoptional, high exclusion cost; and 4) joint impact-avoidance nonoptional low exclusion cost. The last category is the empty set because it is impossible to exclude someone from consuming a good who cannot avoid consuming the good. Examples of the other three categories are pesented in Table 3.4.

The nature of public goods presents serious problems for decentralized markets. Only one commonly consumed quantity is produced. Regardless of whether or not it is possible to avoid consumption of the good once it is produced, the consumer cannot vary the quantity

Table 3.4

Interaction of Avoidance and Exclusion Costs with Respect to Joint-Impact Goods

	Avoidance Optional	Avoidance Nonoptional
Low exclusion cost	1. Cable television 2. Accees to existing electric, gas, and telephone lines up to capacity 3. Cinema seats up to theater capacity	Empty set
High exclusion cost	1. Broadcast television 2. Outdoor fireworks	1. Defense 2. Ambient air for breathing 3. Flood control 4. Use of air waves for audible sound

Source: A. Allen Schmid. Property, Power and Public Choice. New York: Praeger Publishers, 1978.

purchased and herein lies the problem. The consumer cannot reveal his willingness to pay alternative prices for different quantities.

In the polar case of private goods, the quantity demanded varies at different exclusion prices and reveals preferences. For a given exclusion price, each consumer will increase consumption up until the point where his marginal rate of substitution equals price. For public goods only one quantity is produced. Even when it is possible to exclude those who do not pay from consumption of a public good there is no reason to expect each consumer's marginal rate of substitution of the quantity produced to equal the exclusion price. For any combination of a single exclusion price and quantity, it is impossible for all consumers to equate their marginal rates of substitution with price.

An obvious solution is to charge different prices for public goods for different individuals in accordance with their preferences. However, even when exclusion is possible, decentralized markets can, at best, only partially reveal preferences. The inability to vary quantity eliminates the possibility of revealing preferences in the marketplace. Prices charged to individual consumers cannot be varied unless preferences are revealed. The primary problem of provision of public goods by decentralized markets is not the inability to enforce payment but the inability of the market to reveal optimal prices.

Even if preferences were known, private producers could not limit consumption to those who pay for them and therefore, could not expect to collect adequate revenue. The greater the number of people consuming the good, the greater the incentive to enjoy a free ride. The problem of enforcing market prices exists whenever exclusion is difficult regardless of whether or not the good has the additional characteristic of jointness.

From the above discussion, preferences are at least partially revealed when exclusion is possible. However, the jointness characteristic of public goods necessitates modification of the conventional pricing rule[12] regardless of whether or not consumers can be excluded. Assuming exclusion is possible; it then seems appropriate to apply the standard joint products analysis for private goods to public goods to find a quasi-competitive solution. It will be demonstrated, however, that the two cases are not perfectly analogous, and the joint product analysis cannot circumvent the inability of decentralized markets to provide joint impact goods efficiently.

The contrast between private and public goods is illuminated by examining the difference between private and public joint supply. Joint supply of two private goods refers to the physical phenomenon of necessarily producing both goods wherever one of the goods is produced. The quantity produced of one good is determined once the quantity of the other is chosen. In other words, more of one cannot be produced without also producing more of the other.

On the other hand, joint supply of public goods concerns an inability to adjust quantity consumed. Joint impact goods, once produced, are equally available to all individuals. The quantity consumed by one person is identical to the quantity consumed by another.

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[12] In neoclassical economic theory, consumers maximize utility at the point where the utility of an additional unit of a product equals the market price. Producers increase output until the marginal cost of an additional unit of output equals market price. The quantity demanded equals the quantity supplied at the market equilibrium price.

In short, jointness is a characteristic of a good. Jointness with respect to a private good refers to the inability of a producer to adjust the quantities of two goods produced independently. Jointness with respect to a public good refers to the inability of two consumers to purchase different amounts of the same good.

The classic example of private joint supply is wool and mutton. Figure 3.6 depicts the situation for two consumers. The aggregate demand for mutton and wool is determined by horizontally summing the individual demands for mutton and wool, respectively. The aggregate demand for sheep, in turn, is found by summing the aggregate demand for mutton and the demand for wool vertically.

The quantity of sheep demanded can then be determined by applying standard partial equilibrium analysis. The utility maximizing solution is to increase consumption until marginal utility equals the market price. The resulting quantity of sheep uniquely determines the quantities of mutton and wool when fixed proportions are assumed. The prices for mutton and wool are found by identifying the price corresponding to the quantities along the demand curves.

It is important to note that each individual can adjust his consumption level in accordance with market price to maximize his utility. The situation is perfectly analogous to the private market for goods with no jointness characteristics. Therefore, joint supply of private goods is not a source of market failure.

However, when joint supply analysis is applied to collective goods the conclusion is quite different. Figure 3.7 illustrates this case. Here, the nature of the good is such that each consumer must purchase the same amount of the good. There is no possibility for variation in

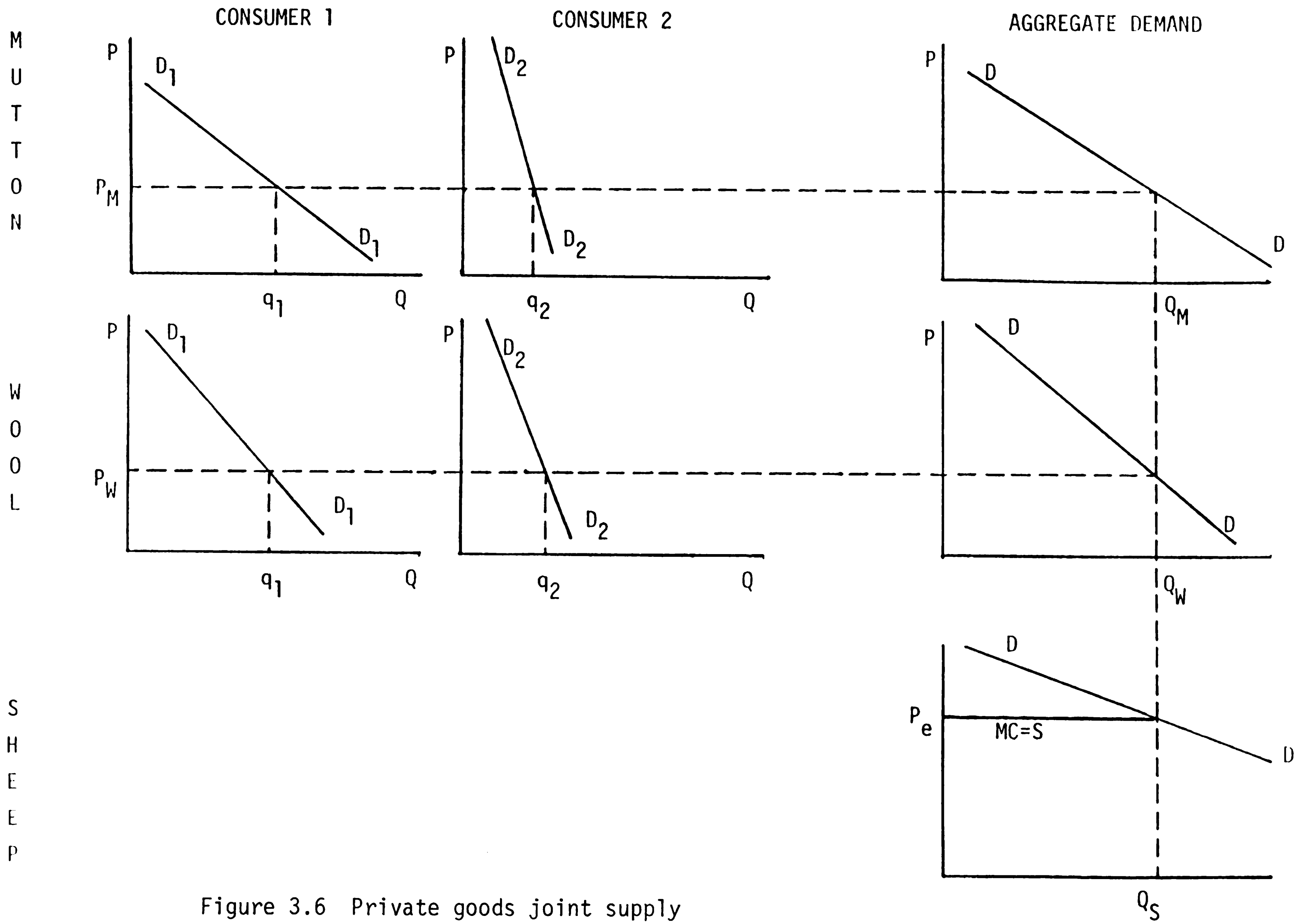

Figure 3.6 Private goods joint supply

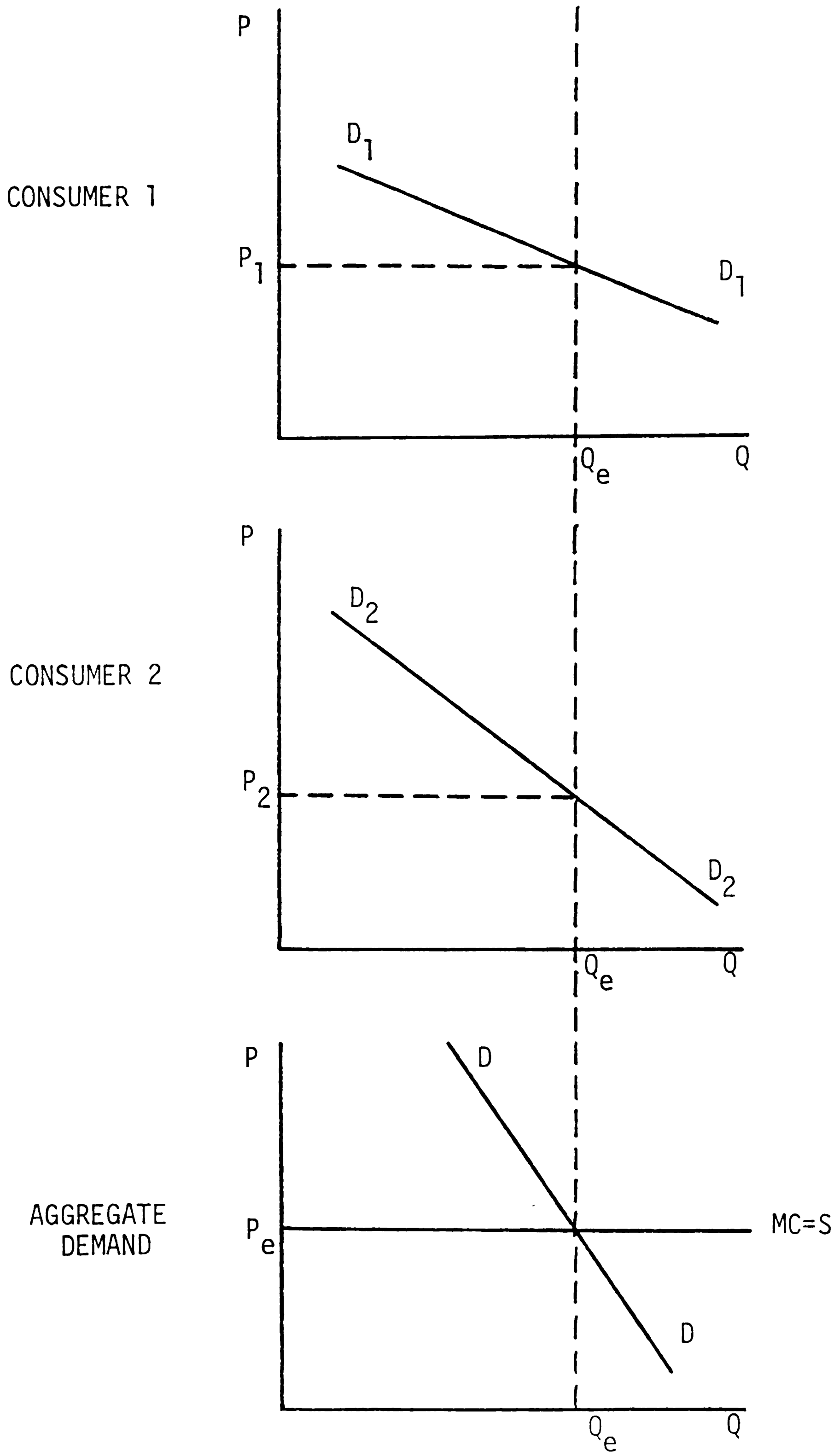

Figure 3.7 Public goods joint impact--vertical summation over all consumers

individual quantity purchased. For this reason, the aggregate demand for the joint impact good is derived by summing individual demands vertically. For a given quantity, the corresponding aggregate price is the sum of the price offered by consumer 1 and the price offered by consumer 2. Price in this context is the amount a person is willing to pay to assure that the good is provided.

In the private goods case, demand curves are summed horizontally to derive the quantity demanded at various market prices. It is incorrect to sum demand curves horizontally for public goods because individuals are forced to purchase equal amounts of the good. A horizontal summation allows for variation in quantity purchased among individuals, which leads to a contradiction.

The efficient solution is to extend production to the point where the average of the marginal utilities for all consumers equals the marginal cost of producing the good. The marginal utility of the last unit produced is not the same for all consumers as it is in the private goods case. This results in different prices charged to different consumers in accordance with their willingness to pay.

This possibility was rejected above for several reasons. It is difficult if not impossible to imagine a feasible market arrangement that would allow for the perfect discrimination among consumers requried to implement this arrangement. Further, even if exclusion were technically possible, it is unlikely that a producer would be able to identify the appropriate charges for each individual precisely because of the inability of consumers to vary quantity and reveal preferences through conventional market mechanisms.

It appears that in the case of public goods, there is a need for a means of revealing preferences and for providing goods other than a decentralized market. Information about consumer preferences can be obtained through interviews or experiments. Interest groups also provide such information.

Numerous alternatives to provision of consumer preference information by decentralized markets exist. They include provision by private organizations such as clubs or cooperatives, formal or informal arrangements among individuals, and supply by the public sector. In all of these cases, even if all individuals have a positive value for a joint impact good there is a problem in articulation of preferences and cost sharing.

Provision of public goods by private groups is riddled with problems similar to those encountered in provision by decentralized markets. These problems are explored in detail by Mancur Olson, Jr., The Logic of Collective Action (1965). He argues that groups will provide less of a collective good than it is in their common interest to provide. He assumes that once a group provides a public good, exclusion of other members of the groups is not feasible.

> This tendency toward suboptimality is due to the fact that a collective good is, by definition, such that other individuals in the group cannot be kept from consuming it once any individual in the group has provided it for himself. Since an individual member thus gets only part of the benefit of any expenditure he makes to obtain more of the collective good, he will discontinue his purchase of the collective good before the optimal amount for the group as a whole has been obtained.

To summarize, goods with high exclusion costs and joint impact goods pose serious problems for decentralized markets. When exclusion is difficult the problem becomes one of enforcing the market price. Enforcement is difficult regardless of whether the good is public or private. For joint impact goods, the market fails to provide an optimal set of prices. This is a problem even when enforcement is possible.

3.3.2 Public Goods, Externalities and Market Failure

It has been shown above that goods with the characteristics of joint supply and high exclusion costs lead to market failure. But market failure is a general term used to encompass any situation in which a perfectly competitive market cannot reach a Pareto optimal price and output level.[13]

Sources of market failure are often described in terms of external effects or externalities. Externality is also a broad term which encompasses several categories of factors which prevent a society from achieving a Pareto optimal solution.

John Head (1962) interprets externalities and exclusion as referring to the same phenomena. Externalities arise as a result of 'nonappropriability', that is, an inability for a private market to assign the appropriate value to a good.

Head defines externality as a condition such that "a change in the production and/or consumption of a good will affect the utility and/or production functions for other goods." The condition is the result of "the divorce of scarcity from effective ownership" such that it is "impossible for private firms and individuals, through ordinary private pricing to appropriate the full social benefits (or to be charged the

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[13]Pareto optimality is reached when goods are allocated such that no one person can be made better off without making someone else worse off. The term is after Vilfredo Pareto (1848-1923) who pioneered work in welfare economics.

full social costs) arising directly from their production and/or consumption of certain goods".

Head points out that this is a phenomenon separate from joint impact goods. Jointness may create externalities but not necessarily. Many instances of jointness, such as concerts, do not pose problems for exclusion. On the other hand, he views joint supply as one of several possible causes of decreasing cost which lead to market failure. Head concludes that any case of market failure can be explained by the inability of the decision maker to appropriate the full benefits (or absorb the full costs) of his actions.

Buchanan (1966) defines externality in terms of jointness. "Any externality becomes a joint-supply relationship" because "an individual's act of consuming or producing a good or service is, at the same time jointly supplying at least one other person with a 'good' (or a 'bad')." He points out that while all externalities can be described in terms of jointness, all examples of joint supply do not create externalities.[14]

These two wholistic approaches for explaining externalities are not as divergent as they first appear. Both authors define externalities in terms of interdependencies among producers and consumers which are nonoptimal. Both emphasize that consumption of some joint impact goods can be avoided and others cannot. When avoidance is nonoptimal, exclusion costs are necessarily high and information needed for price discrimination is not revealed. Neither distinguishes between "resource allocation problems which arise because no decision maker can adjust the

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[14]Buchanan uses the term jointness to refer to the joint supply of private goods.

quantity available to him (that is conventional public goods joint supply) and those that result when activities under the control of one decision maker affect the production or utility functions of another (conventional externalities)" (Burkhead and Miner, 1971).

These comprehensive approaches can be justified by a return to the discussion of private versus public joint supply (jointness in production versus jointness in consumption). In the case of a conventional externality, the activity of one decision maker necessarily results in multiple outputs (i.e., jointness in production). However, the case of an externality, other decision makers cannot avoid consuming at least one of the outputs produced. The externality arises when decision makers are unable to adjust the quantity available to them (i.e., jointness in consumption).

Kenneth Arrow (1970) explains market failure in terms of transaction costs. The organization of any market involves costs. The performance of the market depends upon the willingness of participants to bear these costs and the ability of the market to assign appropriate costs.

Schmid (1978) identifies three types of transaction costs; contractual, information, and policing. Contractual costs are the costs of "reaching an agreement with another party". Information costs are incurred when an individual seeks information in order to interact in the market and reduce uncertainty. Policing costs are a part of exclusion costs. Contractual costs include lawyers fees, brokerage fees and the opportunity cost of bargaining time. Information and uncertainty costs result from imperfect knowledge concerning future states, such as aggregate supply and demand, price, and quality.

For Arrow, externalities manifest themselves in high transaction costs. He distinguishes two types of externalities which both lead to high transaction costs and consequently market failure. The first type results purely as a consequence of the organization of the market. The second type of externality occurs due to the nature of the good and would arise regardless of the form of market organization. Transaction costs are related to both the form of market organization and the intrinsic properties of the good provided.

Private markets fail, according to Arrow, when "transaction costs are so high that the existence of the market is no longer worthwhile". When transaction costs are extremely high, arrangements other than the conventional private market system may be preferable. It should be kept in mind, however, that alternative systems of resource allocation also involve transaction costs.

Transaction costs arise whenever two economic actors interact. They are the consequence of human interdependence in economic activities regardless of the characteristics of the goods or services involved. The magnitude of the transaction costs are, however, dependent on the nature of the goods.

Schmid discussed externalities in terms of the effects of interdependence. Interdependencies exist for private goods and joint impact goods. Schmid identifies three types of interdependence or externalities. They are: 1) technological, 2) pecuniary, and 3) political.

> A technological externality or impact is one where somebody physically affects you or your good directly. A pecuniary externality is one where the good remains physically intact, but its value in exchange is affected. A political externality can be either technological or pecuniary, but the source is the working of government when it changes the rules of the game or makes administrative transactions.

Technological externalities are present primarily whenever consumption or use in production by one person precludes consumption (or use in production) by another. Under this interpretation all private goods present technological externalities. This usage is much broader than the more standard interpretation and emphasizes the omnipotence of interdependence among economic actors.

The classic example of a technological externality is pollution. Use of air or water for waste disposal by industry precludes the enjoyment of clean air or water by others.

Interdependencies also result from joint impact goods where consumption by one person does not reduce the amount available to others. The quantity and quality of the good is identical for each individual. Whenever one person influences the supply of joint impact goods it changes the amount available to another. If the good is nonoptional "goods chosen by B enter A's consumption function as a physical thing and thus are a variety of technological externality". It follows that technological externalities depend in part upon "rules that determine who chooses government or private purchases of nonoptional joint-impact goods".

Pecuniary externalities are also omnipotent unless exchange is prohibited. Pecuniary externalities occur when the value of resources changes due to the economic activities of others. The direction and magnitude of pecuniary externalities signals the reallocation of resources.

Pecuniary externalities exist for both joint impact and private goods. With respect to joint impact goods, where exlusion is difficult, purchases by one group or individual decreases the cost to others.

Political actions shift technical and pecuniary externalities from one person to another. The provision of goods by the public sector causes some people to pay for a good that they don't want. The value of assets used for provision of similar goods in the private sector is also affected.

When externalities are defined as sources of interdependence, they do not have an obvious normative interpretation. Externalities are not 'bads' that can be eliminated. Protection from trespass for one person is exclusion for another. Laws and rules of the marketplace influence the direction and magnitude of externalities. When preferences differ, externalities can be shifted but not eliminated.

3.3.3 Information, Market Value and Pest Management

It is clear from the material presented thus far that pest control decisions are always made without perfect knowledge. The relationships among control tactics, pests, crops, natural enemies and weather are not known with certainty. Neither can future states be predicted with precision. Indeed, the acquisition, interpretation and application of information is the state of the art in pest management.

Although management systems may never produce ideal behavior of the pest crop system, management decisions can be improved by pest management programs. At least three categories of information are needed for pest management decisions. They are: 1) technical, 2) market and 3) government. For each of these there is a positive, normative and temporal dimension. The categories of information can also be interpreted as categories of interdependencies among users of pesticides, producers of pesticides, consumers, government agencies and society as a whole.

At this point we can return to the question posed at the beginning of this section. That is, how (under what institutional arrangements) should pest management information be provided?

The implication of section 3.2 is that when the ideal condition of perfect knowledge is not met, information has value in the context of decision making. Decision makers will seek more information until the marginal cost of information exceeds the marginal utility of the additional information. That is, unless the learning process is terminated for some external reason. It follows that the allocation of resources is not costless. Further, the supply and demand for information itself raises questions of resource allocation.

The theory presented in 3.3.1 and 3.3.2 provides a taxonomic framework for examining conditions that lead to a suboptimal allocation of resources by a decentralized market system. It remains to apply these concepts to pest management and the information generated by pest management programs.

It will be shown that decentralized markets will not allocate adequate resources to the provision of pest management information for two reasons.

1) The philosophy of pest management suggests that interdependencies created by pest control strategies, and particularly pesticide use, should be taken into account in pest control decisions. These interdependencies may or may not be accounted for by decentralized markets but should still be part of pest management decisions. It

follows that market and nonmarket values are part of the decision-making process.

2) Pest management information cannot be characterized as a purely private good.

Each of these areas will be discussed separately. Finally, alternative institutional arrangements for pest management programs will be outlined.

To begin with, a return to the definition of pest management is in order. In one definition, pest management is described as "the reduction of pest problems by actions selected . . . to be in the best interest of mankind" (Rabb, 1970). Following the FAO definition (section 2.2) pest management utilizes "all techniques and methods that are suitable . . . in the context of the associated environment." In these and other definitions the interdependencies among members of society resulting from pesticide use are recognized. Interdependencies resulting from pesticide use exist among pesticide producers, pesticide users and the rest of society.

Technical externalities arise from the presence of pesticide residuals and waste from pesticide production in the environment. The health hazards created by the dumping of wastes, pesticide drifts and other uncontrolled paths through which chemicals enter the food chain are being uncovered at an alarming rate.

Some of the benefits of pesticide use are realized by society in the low cost of food. All of the undesirable effects of pesticide use are not reflected in the market price of food.

Important interdependencies related to pest control exist among farmers. Typically, farmer A only attempts to control pests in his own

field. Yet the strategy followed enters the production function of other growers. Likewise, the management strategies followed by other growers enter farmer A's production function.

Pesticide drift becomes a problem when pesticides used to control one crop are damaging to another. For example, herbicides used to control nightshades are toxic to tomatoes.

Pesticide use may also result in a secondary pest outbreak. When the primary pest has been controlled another species population may explode because competition for food has been eliminated. This phenomenon may be the result of an individual's actions, a neighbor's actions or both.

Each farmer's application of pesticides decreases the pool of susceptible pests, resulting in a more resistant pest population. A recognized consequence of continuous use of a pesticide is a decline in the effectiveness of that pesticide. The value of the pesticide in production is altered by its use. Pesticide producers are also affected because the life of the pesticide is shortened.

Government regulations are another source of interdependencies. They are an administrative attempt to force nonmarket values into the pest control decision. Licensing of pesticide applicators, certification of pesticides, and regulation of waste disposal all create costs for the producers and users of pesticides and for society as a whole by way of cost of enforcement.

Certifying a pesticide for use on only a few crops reduces the value of the pesticide to its manufacturer. At the extreme, banning a pesticide reduces its value to zero. Concurrently, a successful ban eliminates the negative consequences of that pesticide.

A ban means that the government has determined that the "bads" from use outweigh the "goods". Further, the government expects that this negative balance will not be reflected fully in the marketplace.

Other interdependencies exist among farmers, farm laborers, bee-keepers, hunters and fishermen. Many of these interrelationships cannot be captured by conventional markets because they are difficult to quantify and exclusion costs are high. The remainder of this discussion will focus on the characteristics of information that affect the allocation of resources for supply and acquisition of information.

At least two forms of information are involved in any pest control program. The first is the pest control guidelines and the second is the information needed to implement the guidelines (Sec. 3.2.5). The latter usually involves monitoring of a specific field for a specific pest. Both forms of information are inputs into the decision making process. The selection of a pest control strategy is the output.

None of the information is consumed in the process. The amount of information available to A is not reduced when it is utilized by B. Therefore, information is a joint impact good. Information avoidance is optional with respect to pest control guidelines and field specific population counts.

Once pest control guidelines have been developed it is difficult to exclude individuals from obtaining them. In theory, copyright and patent laws make exclusion possible but policing costs make this unrealistic in most cases. Guidelines developed by the public sector are usually made public information with no user cost. Nominal fees may be charged for publications but once information has been disseminated it is difficult to exclude individuals from obtaining it. In any case, the development costs are not recaptured.

The cost of producing information is high relative to the cost of disseminating it. The marginal cost of additional users is decreasing. Therefore, the market could not determine the optimal number of users or the optimal amount of information to produce even if exclusion were possible.

With respect to the information needed for implementing control guidelines, the information obtained in one field may not be appropriate for a neighbor's field. The value of the information from one user to the next will not be the same. Even if monitoring information is available to A after it is utilized by B, it may not have the same value to A as to B. A may be willing to pay for monitoring information for his field in order to utilize the guideline information effectively.

The output resulting from the use of the guideline information and monitoring information is a pest control decision. Once a decision is made and a control strategy is followed, the information used in the decision process is at least partially revealed. In this sense exclusion costs are high.

An example is the decision to spray. A grower may decide to spray simply because he observes his neighbor spraying. In a sense, his decision to spray is based upon the same information as his neighbor's decision. But that information may not be appropriate for making both spray decisions.

It is not a question of measurement error. It is a question of sampling from one population and assuming it is a random sample from another population.

For certain insect pests that are very mobile and whose infestations tend to be regional rather than field specific, population counts from one field may be adequate for decisions made for another field. One enterprising commercial aerial applicator attempted to drum up business by flying an empty plane over fields hoping that nearby growers would assume it was time to apply pesticides.

Because of the joint impact and high exclusion cost nature of information, decentralized markets fail to reveal the prices indivduals are willing to pay. Production of information by one group provides information to others because of its characteristic of jointness. The difficulty of exclusion makes it impossible for suppliers to receive adequate compensation. This is an example of Arrow's 'nonappropriability'.

The public good characteristics of information have lead Norgaard (1976) to conclude that "the production and dissemination of knowlege warrant distinctive public support. This is true especially in the case of pest management knowledge because of the important health and ecological ramifications of pesticide use".

This sentiment was also expressed in an Office of Technology Assessment report (1979). The report concluded that there is a lack of adequate information delivery systems necessary to support pest management decisions. Most of their suggestions to improve the situation were for public provision of information. The options included:

1) Federal support for IPM training.
2) Creation of a federally coordinated pest and weather monitoring program.
3) Support for public information delivery systems.

Other recommendations were directed at increasing the use of public IPM information. They suggested different forms of government actions including grower education, and incentives to growers to increase grower adoption of IPM.

A third category of recommendations included offering incentives for the formation of private information delivery. The report did not consider that providing information by the public sector might itself work as a disincentive for the private provision of information.

It is often assumed that once growers are aware of the value of information and a demand is created, delivery systems will appear in the private sector. The role of the public sector is to get the ball rolling and then get out of the market. This has traditionally been the approach of the extension service. This scenario is consistent with transaction costs being the only barriers to provision of information. It does not recognize the problems of exclusion associated with information.

The public supply of information introduces new interdependencies into the economy. Technological externalities arise when control strategies change as a result of the information. Pecuniary externalities also arise because the value of information provided by private sources is decreased if the public information is directed at similar users.

The effect of public information on private information was analyzed in a study of the supply and demand for private consultants in the cotton industry conducted by Carlson (1980). He identified two relationships between public and private supply of information. First, since public information is available to private consultants, more extension efforts will reduce the cost of private supply of consultants. In other words, public sector research in the area of pest management subsidizes the private sector by providing low cost information. On the other hand, increasing the supply of extension specialist information can lead to a substitution effect and lower demand for private consultants.

The joint effect was measured in the reduced form equation for private consultants for ten cotton regions in the U.S.:

$$T = t(P, V, I, N\ S)$$

where

T = private consultants--measured as the number of consultants per million crop acres

P = expected pest level--measured as pest control expenditures per crop acre in the previous year

V = crop value--measured as value per acre produced

I = public information--measured the number of extension and state IPM specialists

N = stock of knowledge of farmers and consultants in a region--measured by regional cotton production

S = farm size

Crop density, consultants' fees, farmer opportunity cost, extension information cost and all other input prices were assumed constant across regions.

The estimated equation with t values in parenthesis was:

$$T = -.53 + .47P + .07V + 1.49S + .03N - .37I$$

$$(2.00)\ (2.26)\ (.93)\ (11.46)\ (1.92)$$

The cumulative effect of public IPM services on private consultants in a region was negative. The elasticity calculated for public supply was -.4. A 1 percent increase in public IPM information corresponds to a .4 percent decrease in private consultants.

It is highly questionable whether or not the stock of knowledge of farmers and consultants in a region is appropriately measured by regional cotton production. Regional cotton production could also be interpreted as a measure of soil quality or the suitability of climate for cotton production in a region. This problem is recognized by the author.

> The relatively large impact of cotton production probably measures season length and pest complexity, as well as accumulated experience. A data set which had direct measures of experience could separate these effects. The highly significant effect of cotton production on consulting needs further analysis (p. 1006).

Despite some limitations, the work is an important attempt to represent systematically the supply and demand for privately and publicly provided pest management information.

Another issue concerning public vs. private supply of information should be brought out. That is, the information provided by the public sector may not be the same as that supplied by the private sector. In particular, the control tactics included in the information package will differ.

Information provided by the public sector has a regional orientation. It represents an attempt, at the very least, to work with the interdependencies that arise from pesticide use, especially those that are not reflected in conventional markets. Therefore, pest management information is viewed in a regional context with a multi-year planning horizon.

For example, the introduction of parasites can only be effective on a regional basis and after several years. In this context, high cost of exclusion and jointness are not problems but advantages. The objective is to involve as many growers as possible.

Quarantine and inspection stations in place to limit the migration of pests are also only effective on a regional basis. These tactics are usually initiated by the public sector. The information private consultants provide is as firm specific as possible. The primary objective of providing the information is profit maximization at the firm level. The tactics considered, therefore, may not be regionally oriented. A reduction of pesticide use is primarily a short run benefit in that grower costs are lowered.

The most common source of information from the private sector is chemical salesmen. Often chemical fieldmen offer monitoring service. The obvious claim of a conflict of interests is countered by the fieldman's desire to retain satisfied customers year after year. This means not recommending unwarranted controls. The distinction often made between private consultants and chemical fieldmen is collapsing as both groups provide more sophisticated pest management information. It may be more accurate to refer to both groups as private pest control advisors.

The discussion thus far has focused on the polar cases of public and private provision of information. The possibility of collective action will now be addressed. Following Olson (1965), collective action is more likely to take place if: a) there is a clear understanding of the interrelationships among the members of the group, b) all parties can benefit without an elaborate compensation mechanism, and c) a suitable institution for decision making and enforcement already exists.

As growers become increasingly aware of the problems of resistance, resurgance and secondary outbreaks, the benefits of collective action become more obvious. Economies of scale in information gathering, interpretation and decision making can be captured by a group, but not by individuals.

Economies of scale introduce problems for charging members for services. The cost of data collection, analysis and delivery may be the same for 16 acres as for 160 acres of the same crop. Therefore, collective supply of information may be less feasible for small or diversified farms.

Typically, pest management organizations have been initiated with the help of cooperative extension. The group may be completely new, or services added to an organization originally formed to provide other management services such as soil testing. Hepp (1977) identified five categories of grower-owned organizations for the provision of pest management information. They are distinguisable by the services provided by the organization, the role of the growers, and the role of extension personnel. The organization types are:

1. Grower-owned organizations supporting and directing an extension pest management program. The organization provides scouting and counseling services and collects fees. Extension performs organizational management, leadership and education.

Growers direct the specific services provided (e.g., which crops are monitored, how often, etc.).

2. Farmer-directed pest management cooperative. This organization is distinguished from the one above in that growers play a larger role in organizational management and decision making.

3. Manager-directed pest management cooperatives. Part-time or full-time managers are hired to operate the cooperative. Extension is less involved with business management but still involved in education.

4. New organizations financially supported and organized by existing input supply or marketing cooperatives. Local cooperatives form a separate pest management consulting business rather than growers organizing the cooperative.

5. Pest management service from an existing cooperative. Pest management services are provided in addition to the other services provided. The operation and management is carried out by the existing management system.

Pest management information is provided in a number of other ways by the private sector. These include grower organizations, marketing orders, food processors, agricultural marketing cooperatives, commodity brokers and trade publications.

Money collected from members of grower organizations or cooperatives is typically used for generic advertising and research. Research is often directed at pest management. The research results are made available to members through meetings, newsletters and other publications. Marketing coops and large brokers may have field representatives who aid growers in identifying pest problems and solutions.

The public sector can be involved in the provision of pest management information by creating information delivery systems from public funds or providing incentives for private provision of information (e.g., subsidies or tax breaks). Between these two extremes, the extension service can aid in establishing grower-owned cooperatives and maintaining a role within these organizations. One thing is clear, the public sector will always be involved in the provision of pest management information through research and the educational function of extension.

Any number of the institutional structures outlined above can exist simultaneously. The type of organizations that evolve depends greatly upon the objectives of growers and society as a whole.

3.4 Evaluation of Information Systems

The information system paradigm provides a framework for analysis of the design of an information system. It remains to develop a method for the evaluation of the performance of an information system. Three general approaches will be presented.

The first is an application of the decision theory approach and employs the uncertainty framework outlined above in 3.2.4. Following this approach, incomplete information (i.e. imperfect knowledge) about any of the constraints facing the firm is a source of uncertainty. The expected utility of an action is dependent upon available information. The second approach is to measure the area under the demand curve before and after supply adjustments are made based on the addition of information. The third approach views information as an input into the production process and estimates the marginal return to information.

3.4.1 Decision Theory Approach

Incomplete information about a production function necessarily means uncertainty as to the outputs of the production process. The production function no longer determines a unique outcome. Rather the result of production is presented by a probability density function.

Even if the production function is unambiguous, inputs to the production function may be uncertain. For example, pesticide application rates may be uneven due to weather conditions or other factors. Again, a unique set of inputs will not yield a unique quantity of output. The optimal set of inputs will not be the same under imperfect knowledge as in the uncertainty case of perfect knowledge (Pope and Just, 1977).

Similarly, incomplete information about input or product prices can be described in terms of uncertainty. If prices are defined by a probability function, the best technology cannot be determined with certainty.

Stated in the more general terms of decision theory, several future "states of nature" are possible over which the firm has limited or no control. The decision maker does not know with certainty which of these states of nature will exist but can assign a probability value to each state. In addition, several "action choices" are available to the firm. The result of a production decision (payoff from an action choice) depends upon the possible states of nature, and the probability distribution of the states. Restating the formal representation of this framework presented in 3.2.4:

$$E(U(A_i)) = \sum_j U(A_i, X_j) P(X_j) \tag{3-36}$$

The optimal action is the one which maximizes expected utility.

Let A* be the action choice with the highest utility. Further let the decision rule for selecting an action strategy be to choose the action with the maximum utility. This can be expressed as:

$$E(U(A^*)) = \max_j: \sum_j U(A_i, X_j) P(X_j) \tag{3-37}$$

Additional information will modify the probability distribution, $P(X_j)$, and ultimately the production decision. But information is not costless. Let the cost of information be C(I). Then (3-36) can be modified to include information as follows:

$$E(U(A_i | I)) = \Sigma U(A_i, X_j) P(X_j | I) - U(C(I)) \tag{3-38}$$

The conditional probability, $P(X_j | I)$ can be obtained using Bayes theorem (see 3.2.5). The payoff matrixes associated with alternative information systems can be developed using (3-38). The selection of the action choice is a function of available information. Let h be a decision function which chooses the action with the highest utility for the available information. Let A** be the optimal action. Then

$$h(I) = A^{**} \tag{3-39}$$

and

$$E(U(A^{**})) = \max_h [\sum_j U(h(I), X_j) P(X_j | I) - U(C(I))] \tag{3-40}$$

This approach has been utilized in empirical work by Baquet (1976) to determine the value of frost forecasting information in preventing

frost damage in orchards and applied to the forecasting of peach rot by Carlson (1970). In both studies payoff matrixes were developed to identify the optimal strategy for each possible forecast.

Baquet describes the utility of a set of forecasts, Z_k as the difference between the utility of the optimal strategy when forecast information is available and the utility of the optimal strategy selected without the benefit of forecast information. This can be represented mathematically as

$$E(U(Z_k)) = E(U(A^{**}_k)) - E(U(A^*)) \qquad (3\text{-}41)$$

$E(U(A^{**}_k)$ can be determined by substituting Z_k for I in equation 3-40 and noting that $h(Z_k) = A^{**}_k$. $E(U(A^*))$ is defined by equation (3-37).

In both studies, each forecast uniquely determined an action choice. It follows that the probability that an action will be followed is equal to the probability that a forecast will be made which will designate that strategy as optimal. Thus the gain in expected utility from using forecasts can be computed using the probabilities of the forecasts, Z_k, to weigh the difference between expected utilities of strategies chosen using the forecast information and the strategies chosen without the information. Equation (3-41) can be rewritten as:

$$E(U(Z)) = \sum_{k=1}^{m} [\sum_{j=1}^{n} U(A^{**}_k, X_j)\ P(X_j | Z_k) - \sum_{j=1}^{n} U(A^*, X_j)\ P(X_j)]\ P(Z_k) \qquad (3\text{-}42)$$

The advantage of this approach is that it allows decision makers to adjust their choice of strategies as information becomes available. However, there are several assumptions underlying this approach worth mentioning. First, the consequence of an action choice is deterministic not stochastic. That is, given an action choice and a state of nature, the outcome is known with certainty. Second, the probability distribution of the states of nature is modified by information according to Bayes theorem and all decision makers have identical prior distributions. Third, the optimal action choice may not be uniquely determined from the available information. In other words, a decision maker may be indifferent between two action choices. Fourth, the preference ordering of action choices may be different for different utility functions.

If these conditions are met, information systems can readily be evaluated using this approach provided the conditional probabilities of states of nature given an information set can be computed. Estimating the probabilities of alternative events is not a simple task. For this reason, application of the approach has been limited to firm level problems.

3.4.2 Net Social Benefits Approach

A second approach, makes possible evaluation of alternative information systems by estimating the net social benefits associated with each system. This approach has been utilized primarily to estimate the value of statistical reporting of prices and aggregate supply (Hayami and Peterson, 1972).

The underlying model assumes that producers have an opportunity to adjust output in response to information and further, that output is adjusted along their supply curves. The adjustment process is analogous to the simple cobweb model.

Let equilibrium price be represented as P_e and equilibrium quantity by Q_e, the socially optimal solution (Figure 3.8). Suppose, however, that producers are unable to control their actual production for the period and produce a quantity, Q_1, greater than the equilibrium quantity, Q_e. If producers have perfect knowledge of the demand curve and an accurate prediction of Q_1, then following the adjustment process outlined by the cobweb model, producers will cut back supply to Q_A which results in price P_A. The net social loss is the area between the demand curve and the supply curve between Q_A and Q_e (abc).

Suppose that a statistical reporting agency overestimates output and predicts Q_B. Then producers will adjust by cutting back supply to Q_2 and the net social loss is measured as the triangle ade. Of course, following this reasoning, an underestimate of supply will reduce social loss if supply is greater than equilibrium supply. Predicting Q_3 results in a net social loss of aef. For supply below the equilibrium level, an underestimate increases social loss.

In the case of supply above equilibrium, the reduction in social loss by an underestimate does not offset the increase in social loss from an overestimate. The difference is shown by the shaded area in Figure 3.8.

The net social benefit (NSB) of perfect information is the difference between the social loss with perfect information and the average social loss with imperfect information. Mathematically,

$$NSB = abc - 1/2\ (ade + aef) \qquad (3\text{-}43)$$

Of course, no information system is expected to produce perfect information. The value of increased accuracy can be determined by comparing the net social losses associated with different information

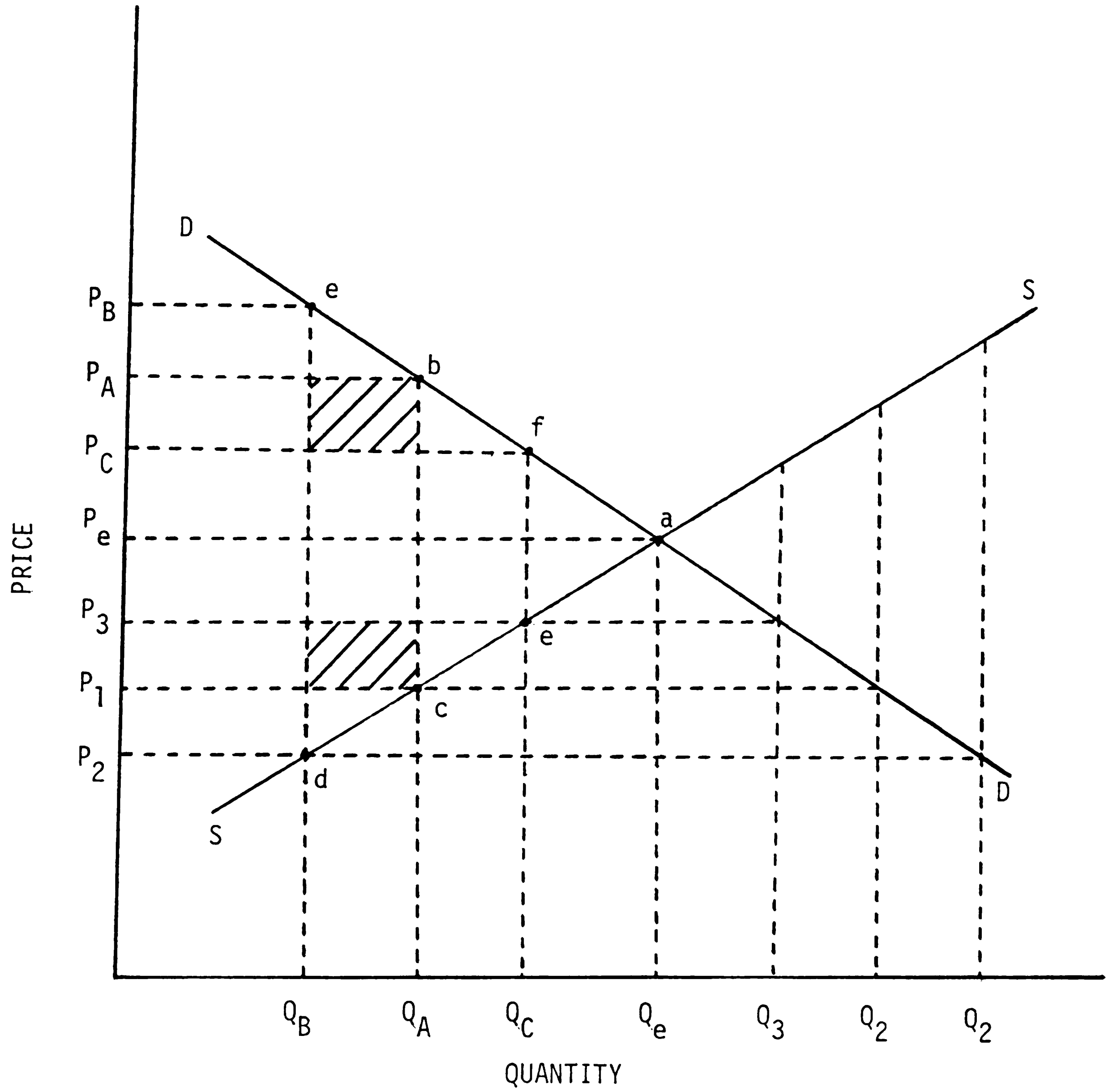

Figure 3.8 Supply adjustment with imperfect information

systems. This approach requires estimation of aggregate supply and demand curves. Elasticities from other studies can be used.

3.4.3 Production Function Approach

A third possible way to evaluate information systems is the production function approach. This approach is often used in the assessment of returns to research and/or agricultural extension. If the extension activities are defined as the dissemination of information (on crops, livestock, management, etc.), then returns to extension can be interpreted as returns to an information system.

Empirical studies often choose some form of the Cobb-Douglas production function to specify the relationship between the total value of farm output and extension. The following was employed by Huffman (1978):

$$\ln Y = A + B\ln X + C\ln Z + g\mathrm{Ext} \tag{3-44}$$

where

Y = total value of farm output

X = vector of variable inputs

Z = vector of fixed inputs

Ext = a measure of agricultural extension

The variable Ext can be measured in terms of dollars spent for extension activities. It is usually assumed that there is some lag between the implementation of an extension program and its effect on productivity. For this reason Ext is often lagged in the formulation of the production function.

It can be argued that returns to information from extension cannot be separated from returns to production inputs. If information affects the output or input mix then increases in efficiency should be captured in the coefficients of the input variables.

Even if the functional form is accepted, it is difficult to separate the effects of private information sources from extension information. In fact, none of the three approaches can distinguish between privately provided information and publicly provided information except perhaps through the cost of the information service.

CHAPTER IV

SIMULATION AND PEST MANAGEMENT

4.1 Introduction

The objective of modeling efforts with respect to pest management has been to better understand specific pest-crop ecosystems and from this understanding design pest management programs. A second, often overlooked objective, is to point out areas that are poorly understood in order to guide future research.

This chapter discusses the use of mathematical models in analysis of crop protection systems and the limitations of a modeling approach attributable to the abstractions from reality required by the modeling process. The first section describes the steps followed in constructing a model with particular attention given to the inclusion of control parameters. Issues that arise when using mathematical models in the analysis of management strategies are discussed. Some implications for the role of social scientists in model development are presented.

A model of the alfalfa-alfalfa weevil pest crop ecosystem developed as part of the International Biological Program on Biological Control of Insect Pests subproject on alfalfa will be described in detail in the second section. The third section outlines a decision model for alfalfa weevil control. This model linked with the alfalfa-alfalfa weevil model will be applied to the analysis of information systems in the final two chapters.

4.2 The Use of Mathematical Models in Pest Management

Mathematical models of ecosystems are, by definition, simplifications of the ecosystems they mirror.[1] Models are constructed to describe, predict and/or analyze the performance of systems under various sets of conditions. The objective may be to improve understanding of the system, evaluate the performance of the system or to develop control guidelines to maximize the performance of the system. In any case, the value of a model lies in its correspondence to the real world insofar as it contains practically important variables (Knight, 1921).

A useful distinction can be drawn between descriptive, predictive and prescriptive mathematical models. Descriptive models are used to explain the way a system behaves. They aid in isolating the aspects of a system that are poorly understood, unifying existing research and directing future research. Descriptive models consist of equations that describe the components of a system and the relationships that exist between the components. The effect of changes in parameter values (e.g. temperature and harvest date) on the state of the system can be simulated over time by solving the equation set at discrete time intervals.

For practical purposes the model cannot contain all possible variables or relationships among variables. It is the role of the modeler to decide what variables are important for the description of the system and which can be omitted. These judgments are often (but not necessarily) made within a decision making context.

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[1]The term model will hereafter refer to mathematical models.

Predictive models are used to predict the performance of a system under various sets of hypothetical conditions. Predictive models are usually based on descriptive models and past experience. In particular predictive models are used to predict the consequences of various management schemes. Of course, the predicted consequences are limited by the variables included in the model. In other words, the model cannot predict a change in the value of a variable that is not included in the model. Likewise, the model cannot predict the consequence of a management scheme that has not been clearly defined.

Prescriptive models are decision making models. They can be used to select a management scheme. Prescriptive models require the definition of a problem and a list of possible solutions. They encompass information about the constraints facing the decision maker.

Prescriptive models utilize predictive models to predict the outcomes of each possible management scheme. A normative common denominator must be selected in order to compare the outcomes. In other words, there must be a consistent way of assigning values to the outcomes.

Next a decision rule must be chosen for comparing the values of the outcomes. The maximum possible outcome may be different following different decision criteria.

Finally, a unique maximizing solution may not exist. It may be that applying a decision rule to a predictive model will not be able to order one management scheme as preferable to another.

Which attributes of the system are determined to be important depends on the objective or ultimate use of the modeling effort. This link between the construction and application of the model necessitates judgments to be made by the modelers and users of the model. Yet users of scientific models often ignore or are unaware of the imbedded value judgments or their consequences.

It is clear that evaluation of alternative management strategies requires assigning values to the units of measure that describe the behavior of the system. However, value judgments are made in every stage of the modeling process. From the onset, the modeler must choose the system to be studied, which aspects of the system are significant, how to represent the system mathematically, and data sources. All of these decisions introduce values into the analysis which affect the system performance predicted by the model, the control strategies possible, and ultimately the evaluation of the management strategies.

The selection of the problem to study represents a choice. From that point on, model construction requires decisions to be made reflecting the purpose, priorities and perceptions of the modeler. The systems boundaries established dictate what relationships can be included in the model. Manetsch and Park dichotomize the universe into the "system" (to be modeled) and the "environment" (the rest of the universe). They suggest that the system and environment be defined "so that the causal links from the system to the environment are 'weak'. That is, so that the effects of the system upon its enviroment can "safely be neglected" (Manetsch and Park 1974). Eugene Odum (1977) conceptualizes the system studied as part of a hierarchy of other systems. He suggests that a model look at the system next largest to the one of interest so that no important relationships are lost. In either case, problem definition means the selection of system components and variables perceived to be significant for the problem at hand. By necessity, certain phenomena are omitted or highly abstracted.

The spatial and temporal units in which the state and rate variables are defined must be established before any mathematical representation is possible. Simulation models isolate components of nature on a very small scale. In the alfalfa ecosystem model described below, the spatial unit is one square meter and the unit of time is one day. This approach allows for a richness in the model but also poses problems for interpretation of the model results for decision making. Clearly, any crop protection program is concerned with management of areas larger than one square meter. Further, yield per square meter is not a unit of measure that is useful to decison makers.

An obvious solution is simply to multiply the results by some number which will provide an estimate of yield per acre or yield per hectare. However, it is important to be aware of certain phenomena which are ignored in this process. Whether or not a variable is endogenous or exogenous to the system depends on the level of aggregation assumed.

If we interpret the design of the model as the firm level, that is, as a model of an isolated field, we ignore several environmental relationships important to pest management. The movement of alfalfa weevils and parasites from one field to another, the effect of a neighbor's control program on weevil and parasite populations and the development of pest resistance to insecticides are a few examples. A single age distribution for the plant, pest and parasite populations by the model is reasonable. It is also reasonable to consider the cost of control and the value of the crop as exogenous to the system under this interpretation.

If, on the other hand, the model design is interpreted as a model of alfalfa production for a region, ignoring the movement of pest and parasite populations in and out of the system may be appropriate. The development of resistance to insecticides by the weevil over time could be built into the model with some degree of difficulty. The value of maintaining a high parasite population also becomes meaningful.

However, this level of aggregation introduces other problems. A single management strategy and yield must be an oversimplification. It is unlikely that all growers in a region will cut or spray their alfalfa crop the same number of times in a season let alone on the same day. Alfalfa stands are of different varieties and ages producing different quantities and quality hay even under the same management practices. On a regional level the cost of control and the value of hay will no longer be exogenous to the system.

The system definition determines the alternative control strategies to be compared by the decision maker. The alfalfa ecosystem model includes only one pest and one crop. Therefore, crop rotation is not a possible control measure. Neither is growing alfalfa in locations where pest populations have traditionally been low. Other constraints on control parameters may reflect societal values. The pesticides available for use, and therefore, the survival rate due to insecticides is determined in part by government regulation.

The control strategies possible are limited by the temporal dimension of the model. Many crop models only simulate the growing season. Therefore, multi-year planning is not possible.

The benefits from reduced insecticide use most commonly cited are: 1) slowed development of resistance by the pest; 2) a higher survival rate for predators and parasites of the pest; 3) reduced environmental contamination; and 4) reduced cost of control. Only the last of these is a short run benefit. The other three can only be realized over several years. Quite often the overwintering habits of pests are poorly understood, making year to year estimates of infestation difficult. Therefore, the benefits of specific control strategies over time may be ignored or inaccurate.

To summarize, limitations of the applicability of mathematical models due to model specification have been discussed. Specificallly, the usefulness of a model is restricted by the problem definition as well as the temporal and spatial parameters selected to direct the modeling process. The limitations become increasingly apparent as innovative approaches to crop protection are developed through trial and error methods.

The need for comprehensive crop management programs that reflect the range of pests existing on an individual farm and within a region points to the construction of multi-pest, multi-crop models from a broader problem presentation. The management strategy followed by one grower has been shown to influence the efficacy of the management strategy adopted by another grower. Modeling efforts that exclude such externalities fail accurately to reveal the benefits and costs of crop protection. Finally, the management strategies followed in one year modify the success of a management strategy adopted in the future. This problem exists within a firm and between firms.

Scientists often look at a small piece of a system and do not think in a decision making framework. This is in part because their goal may be explanation of the system and not to develop methods for control of the system. Too often the social scientist is presented with data and information and asked to 'analyze' its economic implications. This task usually takes the form of developing a decision model driven by research already completed.

Unless the social scientist is involved in the design of the research from the beginning, it is unlikely that the information base will include specific phenomena he or she considers pertinent to the ensuing analysis, either because that aspect of the system has been ignored or because it is poorly understood or both. This is not to say that social scientists are not guilty of ignoring critical components and interactions within a system or of being unable to provide information to aid in better understanding those aspects of the system. Although Agricultural Economists have traditionally been concerned with improving system performance, perhaps too many resources have been devoted to developing the mathematics of optimization within narrow systems bounds.

This section has focused on the relationship between the design of mathematical models and their usefulness in the decision-making process. Nothing has been said about the decision criteria by which management strategies are compared. Yet this is usually where a discussion about values in decision making begins. The point is that judgments which strongly affect the outcome of a model and consequently the evaluation of the system are made throughout the modeling process. Briefly, description affects prescription. This relationship should never be overlooked in applying models to crop protection research.

Any modeling effort requires a simplification of the system being studied. The modeler must select which aspects of the system to include. Oversimplification may lead to a model that is useless for the purposes at hand. At the other extreme, a very complex model may be impossible to understand or too large and expensive to run (Gutierrez et al., 1979). The factors to be included in the model are determined by the objectives of the modelers and their perception of the system. It is necessary that the system be described in such a manner that the components and interactions beween the components of the system can be measured and quantified in a meaningful way.

Once the components of the system are identified, an analytical framework must be chosen. The principles of population ecology are readily applied to the simulation of crop production and protection. A crop can be viewed as a population of plants, each consisting of populations of plant parts (e.g., roots, stems, buds and leaves). Growth of plant parts is analogous to birth and development in animals. Similarly weeds, insects, pathogens and other pests can be described as populations of individuals.

In the earliest attempts at population models all individuals were considered to be identical (Nicholson and Bailey, 1935). That is, they were equally likely to survive in a given environment. Age dependent mortality could not be mimicked. Later models (Leslie, 1945) introduced age distribution among individuals to identify physiologically identical organisms. Age distribution can be represented as a continuous function or by dividing the population into discrete age classes. In either

case, the effects of various factors such as harvesting, insecticides, or weather on all individuals of the same species is no longer necessarily equivalent.

The next step in constructing the model is to define variables. They can be separated into two major categories. Variables describing the status or condition of a system are called state variables. Those describing the rates of change of factors described by state variables are called rate variables. For example, the number of individuals in an age class is a state variable. The maturation function for an age class is a rate variable.

Control variables are a special class of state variables. The values of state variables can be altered by man. For example, day length is not a control variable in a field crop situation because it cannot be altered by man. It is a state variable, however. In a greenhouse situation, day length is a control variable because day length can be lengthened through the use of artificial lights and shortened using black curtains.

The inclusion of control variables takes the ecosystem model out of the context of explanation and into the context of decision making. Once this shift in perspective occurs, the model must include a management component that generates values for the control variables defined.

Once the state and rate variables have been selected, mathematical expressions can be constructed that determine the values of the state and rate values over time.

4.3 Model of the Alfalfa-Alfalfa Weevil Agroecosystem

The agroecosystem model presented here is comprised of three major components (1) The alfalfa weevil submodel; (2) The alfalfa plant sub-model; and (3) The management sub-model. Each will be discussed briefly and then in more detail in the following sections.

The alfalfa weevil model used in this study was developed by William Ruesink, University of Illinois. The main components of the pest submodel are the alfalfa weevil and its primary parasite *Bathyplectes curculionis*. No other pests are included. Each of these components is further divided into discrete age classes. The alfalfa weevil life cycle is divided into thirteen age classes. That of the parasite is divided into three age classes (Figure 4.1). The number of individuals in any given age class changes with time. It is reduced as individuals mature and enter the next age class, and increases as individuals from the preceeding age class mature. The maturation rate is a function of temperature and is calculated separately for each age class. Oviposition (the laying of eggs) is simulated as maturation from the ovipositing adult stage to the egg stage.

The number of individuals in any given age class is also determined by the survival rates of the individuals entering the age class and the individuals remaining in the age class at any point in time. The survival rate depends in part on the effectiveness of the parasites. Briefly, the adult parasite attacks both the second and third instar larvae by laying their eggs inside the larvae. The parasite eggs mature and eventually eat and kill the weevil larvae. This process is described diagramatically in Figure 4.1.

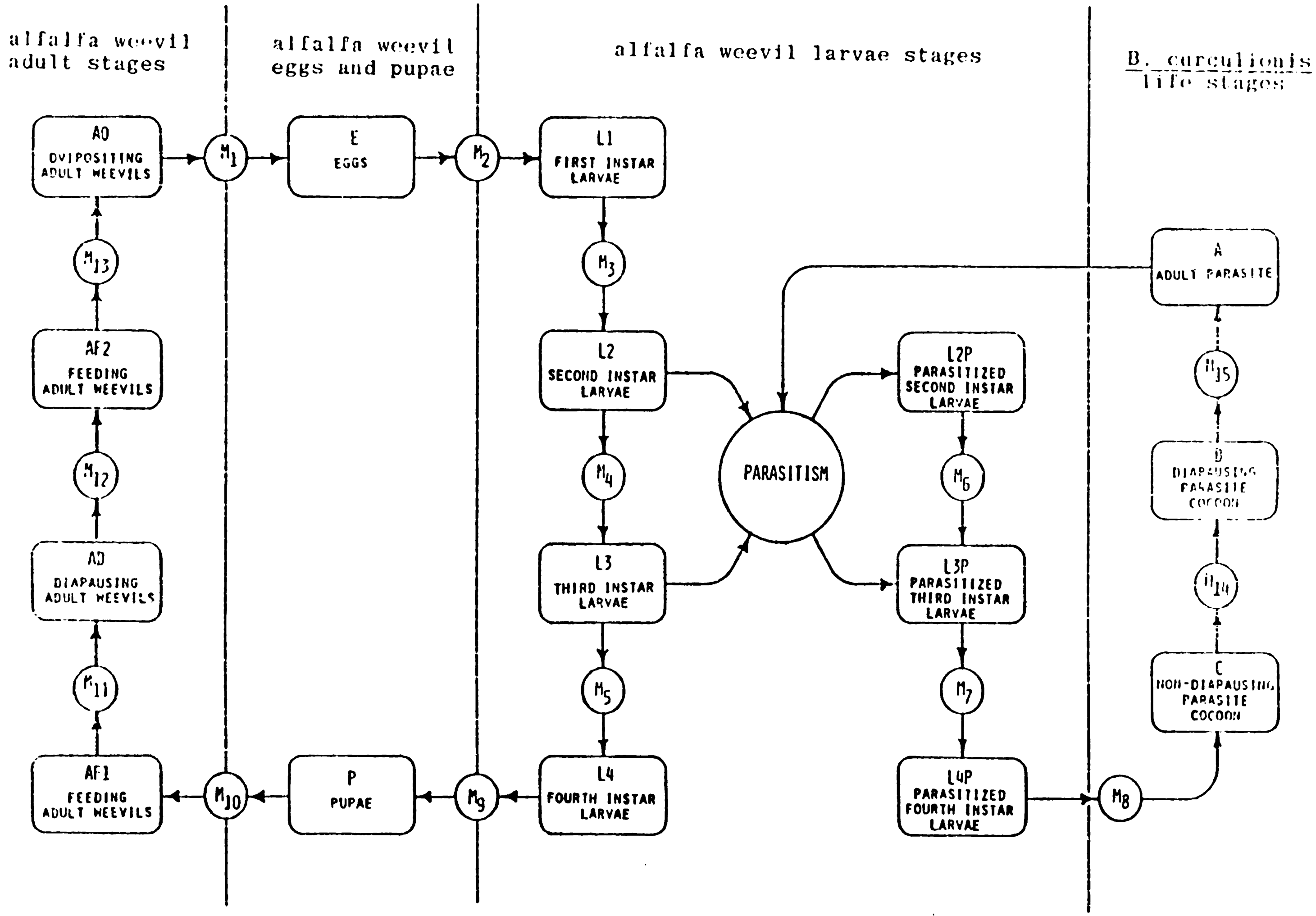

Figure 4.1. Flow chart description of the alfalfa weevil and <u>B. curculionis</u> life cycles. The maturation rate for each life stage i is m_i.

A set of difference equations predict the population levels for each age class over time from other state and rate variables. The difference equations are solved recursively. That is, the values of the state and rate variables at time t are used to calculate the values of the state variables at time t+1, the values at time t+1 are used to calculate the values at time t+2, and so forth. Numerical analysis of this type requires the specification of initial conditions.

Expressions for rate variables are solved analytically for each time period. In this model rates are defined by mathematical expressions that depend on present values of the state variables. For example, the survival rate $s_i(t)$ for age class i and time period t is a function of environmental conditions and pest control decisions for time period t.

The plant component of the alfalfa-alfalfa weevil model was developed by Dr. Gary Fick of Cornell University. ALSIM (ALfalfa SIMulation) is a model of material which flows between the environment and the alfalfa plants and within the plants. The state variables are expressed in grams of dry matter per square meter of field surface area as opposed to numbers of plants per square meter. Total yield is measured as the sum of the leaf and stem variables. Values of the state variables are updated in each time period based on rate equations (Figure 4.2).

The objective of pest management is to reduce crop losses due to pest damage by combining the available control methods. There are several possible methods for control of alfalfa weevil in alfalfa.

A means of biological control is the larval parasite described earlier. The parasite lays its eggs in the weevil larvae. The emerging

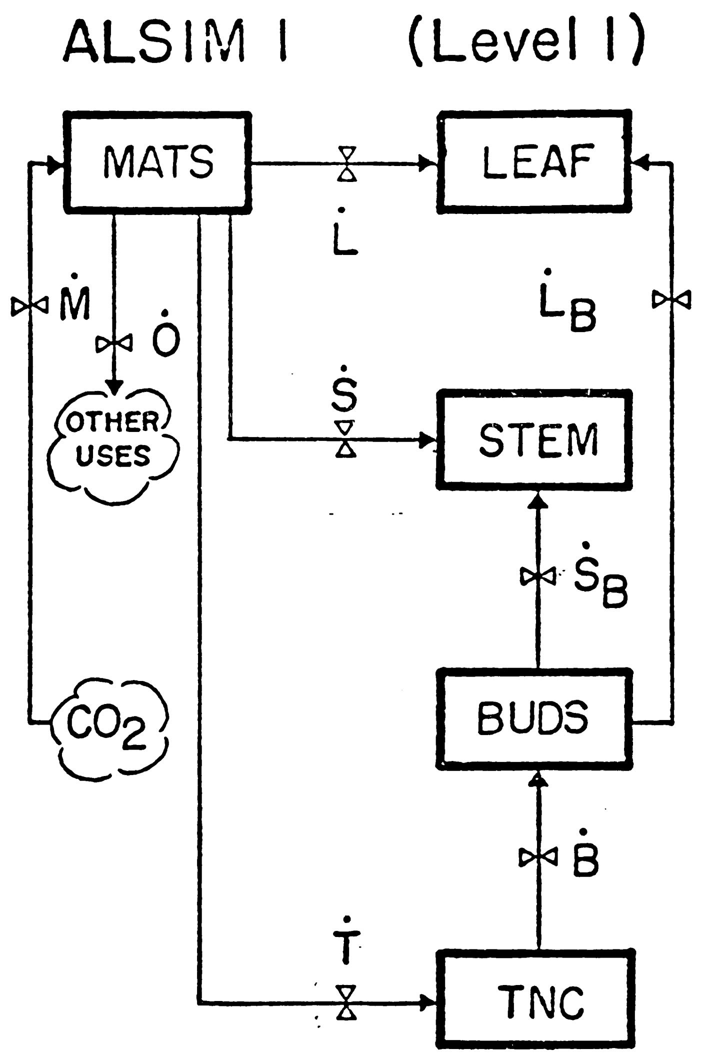

Fig.4.2 ALSIM 1 (LEVEL 1) is based on this model of material flow in the alfalfa crop. Rectangles represent the parts of the system modelled; arrows, the pathways of material flow; valve symbols, the rates controlling material flow; cloud symbols, parts of the system not treated in the model. Variable names are defined in the description of the model.

parasite larvae feed on the weevil larvae and eventually kill the weevil larvae.

Timing of the first cutting is another control measure. The act of harvesting alfalfa removes or kills many of the alfalfa weevils. The number of weevils that survive a harvest is age dependent. Most of the eggs and larvae do not survive a harvest, while the survival rate for the pupae and adult stages is much higher. Alfalfa is a perrenial crop cut up to four times during a season in Michigan. Crop loss due to weevil feeding can be reduced by harvesting when most of the weevil population is in life stages vulnerable to harvesting.

The method of harvesting also affects the survival rate. Mortalities due to harvest are relatively higher when the alfalfa is green chopped as opposed to cut with a sickle bar mower.

Insecticide application is the most common method of weevil control. Several insecticides are registered for use on alfalfa. One distinguishing characteristic of insecticides is their residual period. That is, the number of days they remain effectual after spraying. The toxicity of an insecticide decreases over time. Therefore, the survival rate due to insecticides is lowest on the day of applicaton and reaches 100% at the end of the residual period when the insecticide is no longer effective.

Insecticide mortality varies by age class. The egg and pupal stages of the weevil and the cocoon stages of the parasite are virtually unharmed by insecticides. The timing of the spray is critical for the best control of the weevil. Spraying too early may miss the larval stages of the weevil while spraying too late may not be in time to avoid crop damage.

In this study, the control variables to be manipulated in the management submodel are: (1) the timing of harvests and (2) the timing of insecticides. Parasites are present but not directly controlled.

Each of the submodels is linked together. The survival rate of the weevil population is a function of weather and management. Therefore, the control variables mentioned above can be linked to the pest model by adjusting the survival rates according to the control strategy employed. Also the management model directly affects the plant model through the timing of harvest.

The plant and pest models are linked through the weevil feeding on the plants. Feeding reduces the leaf, stem and bud areas of the plants. Also, if the plant population is destroyed, the insect population will decrease from lack of food.

To summarize, there are three main components of the model used in this study. They are (1) the alfalfa weevil population model, (2) the alfalfa plant model and (3) the management model. Each will be described in detail below. Then the linking of each component will be discussed.

4.3.1 Alfalfa Plant Simulation - ALSIM

ALSIM (ALfalfa SIMulation) is a computer program developed to simulate the growth and management of alfalfa. The modeling effort was carried out by Dr. Gary Fick of Cornell University originally as part of a project entitled "Integrated Pest Management - the Principles, Strategies and Tactics of Pest Population Regulation and Control in Major Crop Ecosystems" supported by a grant from the National Science Foundation and the Environmental Protection Agency.

ALSIM simulates dry matter yields of alfalfa for various cutting management using time steps of one day. Adequate soil moisture and fertility are assumed. The model also assumes the stand is at peak production. No adjustments are made for the age of the stand over time. Therefore, the model predicts optimal yield rather than expected yield.

There are five state variables in the core of the model (Figure 4.2). All are expressed in grams of dry matter per square meter of field surface area. They are:

1. MATS - material available for top growth and storage
2. LEAF - yield of leaves
3. STEM - yield of stems
4. TNC - yield of total nonstructural carbohydrates accumulated in the upper 10 cm of taproots
5. BUDS - yield of buds

MATS defines the supply of fixed carbon available to produce leaves (LEAF), stems (STEM) and nonstructural carbohydrates accumulated in taproots (TNC). TNC is the source of material for bud formation. In turn, leaves and stems are generated by the elongation of basal buds (BUDS).

The sections of the main program are arranged in the following order:

1. Initial section: input data and initialization calculations made at the start of the run
2. Crop weather section
3. MATS section
4. LEAF section
5. STEM section
6. TNC section

7. BUD section

8. Run control section - specifies time step between calculation of state variables, the number of days between printed output, output and format of output

The values of the state variables are updated daily in the appropriate section of the program using several rate equations. The new values of the state variables are computed as the sum of the current state level and the change in the state level over one day as follows:

$$V(t+1) = V(t) + RV\,(t)\,dt \qquad (4\text{-}3)$$

where

V(t) = yield of state variable V at time t;

V(t+1) = yield of state variable V at time t+1;

RV(t) = rate of change in V as computed at time t; and

dt = one day.

There are 14 rate variables in ALSIM. They are updated for each time period and are dimensioned in grams of dry matter per square meter of field surface per day.

1. M - potential rate of top growth and storage
2. L - growth rate of leaves
3. S - growth rate of stems
4. T - storage rate of TNC
5. O - other uses of MATS
6. B - growth rate of buds
7. L_B - growth rate of leaves coming from bud elongation
8. S_B - growth rate of stems coming from bud elongation
9. D_L - senescence rate of leaves
10. D_S - senescence rate of stems

11. F_L - freezing rate of leaves

12. F_S - freezing rate of stems

13. H_L - harvest rate of leaves

14. H_S - harvest rate of stems

The total rate of change for a state variable may be a function of several sources of change. For example, the rate variable for state variable STEM, is the difference between the growth rate of the stem and the maximum leaf loss attributable to harvest, freezing or senescence. It is calculated as:

$$RV_S(t) = S(t) - \max\ (H_S(t),\ F_S(t),\ D_S(t)) \qquad (4\text{-}4)$$

Where:

$RV_S(t)$ = the total rate of change in STEM at time t.

In the original model leaves, stems and buds could be removed by three processes: (1) death because of old age (senescence); (2) a killing frost or; (3) harvesting. In linking ALSIM with the insect model a fourth defoliation process was added to account for insect feeding.

4.3.2 Alfalfa Weevil Model

A model of the alfalfa weevil was developed under the direction of Dr. William Ruesink of the University of Illinois as part of the International Biological Program's integrated pest management subproject on alfalfa sponsored by NSF-EPA. The model simulates the life system of the alfalfa weevil and its primary parasite *Bathyplectes curculinois*.

The alfalfa weevil life cycle is divided into 13 stages. The parasite is represented by three stages (Figure 4.1) for a total of 16 stages. The model assumes that the second and third instars are attacked in equal proportion and that the first and fourth instars are never attacked. The stages for the alfalfa weevil are:

1. AO - ovipositing adult
2. E - egg
3. L1 - first instar larvae
4. L2 - second instar larvae
5. L3 - third instar larvae
6. L4 - fourth instar larvae
7. P - pupae
8. AF1 - feeding adults
9. AD - diapausing adults
10. AF2 - feeding adults
11. L2P - parasitized second instar larvae
12. L3P - parasitized third instar larvae
13. L4P - parasitized fourth instar larvae

The stages for the parasite are:

14. C - non-diapause cocoon stage
15. D - diapausing cocoon stage
16. A - adult

Changes in alfalfa weevil population due to parasitism are accounted for by calculating the number of parasitized larvae separately from the nonparasitized larvae. The population is reduced when parasitized fourth instar larvae enter the nondiapause cocoon stage of the parasite rather than the pupal stage of the weevil.

As individuals mature, they move from one life stage to the next. The number of individuals in each life stage is updated in the model using a one day time step. This requires estimation of the maturation rate for each life stage on each day. The procedure used in the alfalfa model will be described in detail below.

Each stage is divided into a number of cells. As an individual matures, it moves from the first cell in the stage to the last cell in that stage. From there the individual moves to the first cell of the next stage and so forth. The development of individuals can be conceptualized as moving through a train of boxcars where the first ten are painted red, the next fifteen are painted blue and the next five are painted yellow. This is analogous to three life stages. An individual must start in the first red boxcar and move to the second, third and so on. It cannot skip any boxcars to get to the end of the train. Once it has moved to the tenth boxcar it can get to the first blue boxcar. Once it has moved from the first blue boxcar to the fifteenth blue boxcar it can move to the first yellow boxcar and so forth. The laying of eggs is analogous to moving from the last yellow boxcar back into the red section.

The time interval used for maturation in the model is one calender day. The number of individuals in each life stage is updated each day. To determine the new number of individuals in each stage from the numbers in each stage on the previous day, two flows must be computed for each stage. They are (1) the number of individuals entering the stage from the previous stage, and (2) the number of individuals remaining in the stage. To accomplish this, a daily maturation rate is calculated for each stage.

In the alfalfa weevil model, the rate of physiological development is simulated by the number of cells that an individual advances in a day. A conceptual outline for updating the life stages will be explained, continuing the boxcar analogy. A rigorous description of the alfalfa weevil model will follow.

Let's suppose that the individuals in the red section move 2 boxcars a day and that the individuals in the blue section that follows mature 3 boxcars a day. Recall that there are ten red boxcars. The individuals in the first through eighth red boxcars will advance two boxcars to the third through tenth red boxcars and will remain within the red section. The individuals in cars nine and ten will move to the blue stage.

As soon as the individuals in the red stage mature into the blue stage the maturation rate switches from that of the red section (2 cells a day) to the maturation rate of the blue section (3 cells a day). The individuals that mature into the blue section in a day are in a sense placed in a momentary waiting room and then distributed equally among the first three boxcars in the blue section (since three is the maturation rate of the blue section).

There are fifteen boxcars in the blue section. If the daily maturation is three boxcars, then all of the individuals in the first seven boxcars on the previous day will remain in the blue section even after advancing three cars. The individuals that were in the last three cars the day before will move on to the yellow section.

Therefore, the number of individuals in the blue section is the sum of the number of individuals that moved in from the red section plus the number of individuals that moved within the blue section but did not get as far as the yellow section.

The procedure for updating the population counts in each cell of each stage is as follows:

1. Calculate the maturation rate for each life stage as the number of cells the individuals in each stage will advance.
2. Determine the number of individuals that will remain in each life stage.
3. Determine the distribution of the individuals remaining in each life stage among the cells in that life stage.
4. Determine the number of individuals entering each life stage from the previous life stage.
5. Determine the distribution of the individuals entering each stage from the previous life stage among the cells of that stage.
6. Calculate the population in each cell of each life stage as the sum of the individuals in step 3 and the individuals in step 5.

The actual calculation of the maturation rates in the alfalfa model will now be described.

Step 1

Rates of physiological development are a function of temperature. The effect of temperature on rate of development estimated by Ruesink is of the form proposed by Davidson (1944).

$$r_i(t) = \frac{a_i}{1+e^{[b_i - c_i * T(t)]}} \qquad (4\text{-}5)$$

Where:

$r_i(t)$ = instantaneous rate of development at time t for stage i;

$T(t)$ = instantaneous temperature at time t; and

a_i, b_i, c_i = constants.

The instantaneous temperature is approximated from the high and low temperatures for the day using the following equation:

$$T(t) = 1/2\ T_H(k) + T_L(k) + 1/2\ (T_H(k) - T_L(k))\ COS2\pi t \qquad (4\text{-}6)$$

where:

$T_L(k)$ = the low centigrade temperate on day k; and

$T_H(k)$ = the high centigrade temperature for day k.

Integrating equation (4-5) over the time interval of one day yields an average rate of development for stage i on day k, $R_i(k)$. It is calculated as:

$$R_i(k) = \int\ r_i(t)\ dt \qquad (4\text{-}7)$$

Let n_i be the total number of cells in stage i. Then

$$n_i{*}R_i(k) \qquad (4\text{-}8a)$$

is the number of cells an individual can mature during day k. This number may be different for each stage. Further, the value calculated may or may not be an integer.

An individual cannot mature a fraction of a stage. A procedure was developed for handling non-integer values of equation (4-8a). The daily maturation for stage i can be represented as:

$$n_i{*}R_i(k) = m_i + p_i \qquad (4\text{-}8b)$$

where m_i is an integer and p_i is a fraction less than one and greater than or equal to zero.

Then the maturation rate is greater than or equal to m_i and strictly less than m_i+1. Let X_{ij} represent the number of individuals in the jth cell of the ith stage. Then by convention $(p{*}X_{ij})$ individuals will move through m_i+1 cells and the remaining $(1-p)*X_{ij}$ individuals will advance m_i cells.

For example, suppose the movement for individuals in the third life stage is calculated to be 4¼ on day 120. Then some of the individuals will move four cells and some five cells. By convention, one fourth will advance five cells, and three fourths will move through only four cells.

Step 2

All individuals in a cell in stage i will advance m_i or m_i+1 cells during day k. Therefore, all individuals in cells numbered less than n_i-m_i will remain in stage i. And $(1-p)*X_{i,n_i-m_i}$ individuals will advance m_i cells from cell n_i-m_i to cell n_i.

Step 3

All individuals that were in stage i on day (k-1) will advance to a cell beyond m_i on day k. For cell m_i+1, a maximum of $(1-p)*(X_{ij}(k-1))$ individuals will advance m_i cells from cell one to cell m_i+1. For cells greater than m_i+1 and less than n_i within stage i, a maximum of $(1-p)*X_{i,j-m_i}(k-1)$ individuals will enter cell j from cell $j-m_i$ and $(p*X_{i,j-m_i-1}(k-1)$ individuals will enter cell j from cell $j-m_i-1$.

Step 4

All individuals in stage i-1 will advance m_{i-1} or $m_{i-1}+1$ cells during day k. Therefore, all individuals in cells numbered $n_{i-1}-m_{i-1}+1$ or greater will move into stage i. And $(p_i*X_{i-1,n_{i-1}-m_{i-1}})$ individuals will enter stage i from cell $n_{i-1}-m_{i-1}$ of stage i-1.

Step 5

Individuals moving into the i^{th} stage from the previous stage[2] on day k will advance m_i or m+1 cells. Therefore, individuals entering stage i cannot move beyond cell m_i+1 on day k. It follows that the individuals entering stage i cannot affect the number of individuals in cells beyond cell m+1. Further, cells 1 through m can only be filled by individuals moving out of the previous stage and into stage i.

It is necessary to determine the distribution of the individuals entering stage i among the m+1 cells they enter. Let $Y_{i-1}(k)$ be the number of individuals entering stage i from stage i-1 on day k.[2]

There are $Y_{i-1}(k)$ individuals entering stage i. Each enters into one of the first m_i+1 cells. If we assume that $\frac{m_i}{m_i+p_i} * Y_{i-1}(k)$ individuals are distributed equally in the first m_i cells, then $\frac{1}{m_i+p_i} * Y_{i-1}(k)$ individuals enter each of the first m_i cells. The remaining $\frac{p_i}{m_i+p_i} * Y_{i-1}(k)$ individuals enter cell m_i+1. All of the individuals entering stage i are accounted for since:

$$\frac{m_i}{m_i+p_i} * Y_{i-1}(k) + \frac{p_i}{m_i+p_i} * Y_{i-1}(k) = Y_{i-1}(k)$$

Step 6

It is clear from steps three and five that three equations are needed to update the population values in each cell of each stage; one for cells greater than m_i+1, one for cell m_i+1 and one for cells less than m_i*1. The results of Steps 3 and Step 5 are summed formally in the following equations:

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[2]The actual subscript will not always be i-1. For example, the stage previous to stage 1, ovipositing adult weevils is stage 10, feeding adults. For simplicity i-1 will be used in this discussion.

$$X_{ij}(k) = S_i(k-1)*[(1-p)*X_{i,j-m}(k-1) + p*X_{i,j-m-1}(k-1)],$$
$$m_i+1 < j < n_i \qquad (4-9)$$

$$X_{ij}(k) = S_i(k-1)*(1-p_i)*X_{i1}(k-1) + \frac{p_i}{m_i+p_i}*Y_{i-1}(k), \ j = m_i+1 \qquad (4-10)$$

$$X_{ij}(k) = \frac{Y_{i-1}(k)}{m_i+p_i}, \ 1 < j < m+1 \qquad (4-11)$$

The survival rate, $S_i(k)$ is an adjustment for mortalities. The survival rate is decreased due to: (1) spraying; (2) harvesting; (3) starvation and other causes (Table 4.1). Survival rates due to each of these causes are determined separately and then combined to define a single survival rate incorporating all three factors to be used in updating the population of each life stage.

Let $SS_i(k)$ be the survival rate for life stage i at time k when no insecticides are applied and no harvest takes place. $SS_i(k)$ is the percentage of the population in stage i at time k that survives in the next time period, k+1.

Further, let $SR_i(k)$ be the survival rate for life stage i at time k due to insecticide application at time t. Let $SH_i(t)$ be the survival rate for life stage i at time k attributable to harvesting as time k. The overall survival rate, $S_i(k)$ is expressed as:

$$S_i(k)=SS_i(k)*SR_i(k)*SH_i(k) \qquad (4-12)$$

If no harvest occurs at time k then $SH_i(k)$ equals one. Similarly, if no insecticide application is made at time k then $SR_i(k)$ equals one. Equation (4-12) reduces to:

$$S_i(k) = SS_i(k)$$

If, for example, a harvest is made at time k and only half of the population in life stage i survive then $SH_i(k)$ = .5. Further assume

Table 4.1

SURVIVAL RATES DUE TO INSECTICIDE AND HARVESTING AND OTHER CAUSES

Life Stage	Daily Insecticide Survival Rates[a/] 1[b/]	2	3	4	5	6	Harvesting Survival Rates Sickle Bar Mower	Green Chop	Maximum Survival Rates
A_0	.40	.52	.55	.60	.70	1.00	.80	.30	c/
E	1.00	1.00	1.00	1.00	1.00	1.00	.15	.05	1.00
L_1	.80	.84	.85	.87	.90	1.00	.00	.00	1.00
L_2	.40	.52	.55	.60	.70	1.00	.10	.02	1.00
L_3	.40	.52	.55	.60	.70	1.00	.30	.05	1.00
L_4	.40	.52	.55	.60	.70	1.00	.30	.05	1.00
P	1.00	1.00	1.00	1.00	1.00	1.00	.30	.30	.85
AF1	.40	.52	.55	.60	.70	1.00	.80	.30	.995
AD	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	.995
AF2	.40	.52	.55	.60	.70	1.00	.80	.30	.995
L2P	.40	.52	.55	.60	.70	1.00	.10	.02	1.00
L3P	.40	.52	.55	.60	.70	1.00	.30	.05	1.00
L4P	.40	.52	.55	.60	.70	1.00	.30	.05	1.00
C	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	.9918
D	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	.9918
A	.40	.52	.55	.60	.70	1.00	.80	.30	.9975

[a]Survival rates are based on a five day residual period for the insecticide.

[b]The day of the residual period is indicated. The day of spraying is considered the first day of the residual period.

[c]The survival rate for the ovipositing adult weevils is a function of the daily development rate.

that no insecticide application has been made. Then equation (4-12) is calculated as:

$S_i(k) = SS_i(k)*1.0*.5$

In this example, the survival rate is half of what it would have otherwise been if harvest had been postponed.

The egg, pupae and diapausing stages of the alfalfa weevil and the cocoon and diapausing stages of the parasite are unaffected by insecticides. The other stages, with the exception of the first instar larvae, have an initial insecticide survival rate of .4 on the day a spray is administered. The first instar larvae have a higher survival rate of .8.

The model has the option of five different residual periods for the insecticide to be initialized at the start of the simulation. The insecticide survival rate increases over the residual period reaching 1 the day after the residual period ends, using the following formulas:

$$SR_i(k)=(1 + SR_i(k-1)*(c-r))/(c-r+1) \qquad \text{for } c-r > 0,\ r = 0 \qquad (4\text{-}13a)$$

$$SR_i(k)=1 \qquad \text{otherwise} \qquad (4\text{-}13b)$$

Where:

$SR_i(k)$ = insecticide survival rate on day k for stage i;

$SR_i(k-1)$ = insecticide survival rate on previous day;

r = number of days since insecticide application; and

c = number of days in insecticide residual period.

The survival rates due to harvesting depend on the type of cutting. Two options are available, green chop or sickle bar mower. In both cutting systems the diapausing adult weevils and the two cocoon stages of the parasite are unaffected by harvesting. The harvesting survival rate is significantly higher for alfalfa cut with a sickle bar mower than green chopped (Table 4.1). If a harvest occurs during the residual period of an insecticide, the effect of the insecticide is negated. The survival rate in effect on the day of harvest is simply the survival rate for harvesting. The day after the harvest all survival rates due to harvesting and insecticides are set equal to one regardless of whether or not the harvest took place during the residual period.

The same harvest cannot be cut with a sickle bar mower and green chopped. Also a harvest and a spray cannot occur on the same day.

Mortality due to starvation is a function of total food available and total food desired. The relationship of the starvation rate to the total survival rate will be described in detail in the discussion of linking the plant and pest models below.

The survival rate due to other causes can be interpreted as the maximum survival rate. It is equal to 1 for the larval and egg stages of the weevil, .86 for the pupae stage and .995 for the adult stages except oviposition. The maximum survival rate for ovipositing adult weevils is a function of the daily average development rate from equation (4-7) as follows:

$$SS_1(k) = 1-.001*R_1(k)/n_1 \qquad (4\text{-}14)$$

Where:

$SS_1(k)$ = the maximum survival rate of ovipositing adult weevils on day k;

$R_1(k)$ = the average development rate for ovipositing adults on day k; and

n_1 = the number of cells in the oviposition stage.

To summarize, the overall survival rate is calculated by multiplying the maximum survival rate by the survival rate for insecticide and harvesting as follows:

$$S_i(k) = SS_i(k)*SR_i(k)*SH_i(k) \qquad (4\text{-}15)$$

where:

$S_i(k)$ = survival rate for stage i on day k;

$SS_i(k)$ = maximum survival rate for stage i on day k;

$SR_i(k)$ = survival rate due to insecticides; and

$SH_i(k)$ = survival rate due to harvesting.

The value of $S_i(k)$ is used in equations (4-8) - (4-11) to determine the number of surviving individuals leaving each stage and updating the number of individuals in each stage.

4.3.3 Linking the Alfalfa Plant and Alfalfa Weevil Models

The two models described above have been combined to simulate an alfalfa-alfalfa weevil agroecosystem managed by alternative harvesting and insecticide strategies under various temperature conditions. The level of alfalfa weevil feeding affects the plant while the status of the plant determines the availability of food and shelter for the weevil.

The amount of food desired daily is computed for each stage separately and then summed to determine the total food desired by the weevil. With the exception of prediapausing adult weevils, all individuals within a stage are assumed to desire the same quantity of food based on the following formula:

$$Y2_i(k) = C_i * R_j(k) * \sum_{j=1} X_{ij} \qquad i = 8 \qquad (4\text{-}16)$$

Where:

$Y2_i(k)$ = food desired by individuals in stage i on day k;

C_i = a constant;

$R_j(k)$ = average rate of development for stage i on day k;

x_{ij} = number of individuals in the j^{th} cell of stage i; and

n_i = number of cells in stage i.

Only the larval and nondiapausing adult stages feed on the plant. The number of eggs, pupae, diapausing adults and parasites does not contribute to the food desired. The constant term takes a zero value for the nonfeeding stages.

The maximum rate at which the nonparasitized larvae eat increases as they age. The amount of food desired by parasitized larvae also increases as they age but not to the extent that the amount increases for nonparasitized larvae. This is reflected in the constant term. The value of C increases with the instar number.

Adults emerging from the pupae stage desire more food as they age within the stage. This means that individuals in lower numbered cells desire less food than individuals in higher numbered cells. The food desired by the prediapausing adult stage is computed as:

$$Y2_8(k) = \sum_{J=1} X_{8j}(k)*R_8(k) - j*X_{8,j}(k)*R_8(k)/n_8 \qquad (4\text{-}17)$$

The amount of food desired by the ovipositing adults is adjusted by the amount of energy they have stored, or "food reserve level" and the temperature. The higher the food reserve level the less food is desired. The upper threshold for physical development is 86°F (30°C). Therefore, no feeding occurs above this temperature. These two factors are incorporated into the feeding equation (4-16) for ovipositing adults as follows:

$$Y2_1(k) = C_1*R_1(k)*(2-F(k))* \sum_{j=1} X_{ij};\ T_H(k) < 25 \qquad (4-18)$$

$$Y2_1(k) = C_1*R_1(k)*(2-F(k)*(30-T_H(k))*\sum_{j=1} X_{ij}/5,$$

$$25 < T_H(k) < 30 \qquad (4-19)$$

$$Y2_1(k) = 0; \qquad 30 \leq T_H(k) \qquad (4-20)$$

The food reserve level is calculated as:

$$F(k) = F(k-1) + [.2*Y3_1(k-1) -.004*Y1_1(k-1)$$

$$-.004*E(F(k-1))]/ \sum_{j=1}^{n_i} X_{1j} \qquad (4-21)$$

where:

$F(k)$ = food reserve level on day k;

$Y3_1(k-1)$ = total food eaten by individuals in the oviposition stage of the alfalfa weevil on day k-1;

$Y2_1(k-1)$ = total food desired by individuals in the oviposition stage of the alfalfa weevil at day k-1;

$Y1_1(k-1)$ = total number of eggs laid by ovipositing adult weevils;

$E(F(k-1))$ = respiration rate on day k-1;

X_{ij} = number of individuals in the j^{th} cell of the oviposition stage; and

n_i = number of cells in the ith stage.

The food reserve level is increased by feeding and decreased by the laying of eggs and respiration which require the expenditure of energy. The food reserve level is constrained to a value ranging from 0 to 2.

The food reserve level also affect the rate of oviposition (the number of eggs laid) for adult weevils. The number of individuals leaving the oviposition stage equals the number of eggs laid and is computed as:

$$Y1_1(k) = Y3_1(k)*R_1(k)*G[F(k),X_1(k)]/Y2_1(k); \quad Y2_1(k) > 0 \qquad (4\text{-}22)$$

$$Y1_1(k) = 0; \quad Y2_1(k) = 0 \qquad (4\text{-}23)$$

The function G adjusts the oviposition rate by the food reserve level and the distribution of individuals among the cells of the oviposition stage. The value of G and, hence, of $Y1_1$ increases as the food reserve level increases. The oviposition rate increases from the first to the second cell of the stage and then decreases at a constant rate as the cell number increases.

A third way in which the status of the plant can limit weevil population is through starvation. The survival rate is adjusted for the situation in which the total food desired is greater than the total food available in the following manner:

$$SM_i(k) = [(a_i + b_i*\sum_{i=1}^{16} Y3_i(k))/ \sum_{i=1}^{16} Y2_i(k)]*SS_i(k) \qquad (4\text{-}24)$$

where:

$SM_i(k)$ = the maximum survival rate adjusted for mortalities due to starvation for stage i;

a_i, b_i = constants for stage i;

Σ $Y3_i(k)$ = total food eaten on day k by the weevils in stage i;

Σ $Y2_i(k)$ = total food desired by the weevil on day k; and

$SS_i(k)$ = the maximum survival rate for stage i on day k in stage i.

The term $SM_i(k)$ can be interpreted as the survival rate of stage i on day k due to causes other than insecticides or harvesting.

Starvation only occurs when the total amount of food desired is less than the total amount of food available. Of course, nonfeeding life stages cannot suffer mortalities due to starvation. The larval stages of the weevil are reduced in greater proportion due to an inadequate food source than are the feeding adult stages. Further, parasitized larvae are less affected than non-parasitized larvae (Table 4.1).

The plant also provides shelter for the adult weevils during diapause. The alfalfa weevil enters diapause in late August to escape the heat and high humidity of late summer. At this time, the weevils look for a covered area in which to diapause. Therefore, the amount of cover available from the plants influences the percentage of the weevils that remain in the field and the percentage of weevils that seek diapause sites outside the field. This phenomena is described in the equation:

$$PY_8(k) = .8*(1-e^r)*e^{-.01}*(LEAF+STEM) \qquad (4\text{-}25)$$

where:

$PY_8(k)$ = the percent of adult weevils leaving the AF1 stage and entering diapause on day k remaining in the field;

r = the respiration rate of the prediapausing adults;

LEAF = yield of leaves in g/m^2; and

STEM = yield of stems in g/m^2.

The percentage of weevils entering diapause and remaining in the field is positively related to the values of LEAF and STEM. The percentage of weevils that do not remain in the field are assumed to diapause elsewhere and not to return to the field. The number of individuals entering diapause on a particular day and remaining in the system is then:

$$Y_8(k) = S_8(k)*PY_8(k)*Y_8(k) \qquad (4\text{-}26)$$

where:

$Y_8(k)$ = the number of adult weevils entering diapause and remaining in the field;

$S_8(k)$ = the survival rate of prediapause adult weevils;

$PY_8(k)$ = the percentage of adult weevils entering diapause and remaining in the field; and

$Y_8(k)$ = the number of weevils maturing out of the prediapause adult stage.

Equations (4-25) and (4-26) allow for weevils to leave the field, but not to return to the field. It should also be noted that the model does not allow for weevils from other locations to enter the system. Therefore, equations (4-25) and (4-26) determine the number of weevils that overwinter in the field the initial population for the next growing season, and hence, the populations for all subsequent growing seasons. In other words, the level of infestation in a given year is related to the status of the crop in the previous year while the adult weevils were entering diapause. This means that the model results for one year are sensitive to the timing of cuttings in late summer and fall of the previous season if the model is run for more than one season.

Until this point, the discussion has focused on the impact of the plant status on weevil population. The impact of weevil feeding on plant development and crop production will now be addressed.

The alfalfa weevil feeds solely on the leaves of the plants unless the food supplied by the leaves is less than the food desired by all life stages of the weevil. In this case the weevil will feed on the buds. During the winter months when the plants are dormant, the only food available to the weevil is the basal buds of the plants.

Reduction of the leaves by weevil feeding directly impacts each section of the plant model. The potential growth rate of top growth in the MATS section is a function of solar radiation absorbed by the plants which is positively related to the total leaf area. The materials available for top growth and storage for that day are, therefore, positively related to the measure of leaves on that day.

The growth rates of both leaves (GRL) and stems (GRS) are a function of materials available for growth (MATS) which is a function of the leaves remaining from the previous day. The amounts of the available materials used for leaf and stem growth respectively are also determined in part by the measure of leaves. Keeping in mind that the available materials are essentially used either for leaf growth, stem growth or storage in the roots. It follows that the rate of TNC accumulation in the roots (STOR) is influenced by the amount of existing leaves in several ways.

When more materials are available for top growth and storage the potential rate of TNC storage in the roots is higher. Therefore, the actual change in TNC storage corresponding to a change in available materials will depend on the changes in stem and leaf growth as well as the materials available. The growth rate of leaves (i.e. the quantity of available materials used for leaf growth) may either increase or decrease with a reduction in the quantity of leaves depending on the day length, temperature and status of the plant.

Two effects occur simultaneously when leaf area is reduced. During the growing season, a reduction in the quantity of leaves will always bring about an increase in the percentage of available energy the plant will put into growing leaves and a decrease in the percentage it will put into growing stems and/or root storage. The reduction in leaves will also reduce the total amount of available energy for growth.

The plant will respond by increasing the portion of the shrinking energy pie allotted to leaf growing relative to stem growth and energy storage. The net result may either be an increase or decrease in the total energy allotted to leaf growth depending on the change in the size of the pie brought about by the leaf reduction. In either case the growth rate of the stems and the storage of TNC in the roots will decrease.

The growth rate of buds will decrease as a result of defoliation. If the weevils also feed on the buds, the growth of the stems and leaves from bud elongation will be reduced.

4.4 Modification of the Model to Include Hay Quality

Information only has value in the context of a decision. In order to determine the monetary value of information, the yield associated with each information system must also be assigned a monetary value. The value of the alfalfa yield per acre is a function of both the quantity and quality of the hay. Both are affected by the choice of management strategy.

While the model presented predicts the quantity of hay under different strategies, it does not include quality considerations. The management tactics considered include timing of harvest, insecticide applications and parasite population. All are geared towards the reduction of pest numbers to decrease crop loss. Therefore, the effect of management on quality must consider the effect of harvest date on quality and the effect of larval feeding on quality.

It is generally assumed that the quality of alfalfa is lower at later harvest dates. This is due to both changes in the chemical composition of the leaves and stems, and a change in the leaf to stem ratio with advancing maturity of plants. In the study of several forages including alfalfa by Mowart et al. (1965), *in vitro* digestible dry matter and percent crude protein decreased with maturity of the plant. The percentage of *in vitro* digestible nutrients decreased at a much greater rate for alfalfa stems than leaves. The percentage crude protein content of both leaves and stems decreased at about the same rate.

One hypothesis is that larval feeding reduces the quality of alfalfa because the leaf-stem ratio is reduced (Flessel and Niemczyk, 1971). This hypothesis is based on the observation that alfalfa weevil larvae feed primarily on the leaves of alfalfa plants and that the nutrient content of leaves is higher than for stems. However, empirical work has not supported this hypothesis. The most plausible explanation is that while larvae do feed on leaves, the reduction in leaf area also retards stem growth, leaving the leaf-stem ratio unchanged.

Lui and Fick (1975) measured the effect of the alfalfa weevil on yield and quality of alfalfa herbage in New York for two-cut and three-cut systems in two consecutive test years. The effect of weevil feeding on quality of total herbage, as measured by crude protein and *in vitro* true digestibility was not statistically significant. The effect of feeding on leaf weight, as a percent of total plant weight, was also insignificant apparently because stem growth was also adversely influenced. Hastings and Pepper (1953) also found percent protein to be unchanged by larval feeding.

Hintz, Wilson and Armbrust (1976) estimated the yield loss attributed to one larvae per stem using regression analysis. The effect of larval feeding on in vitro dry matter digestibility and crude protein was also studied. Reduction in quality (percent in vitro digestible nutrients and percent crude protein) attributable to larval feeding was significant in only one of the three study years. For that year, quality decreased at a decreasing rate as larval density increased.

Wilson, et al. (1979) also observed reductions in yield attributable to alfalfa weevil. They found larval feeding significantly reduced the percent crude protein of the first cutting. Their results are consistent with theoretical work but inconsistent with other empirical work cited above. (Lui and Fick, 1975; Hastings and Pepper, 1953; Hintz, Wilson and Armbrust, 1976).

The work cited supports the claim that later cutting of alfalfa decreases quality but larval feeding does not. Data collected in Central Michigan in 1972 and 1974 was used to measure the effect of harvest date on various quality measures and test the hypothesis that larval feeding reduces quality. The experiment is described in detail in sec. 4.7.

Percentages of acid detergent fiber, protein and in vitro digestible organic matter were used as measures of alfalfa quality (Table 4.2). Yield, quality and larvae population were measured for 1972 and 1974. The affect of larval population and harvest date on each quality measure was analyzed. Harvest data was measured in degree days

Table 4.2

MEANS OF YIELD AND QUALITY OF TREATED AND UNTREATED ALFALFA CUT AT DIFFERENT DATES[a]

			Untreated					Treated				
Year	Date of Harvest	Degree Days Base 41°[b]	Yield Tons/Acre	Moisture %	In Vitro Digestible Nutrients %	Crude Protein %	Acid Detergent Fiber %	Yield Tons/Acre	Moisture %	In Vitro Digestible Nutrients %	Crude Protein %	Acid Detergent Fiber %
1972	5/24	679	1.5	84.6	75.1	25.1	22.6	1.8	84.5	74.9	24.1	23.8
	6/5	953	2.2	80.1	65.5	18.5	33.8	3.0	82.1	68.6	19.4	30.7
	6/14	1,178	2.7	79.5	61.9	17.1	36.9	3.9	82.0	65.5	17.3	35.3
	6/27	1,480	3.1	77.5	61.5	16.1	36.2	3.6	59.8	59.8	14.7	40.1
1974												
	5/20	591	1.6	83.3	66.0	26.1	20.3	1.7	82.0	66.1	25.9	20.5
	5/31	811	2.3	83.9	65.3	22.9	27.8	2.4	84.4	64.9	23.0	27.2
	6/10	1,093	2.4	81.4	61.1	20.1	33.5	2.9	82.6	62.3	20.5	32.9
	6/20	1,302	2.7	79.7	57.8	19.7	35.1	3.4	81.4	58.8	19.5	34.7
	7/1	1,563	3.7	72.7	56.9	17.8	35.5	4.4	73.8	56.4	17.3	36.3

[a] All nutrient values are presented on a dry matter basis.

[b] Calculated using the B-E method adjusted for temperatures above 86 degrees F (Baskerville and Emin, 1969).

base 41°F and larval population in larvae degree days.[3]

There was no significant difference (P < 10%) between the sprayed and unsprayed plots for any of the quality measures. Controlling larval feeding did not influence the quality of the alfalfa appreciably. Although yields of leaves and stems were not measured separately, it is assumed that stem growth is retarded by feeding on leaves.

The quality measures were significantly different for the two years. This can probably be explained by the differences in the age and variety of the stands used in the experiment.

Differences in quality measures were statistically significant for the different harvest dates for each season. Percentages of acid-detergent fiber (F), crude protein (P) and *in vitro* digestible nutrients (INVDN) were estimated as linear functions of accumulated degree days at the time of harvest (D) for each year (Table 4.3). Earlier cutting increased percentage of crude protein in *in vitro* digestible nutrients, while decreasing the percentages of fiber.

Looking at both years of data, the values for crude protein ranged from 16 to 26 percent, from 20 to 37 percent for fiber and from 60 to 75 percent for *in vitro* digestible dry matter. The relative sensitivity of the quality measures to harvest date is not obvious from the values of the coefficients. Although the absolute change of any quality measure for a given change in growing degree days is greatest for INVDN (i.e., the coefficient of D is largest), the change is less than for

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[3]Larvae degree days is accumulative measure of the number of larvae that have been feeding over a period of time. The procedure for calculation is described in 3.2.

Table 4.3

THE EFFECT OF TEMPERATURE ACCUMULATION ON
QUALITY MEASURES OF ALFALFA

Quality Measure	Year	Intercept	dd41	R^2
% Crude Protein	1974	30.22 (.59)	-.008 (.0005)	.87
	1972	31.00 (1.28)	-.011 (.001)	.76
% Acid Detergent Fiber	1974	13.46 (1.18)	-0.16 (.001)	.86
	1972	12.74 (2.03)	-.018 (.002)	.77
% in vitro Digestible Nutrients	1974	72.81 (.99)	-.010 (.0009)	.79
	1972	85.40 (1.97)	-.018 (.002)	.77

Numbers in parentheses are standard errors percent fiber or percent crude protein. That is, the proportion by which INVDN changes is less for a given change in growing degree days.

In order to compare the relative effects of harvest date among the quality measures the average percent change in the quality measure (e.g., the percent change in the percent crude protein) associated with the average percent change in degree days between harvests was calculated for each quality measure. The ratios of the percent change in the quality measure to the percent change in degree days ranged from .42 to .62 averaging .56 for F and P. The average ratio for INVDN was .28.

The results can be interpreted as follows: On the average a 1 pecent change in degree days is associated with a .56 percent change in F and P. On the other hand, a 1 percent change in degree days is associated with a .28 percent change in INVDN. INVDN was found to be relatively less sensitive to changes in harvest date than either percent crude protein or percent fiber. No statistically significant ($P<10\%$) difference in the relative responsiveness of percent crude protein and percent fiber to harvest date was found.

It was decided that percent crude protein would act as an adequate proxy for quality. Statistical tests demonstrated that pooling the data for both years would result in a specification error in the regression equation. Therefore, only the coefficients derived from the 1972 data were used. The 1972 data was selected because it was consistent with other data sets.

The relationship between quality and harvest data is captured in the following equation:

$$PRO = 31.0013 - .01115*DD41 \qquad (4\text{-}27)$$
$$(1.28) \qquad (.001)$$

The numbers in parentheses are standard deviations. DD41 is degree days base 41°F (5°C) the developmental threshold for alfalfa plant growth (Holt, 1975). PRO is the percentage crude protein estimated by using the Kieldahl procedure for determining nitrogen content. The value of R^2 for the equation is .76. The coefficient of DD41 has the expected sign and is significant at the .01 level.

It remains to assign monetary values for different protein levels. Because alfalfa is primarily used as feed for the operation that grows it, there is no real market for alfalfa in Michigan. The value of different quality hay can be estimated as value in use. This was accomplished using a model devloped at Michigan State University to simulate the effect of feed mix on milk production for a single cow (Black and Hlubik, 1978). The percentage protein available to the cow is approximately 2 percent lower than the percentage measured as cut. This is due to a decline in quality from field to storage. The model is driven off the amount of protein available to the cow.

Ration balancing runs were made for 16 percent protein (low quality) and 20 percent protein (high quality) alfalfa holding milk production and cost of the ration constant (Table 4.4). As would be expected, the amount of soybean meal and shelled corn required to balance the ration is lower for the higher quality alfalfa and the amount of corn silage is higher. The savings from feeding less of the high-cost ingredients and more of the low-cost corn silage is used to capture the value of high quality alfalfa.

Table 4.4 Ration Composition and Ingredient Costs for Feeding High Quality and Low Quality Alfalfa for a Constant Level of Dairy Production and Ration Cost

HIGH QUALITY ALFALFA (20% Protein)

	Amount Fed	Cost	Total Cost
	KG	¢/KG	¢
Alfalfa	.230	10.15	2.33
Corn Silage	.230	6.70	1.54
Shelled Corn	.487	11.56	5.63
Soybean Meal	.049	26.59	1.30
TOTAL			10.80

LOW QUALITY ALFALFA (16% Protein)

	Amount Fed	Cost	Total Cost
	KG	¢/KG	¢
Alfalfa	.191	7.03	1.34
Corn Silage	.191	6.70	1.28
Shelled Corn	.547	11.56	6.32
Soybean Meal	.070	26.59	1.86
TOTAL			10.80

The linear equation was fit between the two points estimated. The resulting equation is:

$$VALUE = -54.3 + 7.7875*PA \qquad (4\text{-}28)$$

where:

PA is the percentage of protein available to the cow.

Equations 4-27 and 4-28 were used to assign monetary values to the yield predicted by the simulation model. This quantitative measure facilitated comparison of alternative control tactics and information included in alternative decision algorithms.

4.5 Management Model

Pest control guidelines are algorithms for the implementation of pest control strategies. By definition an algorithm is a procedure for solving a problem. Pest control guidelines specify how to produce output information from input information. The output information is a suggested course of action for a particular grower. The input information required is specific to the algorithm or guideline.

The set of possible recommendations (output information) is also specific to the algorithm. For example, if an algorithm is designed to generate a spray recommendation no set of input data will generate a recommended harvest date. On the other hand, if the algorithm requires temperature data but no temperature data is available, the algorithm cannot be operationalized.

Algorithms for pest control decision making are designed in a number of ways. Typically, guidelines take the form of economic thresholds for specific crops, pests and climates. Economic threshold is defined as the pest population at which control measures should be initiated (Stern, 1959). A distinction is made between a static and dynamic threshold. The use of the term dynamic and static by entomologists is not synonymous to the use by economists.

The definition of the terms static and dynamic to describe decision models in economic theory can be attributed to J.R. Hicks, Value and Capital, 2nd ed. (1946). "I call Economic Statics those parts of economic theory where we do not trouble about dating; Economic Dynamics those parts where only quantity must be dated." Following this definition, a static model describes decision making in an unchanging environment. A dynamic model would be a theory of how individuals make decisions in a changing environment, or theory about how the world changes.

To an entomologist both static and dynamic thresholds are used to make decisions in a changing environment. It is not a question of whether or not the variables observed to make the decision change over time. Rather it is a question of whether or not the decision criteria "must be dated".

A static threshold is one that does not change over time. That is, the critical population level does not vary with the status of the plant, the time until harvest or the weather forecast. Therefore, the only information needed to make a pest control decision using a static threshold is the threshold level and the pest population in the field. A static threshold may vary with location.

In contrast, a dynamic threshold changes with time. Consequently, the control decision is more complex than for a static threshold. The threshold may change with the accumulated degree days, or plant status as well as with the pest level in the field.

In both cases, the threshold is developed from accumulated knowledge. Implementation requires real-time information from monitoring. How effective a management strategy based on a threshold is depends upon the accuracy of the threshold and the accuracy of the monitoring activity. To some extent there is a tradeoff between the accuracy of the threshold and the monitoring information.

Of course, not all pest control strategies depend upon monitoring information. For example, routine sprays, crop rotation and the "do nothing" alternative do not require assessment of the current pest-crop situation. The control decision might be based on past experience (pests have not been a problem in this field) or the advice of others.

Another alternative to explicit thresholds is cost-benefit analysis. In this approach expected costs and benefits of control are calculated based upon monitoring information. The threshold concept is implicit in this procedure but not explicit.

Three basic approaches to the control of alfalfa weevil are: (1) timing of harvest, (2) timing of insecticide application, and (3) managing parasite populations. The strategies are not independent. Early harvest may eliminate the need for a spray. Spraying and harvesting reduce the pest population but also the parasite populations.

Seven alternative guidelines for control of alfalfa weevil will be defined. Each of these guidelines comprises a decision making algorithm. Each is a distinct management model. The information requirements for operationalizing each will be made explicit. For each set of guidelines, unless an early harvest is recommended, the first harvest is made after 1200 degree days (base 41°F) have accumulated after January 1. The second and third harvests are set at 1200 degree days after the previous harvest. This harvest schedule will be referred to as the default schedule.

A harvest is simulated by cutting all of the alfalfa in one day. In practice a harvest takes place over several days because of machinery limitations. Therefore, the yields and quality measures generated by the simulation model should be viewed as averages for the three to four day periods over which a harvest would actually take place.

When hay is rained on, after it is cut and before it is baled, leaves are knocked off and the quality is greatly reduced. Also, there is a chance of mold. The model does not simulate sporatic rainfall, however, and cannot account for this phenomenon. Therefore, the quality measures generated by the model are optimal and not average values.

1. Dynamic Threshold Derived from the Simulation Model. A set of control guidelines was developed by William Ruesink based on the results of multiple runs on the alfalfa-alfalfa weevil model (described in section 4.3) using real weather data from Illinois (Table 4.5). Insecticide application is recommended (or not) based on the height of the alfalfa plant, accumulated degree days and the larvae count. Specifically, the information that must be acquired for implementation is:

a. Accumulated degree days after January 1 base 48°F

b. Number of larvae on a 30-stem sample

c. The average height of 10 stems from the original 30-stem sample

The guidelines are based on the following conceptualization. A spray should (should not) be applied if, and only if, X number of larvae are observed at biological time Y degree days. In that case, the value of the expected crop loss will (will not) exceed the cost of control.

Implicit in this approach is a prediction of pest population based upon current larvae numbers and degree days and the associated crop loss based upon the predicted pest population and the current status of the plant.

The frequency of sampling is directed by the field observations. Unwarranted monitoring is avoided when larvae populations are unthreateningly low and the "larvae season" is over. The cost of the strategy is equal to the cost of monitoring plus the cost of any insecticide that may be applied.

Table 4.5 Alfalfa weevil pest management recommendation chart 1 number of larvae collected from a 30-stem sample

	Alfalfa Height (inches)																
Total degree-days (dd)	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18+
190-210																	
SPRAY	27	47	67	85	100	115	130										
Resample in 50 dd	0-26	0-46	0-66	0-84	0-99	0-114	0-129										
240-260																	
SPRAY	21	30	39	47	55	62	69	69	69								
Resample in 50 dd	0-20	0-29	0-38	0-46	0-54	0-61	0-68	0-68	0-68								
290-310																	
SPRAY		25	37	52	67	75	83	94	105	105	105						
Resample in 50 dd		0-24	0-36	0-51	0-66	0-74	0-82	0-93	0-104	0-104	0-104						
340-360																	
SPRAY					82	82	82	82	82	82	82	82	82	82	82		
Resample in 50 dd					14-81	14-81	14-81	14-81	14-81	14-81	17-81	17-81	17-81	17-81	17-81		
Resample in 100 dd[a]					0-13	0-13	0-13	0-13	0-13	0-13	0-16	0-16	0-16	0-16	0-16		

Table 4.5 - Continued

Total degree-days (dd)	Alfalfa Height (inches) 2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18+
390-510																	
SPRAY										52	52	58	64	68	72	74	80
Resample in 50 dd										8-51	8-51	8-57	14-63	14-67	14-71	18-75	18-79
Resample in 100 dd										0-7	0-7	0-7	0-13	0-13	0-15	0-17	0-17
340 to harvest (See chart 2)																	
100 after harvest																	
SPRAY	23	33	43	48	53	58	63										
Resample in 50 dd	17-22	17-32	17-42	20-47	23-52	23-57	23-62										
Resample in 100 dd[b]	0-16	0-16	0-16	0-19	0-22	0-22	0-22										
150 or more after harvest (See chart 2)																	

[a] If this field was sprayed more than 7 days ago, you can wait 200 degree-days to resample.

[b] If last preharvest sample had less than 30 larvae, the weevil season is over and you can quit sampling.

Table 4.5 (cont.) Alfalfa Weevil Pest Management Recommendation Chart 2

Total degree-days (dd)	Change in number of larvae since last sample		
	Decreased 10 or more	Within 10	Increased 10 or more
540 to harvest			
SPRAY or harvest	73	63	53
Resample in 50 dd	23-72	18-62	13-52
Resample in 100 dd[a]	0-22	0-17	0-12
150 or more after harvest			
SPRAY	78	58	48
Resample in 50 dd	28-77	18-57	0-47
Quit sampling	0-27	0-17	

[a] If sprayed more than 7 days ago, you can wait 200 degree-days to resample.

Source: W. Ruesink, C.A. Shoemaker, A.P. Gutierrez and G.W. Fick. "The Systems Approach to Research and Decision Making for Alfalfa Pest Control," in New Technologies of Pest Control, John Wiley & Sons, Inc. 1980.

2. Routine Sprays--Before and After the First Harvest. For maximum crop protection, an insecticide should be applied no earlier than two weeks in advance of the expected cutting date. It is possible that the spray would be unnecessary but a spray minimizes the risk of crop loss. The regrowth following the first cutting is highly vulnerable to damage by feeding larvae. It should be sprayed with an insecticide for maximum protection. The only information required for this strategy is the expected date of cutting, which is not influenced by weevil density.

The first harvest is taken at 1200 degree days (base 41°F) accumulated after January 1. The first spray is applied approximately 200 degree days before the first harvest. The cost of the strategy is the cost of two spray applications.

3. Static Threshold. A spray is applied when there are more than 400 larvae per square meter. Quite often a grower will harvest early if a spray appears to be warranted within a few days of the anticipated harvest. For the purposes at hand, it is assumed that other constraints on the manager's time make prescheduled harvesting impossible. When a spray is recommended with 100 degree days of harvest, the recommendation is changed to don't spray and the harvest date is left unchanged. The cost is the cost of monitoring plus the cost of any spray applications made.

4. Harvest According to Schedule. The "do nothing" approach does not require monitoring of pest populations. It does require specification of a harvest schedule. This strategy corresponds to a control treatment. There is no cost associated with this program.

5. Cost-Benefit Analysis. An alternative to delineating an explicit threshold is cost-benefit analysis. The default values for cutting dates are used as a base. That is, the first harvest is made after 1200 degree days (base 41°F) have accumulated after January 1 unless an earlier cutting date is recommended by the guidelines. The second and third cuttings are each 1200 degree days after the previous cutting.

The control strategies considered are cut early or spray before the first harvest. The values of the first cutting for each strategy are predicted each time the field is monitored. The value of the crop is predicted for each possible harvest date up until the default harvest date. The value of the crop is also predicted for the default harvest date and a spray application for each day up until 100 degree days of harvest.

The cost of the early harvest strategy is equal to the cost of monitoring. The cost of the spray strategy is equal to the cost of monitoring plus the cost of any spray application.

On each sampling date the predicted net income is computed for each possible spray date and each possible harvest date. The predicted net income is calculated by subtracting the cost of the strategy from the predicted value of the crop. The control strategy associated with the maximum predicted net income is then identified as the best management strategy.

If the best strategy is "harvest today" or "spray today" a harvest or spray will be carried out. If the best strategy is to harvest or spray on a date before the next scheduled monitoring date then the harvest or spray date will be set in the simulation model to follow the recommendation. If the best strategy is to harvest or spray on a date after the next scheduled monitoring date, the process will be repeated on the next monitoring date and the predicted profits will be updated with the additional information obtained.

The algorithm for predicting crop value for alternative management strategies was developed from multiple runs of the alfalfa-alfalfa weevil simulation model. The steps to the algorithm are as follows:

1. For each monitoring date calculate:
   a. DD41- growing degree days base 41°F accumulated after January 1
   b. DD48- growing degree days base 48°F accumulated after January 1
   c. LDD- accumulated larvae degree days (defined in 3.2.3)
2. Predict values of DD41 and DD48 for each possible cutting date.
3. Predict LDD from the predictions for DD48 and today's observed value of LDD.
4. Predict LDDS (larvae degree days at default harvest date) for each spray date from predictions for DD48 and today's observed value of LDD.
5. Predict yield for each cutting date based on predictions of LDD and DD41.
6. Predict yield for each spray date based on predictions of LDD and DD41.
7. Predict protein value of hay for each harvest date from predictions of DD41.
8. Calculate the value of the yield for each harvest date and each spray date from predicted yields and protein values.

9. Compare the expected values of the yields minus the cost of monitoring and determine the optimal cutting date or spray date.

10. Set harvest date or spray date if they occur before the next scheduled monitoring day. Otherwise repeat all steps on date of next monitoring.

The details of each step will be discussed below. Prediction of DD41 and DD48 is based on the following equation:

$$DD_{t+i} = D_t + (P_{t+i} - P_t) * DD_{tot} \qquad (4\text{-}29)$$

where:

DD_{t+i} = degree days i days after today;

DD_t = degree days today;

P_{t+i} = percentage of the total degree days for the year usually accumulated by day t+i;

P_t = percentage of the total degree days for the year usually accumulated by day t; and

DD_{tot} = average total number of degree days for a year.

P_{t+i} and P_t are the average percentages from multiple runs of the simulation. The value of $(P_{t+i} - P_t)$ is the expected percentage increase in degree days from day until day t+i. Then $(P_{t+i} - P_t)*DD_{tot}$ is the expected increase in degree days from day t until day t+i. Notice that this increase is independent of today's degree day count.

The underlying assumption is that although the temperature may have been above average today, there is no reason to believe it will be above average next week. A second assumption is that while temperature may vary throughout the year, the total number of degree days for the year does not vary greatly. These assumptions were verified by the 15 years of temperature data used to run the model.

On the other hand, the number of larvae degree days did vary greatly from year to year. The appraoch taken to predict larvae degree days (LDD) for day t+i was predicted from today's observation based on the following relationship:

$$\frac{P_t}{100} = \frac{LDD_t}{LDD_{tot}} \qquad (4\text{-}30)$$

and

$$\frac{P_{t+i}}{100} = \frac{LDD_{t+i}}{LDD_{tot}} \qquad (4\text{-}31)$$

Solving (4-30) and (4-31) for LDD_{t+i} yields:

$$LDD_{t+i} = \frac{P_{t+i}}{P_t} * LDD_t \qquad (4\text{-}32)$$

Where:

P_t = the percentage of the total number of larvae degree days expected by day t;

P_{t+i} = the percentage of the total number of larvae degree days expected by day t+i;

LDD_t = Larvae degree days observed today;

LDD_{t+i} = predicted number of larvae days for i days from today; and

LDD_{tot} = total number of larvae degree days for the season.

Implicit in this formulation is the assumption that if the number of larvae degree days is high (low) today it will continue to be high (low) for the rest of the season. The assumption is borne out by multiple runs of the model. The percentages are predicted from the predicted values of DD48.

The value of the hay per ton on alternative dates is based on the quality analysis presented in section 4.4. Predicted values of DD41 are used.

$$PRO = 31.0031 - .01115*DD41 \quad (4\text{-}27)$$

$$VALUE = -54.3 + 7.875*PA \quad (4\text{-}28)$$

The effect of growing degree days and larval feeding (estimated by larvae degree days) was estimated by the following equation using results of multiple runs of the model. The yield per hectare on day t+i ($YIELD_{t+i}$) is estimated as:

$$YIELD_{t+i} = -34.46 + 5.7* \ln (DD41_{t+i}) - (7.97 * 10^{-6}) * LDD_{t+i} \quad (4\text{-}33)$$

Finally, for each cutting date the expected value of the harvest is:

$$NET_{t+i} = VALUE_{t+i} * YIELD_{t+i} - COST_{t+i} \quad (4\text{-}34)$$

The cutting date or spray date is selected by maximizing net income with respect to t+i. The algorithm is performed on each sampling date until the optimal t+i is found to be before the next scheduled monitoring.

On each sampling date the predictions are updated using the new values of DD41, DD48 and LDD. By the nature of the construction of these variables information already obtained is not discarded because DD41, DD48 and LDD are cumulative measures.

6. Early Harvest of the First Cutting. This decision rule is identical to Rule 4 except that the first cutting is made after 900 degree days (base 41°F) have accumulated after January 1 as opposed to 1200 in Rule 4. In other words, the default date for the first harvest

is changed. The biological time between the first and second, and second and third, is 1200 degree days, as it is in all other rules. There is no cost to this strategy.

7. Routine Single Spray. This decision rule is identical to Rule 2 except that a spray is required before the first harvest but not after. The spray is applied 200 degree days before the first cut. The cost is the cost of the spray.

The cost of monitoring the larvae population was assumed to be $7.00 a hectare ($2.75 per acre). The cost of spraying was assumed to be $22.00 per hectare ($9.00 per acre). These values are based on 1981 prices (Table 4.6).

4.6 Modification of the Model for Michigan Conditions

The alfalfa-alfalfa weevil model can be run for any alfalfa growing region in the United States. In order to run the model for a specific location, certain input data for the model has to be specified for that location. The input data required includes the latitude, average monthly solar radiation and daily high and low temperature data.

As mentioned above, the location-specific data required by the model are latitude, average monthly solar radiation and daily high and low temperatures. Gull Lake, Michigan was chosen for running the model under Michigan conditions for several reasons. First, Gull Lake is in a major alfalfa growing region in the state. Second, there is a weather station there and the data required is available for several years. Finally, field trials on alfalfa production have been conducted at the Experiment Station at Gull Lake which makes possible verification of the model results.

Table 4.6
COSTS AND RECOMMENDED APPLICATION RATES
FOR INSECTICIDES USED TO CONTROL ALFALFA WEEVIL

Insecticide[a/]	Price $/gallon	Active Ingredients %	Application Rate pints/acre	Cost $/acre
carbofuran (Furadan)	$42.68	40.64%	2	$10.69
azinphosmethyl (Guthion)	19.00	74.00	1-3	2.37-7.13
carbaryl (Sevin)	14.69	50.00	1½	2.75

[a/] Common name, trade name in parentheses.

Source: Grower Services, Lansing, Michigan.

Several problems arose in running the model using Michigan temperature and solar radiation data. First, the parasitism logic failed to perform satisfactorily. The life cycle of the alfalfa weevil and parasite were "out of sync" so that no larvae were ever parasitized. At the stage when the parasites were looking for hosts, virtually no weevils were in the larval stages. This problem was corrected by changing the date of the end of dormancy for the parasite from April 12 (based on observations in Illinois) to May 18 (an appropriate date for Michigan).[4]

Another test of correspondence was based on the fact that in Michigan very few eggs are laid in the fall and those that are do not survive the winter. In warmer climates, this is not the case. Hence, the model allows for fall laid eggs but the temperatures in Michigan should not allow them to survive the winter.

Running the model through the winter, it was found that if enough adults remained in the field in the fall, then an abundance of eggs would be laid. A percentage of these eggs would die daily. However, enough would survive to generate larvae in February and March. This phenomenon has never occurred in Michigan.

The problem was traced to one equation (4-25) which determines the number of adults remaining in the field in fall to over winter based on the status of the plant. The logic goes as follows: More foliage in the field provides a more appealing overwintering sight for the adult weevils. A greater percentage stay in the field when the amount of

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[4]These dates were selected by William Ruesink based on his experience with alfalfa weevil. May 18 was suggested in a personal conversation.

leaves and stems is greater. Therefore, the timing of the third cutting has a tremendous impact on the population for the next year. At the extreme, numerous eggs are laid and larvae emerge in very early spring.

While the model does allow for weevils to migrate from the field, it does not allow for migration into the field. Therefore, running the model for several continuous years, the population in one year is highly dependent on the population from the year before.

The problem of eggs surviving the winter was circumvented by ensuring that the last harvest of the year did not occur before mid-September. However, not enough is known about the overwintering habits of the weevil for migration into fields to run the model for several continuous seasons. Therefore, both the plant and pest variables of the model are reinitialized each year. Thus, running the model for several years creates independent yearly samples.

This change improves the accuracy of the model for single year management strategies but eliminates the possibility of using the model for developing or evaluating a multi-year pest management scheme. In its present form the model is not useful for solving multi-year planning strategies such as a build-up of the parasite population.

The plant model also had to be modified to perform adequately for Michigan conditions. ALSIM was originally built using average monthly temperature data setting the temperature on the 15th of the month equal to the monthly average, and extrapolating between the 15th of one month and the 15th of the next month to approximate daily temperature for the days in between. This procedure eliminates daily trends in temperature.

The version of ALSIM used in the alfalfa-alfalfa weevil model runs off actual daily weather data. Fluctuations in temperature from day-to-day did not hamper the performance of the model using temperature from Illinois. However, the climate in Michigan is much more prone to large variation in temperature from day-to-day and late spring freezes.

Without going into too much detail, the production of MATS in ALSIM is halted for at least five days whenever the daily low temperature is under 23°F. This simulates the state of dormancy. Occurrences of extremely low temperatures in late spring in Gull Lake slowed plant growth down to such a great extent that all three cuttings were affected.

To correct for this, the dormancy logic of ALSIM was changed so that the plant entered dormancy when the average of the low temperatures for the last two days was under 23°F.[5] This reduced the impact of severe variation in temperature from one day to the next. The effect of the change in dormancy logic for 1966-1969 for each of the three cuttings is presented in Table 4.7.

The version of ALSIM used assumes soil moisture does not limit growth. Also, the growth equations were developed from data on the first cutting of alfalfa. Therefore, it would be expected that the model would overestimate second and third cutting yields which are usually subject to moisture stress in Michigan. Other differences between the growth of the first cutting and subsequent cuttings will not be reflected by the model. It should also be mentioned that the model was developed to simulate a three-cut system although a four-cut system is recommended in Michigan to maximize yield (Tesar, 1978).

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[5]This modification was suggested by Gary Fick in a personal conversation.

Table 4.7

Effect of Change in Dormancy Logic, 1966-1969

Year	Harvest	Old Yield	New Yield
1966	1	3.169	5.609
	2	.016	3.266
	3	2.987	3.750
1967	1	4.614	6.368
	2	3.581	3.962
	3	3.863	3.972
1968	1	6.308	6.842
	2	3.756	3.887
	3	3.716	3.760
1969	1	5.296	6.368
	2	3.489	3.728
	3	3.621	3.727

4.7 Validation and Verification of the Alfalfa-Alfalfa Weevil Model

The model presented was not developed with the intention of predicting real world phenomena. Instead, runs of the model are intended to simulate the performance of a cropping system under various sets of plausible conditions which may or may not have occurred in the real world.

The plant component and pest component of the model were developed separately and then linked. Both used information from a variety of sources including informed judgment. While each aspect of the model may be easily justified, it is important to test the performance of the model as a whole.

Quite often the shortcomings of a model result from the omission of variables or the omission of specific relationships among variables. These omissions may be the result of the simplication required by the modeling process or a poor understanding of certain aspects of the system. Omissions can result in misspecifications of the model in exactly the same way that incorrect relationships can.

With these ideas in mind, testing the model involves more than checking for the correct signs and magnitudes of coefficients of equations in the model. The model must perform as a system.

Four tests of objectivity are applied.[6] These tests of objectivity are:

1. coherence -- logical internal consistency of the concepts used;

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[6]The tests of objectivity are used as a criterion for validation and verification in G.L. Johnson and C. Leroy Quance, The Overproduction Trap in U.S. Agriculture (Baltimore: John Hopkins Press, 1972), pp. 44-48.

2. clarity -- interpersonal transmissibility of the concepts used and the results;

3. correspondence -- consistency with observed experience; and

4. workability -- usefulness in problem solving.

The model is verified by testing its consistency with the real world. If the model results do not correspond to a commonly held view of system performance, then it fails the test of correspondence. The model is not valid unless it is logically sound. A model may be internally consistent and pass the test of coherence but not the test of correspondence. Neither of these tests can be performed unless the model is clear and unambiguous. This is the test of clarity. If the model is applied to problem solving it must provide useful answers. The model may be more appropriate for certain problems than others. The test of workability is relevant to the specific use of the model. It is a special case of correspondence.

COHERENCE AND CLARITY

The alfalfa-alfalfa weevil model has been used by a number of researchers over several years. It is well documented and clearly organized. However, two problems with the internal logic were found in the ALSIM subroutine.

First, the variable LDAFB was misspecified as an integer variable. This means the value for the variable is always rounded down to the nearest whole number. It should have been specified as a real variable. That is, a variable that has a fractional component. This correction was made and brought to the attention of the author of the model.

Second, the logic for calculating the loss of leaves to senescence (variable SRL) was inconsistent. Three equations are specified for calculating SRL, one for days with more than sixteen hours of daylight, a second for days with less than twelve hours of daylight and a third for daylengths between these two cutoffs. However, the program used the equation for long days whenever it encountered a short day, and used the equation for short days when it encountered a long day. This logic was corrected.

CORRESPONDENCE

Tests of correspondence were carried out using two years of field data to verify the model. The data was collected as part of an experiment to analyze the effect of cutting data and alfalfa weevil feeding on the quantity and quality of the first cutting of alfalfa.

Experimental plots were laid out on stands of alfalfa near Mason, Michigan in 1972 and near Owosso, Michigan in 1974. The experiment was also conducted in 1973, but the alfalfa growth was not adequate to justify harvesting due to severe frost damage early in the growing season.

Four replications were laid out. Each replication was divided into four plots in 1972 and five plots in 1974. Each of these subplots was then divided into two plots. For each pair of plots, one was treated with insecticide and one was left untreated. The alfalfa was cut on four different dates in 1972 and five different dates in 1974. The populations of alfalfa weevil larvae were counted roughly every five days throughout both experiments (Table 4.8). The model was run using

Table 4.8

NUMBER OF LARVAE PER TWENTY SWEEP SAMPLE

			Number of Larvae									
			Untreated Plots					Treated Plots				
Year	Sampling Date	Degree Days Base 48°F a/	1	2	3	4	Average	1	2	3	4	Average
72	5/10	183.26	0	0	0	0	0.00	0	0	0	0	0.00
	5/16	252.18	3	2	0	0	1.25	0	0	0	0	0.00
	5/19	304.68	18	37	42	15	28.00	6	6	6	3	5.25
	5/24	406.18	410	249	175	169	250.75	117	105	126	124	118.00
	6/2	536.08	1185	698	572	240	673.75	43	38	21	7	27.25
	6/5	600.58	1369	1073	1335	849	1156.50	71	55	52	44	55.50
	6/9	681.58	498	506	632	422	512.25	10	11	10	8	9.75
	6/14	768.48	725	546	548	356	543.75	1	8	7	4	5.00
	6/19	863.31	178	313	255	130	219.00	29	27	20	5	20.25
	6/27	981.20	123	129	65	49	91.50	22	3	2	1	7.00
	7/3	1114.00	26	43	37	18	31.00	7	8	12	10	9.25
74	4/26	130.77	0	0	0	0	0.00	0	0	0	0	0.00
	4/30	202.77	0	0	0	0	0.00	0	0	0	0	0.00
	5/3	221.67	4	4	0	0	2.00	0	0	0	0	0.00
	5/9	229.37	0	1	0	1	.50	0	0	0	0	0.00
	5/14	249.38	3	0	2	1	1.75	3	0	2	1	1.50
	5/17	283.19	9	7	7	6	7.25	2	5	3	4	3.50
	5/20	311.17	14	33	44	47	34.50	14	3	8	6	7.75
	5/23	372.67	51	40	46	60	49.25	34	18	9	17	18.50
	5/27	402.14	102	141	154	214	152.75	10	8	6	4	7.00
	5/31	458.14	178	220	331	335	266.00	46	22	11	26	26.25
	6/4	521.15	270	442	404	730	416.50	7	40	39	1	21.75
	6/7	596.15	878	874	708	964	856.00	2	2	1	9	3.50
	6/10	671.15	371	408	490	676	486.25	57	14	23	21	28.75
	6/14	722.08	439	774	803	710	681.50	71	87	47	41	61.50
	6/17	755.72	176	369	403	227	293.75	4	7	1	2	3.50
	6/20	811.72	118	232	239	150	184.75	7	1	5	4	4.25
	6/25	885.35	2	1	7	2	3.00	2	0	3	0	1.25
	7/1	997.35	1	3	1	1	1.50	5	5	3	7	5.00

[a]Calculated using the B-E method (Baskerville and Emin, 1969) and adjusted for temperatures above 86°F.

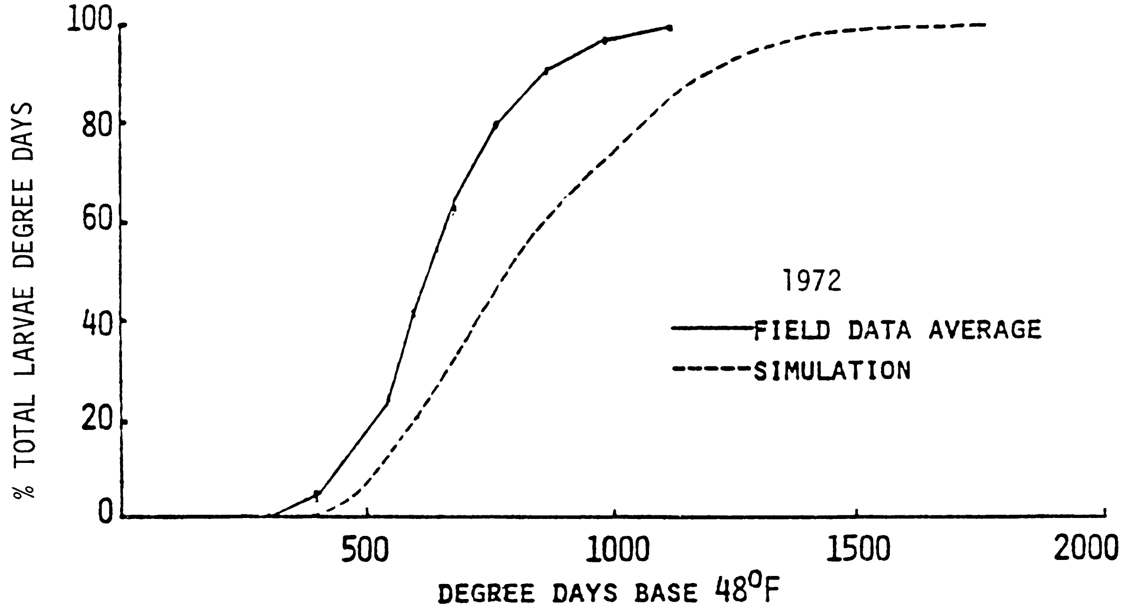
1972 and 1974 weather data from East Lansing and Owosso, the nearest weather stations to the test plots.

Comparison of field observations of larval populations and simulation results posed a problem. The field data was measured in terms of 20 sweep net samples while the simulation was based on the number of larvae per square meter.

Two approaches were taken to circumvent this problem. First, the percentages of the total population accumulated over time were calculated for the field data and the model results for both years. For the field data the average of the four replications of untreated plots was used. The results are shown diagramatically in Figure 4.3. In both years the larval population was present for approximately two weeks longer than the field observations.

The second approach is presented in Figure 4.4. The field data and simulation results were plotted on the same graph using two different scales on the X-axis. The scales were set up so that the peak population from the field data equals the peak population in the simulation results. In other words, the peak populations for both sets of data were forced to be equivalent. In both years the populations from the field data peaked roughly a week before the simulated populations. The model populations decreased less rapidly and continued longer into the season.

Comparison of alfalfa yields did not present problems of scale. The model was run using 1972 and 1974 weather data and holding the pest population at zero. The model results were compared to the field plots treated with insecticides. Both the field plot samples and the model were measured on a dry weight basis.



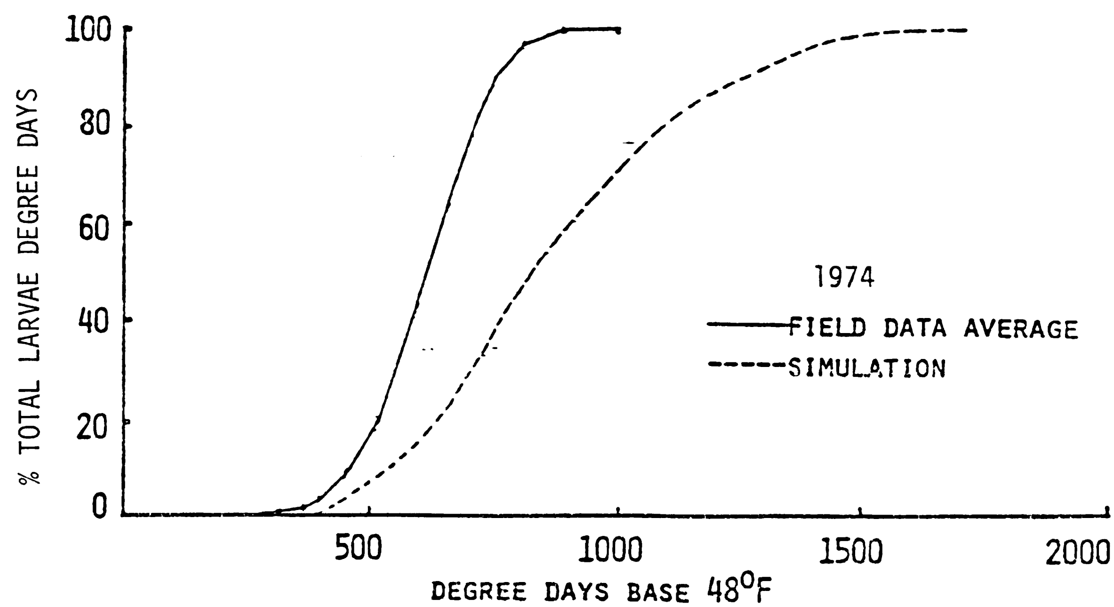


Figure 4.3 Simulated and actual percentages of larvae degree days for 1972 and 1974. The field data curve is the average of the four replications.

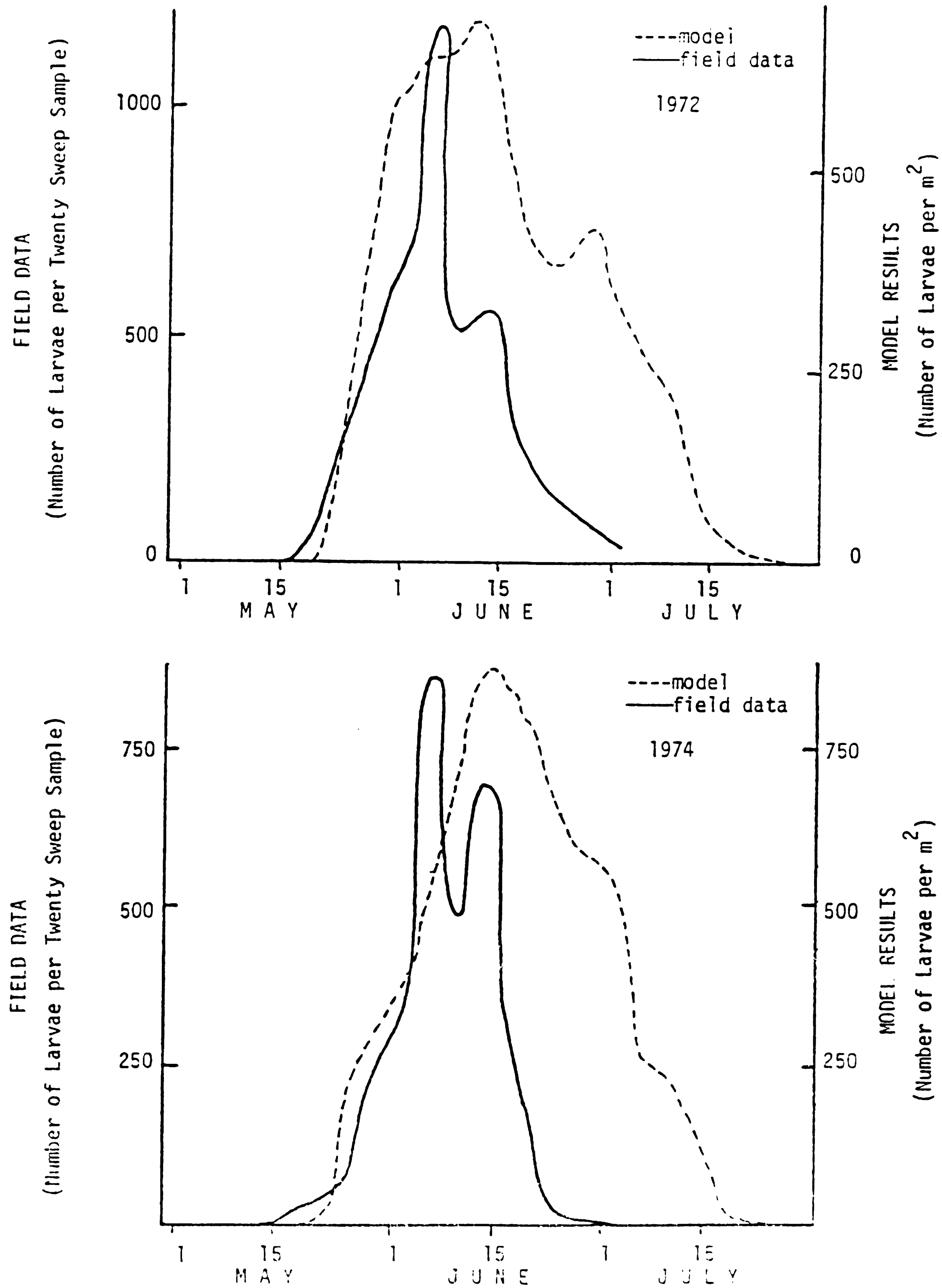


Figure 4.4 Comparison of field observations of average larval populations to simulation results, 1972 and 1974.

The model was run twice for each year, beginning the simulation on September 1 and April 1, using initial conditions recommended by the author of the model (personal communication with Dr. Fick). In all cases, the model predicted yields lower than the field observations. The difference is greater for the later cutting dates than for the earlier cutting dates (Table 4.9). Initialization in September resulted in slightly lower values than did initialization in April.

Part of the discrepancy between the field observations and model results may be because average yields of alfalfa in Michigan are higher than average yields in New York and the model was developed using New York data. The difference in yields generated by the model initialized on different dates is attributable to the loss in TNC over the winter.[7]

One of the shortcomings of ALSIM is an underestimation of TNC over time. The author of ALSIM illustrated this problem by comparing model results and field data for Aurora, New York (Fick, 1979). The tendency is to underestimate TNC midseason (Figure 4.5).

Using Michigan weather conditions, the underestimation of TNC was accentuated by the early cutting regime used in the management model. The early first cuttings placed the second and third cuttings at a time when TNC was underestimated. This created unrealistically low yields for the second and third cuttings in one particular year, 1977. Modification of the simulation results to compensate for this problem are presented in section 4.8.

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[7]The explanations offered were proposed by Dr. Gary Fick in a personal communication.

Table 4.9

Comparison of Field Data for Treated Plots and ALSIM Predictions

Year	Date	Degree Days	Yield (metric tons/hectare)				
			Field Data	Model 9/1[a]	Difference	Model 4/1[b]	Difference
1972	5/24	679	4.03	3.77	- .26	3.90	- .13
	6/5	953	6.72	5.18	-1.54	5.27	-1.45
	6/14	1178	8.74	5.93	-2.81	6.01	-2.73
	6/27	1480	8.06	6.78	-1.28	6.83	-1.23
1974	5/20	591	3.81	3.34	- .47	3.47	- .34
	5/31	811	5.38	4.75	- .63	4.87	- .51
	6/10	1093	6.50	5.69	- .81	5.78	- .72
	6/20	1302	7.62	6.44	-1.18	6.50	-1.12
	7/1	1563	9.86	6.99	-2.87	7.02	-2.84

[a] Model initialized on September 1 (day 244). Stem = 2, Buds = 1, Leaf = 18. TNC = 28.

[b] Model initialized on April 1 (day 91). Stem = 0, Buds = 10, Leaf = 0. TNC = 75.

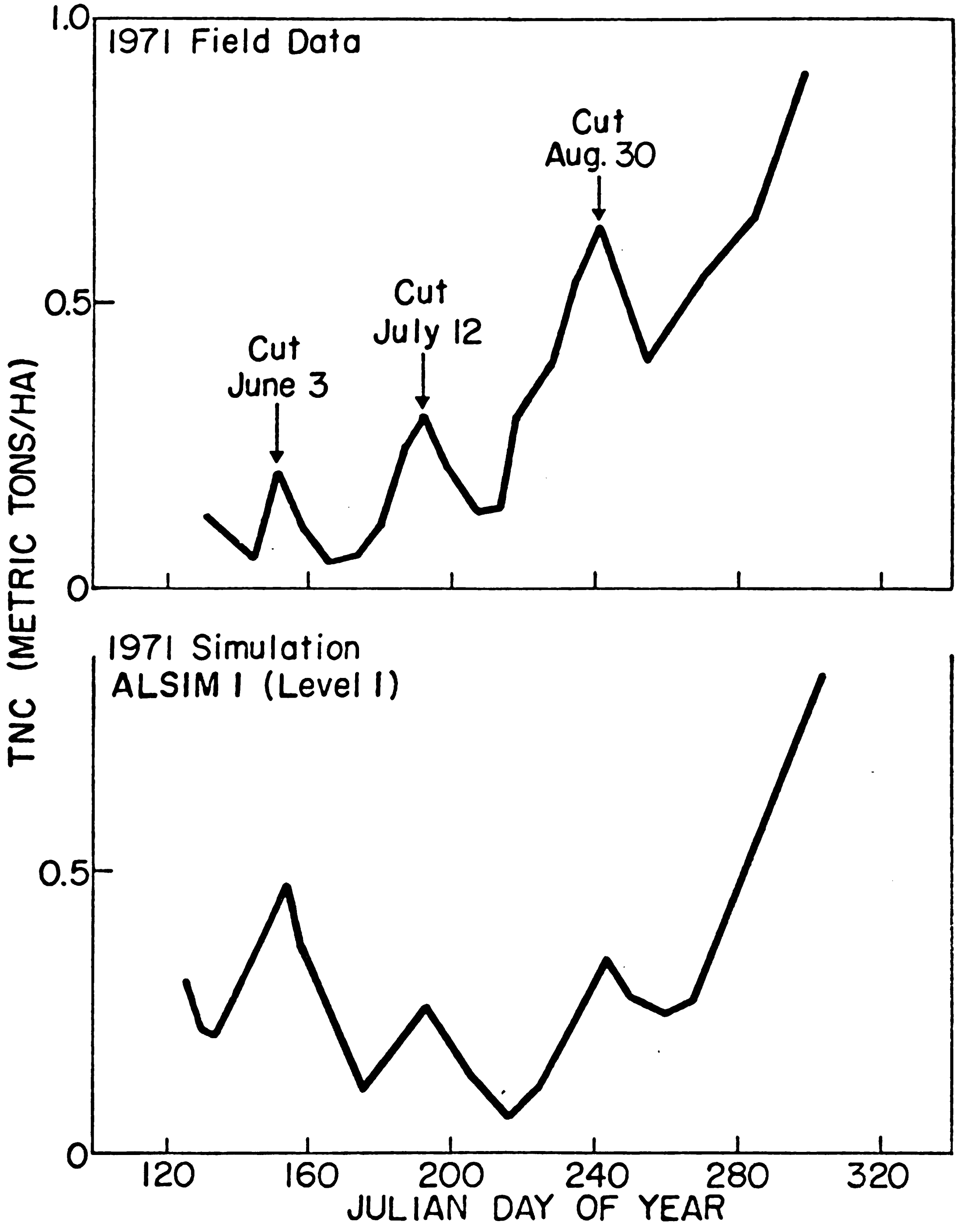

Figure 4.5 Comparison of field data and TNC values generated by ALSIM 1 for Aurora, New York.

Source: Fick, G.W., Alsim 1 (level 1) Users' Manual. Dept. of Agronomy, mimeo 75-20. Cornell University, Ithaca, New York, March 1979.

WORKABILITY

Several areas in which the model failed to correspond to feasible real world events were identified. To a great extent, these resulted from running the model under climatic conditions in Michigan and appropriate adjustments were made. It was decided that the model performance was not adequate for running several consecutive years, and the model variables are reinitialized each fall. These changes dictate the appropriate use of the model in problem solving. In particular, the current version of the model should be used for pest control strategies with a one-year planning horizon, the firm level, and climatic conditions similar to Michigan. It should also be mentioned that the model involves a single pest and a single crop.

4.8 Modification of Simulation Results

Observations that are much larger or much smaller than other observations in a data set are sometimes a cause of concern. If they are the result of a measurement error or other extraneous effects they can bias results. On the other hand, an extreme observation may convey important information. They may indicate misspecification of a model or the inability of a model to perform adequately outside the range of data from which it was developed.

The results of the simulation model are the dollar values of the three cuttings for each rule. One extreme observation was generated by the simulation model for the early harvest schedule (rule 6) in year 1977. Although 1977 was the poorest year for all algorithms, it accounted for 66% of the variance around the mean for decision rule 6. Rule 6 had the largest coefficient of variation (.20). The coefficient

of variation for all other rules ranged from .09 (rules 1,2 and 7) to .13 (rule 5).

The data point for rule 6 in 1977 was tested to determine whether or not it was an extreme observation. The standardized residual for this data point is calculated as:

$$\frac{(Y_{77,6} - Y_{6.})*t(r-1)}{(\sum_{ij}(Y_{ij} - Y_{j.})^2)^{\frac{1}{2}}} = 8.56$$

Where:

$Y_{77,6}$ - is the value for 1977, treatment 6;

Y - is the grand mean for all observations;

Y_{ij} - is the value for rule j in year i;

$Y_{j.}$ - is the average value for treatment j;

t - is the number of treatments; and

r - is the number of years.

This means that the residual for this observation is over eight standard deviations from the average value. The probability of this occurring is less than one in 10,000. It is cause to investigate the circumstances that contributed to the extreme observation.

The extremely low gross income in 1977 for rule 6 can be explained by looking at the yields for each of the three cuttings that year. While the yield for the first cutting for rule 6 was high, the yields for the second and third cuttings were extremely low.

The low production for the second and third cuttings can be explained by comparing the first cutting dates for rules 5 and 6. The cutting dates for rule 5 and 6 are within 3 days of each other for every year except 1977 when the first cutting date for rule 6 was May 17 and for rule 5 was May 31.

The temperatures during March and April of 1977 were unusually high. This meant that the criteria for taking the first cutting under rule 6 (cut at 900 degree days) was met inordinately early in the season. The early cutting date maximized gross income for the first cutting but did not allow the plants to build up sufficient reserves to grow adequately for the second and third cuttings.

Root reserve accumulation is a function of degree days and time. Therefore, although the accumulated degree days between cuttings was sufficient, not enough time had elapsed before the first cutting for adequate nonstructural carbohydrate accumulation in the taproots (TNC).

For these reasons, the data point for rule 6 in 1977 was dropped from the analysis. Leaving the data point missing would bias the results for rule 6 upwards because 1977 was the poorest year for all of the decision rules. Therefore, a data point was generated using regression analysis on the 104 remaining data points.

Two sets of dummy variables were created, one for the decision rule and one for the year, to estimate the effect of year and the decision rule on gross income. It should be noted that using a dummy variable for the year is in effect creating a dummy variable for the weather conditions in that year.

The equation estimated was of the form:

$$Y_{ij} = \mu + \beta_i + \tau_j + \varepsilon_{ij} \qquad (4\text{-}29)$$

Where:

Y_{ij} = income in year i under rule j;

μ = grand mean;

β_i = effect of year i;

τ_j = effect of decision rule j; and

ε_{ij} = error term.

The results of the regression are given in Table 4.10. The data point for year 1977 and decision rule 6 was generated from these results as:

$$Y_{77,6} = \mu + \beta_{12} + \tau_6 = 729.37 \quad (4\text{-}30)$$

This value of gross income was used in place of the value resulting from the simulation in all of the analysis below.

Table 4.10 Estimates of the Year and Decision Rule Effects on Gross Income

parameter	notation	estimate	t-statistic	standard error of estimate
Mean	μ	852.7	86.9	9.8
Year				
1966	β_1	-75.1	-6.4	11.7
1967	β_2	132.3	11.3	11.7
1968	β_3	112.9	9.6	11.7
1969	β_4	67.7	5.8	11.7
1970	β_5	82.0	7.0	11.7
1971	β_6	-2.9	0.2	11.7
1972	β_7	42.0	3.59	11.7
1973	β_8	-45.3	-3.87	11.7
1974	β_9	4.6	.37	11.7
1975	β_{10}	-109.4	-9.31	11.7
1976	β_{11}	62.6	5.34	11.7
1977	β_{12}	-196.1	-16.04	12.2
1978	β_{13}	-40.0	-3.41	11.7
1979	β_{14}	48.3	4.12	11.7
1980	β_{15}	0		
Decision Rule				
1	τ_1	-4.3	.54	8.0
2	τ_2	2.3	.28	8.0
3	τ_3	-6.4	.80	8.0
4	τ_4	-17.1	-2.13	8.0
5	τ_5	66.9	8.36	8.0
6	τ_6	72.8	8.91	8.2
7	τ_7	0		

CHAPTER V

METHOD FOR EVALUATION

The alfalfa-alfalfa weevil model was run for each of the seven decision rules for 15 years of temperature data for Gull Lake, Michigan. The model was reinitialized each year in September.

The simulations were run under the ideal conditions of daily sampling and no sampling error. Where appropriate, various sampling regimes were introduced for sensitivity analysis. The model was rerun under these conditions using the same 15 years of weather data.

The results of the simulation were compared by determining the net incomes for each rule for each year. Rules were ranked in order of preference. Various decision rules were used to compute the ranking. Also, the value of the pest management programs was calculated as a measure of the value of the information imbedded in each program. The exact procedures and definitions are discussed below.

5.1 Net Income

The term "income" alone is generally assumed to be in value terms. Thus, the income from an acre of land is the dollar value of the hay produced. It is the multiple of the units of output per acre and the dollar value per unit. Adding the prefix "gross" emphasizes that no adjustments have been made to account for the cost of production.

In this analysis the units of output are measured in metric tons per hectare per year. The number of tons for each cutting is generated by the simulation model. The dollar value per ton of alfalfa hay is measured on the basis of value as feed (not market value) using equations 4-27 and 4-28. Following these equations, value is based upon the percent protein in the hay which is estimated from the degree days accumulated since the previous cutting (or January 1 in the case of the first cutting). The number of tons for each cutting is multiplied by the value per ton for that cutting to obtain the gross income. The annual gross income is the summation of the gross incomes for the three cuttings per season.

In this discussion the term "net income" will refer to income above the cost of monitoring and spraying. It is the revenue after the cost of the management program has been subtracted from gross income. The cost of monitoring is $7 per hectare ($2.75 per acre) and the cost of spraying is $22 per spray per hectare ($9.00 per acre). These values are based on 1981 prices (Table 4.6). Net income is not used to refer to income above all production costs. In other words, net income is not synonomous with profit.

Rules 1, 3 and 5 require monitoring every year. For all other rules the cost of monitoring is zero. Rule 7 involves one spray per year and rule 2 requires two sprays per year. Rule 1 and 3 and 5 may involve spraying in some years and not others depending on the recommendations produced by the decision algorithms. The spray costs for rules 4 and 6 are always zero.

It is assumed that the production costs other than the cost of the pest management program are essentially the same for all situations. Therefore, the definition of net income applied here is appropriate for an ordinal comparison of income flows generated by each management model. Defining net income as income above all costs would change the absolute values but not the relative values of the income streams. It should be noted that the net income is equivalent to the gross income for the no control strategy using this definition of net income.

5.2 Value of Pest Management Programs, Monitoring, and Insecticide Applications

The differences in gross income resulting from each decision algorithm lie in the degree of damage avoided. The management scheme does not change the potential income for any given year, rather it changes the percentage of that potential income that is captured. Potential income is determined by the growing conditions for the alfalfa, (in this case temperature) in a pest free environment. In this model management has no influence over potential income because adequate moisture and fertility is assumed and no modification of soil, moisture or climate is possible.

The benefit from spray applications is calculated in this analysis as the difference between the net income above monitoring costs (gross income minus monitoring costs) and the income from no control. Similarly, the benefit from monitoring is calculated as the difference between the net income above spray costs (gross income minus spraying costs) and gross income from no control.

5.3 Sampling Interval

For decision rule 3 (the static threshold) and rule 5 (cost-benefit analysis) the decision algorithm was applied every day, every third day, every seventh day and every fourteenth day of the simulation. This "simulated" different intervals between sampling or intensity of monitoring. It was assumed in these runs that the pest population was not observed on days when no sample was taken. No decisions were made on nonsampling days.

This procedure was not followed for rules 4, 6, or 7 because they do not involve monitoring of the pest population. It was not applied to rule 1 (the dynamic threshold) because the algorithm specifies how long to wait between samples based on the monitoring information.

5.4 Analysis of Simulation Results

The procedure followed to generate net income distributions for each decision rule have been described above. Interpretation of these results requires comparison of the income distributions in some way. Several approaches were used. A discussion of the merits and limitations of each folllows.

5.4.1 Analysis of Simulation Results by Comparison of Means

One approach to analysis of the simulation results is to compare the average net income for each control strategy to the average net income for each other strategy. There are seven control strategies for a total of (7*6)/2=21 comparisons. A decision maker using this approach will be indifferent between two strategies if the means cannot be shown to be significantly different with some specified degree of confidence. Similarly, a strategy will be preferred to another if the mean can be shown to be significantly larger.

Numerous tests for comparison of means have been proposed in the literature. Each presents a different test criterion for accepting the null hypothesis that the means are equivalent. Whether or not the difference between two means can be called significant is related to the particular test used and the confidence level applied.

Failure to reject the null hypothesis, that two or more of the means are equal does not lead to the conclusion that the means are equal. It implies only that the difference between means, if any, is not large enough to be detected with the given sample size and the specified confidence level.

The problem at hand can be conceptualized as a randomized block design using a biometrics approach. Each control strategy is a treatment and each year is a repetition or block. Each observation of net income is given a two-way classification according to the block (year) and treatment (control strategy). The observations are assumed to be a random sample from a larger population.

In a randomized block design blocks represent naturally occurring differences that affect the values of the observations but are independent of the treatments. The weather in certain years is more likely to produce a good alfalfa crop than in other years, regardless of the control strategy followed. By using a randomized block design, the variability attributable to weather can be separated from the experimental error and will not affect differences among treatment means.

The following structural model is used:

$$Y_{ij} = u + b_i + a_j + e_{ij}$$

Where

u = grand mean;

b_i = effect of treatment i;

a_j = effect of block j, and

e_{ij} = error term.

The error terms for each treatment are assumed to be normally distributed with a mean of 0 and a variance σ_i^2. The a_j's and b_i's are measures of deviation from the overall mean. By construction $\sum_j a_j = 0$ and $\sum_i b_i = 0$.

The means of the net income for each decision rule are given as:

$$\overline{Y}_i = \frac{1}{n} \sum_{j=1}^{n} Y_{ij} = (nu + nb_i + \sum_{j=1}^{n} a_j + \sum_{j=1}^{n} e_{ij}) = u + b_i + e_i$$

We want to test the hypothesis that the means from two different strategies are equivalent. For example, comparing rules 1 and 2 the null hypothesis is:

$$H_0: \ \overline{Y}_1 - \overline{Y}_2 = 0.$$

From the equation for means above the differences can be expressed as:

$$\overline{Y}_1 - \overline{Y}_2 = (b_1 - b_2) + (\overline{e}_1 - \overline{e}_2).$$

The value of $b_1 - b_2$ is a constant and under the null hypothesis of equal means $b_1 - b_2 = 0$. The variability of the difference of the means is derived from the differences of the e's. The variance of the differences of the means is an estimate of:

$$(\sigma_1^2 + \sigma_2^2)/n \text{ or}$$

$$2\sigma^2$$

if the e_1's and e_2's have a common variance. If S is an estimate of σ, then $2S^2/n$ is an estimate of the variance of the difference of the means.

It was mentioned above that there are numerous tests for comparison of means. A brief description of several alternative tests follows.

Perhaps the most direct approach is to use a t-test on every pair of means. This approach assumes that the observations of net income for each decision rule are a random sample from a larger population. The

average of the observations is an estimate of the mean of that parent population.

The t-statistic measures the distance of a random variable from its hypothesized mean in units of standard deviations of the random variable. The numerator of the t-statistic is the difference between the random variable and an hypothesized mean. The denominator is the standard deviation of the random variable.

In this case the random variable is the difference between two average net incomes and the hypothesized mean is zero.

The numerator, then, is simply the difference between the average net incomes. The denominator of the t-statistic is the standard deviation difference of the two mean net incomes. In notational form:

$$t = (\overline{Y}_1 - \overline{Y}_2)/S*(2/n)^{\frac{1}{2}}$$

Where:

t = the t-statistic;

$\overline{Y}_1$ = the mean net income for the first decision rule;

$\overline{Y}_2$ = the mean net income for another decision rule; and

$S*(2/n)^{\frac{1}{2}}$ = the standard deviation of difference between the two means.

When the underlying distributions are normal and the null hypothesis is true, this statistic will be distributed as the student's t distribution. When the statistic is too large, we conclude that it is because the difference of the actual means is not equal to zero.

Use of the t-test requires that the distributions being compared are normal. The net income distributions were tested using the Chi-squared goodness of fit test and the null hypothesis was accepted.

Also, the variances of the distributions were found to be identical at the .05 significance level.

Multiple t-tests are undesirable because of the number of tests that are necessary. Fisher's Least Significant Difference test circumvents this problem by computing the smallest difference, lsd, that would be significant.

The lsd is computed by a simple manipulation of the above formula. The null hypothesis is rejected when:

$$\overline{Y}_i - \overline{Y}_j \geq t_{\alpha,v}*S*(2/n)^{\frac{1}{2}}$$

The factor on the right-hand side is the lsd.

The least significant difference test has been criticized in the literature because of the high experiment-wise error rate. Suppose that each comparison is performed at the .05 level. Then there are twenty-one comparisons, each with a 5% probability of a false rejection of the null hypothesis (Type 1 error). An upper bound for the probability of making at least one Type I error (the experiment-wise error rate) is:

$$1 - (1-.05)^{21} = .66$$

It has been argued that the experiment-wise error rate is not important when the family of comparisons is not the conceptual unit of interest. However, there is no concensus in the literature on this point.

Numerous alternatives to the least significant difference test have been designed to take experiment-wise error rate into account. They include Duncan's New Multiple Range Test, Tukey's w Procedure and Scheffe's Test (Steele and Torrie, 1980).

Each consists of computing a critical value and applying it to the differences between all pairs of means. When the difference is larger than the critical value, then the null hypothesis of no difference between the means is rejected at the significant level specified. However, protection against Type I error reduces the likelihood of declaring differences to be significant. The probability of Type II error (accepting the null hypothesis when it is false) increases as the probability of making a Type I error decreases.

In recognition of this problem, Waller and Duncan developed The Waller-Duncan k-ratio test (Waller and Duncan, 1969). The test uses an error weight of Type I and Type II errors to derive the critical value. No significance level is involved. The authors suggest that k-ratios of 50:1, 100:1, and 500:1 give similar results to significance levels of .10, .05 and .01. The critical value is also related to the analysis of variance F value for the entire experiment. The larger the value of F, the smaller the critical value for the test.

The Waller-Duncan k-ratio test was used for this analysis because of the power of the test without loss of consideration of Type I error.

5.4.2 Comparison of Income Distributions Using Stochastic Dominance

The statistical procedures based on analysis of variance for comparison of means assumes that an individual choosing among alternatives is equally concerned with avoiding a loss and realizing a gain of the same magnitude. In reality, an individual may not be indifferent between two equal amounts when one is achieved with certainty and the other is obtained on the average.

Several criteria for ranking the decision rules have been developed which make specific assumptions about attitudes toward risky outcomes. Two criteria are first degree stochastic dominance and second degree stochastic dominance (sec. 3.2.4). Both assume that the income distributions for each decision rule are known with certainty. The net income distributions were compared using first and second degree stochastic dominance.

Pest management decisions are made without perfect knowledge of the outcomes associated with alternative strategies. Risk enters the pest management decision making process through (1) biology, (2) technology and (3) institutions. All three are interrelated. New methods of control including new pesticides are continuously introduced changing the technology available for production. Changing regulation of pest controls contributes to the variation in technology. Organization of the delivery of pest control information is changing rapidly. Economic events change prices. With price changes the value of the crop loss and cost of control vary.

The primary source of variation in crop production is weather. Stochastic factors in agriculture include spacial and temporal variation in pest types and population levels and variation in damage (both yield and quality) per pest. Susceptibility of pests to controls also varies as the genetic characteristics of the pest change over time. The effect of controls on other crops and the quality of crops is not known with certainty.

Uncertainty in pest management suggests the need for using a decision framework incorporating risk. Decisions made with imperfect knowledge can be characterized by a probability distribution function for all possible outcomes. This distribution can be used to choose a control strategy once an individual's attitude toward risk (willingness to gamble) is known.

An individual's attitude toward risk will affect the selection of a control strategy, all other factors held equal. Given that the individual's preferences for risk vary, it is not possible to determine a unique optimal control strategy that will maximize utility for individuals with different risk preferences. However, by categorizing indivduals as risk averse, risk neutral or risk preferers, it is possible to rank control strategies for groups of decision makers using the first and second degree stochastic dominance efficiency criteria.

Using the stochastic dominance criteria assume that the results of the simulation model comprise the actual income distribution for each decision rule. That is, the distributions generated are not random and are not samples from a larger population. Consequently, the probability of a Type I error cannot be estimated.

CHAPTER VI

EVALUATION OF ALFALFA PEST MANAGEMENT PROGRAMS

It was assumed that the information required for each decision rule was available to the grower at the cost specified in the model. Multi-year and regional planning strategies were not considered. Therefore, the results apply to a firm level decision making process based upon maximization of net income in a single season.

The decision algorithms are categorized below according to the tactics they involve and the need for monitoring. The categories will aid in understanding the discussion. It should be noted that the categories are not mutually exclusive.

1. Spray Recommendations

    Rule 1 - dynamic threshold

    Rule 2 - routine spray before and after the first cut

    Rule 3 - static threshold

    Rule 7 - routine spray before the first harvest

2. Early Cutting

    Rule 5 - cost-benefit analysis

    Rule 6 - early cutting date set

3. Monitoring of Pest Required

    Rule 1 - dynamic threshold

    Rule 3 - static threshold

    Rule 5 - cost-benefit analysis

4. No Monitoring of Pests Required

Rule 2 - routine sprays (two sprays)

Rule 4 - conventional cutting schedule

Rule 6 - early cutting schedule

Rule 7 - routine spray (one spray)

6.1 Net Income Above Spray and Monitoring Costs

Net income distributions above monitoring and spray costs for each decision rule are shown in Table 6.1. The means, standard deviation, variance and coefficient of variation are given for each distribution. The early cutting schedule (Rule 6) had the highest average net income ($920). For this rule gross and net incomes were the same because there is no monitoring or spraying. Cost-benefit analysis showed the next highest average net income ($907) with an annual monitoring cost of $7. This decision rule also had the second highest gross income.

Rule 2 (two routine sprays) had the lowest average net income ($806). Interestingly, Rule 2 had the third highest average gross income ($850) following cost-benefit analysis and the early cutting schedule. This means that the cost of applying two sprays on the average exceeds the benefit from those sprays. The average net incomes from the single spray rules (1, 3 and 7) differed from each other by a magnitude of four dollars or less and had the fourth, fifth and sixth ranked average net incomes.

The no control strategy had the third highest average net income but the lowest average gross income. This difference in ranking resulted from the fact that the value of the crop loss avoided did not

TABLE 6.1

NET INCOME ABOVE MONITORING AND SPRAY COSTS FOR EACH YEAR

Rule	1	2	3	4	5	6	7
Year			---- $/hectare ----				
1966	755	746	755	762	830	837	763
1967	951	938	962	969	1,062	1,059	959
1968	912	899	923	930	1,087	1,094	919
1969	877	864	877	891	1,013	1,020	884
1970	767	739	767	774	805	810	760
1971	814	801	825	832	931	930	821
1972	874	848	862	881	966	968	869
1973	797	771	797	804	856	864	790
1974	830	804	830	837	949	953	825
1975	744	719	733	751	757	764	740
1976	878	866	878	893	982	1,008	885
1977	639	645	654	605	646	729	661
1978	795	782	795	806	840	852	802
1979	871	857	880	887	967	973	877
1980	816	805	817	832	917	940	825
AVE	821	806	824	830	907	920	825
VARIANCE	6,043	5,772	6,143	7,771	14,061	11,543	5,891
SD	77.738	75.974	78.374	88.154	118.578	107.441	76.752
COEF. VAR.	0.095	0.094	0.095	0.106	0.131	0.117	0.093

justify the cost of the spray for every decision algorithm in almost every year.

The use of insecticide increased gross income in all years over the no control strategy (Rule 4) and gross income always increased more from two sprays (Rule 2) than from one spray (Rules 1, 3 and 7). These results are obtained because in this single pest model, the only impact of insecticide application is to reduce pest population and consequently reduce crop loss. There is no possibility of a secondary pest outbreak or resurgence in the model design. Nor is the development of pest resistance built in. Therefore, the only impact of insecticide application in the model is to decrease the pest population and consequently increase yield and gross income.

These simplifying assumptions are reasonable for alfalfa production in Michigan, although secondary pest outbreaks are possible. There is no possibility of population resurgence because there is only one generation of alfalfa weevils per year in Michigan. Therefore, no possibility exists for an in-migration of adults mid-season.

Another way to compare the net income flows generated by each management model is to order the annual levels from lowest to highest (Table 6.2). The ordering simultaneously produces an ordering of years from poorest to best for each decision algorithm. Interestingly, the resulting ordering of years was very similar for each algorithm although not identical.

1977 was the poorest year for all management models while 1967 and 1968 were the two best years for all models. In other words, a good year for alfalfa tended to be a good year regardless of the management

TABLE 6.2

NET INCOME ABOVE MONITORING AND SPRAY COSTS
ORDERED FROM LOWEST TO HIGHEST INCOME

Rule	1	2	3	4	5	6	7
Rank			---- $/hectare ----				
1	639	645	654	665	646	729	661
2	744	719	733	751	757	764	740
3	755	739	755	762	805	810	760
4	767	746	767	774	830	837	763
5	795	771	795	804	840	852	790
6	797	782	797	806	856	864	802
7	814	801	817	832	917	930	821
8	816	804	825	832	931	940	825
9	830	805	830	837	949	953	825
10	871	848	862	881	966	968	869
11	874	857	877	887	967	973	877
12	877	864	878	891	982	1,008	884
13	878	866	880	893	1,013	1,020	885
14	912	899	923	930	1,062	1,059	919
15	951	938	962	969	1,087	1,094	959
AVERAGE	821	806	824	830	907	920	825
VARIANCE	6,043	5,772	6,143	7,771	14,061	11,543	5,891
SD	78	76	78	88	119	107	77
COEF. VAR.	0.095	0.094	0.095	0.106	0.131	0.117	0.093

techniques used. Conversely, a poor year could not be completely avoided by any of the management schemes.

In 1977, the highest net income was $729 per hectare, the fitted value for Rule 6, (early cutting). The next highest income was $661 per hectare for Rule 7 (1 routine). Rule 3 resulted in a net income of $654 with one spray. The difference between Rules 3 and 7 is that 7 is a routine spray based on degree day accumulation while the spray decision for Rule 3 depends upon a threshold for larvae population. Rule 1 with a different threshold definition for insecticide application resulted in a $639 per hectare net income and Rule 2 with two routine sprays generated $645. The no control strategy (Rule 4) meant $605 per hectare. The net income for cost-benefit analysis (Rule 5) was the third highest $646 per hectare. 1977 was the only year in which Rule 5 did not yield one of the two highest incomes.

The net income for Rule 6 was higher than that for Rule 5 in thirteen of the fifteen years. However, the gross for Rule 5 was the same or greater than the gross income for Rule 6 in eleven out of fifteen years. This result indicates that while monitoring can improve crop performance. The benefits at current market prices do not warrant the going rate for monitoring.

6.1.1 Comparison of Means

The means for each decision rule were compared by applying the Waller-Duncan k-ratio test. This test minimizes a ratio of Type I to Type II errors rather than controlling Type I error rates. A k-ratio is selected rather than a significance level (see section 5.5). A k-ratio of 100 was used. It is comparable to a significance level of .05.

The comparison of means test interprets the simulation results as random samples from a larger population. The means of the observations of income are estimates of the actual means for each decision rule. The standard deviations of the income distributions are used to establish confidence intervals for estimates of the mean.

The results of the Waller-Duncan k-ratio test are presented in Table 6.3a. The least significant difference for the means was 13.99. Means with a difference of less than 13.99 are not found to be significantly different. Three significantly different groups emerged.

Rules 5 and 6 were preferred to all other rules and no ordering was possible between them. Rules 4, 7, 3 and 1 were in the second group. Rule 2 was found to be the least preferred strategy.

The results can be interpreted using the categories presented at the beginning of the chapter. The early cut decision rules were preferred to all other strategies. The no control strategy and single spray rules were in the second group and the two spray strategy was least preferred. The test failed to distinguish between routine single sprays and sprays using thresholds using a k-ratio of 100. It also did not distinguish between a dynamic threshold and a static threshold.

In addition, the test failed to distinguish between the no control strategy (Rule 4) and the single sprays using thresholds (Rules 1 and 3). The routine spray schedules (Rules 2 and 7) were not preferred to the no control strategy when the cost of spray material and application was taken into account.

TABLE 6.3a

Ranking of decision rules based on net income using Waller-Duncan k-Ratio Test

Decision Rule	Mean	Grouping
6	920	A
5	907	A
4	830	B
7	825	B
3	823	B
1	821	B
2	806	C

Waller-Duncan k-ratio Test
k-ratio = 100
least significant difference = 13.99
critical value of t = 1.77

Means followed by the same letter are not significantly different

It is instructive to compare the results of this test to Fisher's Least Significant Difference test for paired comparisons. Using Fisher's Least Significant Difference Test, the critical difference is 13.16 at the .10 significance level and 15.73 at the .05 significance level. The Waller-Duncan k-ratio test with a k-ratio of 100 gives the same ranking as using Fisher's Least Significant Difference at the .10 significance level (Table 6.3b).

The ranking is also the same for Fisher's lsd test at the .05 level except that Rules 2 and 1 cannot be ordered. (Table 6.3c). These observations show the ranking in Table 6.3a to be quite stable.

The least significant difference calculated using the Waller-Duncan procedure with a k-ratio of 100 is equivalent to Fisher's Least Significant Difference at the .083 significance level.

It was stated earlier that the Waller-Duncan test controls experiment-wise error while Fisher's test does not. Thus, the Waller-Duncan test is more conservative and allows greater protection against Type I errors.

In selecting pest management strategies the problem of detecting a difference when none exists may not be a primary concern to an individual decision maker. At worst, the decision maker will reject a management practice that was equally good to the one selected.

If the analysis of alternative pest management practices is used for public policy decisions, then experiment-wise errors are a greater concern. The implementation of monitoring programs, direction of future research and pesticide regulations are all affected by the analysis of alternative pest management programs. Asserting that one pest

TABLE 6.3b

Ranking of decision rules based on net income using Fisher's Least Significant Difference Test at the .10 significance level

Decision Rule	Mean	Grouping
6	920	A
5	907	A
4	830	B
7	825	B
3	823	B
1	821	B
2	806	C

least significant difference - 13.16

Means followed by the same letter are not significantly different

TABLE 6.3c

Ranking of decision rules based on net income using Fisher's Least Significant Difference Test at the .05 significance level

Decision Rule	Mean	Grouping
6	920	A
5	907	A
4	830	B
7	825	B
3	823	B
1	821	BC
2	806	C

least significant difference - 15.73

Means followed by the same letters are not significantly different

management program reaps greater benefits than another when no difference exists may erroneously steer the course of public policy.

The discussion here addresses decisions on a firm level. Therefore, control of the comparison-wise error rate is the primary concern. Further, protection against Type I error at the .10 level rather than a more restrictive level seems appropriate.

6.1.2 Ordering by Stochastic Dominance

First degree stochastic dominance provides an ordering for all decision makers who have an increasing utility function. In this case, it is an increasing utility for money. In other words, the ordering is appropriate for the broad range of decision makers who prefer more to less. They may be risk averse, risk neutral or risk takers.

Second degree stochastic dominance generates an ordering for all decision makers with decreasing marginal utility for money. As the level of wealth increases, their utility increases but at a decreasing rate.

The ordering of decision rules by first and second degree stochastic dominance are presented in Table 6.4. Rules that cannot be ordered are grouped together in Table 6.5. Table 6.4 compares each rule with every other rule. For each comparison a decision maker is expected to prefer one rule to the other or be indifferent between the rules. Table 6.7 provides the same information but in a different format. The emphasis is on identifying groups of decision rules that cannot be ordered by stochastic dominance.

Using first degree stochastic dominance, Rule 6 is preferred to all rules except Rule 5. Rules 5 and 6 cannot be ordered. Rule 5 is

TABLE 6.4

Ordering of decision rules by FSD and SSD based on net income 1/

First Degree Stochastic Dominance

R1 \ R2	1	2	3	4	5	6	7
1	NA	0	-	0	-	-	-
2	0	NA	-	0	-	-	-
3	+	+	NA	0	0	-	-
4	0	0	0	NA	NA	-	0
5	+	+	+	+	NA	-	0
6	+	+	+	+	+	NA	+
7	+	+	+	0	0	-	NA

Second Degree Stochastic Dominance

R1 \ R2	1	2	3	4	5	6	7
1	NA	0	-	0	-	-	-
2	0	NA	-	0	-	-	-
3	+	+	NA	0	-	-	-
4	0	0	0	NA	-	-	0
5	+	+	0	+	NA	-	0
6	+	+	+	+	+	NA	+
7	+	+	+	0	0	-	NA

1/ + means that R1 dominates R2
- menas that R2 dominates R1
0 means the rules cannot be ordered
NA means it is not appropriate to order a rule with itself

TABLE 6.5

Grouping of decision rules based on net income using FSD and SSD

First Degree Stochastic Dominance[1/]

Decision Rule	Mean	Grouping					
6	920	A	B				
5	907	A	B		D		
4	830			C	D	E	F
7	825		B	C	D	E	F
3	823		B	C	D	E	
1	821			C	D	E	F
2	806			C		E	F

1/ Decision rules followed by the same letter cannot be ordered by FSD

Second Degree Stochastic Dominance[2/]

Decision Rule	Mean	Grouping					
6	920	A					
5	907		B		D	E	
4	830			C	D	E	F
7	825		B	C	D		
3	823		B	C		E	
1	821			C			F
2	806			C			F

2/ Decision rules followed by the same letter cannot be ordered by SSD.

preferred to the no control strategy (Rule 4) and the routine two sprays schedule (Rule 2) and the dynamic threshold (Rule 1). A decision maker would be indifferent among Rule 5 and the static threshold spray (Rule 3) and the routine single spray (Rule 7). The no control strategy is dominated by both early cutting schedules (Rules 5 and 6) and cannot be ordered with any of the spray schedules.

The single routine spray (Rule 7) and the static threshold (Rule 3) are both preferred to the two routine sprays (Rule 2). Neither can be ordered with Rules 5, 4, 1 or each other. Both are dominated by Rule 6. Rule 1 is dominated by the early cutting rules (Rules 5 and 6). It cannot be ordered with any other rules. Rule 2 is dominated by Rules 3, 5 and 6. It cannot be ordered with any other rules. Rules 1 and 2 are not preferred to any other rules.

Using second degree stochastic dominance allows for a more complete ordering of decision rules. The rankings for Rules 5 and 6 relative to all other rules are the same under SSD as for FSD. Unlike FSD, SSD allows for the ordering of Rules 5 and 6. Rule 6 is preferred to Rule 5. They could not be ordered using FSD because Rule 5 generated a higher net income than Rule 6 at one point at the upper end of the income distributions. The early decision rules cannot be ordered for any decision makers who have a positive utility for money. When only risk averse decision makers are considered, the scheduled early harvest criteria (Rule 6) is preferred to the early harvest scheduled by monitoring information (Rule 5).

The routine single spray (Rule 7) was preferred to the other spray schedules using SSD. It could not be ordered with Rules 4 and 5. Rule 7 could not be ordered with Rules 1 and 3 using FSD but was preferred to those spray rules using SSD. This result shows that none of the spray rules showed the highest net income in all years.

The static threshold (Rule 3) was preferred to the other spray schedules except Rule 7. It could not be ordered with Rules 4 and 5. Rules 1 and 2 were not preferred to any other rules. They could not be ordered with the no control strategy (Rule 4).

Under the stochastic dominance approach the net income distributions for each decision rule generated by the simulation model are taken to be the true distributions. There is no restriction on the functional form of the distributions. It allows for an ordering of action choices according to a decision maker's attitude toward risk. Type I errors are not controlled. In contrast, the least significant difference tests assured that the results of the simulation model are random samples from a larger data set and are used to estimate the true distributions. The tests rely on the assumptions that the true distributions are normal and have equal variance. They do not produce an ordering that accounts for the decision maker's attitude toward risk. Type I errors are controlled.

It should be noted, that in this case, the assumptions of normality and equal variance are not unreasonable if the simulation results are viewed as a random sample of observations from a larger population. The null hypothesis of normality of the distributions held was not rejected at the .10 significance level. Tests for equality of the variances detected no differences at the .05 level for any of the pairwise comparisons. The variances of Rule 5 and Rule 2 were significantly different at the .10 level, however.

The differences in underlying assumptions do not allow for direct comparison of results. However, under both sets of restrictions, none of the strategies is preferred to the early cutting strategies. This observation gives some stability to the results.

6.2 Value of Pest Management Programs

The differences between the gross income generated under each decision algorithm and the no control strategy are given in Table 6.6. These calculations measure the value of each pest management program for each year. In other words, the value of the program is measured as the increase in gross income attributable to that program. The dollar figure represents the increased income attributable to spraying, monitoring and the information imbedded in the decision algorithm itself.

For the decision rules involving the use of thresholds for spray decisions (Rules 1 and 3) the value of the program is zero in years when no spray is recommended. In those years, the decision maker would have had the same yield without monitoring.

The pest management program with the highest average value was Rule 6 ($89.83 per hectare) followed by Rule 5 ($83.93). Rule 3 had the lowest average value ($10.67 per hectare). The average values of the routine-spray programs, Rules 2 and 7, were $19.33 and $17.07, respectively. This means that on the average, applying two sprays annually instead of one spray increased gross income by only $2.26 per hectare.

The average values of the programs utilizing threshold information for spray decisions, Rules 1 and 3, were $12.73 and $10.67,

TABLE 6.6

VALUE OF PEST MANAGEMENT PROGRAMS

Difference between gross income for each rule and the no control strategy (Rule 4)

Rule	1	2	3	5	6	7
Year			---- $/hectare ----			
1966	22	28	0	75	75	23
1967	11	13	0	100	90	12
1968	11	13	0	164	164	11
1969	15	17	15	129	129	15
1970	0	9	0	38	36	8
1971	11	13	0	106	99	11
1972	0	11	10	92	87	10
1973	0	11	0	59	60	8
1974	0	11	0	119	116	10
1975	0	12	11	13	13	11
1976	14	17	14	96	115	14
1977	63	84	78	48	124	78
1978	18	20	18	41	46	18
1979	13	14	0	87	86	12
1980	13	17	14	92	108	15
						0
						0
AVERAGE	13	19	11	84	90	17
VARIANCE	248	342	396	1,548	1,555	299
SD	16	18	20	39	39	17
COEF. VAR.	1.236	0.957	1.865	0.469	0.439	1.014

respectively. On average, the dynamic threshold used in Rule 1 generated $2.06 more income than the static threshold used in Rule 3.

The average values of the programs using threshold information for early cutting decisions, Rules 5 and 6, were $83.93 per hectare and $89.83 per hectare, respectively. Using Rule 6 means $6.90 more income per acre on average than using Rule 5.

6.3 Value of Insecticide Applications and Monitoring

The value of insecticide applications is shown in Table 6.7 for Rules 1, 2, 3 and 7. Rules 2 and 7 are routine schedules and there is no cost of monitoring. Rule 1 and 3 use monitoring at a cost of $7 per hectare per year. These are the only rules for which insecticide was used as a control strategy. The difference between the values in Tables 6.6 and Table 6.7 is that the cost of monitoring is taken into account in Table 6.7 but not in Table 6.6.

Rules 1 and 3 involve thresholds for spray decisions and did not utilize insecticides in every year. The value of each program is negative $7.00 for years in which no insecticide was applied. In those years, the cost of monitoring was incurred even though no insecticide was applied. Also, no benefit from spraying was derived because no spray was applied. In other words, it cost $7.00 to decide to do nothing.

The two routine sprays showed an average benefit of $19.33 per hectare while one routine spray showed only a slightly lower average benefit of $17.07. The break even cost of an insecticide application for the two scheduled sprays is $9.66. The break even price for the one scheduled spray is $17.07. In other words, once the cost of spraying

TABLE 6.7

VALUE OF SPRAY APPLICATIONS

Differerence between the net income above monitoring costs for each control strategy involving spraying (Rules 1,2,3 and 7) and the no control strategy (Rule 4). For Rules 2 and 7 the monitoring cost is zero. For Rules 1 and 3 the cost of monitoring is $7 per hectare.

Rule	1	2	3	7
Year		---- $/hectare ----		
1966	15	28	-7	23
1967	4	13	-7	12
1968	4	13	-7	11
1969	8	17	8	15
1970	-7	9	-7	8
1971	4	13	-7	11
1972	-7	11	3	10
1973	-7	11	-7	8
1974	-7	11	-7	10
1975	-7	12	4	11
1976	7	17	7	14
1977	56	84	71	78
1978	11	20	11	18
1979	6	14	-7	12
1980	6	17	7	15
AVERAGE	6	19	4	17
VARIANCE	248	342	396	299
SD	16	18	20	17
COEF. VAR.	2.745	0.957	5.425	1.014

goes above $9.66 per hectare it is no longer profitable on the average to apply two sprays. Once the price of a spray goes above $17.07 it is no longer profitable on the average to apply one spray.

The average value of the dynamic threshold (Rule 1) was $5.73 and the average value for the static threshold (Rule 3) was $3.67. If the cost of monitoring had been zero, the average value of Rule 1 would have been $12.73 and $10.67 for Rule 3.

Sprays were recommended in ten years for Rule 1 and seven years for Rule 3. On the average, 2/3 of a spray was made each year for Rule 1 and 7/15 of a spray was made each year for Rule 3. The breakeven cost of a spray for Rule 1 is $8.60 and for Rule 3 is $7.86 at a $7 per year cost of monitoring. With no cost of monitoring the breakeven costs become $19.10 and $22.86 for Rules 1 and 3, respectively.

The average benefit of a spray for the static threshold (Rule 3) exceeded the average benefit from a spray made following the dynamic threshold (Rule 1) when no cost of monitoring was included. The average benefits from both decision rules using thresholds exeeded the average benefit from the routine sprays (Rules 2 and 7). However, when the cost of monitoring is considered, the average net benefits from the routine sprays exeeded the average net benefits from the decision rules using thresholds. At a cost of $22 per spray, the increased income from the spray applications did not cover the cost of the sprays on average for any of the decision rules.

The value of monitoring above spray costs is given in Table 6.8. It is calculated as the difference between net income above spray costs for Rules 1, 3 and 5 and the gross income from no control. Rules 1, 3

TABLE 6.8

VALUE OF MONITORING

Differerence between the net income above spray costs for each control strategy involving monitoring (Rules 1,3 and 5) and the no control strategy (Rule 4). The cost of spraying is $22 per hectare. In years when the recommended strategy is identical to Rule 4, the value of monitoring is zero.

Rule	1	3	5
Year	----	$/hectare	----
1966	0	0	75
1967	-11	0	100
1968	-11	0	164
1969	-7	-7	129
1970	0	0	38
1971	-11	0	106
1972	0	-12	92
1973	0	0	59
1974	0	0	119
1975	0	-11	13
1976	-8	-8	96
1977	41	56	48
1978	-4	-4	41
1979	-9	0	87
1980	-9	-8	92
AVERAGE	-1.93	0.40	83.93
VARIANCE	163	257	1548
SD	13	16	39
COEF. VAR.	-6.60	40.04	0.47

and 5 are the only rules that inolve monitoring for pest population levels.

In years when no spray application is made, Rules 1 and 3 generate the same gross income as the no control strategy. In those years the value of monitoring is zero. The value of a monitoring program is negative when the cost of spraying exceeds the increase in revenue resulting from spraying and reducing crop loss. Similarly, the value of a monitoring program is positive when the revenue increase attributable to spraying exceeds the cost of spraying.

The value of monitoring for Rules 1 and 3 was positive only in 1977. In that year the net gain for Rule 1 was $41 and for Rule 3 was $56. On the average, the value of monitoring was -$1.93 for Rule 1. At a cost of $22 per hectare per spray, monitoring did not pay on the average for Rule 1. For Rule 3 the breakeven price for monitoring was $.40 per hectare per year.

Rule 5 always showed a positive benefit from monitoring. The early cutting dates recommended based on larvae sampling always increased gross revenue. The breakeven cost of monitoring was $83.92 per hectare per year. At a monitoring cost of $7, the average net value of monitoring was $76.93 per hectare per year.

6.4 Sampling Frequency

The simulation model was run monitoring every day, monitoring every three days and monitoring once a week. The "spray or don't spray" decision is made every time sampling occurs for Rules 1 and 3. The monitoring information is compared to the threshold criteria. A spray is applied if the threshold is reached or surpassed provided it is not too close to the scheduled harvest. Similarly, the decision to cut is made on each sampling date for Rule 5.

Infrequent sampling increases the chance of spraying after the threshold is reached. More frequent monitoring results in making spray applications closer to the specified threshold.

Tables 6.9 and 6.10 present the effect of sampling frequency on the net incomes above spray costs and monitoring costs for each year for Rules 3 and 5, respectively. Sampling frequency is not a factor for Rule 1 because the decision algorithm dictates how often samples should be taken.

For Rule 3, the average net income was reduced from $824 for daily sampling and sampling every 3 days to $821 for weekly sampling. Sampling every third day instead of every day meant at most a difference of $1 in any one year. In twelve of the fifteen years the net income was identical for the two sampling regimes. Cutting sampling back to once a week did not have much effect on net income with the exception of 1977. In 1977 net income decreased $57 from postponing sampling and consequently spraying late. Net income was unchanged in seven of the fifteen years.

The value of sampling every day instead of every third was only $.14. Virtually any reduction in cost from switching to a three-day schedule from a daily schedule would pay off.

The value of sampling every 3 days instead of once a week was $3 per year. This means that if a grower could reduce the cost of monitoring from $7 per hectare to $4 per hectare, net income would be the same on average for each sampling regime.

TABLE 6.9

Effect of Sampling Frequency on Net Income Above Spray and Monitoring Costs for Decision Rule 3 - Static Threshold

Year	Days Between Samples 1	3	7
		---- $ ----	
1966	755	755	755
1967	962	962	962
1968	923	923	923
1969	877	877	876
1970	767	767	767
1971	825	825	825
1972	862	861	860
1973	797	797	797
1974	830	830	830
1975	733	732	731
1976	878	877	880
1977	654	655	598
1978	795	795	794
1979	880	880	886
1980	817	817	825
AVERAGE	824	824	821
VARIANCE	6,143	6,118	7,790
SD	78	78	88
COEF. VAR.	0.095	0.095	0.108

TABLE 6.10

Effect of Sampling Frequency on Annual Net Income Above Monitoring Costs for Decision Rule 5 - Dynamic Threshold

Year	Days Between Samples 1	3	7	14
	---- $/hectare ----			
1966	830	824	817	817
1967	1,062	1,045	1,025	1,025
1968	1,087	1,051	1,051	1,045
1969	1,013	995	990	975
1970	805	806	807	807
1971	931	898	865	865
1972	966	947	930	930
1973	856	850	842	842
1974	849	919	914	914
1975	757	747	749	749
1976	982	982	951	951
1977	646	646	646	646
1978	840	836	826	826
1979	967	956	950	947
1980	917	914	907	907
AVERAGE	901	894	885	883
VARIANCE	14,130	12,439	11,583	11,203
SD	119	112	108	106
COEF. VAR.	0.132	0.125	0.122	0.120

Net income was actually increased in three years by sampling once a week instead of daily. In those years no sample was taken on the day that the static threshold was reached and spraying was delayed. In 1977 sampling every third day resulted in a net income of $655 compared to $654 for sampling daily. In 1979, net income was $886 compared to $880 for the two sampling regimes and in 1980 it was $825 compared to $817.

The failure of daily sampling to produce the highest income in every year shows that the static threshold will not always optimize net income. This could be (1) because of the uncertainty regarding weather, pest population growth, and plant growth at the time the decision is made; or (2) because other factors besides larval population should be taken into account when spray decisions are made; or (3) both.

Four sampling regimes were tested for decision Rule 5; sampling every day, every three days, once a week and once every two weeks. The cost benefit analysis used in Rule 5 calculates the income from cutting hay on the day the sample is taken and predicts income for the two weeks after the sample is taken. The date which is predicted to yield the highest income is selected as the harvest date.

If the date falls before the next scheduled sample, then it becomes the harvest date. If it falls after the next scheduled sample, the next sample is taken and a date is selected utilizing the new information. The process continues until the selected harvest date occurs before the next scheduled sample.

This procedure makes it possible to choose any day as the day of first harvest up until the scheduled date for the conventional harvest date (Rule 4). The harvest date is selected based upon more or less information depending on the frequency of sampling which will affect the decision. However, potential harvest dates are not limited to the days on which samples are taken.

The average net income above monitoring costs for daily sampling for Rule 5 was $901, $894 for every three days, $885 for once a week and $883 for sampling every two weeks. The coefficients of variation were .13 for daily sampling and .12 for the other sampling regimes.

The net income from sampling daily averaged $6 per hectare per year more than the net income from sampling every three days, $16 more than sampling once a week and $17 more than sampling every two weeks. The cost of daily sampling would have to be at least $16 more than sampling once a week before it paid to monitoring once a week or less. Similarly, the cost of sampling daily would have to be at least $6 more than sampling every 3 days before average net income would increase from reducing monitoring frequency.

Daily sampling always resulted in a higher income than less frequent sampling with exception of 1970 when the incomes were within $2 of each other. The largest differences in net income occurred in years when income was relatively high. For example, the value of sampling every day instead of once a week was $35 in 1967 when the net income was highest at $1087. In 1980, when the net income for daily sampling was $917, the increase over sampling once a week was only $10. The timing of cutting becomes more critical as potential income increases.

6.5 Recommended Spray Dates and Harvest Dates

The spray dates and harvest dates recommended for selected algorithms are presented in Tables 6.11 and 6.12. The spray dates are given for each of the single spray strategies (Rules 1, 3 and 7). The

TABLE 6.11

SPRAY DATES RECOMMENDED BY DECISION ALGORITHMS

Rule	1	3	7
Year			
1966	6/9	6/14[1]	6/11
1967	6/7	6/10[1]	6/8
1968	6/3	NS	6/4
1969	6/1	6/7	6/5
1970	NS	NS	6/1
1971	6/11	6/12[1]	6/8
1972	NS	6/6	6/5
1973	NS	NS	6/3
1974	NS	NS	6/5
1975	NS	6/6	6/5
1976	6/3	6/3	5/31
1977	5/17	5/20	5/20
1978	6/6	6/8	6/6
1979	6/8	NS	6/6
1980	6/3	6/10	6/7

[1] Spray recommended within 100 degree days (5 days) of harvest so no spray was applied.

NS - No spray was recommended.

TABLE 6.12

HARVEST DATES RECOMMENDED FOR THE FIRST CUTTING BY DECISION ALGORITHMS

Rule	4	5	6
Year			
1966	6/19	6/7	6/7
1967	6/13	6/3	6/4
1968	6/9	5/30	5/30
1969	6/14	5/31	5/31
1970	6/11	6/1	5/30
1971	6/15	6/4	6/5
1972	6/13	6/1	6/2
1973	6/10	6/1	5/30
1974	6/13	6/2	6/1
1975	6/14	5/31	5/31
1976	6/8	5/30	5/27
1977	5/24	5/31	5/17
1978	6/14	6/3	6/1
1979	6/14	5/31	6/2
1980	6/17	6/3	6/2

harvest dates are given for the early cutting strategies (Rules 5 and 6) and the conventional cutting schedule (Rule 4).

In two years the dynamic threshold (Rule 1) made a spray recommendation while the static threshold (Rule 3) did not. In one year the static threshold made a spray recommendation while the dynamic threshold did not. In three years no spray was recommended by either rule.

The spray dates recommended by the static threshold were always later than the spray dates recommended by the dynamic threshold with the exception of one year when the dates were identical. Sprays were avoided in three years for Rule 3 because the date recommended was within 100 degree days of the scheduled harvest. A spray was never recommended within 100 degree days of harvest by Rule 1. It appears that the dynamic threshold levels developed in Illinois and used in Rule 1 are too low for Michigan conditions.

The cutting dates recommended by Rules 5 and 6 were always within three days of each other with the exception of 1977 when the model failed to perform adequately. For that year, a modified data point was generated for Rule 6 (sec. 4.8). This modification did not generate a new cutting date, however. The early cuts ranged from nine to fifteen days earlier than the conventional control strategy.

The cutting date recommended by Rule 6 is based solely on temperature data. In contrast, Rule 5 requires temperature data and a measure of the larvae population. The additional information required to implement Rule 5 did not generate an increase in revenue, nor did it reduce the variability in income flow. Therefore, the monitoring expense for measuring weevil population was not warranted.

CHAPTER VII

SUMMARY AND CONCLUSION

Integrated pest management has been defined as a control system that uses all suitable techniques to repress pest populations to levels below those causing economic injury in a manner that is compatible with the environment. The concept of an economic threshold was developed by Stern et al. (1959) to define the pest level at which control strategies should be implemented.

Several generic models were presented to derive the threshold population mathematically. The solutions differed depending on the variables included in the model by its designer. In particular, the inclusion of parasites, interdependencies among fields and multi-year vs. single year planning significantly altered the results.

While the philosophy of pest management is intuitively appealing, implementation requires an understanding of the interactions of numerous biological and environmental factors. When pest management decisions are put in the context of all on-farm management decisions, the problem is even more complex.

Pest management decisions are made under uncertainty. The grower does not have perfect knowledge of future states of nature or the effectiveness of alternative control strategies. As a result, the ideal conditions of perfect and costless knowledge are not appropriate for analysis of pest management programs.

Pest management information may not be provided adequately by decentralized markets for two basic reasons: 1) the goals of pest management include non-market values sometimes referred to as collective values and 2) information has public goods characteristics. That is, consumption by one person does not reduce the amount available to anybody else. Also it is difficult to exclude people from using information once it has been produced.

Information for which exclusion is possible is likely to be provided by the private sector. But these private programs will not include regional management or the interdependencies of growers.

It is unreasonable for extension workers in the area of pest management to believe that they need only demonstrate the benefits of pest management and the private sector will pick up the ball. A more viable approach has been to aid growers in providing pest management information for themselves through some form of grower organization. This alternative does not depend on the private sector response to grower needs and reduces subsidization of programs by public funds.

It is clear that neither generating nor delivering pest management information is a simple matter. But developing control guidelines and providing that information along with information needed to operationalize the guidelines are not problems to be solved independently. Control guidelines should always be designed with the user in mind. If the information required is too detailed or performance is overly sensitive to sampling error, the guideline is simply an academic exercise.

A paradigm for information systems was presented (Bonnen 1977). Information is the interpretation of data used in the decision making process. In pest management, information is used to make control decisions. Management can be viewed as a process by which information is the input and decisions are the output.

The design of a pest management program is the development of an information system. The information provided to managers is prescriptive. That is, it recommends specific pest control strategies.

Often the recommendation takes the form of pest control guidelines for the timing of implementation of a strategy. These guidelines are developed from an accumulation of knowledge over time for a region.

Guidelines include threshold information. The strategy should not be implemented unless the threshold is reached. A threshold can be defined in an infinite number of ways. They usually require real-time field-specific measurements of pest levels, stage of plant development and/or other factors.

Information has value in the context of the decision being made. The value of the information can be evaluated by comparing the outcomes with and without the information. The outcomes are not known with certainty. Therefore, criteria for selecting among risky alternatives depend on a probability distribution of outcomes associated with each alternative management strategy.

The use of simulation models to generate probability distribution was discussed in general and then applied to the alfalfa weevil problem. The simulation model presented had three submodels: 1) the alfalfa weevil model, 2) the alfalfa plant model and 3) the management model.

The alfalfa weevil model developed in Illinois, and the alfalfa plant model were modified to perform reasonably under Michigan weather conditions. It was determined that the overwintering logic for the alfalfa weevil did not work adequately to run the model for consecutive years. Therefore, the model was reinitialized every fall. The plant model did not perform accurately when the temperature in early spring

was extremely hot or extremely cold. Changes in the model were made accordingly.

The management model had seven versions. Each was an alternative decision rule for determining whether or not to implement a specific control strategy. The strategies were: 1) spray when a dynamic threshold is reached, 2) apply a single routine spray before harvest, 3) spray when a static threshold is reached, 4) do nothing, 5) cut early based on a pest population threshold, 6) cut early regardless of pest population levels and 7) apply one routine spray before harvest and one after harvest. Rules 1, 3 and 5 involved monitoring of pest populations, the others did not.

The income distributions generated by the simulation model for each decision rule were compared several ways using varying sets of assumptions. First, the simulation results were assumed to be a random sample from a larger population. Further, the underlying distributions were assumed to be normally distributed with equal variance. A comparison of means tests showed that under these assumptions, the average net incomes from the two early harvest schedules were significantly higher than for the other strategies at the .05 level. All of the strategies showed a significantly higher mean net income than the routine two sprays at the .10 level. This analysis did not take the decision maker's attitude toward risk into account.

Decision analysis based on the Expected Utility Hypothesis was used to include risk-preference into the analysis. Stochastic dominance techniques assume that the income distributions generated by the simulation model are the true distributions. This assumption does not

control for Type I errors. No assumption is made about the functional form of the distributions.

First degree stochastic dominance provides a preference ordering for all decision makers. Second degree stochastic dominance limits the ordering of action choices to risk-averse decision makers. The ordering is more complete than for FSD but the chance of Type I error increases.

Using first degree stochastic dominance, the early cut rules were also preferred to the other rules and were not significantly different from each other. Using second degree stochastic dominance, Rule 6 was preferred to Rule 5. In any case, the simple cut early rule is at least as effective as cutting based on pest population counts.

The value of each pest management program was calculated. The value of the spray applications did not cover the cost of the spray material on average for any of the programs including spraying. The benefit from sprays only exceeded the cost of sprays in one of the fifteen years.

The results are significant at least in the Great Lake States where fall laid alfalfa weevil eggs do not survive the winter. It is important to note the limitations of the approach taken. First, the model is for a single season and single field. No in-migration of weevils is possible. Also, no long run effects of continued pesticide use such as reduced effectiveness of pesticides or reduction in parasite population are considered .

The monitoring information for pest populations and weather are taken as the true values. No measurement error exists.

The model also assumes that all of the acreage can be sprayed the day after the control recommendation is made. This is not unrealistic.

However, the model also assumes that all of the hay can be cut the day after the recommendation is made, which is not feasible. The results are appropriate if they are considered as the average of the several cuts made. The model does not allow for a reduction in hay quality due to rain on cut hay before it is baled and removed from the field.

Future research needs include the following. First, more information is needed concerning the overwintering habits of the alfalfa weevil adults. Along these lines, the in and out migration from individual fields should be explored. At that time, multi-year strategies can be developed. Secondly, the growth rates of the alfalfa plant in early spring are not adequately understood. Thirdly, future studies should include a sampling error to test the effects of an unbiased error and an upward or downward bias.

Finally, the results of this study strongly indicate that early cutting schedules are preferable to spray application for control of alfalfa weevil in alfalfa even when threshold information is available for the timing of sprays.

For the early harvest strategies, the monitoring of pest population levels was not shown to improve cutting schedules over a scheduled early harvest. For the spray strategies, the dynamic threshold strategies were not preferred to static thresholds or routine single sprays. The implications are (1) that current threshold levels for spray applications are too low and (2) that more research should be concentrated on developing cutting schedules.

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