AN ABSTRACT OF THE THESIS OF

Sue Haley for the degree of Doctor of Philosophy in Entomology presented on March 9, 1990.

Title: AppleMgr: A Prototype Decision Aid for Apple Pest Management

Abstract approved: Redacted for Privacy

Computer decision aids can help integrate and apply diverse sources of information and expertise to problems of integrated pest management (IPM) in agriculture and forestry. AppleMgr combines a rule-based expert system with databases and spreadsheets in a prototype decision aid intended to be expanded and modified for use by extension workers in the Northwest U.S. The program requires an IBM-compatible microcomputer with hard disk. AppleMgr concentrates on the two most important insect pests on apple in the Northwest--codling moth, *Cydia pomonella* (L.), and San Jose scale, *Quadraspidiotus perniciosus* Comstock, and on phytophagous mites, whose control largely depends on predators. The primary goal of AppleMgr is to demonstrate an improved process of decision making in apple IPM.

AppleMgr is composed of modules for diagnosis of pest injury, identification of pest and natural enemy specimens, and management. The first two modules arrive at conclusions through backward-chaining inference from user observations. The management module uses backward chaining supplemented with external calculation programs to find the net benefit of a pesticide application. A method is included to predict yield and fruit size from crop samples. Cullage from codling moth and San Jose scale, mite effect on fruit size, probability of biological mite control and pesticide efficacy are predicted from researchers' data and estimates. Selected relative beneficial and adverse side effects of pesticides are presented in spreadsheets.

An analysis of packing house records for apple crops from eight orchards at three yields using 1987 and 1988 prices and packing charges showed that net crop value varied by up to $8000 per acre. The variability in crop value and the importance of adverse side effects of pesticides suggest that the commonly-used "action thresholds" for treatment are seriously inadequate. AppleMgr may point the way toward more dynamic and realistic methods of IPM decision making.

AppleMgr: A Prototype Decision Aid for Apple Pest Management

by

Sue Haley

A THESIS

submitted to

Oregon State University

in partial fulfillment of
the requirements for the
degree of

Doctor of Philosophy

Completed March 9, 1990

Commencement June 1990

APPROVED:

Redacted for Privacy

Professor of Entomology in charge of major

Redacted for Privacy

Head of Department of Entomology

Redacted for Privacy

Dean of Graduate School

Date thesis is presented March 9, 1990

Typed by Sue Haley

ACKNOWLEDGEMENT

Many people contributed to producing the AppleMgr decision aid. The project was initially proposed by Brian Croft and funded by USDA/CSRS grant 85-CSRS-2-2672 to Western Regional Project 161. Kevin Currans, OSU research assistant in Entomology, provided computer expertise throughout the project and developed the expert system shell and much of the additional program code for the version preceding AppleMgr. His exceptional combination of engineering and human relations skills was invaluable. Karen Theiling, former research assistant in Entomology, helped with initial database programming. Chris Murphy, research assistant in Entomology, suggested the name AppleMgr for the decision aid.

Those who graciously supplied essential information for the pesticide databases and packout analysis include Brian Croft; Stan Hoyt, WSU Tree Fruit Research Center, Wenatchee, WA; Jeff McNerney and Lee Moore of Stadelman's Fruit, Inc., Hood River, OR; Gary Olson, Northwest Chemical Corp., Salem, OR; Helmut Riedl, OSU Mid-Columbia Agric. Research & Ext. Center, Hood River, OR; Leo Sax, Wash. Growers Clearinghouse Assn., Wenatchee, WA; Tim Walls, Duckwall-Pooley Fruit Co., Odell, OR; Peter Westigard, OSU Southern Oregon Exp. Stn., Medford, OR; and Mike Willett, Yakima Area Ext. Agent, Yakima, WA. My debt to Stan Hoyt is especially large for generously providing suggestions, estimates and unpublished data for both the San Jose scale and mite management portions of AppleMgr.

My committee members Arnold Appleby, Ralph Berry, Brian Croft, Fred Rickson and Walt Rudd each made an important contribution to my education. I am grateful to them all for their interest, encouragement, kindness, tolerance and helpful advice. For providing enlightening discussion and moral support throughout my sojourn at OSU I express appreciation to Adam Asquith, Diane Belnavis, Steve Booth, Peg Brant, Jo Brown, Dave Carmean, Kevin Currans, John DeNoma, Jeanine Streeter DeNoma, Ray Drapek, John Dunley, Pete Gonzalves, Elise Heitmanek, Flo Leibowitz, Maggie McGourty, Chris Murphy, Joan Neuman, Gliss Pimentel, Diane Sether, Peter Shearer, Karen Theiling, Hugo Van de Baan, Irene Vanninen and Deanna Watkins.

In Canada, I am grateful to my early teachers of pest management who continued to offer friendship and help throughout my graduate studies in two countries: Bryan Beirne, Thelma Finlayson, John Procter, Jim Rahe and the late John Yorston. Finally, I wish to thank my mother for her unfailing encouragement through my many years in pursuit of interests very different from her own.

To use knowledge and tools in a particular place with good long-term results is not heroic. It is not a grand action visible for a long distance or a long time. It is a small action, but more complex and difficult, more skillful and responsible, more whole and enduring, than most grand actions.

Wendell Berry, "The Gift of Good Land," 1979.

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PREFACE

This thesis reports the process and results of a project to develop a prototype computer aid for decision making in apple pest management in the Northwest U.S. The first chapter gives essential background on the terminology and previous and concurrent work in the field of decision support systems and expert systems for pest management. The objectives of our project, roles of members of the project team and evolution of the decision aid through several versions are described in the second chapter.

American units of measurement and trade names of pesticides are used throughout this thesis because these are the terms used by orchard managers and extension workers in the Northwest U.S. Appendix B gives common names of pesticides. Mention of particular pesticides does not imply endorsement of their use by Oregon State University.

APPLEMGR: A PROTOTYPE DECISION AID FOR APPLE PEST MANAGEMENT

INTRODUCTION

Background

Decision making in apple pest management is an increasingly complex process for several reasons. Many pests such as leafrollers (Vakenti & Madsen 1984, Reissig et al. 1986, Knight & Hull 1989, Suckling et al. 1989), fruitworms (Weires et al. 1980), leafhoppers (Beers 1988), leafminers (Pree et al. 1980, 1986; Hagley et al. 1981, Weires et al. 1982, Maier 1982, Ridgway & Mahr 1985), aphids (Warner & Croft 1982) and mites (Croft et al. 1987, Welty et al. 1989) have become more numerous and difficult to control because natural enemies have been reduced by nonselective pesticides and because effective pesticides have been lost through development of pest resistance and through concerns about human toxicity. Prevention of further problems of this nature demands careful attention to sampling and monitoring of both pests and predators so that unnecessary and damaging pesticide applications may be eliminated. Selection of control tactics, whether chemical or nonchemical, requires knowledge of short and long-term effects on apple trees, pests and many other organisms. Pesticide regulations are likely to require an increasing amount of notification and record-keeping. Thus, while each pest control decision has become more important, the time available for decision making when pests threaten a crop is more limited than ever.

The difficulty of pest management decision making is exacerbated by the worldwide reduction of one-to-one consultation between extension workers and farmers, which is regarded by researchers and extension agents as the most effective means of integrated pest management (IPM) education (Wearing 1988). The problem of assembling and integrating information from diverse sources is acute for both public and private extension workers (Rajotte et al. 1989). Both advisors and farmers could benefit from a technology that would bring more and better information and expertise quickly to bear on pest management decisions. Such a technology is now being developed in computerized decision support systems (DSSs) and expert systems (ESs) (Coulson & Saunders 1987, Doluschitz & Schmisseur 1988).

DSSs are computer programs designed to help managers make decisions by analyzing the problem, presenting information and evaluating alternative solutions. ESs go beyond providing assistance to proposing solutions and giving conclusions or recommendations. ESs attempt to reproduce the problem-solving process of a specialist and usually have a structural separation of the knowledge needed to solve the problem (knowledge base) from the problem-solving procedure (inference engine). The knowledge base is often constructed in the form of rules such as:

If (Location = Fruit) and (Fruit = Small red spots on fruit with gray cones inside)

Then Diagnosis = San Jose scale cap.

To solve complex problems a sequence of rules may be needed in an ES, with each rule setting a value for a parameter such as **Location** or **Fruit** until values for the goal parameters (**Diagnosis**) are reached. If there are relatively few initial conditions and many goals or possible solutions to the problem, forward chaining may be used. In this system, each rule is evaluated (fired) when values are known for all parameters in its premise or "if" clause.

An alternative procedure, called backward chaining, may be used in which a rule that sets a value for a potential goal parameter is the first one considered. Premises of the goal rule are examined to see whether values of their parameters are known. Then rules setting values for these parameters are traced. The control program (inference engine) proceeds backwards up the solution path until it finds values for all the parameters needed to reach the goal parameter. Only those rules needed to set a value for the goal parameter are fired.

In addition to a knowledge base, DSSs and ESs have user interfaces that interact with the program user to obtain information, report conclusions, and explain solution processes. An interface could include questions and answers, a mouse, windows, graphics and other devices.

Where an uncertain item of information is requested or given, the system may associate certainty factors with it to indicate how much reliability is placed in the information by the user or expert. A DSS or ES may also include models, databases, lists, tables, calculation programs, graphs, and spreadsheets to supply values for the rules or present conclusions to the user.

Literature Review

DSSs and ESs have only recently begun to be applied to agriculture and pest management. Applications have proliferated in the last five years as commercial ES shells have appeared. These shells are inference engines usually combined with user interfaces and simple procedures for creating and editing rules or frames to construct knowledge bases. Most applications are in prototype development or pilot testing stages and have not been fully described in publications. For recent reviews see Coulson and Saunders (1987), Latin et al. (1987), Doluschitz and Schmisseur (1988), and Davis and Clark (1989). Table 1 lists some DSSs and ESs for pest management. A few examples are discussed below to illustrate the range of applications now being developed.

An initial task in pest management is to determine the cause of symptoms of an apparent disorder. One program that addresses this need is PREDICT, a diagnostic tool for red pine in Wisconsin. This system identifies 28 damaging agents based on symptoms described to the user in a series

Table 1. Decision support and expert systems for pest management.

Name	Ecosystem	Function	Hardware	Language or Shell	Structure	Intended User	Reference
PMDS		Makes insect phenology models	VAX/UNIX	FORTRAN		Entomologist	Logan 1988
SYSTEX		Identifies insects in genus Signiphora Ashmead	IBM PC/XT	M1	Rules	Entomologist	Woolley & Stone 1987
NERISK		Estimates risk of pesticide to natural enemies	IBM XT	RECOG	Rules, database	Reg. agent researcher	Messing et al. 1989
	Alfalfa	Advises on potato leafhopper management			Model		Quisenberry 1988
	Alfalfa	Makes recommendations for insect pest management	Micro	INSIGHT 2+/Level5	Rules	Grower	Brown 1989
PLEX	Alfalfa	Advises on potato leafhopper management	Macintosh	Bruceshell			Calvin 1989b
POMME	Apple	Recommends insecticides and timing	VAX 11/780	PROLOG	Rules, frames, model	Grower	Roach et al. 1987
APPLES	Apple	Recommends pesticides for IPM	Macintosh	BruceShell	Frames	Grower	Rajotte et al. 1989
	Apple	Diagnoses pest & other problems	MacPlus	PROLOG	Rules	Grower	R. Kemp et al. 1988
	Apple	Assists in crop protection decision making			Rules	Grower	Tette 1988
PEST	Apple	Assists in codling moth management		Turbo-PASCAL			Beers 1989
PLANT/cd	Corn	Predicts black cutworm damage					Boulanger 1983
	Corn	Makes recommendations for insect pest management	Micro	INSIGHT 2+/Level5	Rules	Grower	Brown 1989
MAIZE	Corn	Advises on corn production management	Macintosh	BruceShell			Calvin 1989a

Table 1 continued

COMAX	Cotton	Predicts pest damage to crop	VAX 8250	LISP	Rules, crop model	Grower, county agent	Lemmon 1986
	Cotton	Predicts pink bollworm damage				Grower	Henneberry & Akey 1988
SIRATAC	Cotton	Predicts pest damage & recommends insecticides	VAX	FORTRAN	Models, rules	Grower	Hearn & Brook 1989
	Cotton	Recommends insecticides	Micro	BASIC		Grower	Mumford & Norton 1989
PHILCOT	Cotton	Advises on control of insect pests		KnowledgePro		Entomology student	Mumford & Norton 1989
	Cotton	Aids in control of plant bugs, weevils & bollworms	Micro		Rules	Grower	Luttrell & Brown 1988
COTFLEX	Cotton	Advises on fleahopper & boll weevil management	UNIX	RuleMaster	Rules, models	Grower	Stone & Toman 1989
	Cotton	Advises on insect management	IBM PC	CALEX		Grower, PCA	Plant et al. 1989
	Cotton	Assists in insect management		ART		Grower	Olson 1989
	D. fir seed	Predicts payoff of treatment for 3 insect pests	IBM/APPLE	BASIC	Models, rules	Orchard manager	Hoy & Haverty 1988
PEST	Field crops	Identifies pests & recommends insecticides	MacPlus	PROLOG	Rules	Grower, ext. worker	Pasqual & Mansfield 1988
	Field crops	Indicates research needs in armyworm forecasting				Researcher	Mumford & Norton 1989
INSEX	Forest	Recommends insecticides		C/CLIPS			Coulson 1989a
TOMYCUS	Forest	Identifies bark beetles		LISP			Coulson 1989c
GYPSEX	Forest	Advises on aerial sprays for gypsy moth control	Macintosh	BruceShell			Saunders 1989a
	Forest	Predicts likelihood of Southern pine beetle outbreak	Sun 386i	CLIPS, GRASS	Rules, models, dbase, GIS	Forest manager	Coulson et al. 1989
SBRISK	Forest	Predict probability of outbreak & damage from beetle			Models		Reynolds 1989
IPS	Forest	Diagnoses & recommends control of pine engraver	Micro	INSIGHT 2+/Level5	Rules		Gast 1989
ISPPEX	Forest	Assists in management of southern pine beetle		C/CLIPS			Coulson 1989b

Table 1 continued

	Grain	Identifies insects, weeds & diseases	Micro	INSIGHT 2+/Level5	Rules	Grower	Brown 1989
CHEX	Grain	Recommends herbicides	Micro	Turbo-PROLOG		Grower	Bolte 1989
GRAPES	Grape	Recommends mixtures of insecticides & fungicides	Macintosh	BruceShell, C	Frames	Grower	Saunders et al. 1987
HAZLPEST	Hazelnut	Identifies arthropods, recommends sampling & control	IBM PC	PC Easy	Rules	Grower	Drapek et al. in press
	Muskmelon	Diagnoses & advises on pest & disease management	Micro	PC+	Rules	Grower	Latin et al. 1988
	Oak & maple	Diagnoses galls	Macintosh	Bruceshell			Saunders 1989b
	Papaya	Diagnoses insect and other problems			Rules	Ext. agent, grower	Chia et al. 1988
PEACHES	Peach	Advises on IPM	Macintosh	BruceShell	Frames & rules	Grower	Travis 1989
	Peach	Diagnoses pest & other problems	MS/DOS, CPM	MicroExpert		Grower	Rice 1988
	Peanut	Predicts losses due to pests				Grower, processor	Davidson et al. 1988
RAIN	Pecan	Advises on integrated control of pecan aphids	Micro			Grower	Pickering 1988
IPMP	Peppermint	Assists in insect management	IBM PC	PASCAL	Text, models	Grower, oil buyer	R. Berry et al. 1989
PREDICT	Pine	Diagnoses symptoms of pests & other disorders	IBM PC/XT	EXSYS,INSIGHT 2	Rules	Forester	Schmoldt & Martin 1986
	Pine	Advises on pine tip moth & Pales weevil management				Forest manager	Stephen 1988
HOPPER	Range	Analyses benefit/cost of treatment options	Micro	VP-Expert	Rules	Ext. agent, land manager	W.P. Kemp et al. 1988
BPH	Rice	Advises on control of brown planthopper	Micro	EXSYS	Rules, model	Ext. agent agent	Mumford & Norton 1989

Table 1 continued

	Soybean	Advises on insect & weed management	Micro	INSIGHT 2	Rules	Grower	Brown 1989
SOYBUG	Soybean	Identifies velvetbean caterpillar & advises control	Micro	INSIGHT 2	Rules, model	Grower	Jones et al. 1986
SMARTSOY	Soybean	Advises on insect management				Grower	McClendon et al. 1988
Plant/ds	Soybean	Diagnoses diseases			Rules	Farmer, ext. agent	Michalski et al. 1983
	Stored grain	Advises on insect & fungus management					Brown 1988
GPA	Stored grain	Advises on management of insect pests	Micro	PROLOG	Rules	Grain store manager	Mumford & Norton 1989
BEETGAME	Sugar beet	Simulates pest control decisions	Micro	BASIC		Entomology student	Mumford & Norton 1989
	Sugar beet	Identifies insects, analyses benefit/cost of control	H-P 85 micro	BASIC		Grower	Capinera et al. 1983
	Tobacco	Makes recommendations for insect pest management	Micro	INSIGHT 2+/Level5	Rules	Grower	Brown 1989
	Tobacco	Assists in diagnosis & treatment of pests				Grower	Sowell 1988
	Wheat	Recommends insecticides for wheat pests		Crystal		Grower	Mumford & Norton 1989
EPIPRE	Wheat	Analyses benefit/cost of control of aphid & diseases	Mini		Models	Grower	Reinink 1986
EPINFORM	Wheat	Predicts yield reduction from stripe rust & septoria	IBM PC		Rules	Grower	Caristi et al. 1987
WTDISID	Wheat	Identifies & recommends control of diseases	Micro	INSIGHT 2+/Level5	Rules	Grower	Wiese 1989
WDA	Wheat	Recommends disease controls		BASIC		Grower	Shitienberg & Dimoot 1989
	Winter wheat	Predicts benefit/cost for cereal aphid control	Mini		Model	Grower	Mann et al. 1986

of questions requiring yes/no answers (Schmoldt & Martin 1986). The user may indicate a degree of certainty associated with each answer and the diagnoses are presented along with confidence values. The knowledge base, containing over 400 rules, was developed through interviews with forest pathologists and entomologists at the University of Wisconsin-Madison and the Wisconsin Department of Natural Resources. Two ES shells, EXSYS and INSIGHT 2+, were used to construct parallel systems for performance evaluation on IBM PC/XT microcomputers. In a blind experiment evaluators rated PREDICT's diagnoses comparable to those of pest specialists and superior to those of field foresters (Schmoldt 1987).

Despite the wealth of research in integrated pest management, some developers of ESs whose interests lie primarily in exploring application of computer technology proceed directly from identification of pest insects to recommendation of insecticides. An example of such a system is PEST (Pasqual & Mansfield 1988), which was designed to deal with insect pests of field crops in Western Australia. The system was constructed based on an extension identification key and chemical control guide, with control recommendations updated by a local entomologist. This information was quickly coded into 58 rules using PROLOG for the Macintosh Plus microcomputer. A forward-chaining strategy arrives at several hypotheses of pest identity based on crop and damage symptoms. Then backward-chaining is used to find a description matching that of a pest in the system. The program queries the user to determine whether this description is correct. Pesticide recommendations are given on the same screen immediately following the identity of the pest. The user interface of PEST includes menus, the mouse and icons. Explanations of the expert's reasoning process were not considered necessary, but a running commentary on the screen reminds the user of what is known so far. There is no provision for dealing with missing or uncertain information. Pasqual & Mansfield describe their system as a prototype that may be revised and evaluated.

An ES for selecting treatments for rangeland grasshoppers (W.P. Kemp et al. 1988) uses a more complex process of reaching control decisions for a narrower group of pests. This system is intended for use by land managers and was developed using VP-Expert, a low-cost microcomputer shell. Later it was translated to another shell, PC Expert Professional, to improve the user interface and linkage with other programs (J.S. Berry et al. 1989). About 100 rules were constructed based on the expertise of three experienced entomologists at the Rangeland Insect Laboratory, Bozeman, Montana. Using the method of contra-indication to eliminate unacceptable alternatives, the system first determines all possible treatments (chemical and microbial insecticides) considered acceptable for scientific and technical reasons. Then costs and benefits are calculated for each acceptable treatment and these treatments are ranked by their benefit/cost ratio. User information needed to arrive at acceptable treatments includes location, proximity to environmentally sensitive areas, current weather and the predominant grasshopper species and development stage. The benefit/cost analysis employs user estimates of grasshopper density, forage replacement costs and control costs. A WHY function provides reasons for each question asked of the user. A prototype system was constructed and revised based on criticism by the domain experts in about nine months. It was sent out with an evaluation questionnaire to 10 test sites in the fall of 1988. Researchers are now working on forage production and population dynamics models to be added to the system and plan an eventual link to a geographic information system (J.S. Berry et al. 1989).

A pest management decision aid based on entomological expertise that does not employ an ES shell was constructed by Hoy & Haverty (1988) for Douglas-fir seed orchards on the U. S. Pacific coast. This program is written in BASIC in versions for both Apple II and IBM PC compatible microcomputers. It is intended to help orchard managers make treatment decisions for Douglas-fir cone gall midge, Douglas-fir seed chalcid and Douglas-fir cone moth. A payoff analysis evaluates alternative controls based on default values that can be modified by the user for seven factors: 1) filled seeds per tree, 2) insect attack rates,

3) insecticide efficacy, 4) control cost, 5) probability of frost damage, 6) losses due to phytotoxicity of insecticide and 7) value of seed. Defaults for attack rates of each pest are estimated by the authors from historical data from seed orchards in each of eight geographic provinces. Payoff is computed on the basis of combined predicted attack rates (low, moderate or high) for each pest plus the other six factors. Results are presented in a table of payoffs in dollars per tree expected for each of four actions: 1) an early spray to control midges and cone moths, 2) a late spray to control seed wasps, 3) both sprays or 4) no spray. The user can choose to see a demonstration of the payoff analysis, run the payoff analysis or run utility programs that estimate spray cost, probability of frost damage and flowering date. Copies of the program are available from the authors, but it has not yet been field tested.

SIRATAC is a pest management decision system that has been used by Australian cotton growers since 1976/77 (Hearn & Brook 1989). The program was developed from a prototype by scientists in collaboration with growers. The initial system was a simple rule-based economic model to which models of insect development and mortality, crop development and crop damage were added later. Hearn & Brook (1989) emphasize that "the purposes of the simulation models are defined by the requirements of the decision model. The result is simple simulation models no more complex than needed to provide the information required by the decision model." The program is written in FORTRAN and housed on a VAX minicomputer that was owned by a grower company. Growers paid a charge to use the system through telephone modem. Although SIRATAC was used on 25% of the Australian cotton crop, the grower company was recently liquidated because of financial problems and the delay in reimplementation of the system by computer scientists. Researchers who developed the system did not foresee the continuous requirements for user training and system maintenance. They are now abandoning the advantages of centralized databases and program maintenance to develop a series of microcomputer packages that can be delivered directly to growers.

GrapES is an ES for grape growers in Pennsylvania that integrates disease and insect control recommendations (Saunders et al. 1988). The program was developed for Macintosh microcomputers using the C language and the ES shell, BruceShell. There are individual modules for each insect pest and disease as well as chemical recommendation modules. A vineyard profile is used to store horticultural, weather, pest history and spray history information between sessions. The user can consider a single insect or disease or any combination. Use of each pest module results in a risk rating from "no risk" to "high risk" for that pest based on weather, varietal susceptibility, pest density, economic injury levels, crop phenology and presence or absence of pesticide residues. Risk values are then passed to the pesticide modules which eliminate pesticide alternatives on the basis of legal restrictions and phytotoxicity, determine treatment priorities based on risk, consider tank mix compatibilities, and then rank the remaining pesticide tank mixes on the basis of efficacy. The final result is a table of ranked tank mixes with efficacy ratings and a recommended date for treatment.

Researchers at Pennsylvania State University have also developed an ES for apples (ApplES), which I have personally reviewed (August 14, 1989 version). Like GrapES it is written with BruceShell, uses stored data in an orchard profile and provides recommended tank mixes for combinations of insect, mite and disease problems. It also includes modules that provide pest descriptions with graphics, life histories of pests, scouting information, and information on pesticides. The user interface is particularly attractive. All data entry is accomplished using a mouse to select terms from multiple choice lists and numbers from sliding scales.

Both GrapES and ApplES have been released to selected growers in a carefully designed evaluation program to measure the sociological and economic impact of the new technology (Rajotte et al. 1989). Growers were selected to represent a range of farm size, geographical location and computer experience. Software (and, where necessary, computers on loan) were distributed to growers in July 1988. Telephone interviews were conducted with the participants in August, October and November. The survey found that apple growers used the insect management module of the system the most often , found the recommendations they sought over 85% of the time and at least partially followed the recommendations over 85% of the time. In the August survey over 45% of the participants stated that they had changed their production practices as a result of the ES and over 80% said that "the expert system has stimulated them to monitor their orchard more closely because they more clearly recognized the value of monitoring information." Rajotte et al. (1989) do not report the wording of questions asked in the survey. A sufficiently large and well-trained support staff was provided to quickly correct hardware and software problems and was considered "well worth the expense" by system developers. Commercial release of ApplES is planned for spring 1990.

Other groups are developing DSSs or ESs for apples in Virginia and Ohio. The Virginia Tech group completed a prototype system, POMME (Roach et al. 1987), that includes a model of apple scab phenology and rules that determine the most appropriate insecticides for pest combinations. The program (housed on a VAX 11/780) could not be field tested because of its size and updating problems. The Ohio group "tabled" their efforts toward an apple pest management ES in favor of developing marketing and production expense programs operable on farm computers (Willson et al. 1988).

Inevitably there have been many mistakes made in the early stages of applying DSS and ES techniques to pest management decision making. Initial efforts were directed at simply "trying out" the technology to construct a system with insufficient thought given to potential users, appropriate hardware and software, user interface, field testing and program maintenance. It has been said that a pest management DSS or ES cannot be considered completely successful unless it helps its users make better decisions (Stock 1988). Biologists may not be accustomed to this sort of criterion for evaluating their research. As the SIRATAC experience shows, the length of time and amount of teamwork involving researchers, computer scientists, extension workers and growers necessary to carry through such a project are substantial. Perhaps for these reasons most developers of pest management DSS and ES software have chosen to focus either on one or a few aspects of pest management such as disease diagnosis, pest identification or pesticide selection for a large group of pests (PREDICT, PEST, GrapES, ApplES) or more comprehensive systems involving economic analysis of treatment alternatives for a few pests (HOPPER, Hoy & Haverty DSS). Few have attempted to apply sophisticated IPM models and understanding in constructing their systems.

PROJECT OVERVIEW AND OBJECTIVES

Work on the overall project that produced AppleMgr was directed by Brian Croft, who decided to focus on arthropod pests in constructing a DSS for apple pest management in the Pacific Northwest. In the Western Region, excluding California, 93% of the pesticide sprayed on apple trees is directed against insects and mites (Croft 1983). This emphasis indicates the relatively greater importance of arthropod pests than other types of pests in the tree canopy. The project was intended to produce a prototype computer decision aid that could be expanded and modified for use by researchers and extension workers in the Western Region.

Having worked as an IPM consultant to apple growers in British Columbia since 1977, I considered myself to be a potential user of the DSS. I asked myself how the computer could be used to help me make better decisions in pest management. The early versions of the system were modeled largely on the decision process I now use but find unsatisfactory. The most recent version, AppleMgr, presents what I consider to be an improved decision process.

Computer expertise was provided on the project team by Kevin Currans, a research assistant in the OSU Department of Entomology. He initially sought software tools suitable for construction of a decision system operable on a microcomputer. At the start of the project in 1985 commercial ES shells available for microcomputers did not meet our needs (Currans 1988).

The evolution of the project is illustrated in Fig. 1. We began with the construction of a diagnostic key laid out as a large decision tree chart on paper. We tried to implement the key as well as the management part of our system using RECOG, a DSS tool written for business applications (Goul 1985). RECOG requires the user to answer a series of questions before a rule is fired. All of the questions in a group are asked, regardless of the user's answers to previous questions. This format is inefficient and not suitable for the construction of a key.

In response to difficulties with RECOG, Currans designed a new shell, EXE (Currans 1988), that contains two mechanisms for system development, equation frames and key frames. The key frames allow the user to answer one question at a time, with the answer to this question determining the next question, as in a taxonomic key (Fig. 2). EXE, unlike RECOG, also allows linkage of the knowledge base with external programs. A major difference between EXE and traditional ES shells is that in EXE the order in which the rules fire, and hence the order in which questions are presented to the user, is determined by the person who develops an application rather than by an inference engine.

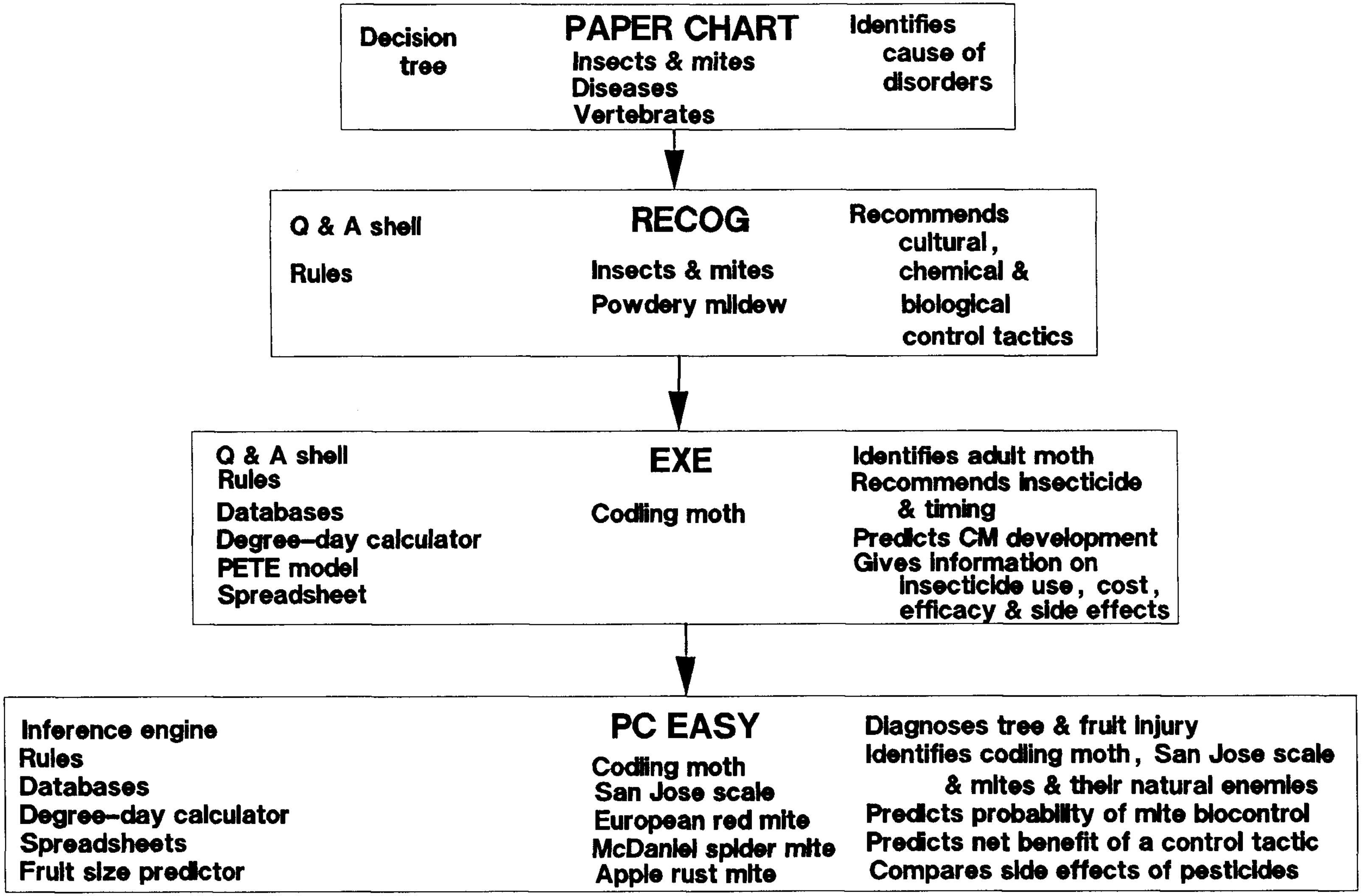


Fig. 1. Evolution of apple decision aid.

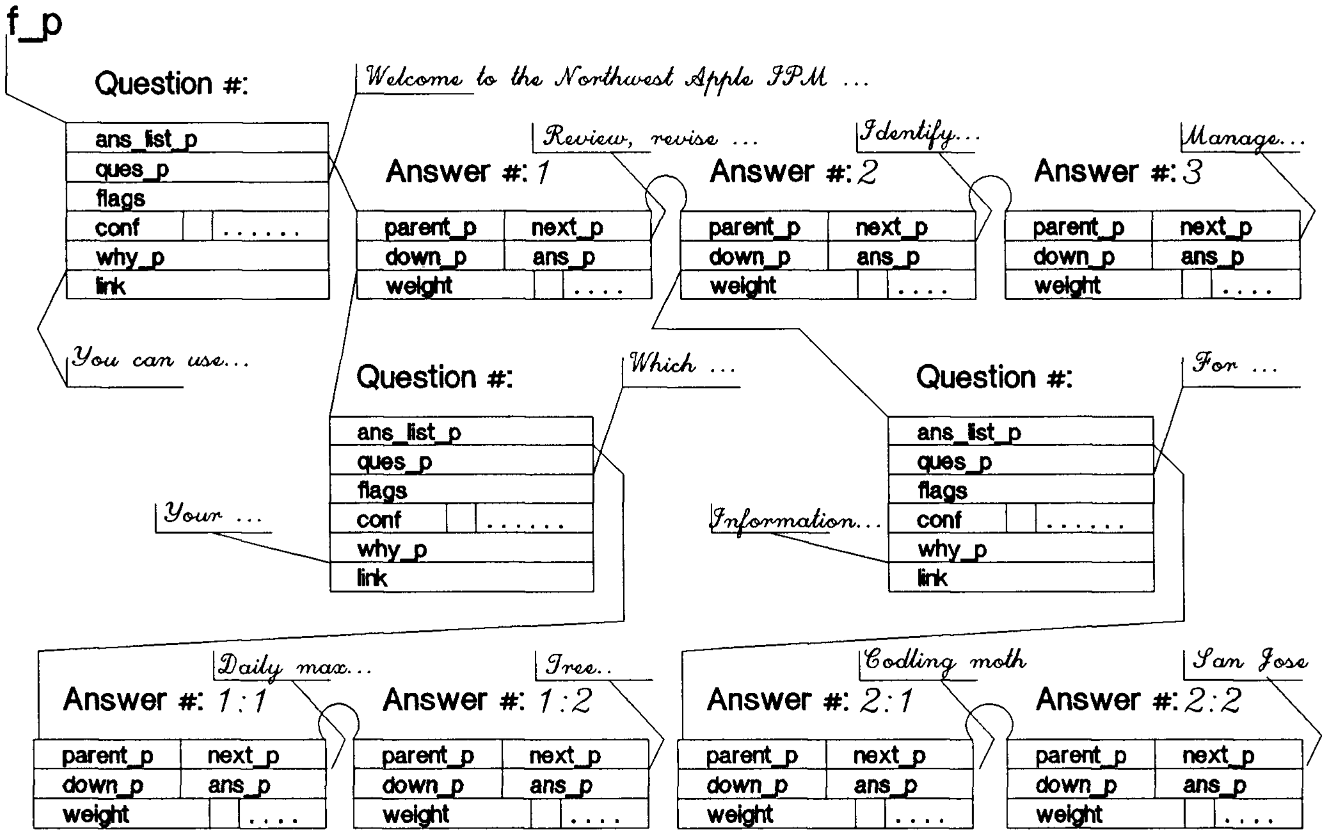


Fig. 2. Key frame structure in EXE shell.

Fig. 3 shows a structural diagram of the EXE version of our DSS, which was originally proposed by Croft and built by Currans and myself.

The most recent version of the decision system, AppleMgr, was constructed using Personal Consultant EASY (Texas Instruments, Inc.), a backward-chaining shell. I have taken the lead in design and development of this system, which is centered on a benefit-cost analysis of control tactics, an idea first outlined in path 6 of the EXE version. AppleMgr concentrates on the two most important insect pests in the Western Region, codling moth, *Cydia pomonella* (L.), and San Jose scale, *Quadraspidiotus perniciosus* Comstock, and on phytophagous mites, whose control largely depends on predators.

In my view the potential user of a computer decision aid, whether farmer or advisor, is a capable manager who needs help in bringing together many kinds of information, including expertise of researchers, but who wishes to evaluate alternative tactics rather than receive a single recommendation. Therefore, the system I have constructed, although using an ES shell and incorporating some expert estimates, gives the user a participatory role throughout a decision making session. My primary goal is to demonstrate an improved process of pest management decision making using computer technology. Specific subobjectives include:

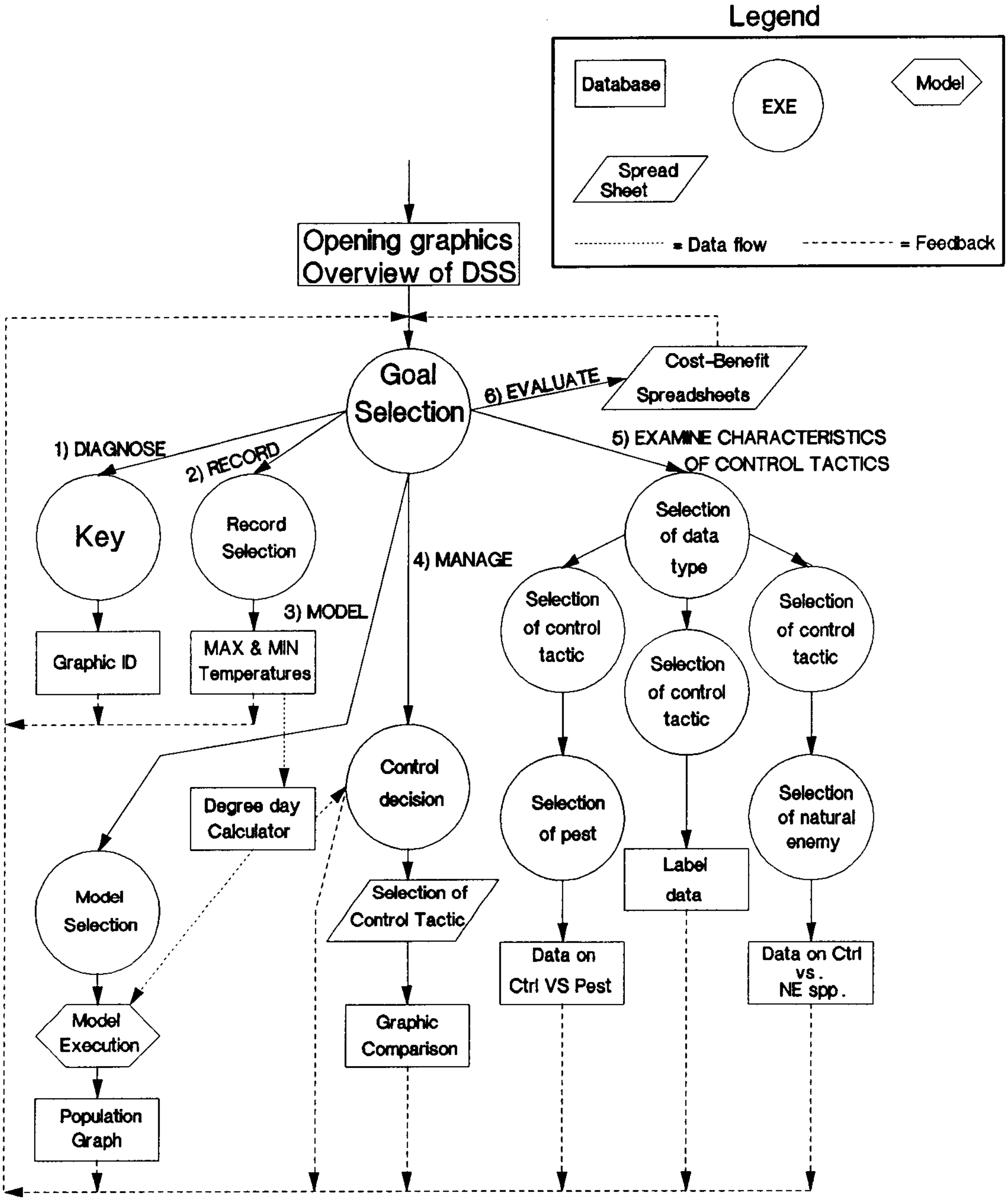


Fig. 3. Structure of EXE version of decision aid.

1) to diagnose pest problems from observed symptoms
2) to identify pests and their natural enemies
3) to estimate crop value
4) to predict combined crop loss from several pests
5) to predict efficacy of biological and chemical control
6) to predict direct and indirect costs of treatment
7) to present relative benefits of several control tactics.

How AppleMgr and its earlier versions were constructed to meet each of these objectives is discussed in the chapters that follow. A final chapter shows how all parts of the system work together to approach a pest management problem.

DIAGNOSIS AND SPECIMEN IDENTIFICATION

Introduction

The first step in approaching a problem that may involve pests is to determine the nature of the problem. Is an observed symptom of an apparent disorder produced by pests or by some other cause such as mechanical or cold weather injury? Are insects or mites found associated with the disorder pests, natural enemies or innocuous species? These questions are basic and can be difficult to answer. They require understanding and experience that extend beyond the bounds of pest management. Too often insects and mites, being relatively easy to see and apparently simple to control, are blamed for injury caused by other agents or simply killed because they are there. Misdiagnosis and misidentification may lead to useless, costly and damaging pesticide applications.

My objectives for this part of the DSS were to diagnose problems and identify specimens using simple clear characters that may be seen in the field with 15-20X magnification. When possible, I chose attributes such as site where found, size, body shape and number of wings that were common to many species. The rules were constructed to provide the quickest and most direct path to a solution.

Methods

By questioning two insect systematists in the OSU Department of Entomology, I attempted to learn a methodology for constructing identification keys.

Apparently there is no explicitly formulated procedure and no particular reason why these keys are nearly always dichotomous. W. G. Rudd (OSU Computer Science Dept.) suggested that a dichotomous key is not the most efficient means of reaching a rapid diagnosis. Therefore, I proceeded from general to more specific questions, often giving several choices to answer each question.

Originally, the diagnostic part of the DSS was constructed as a large decision tree chart on paper. The key, which was organized by part of the apple tree affected, required up to eight levels of questions and answers to reach a conclusion. The original key diagnosed many kinds of disorders (Table 2). In 1985, W. G. Rudd implemented this key using the YAPS production system (Allen 1983) on a 32-bit minicomputer under UNIX.

The diagnostic key was not developed with RECOG because of the unsuitable program structure (Chapter 2). The key frames in EXE (Fig. 2) were used to construct an identification sequence of questions and answers for codling moth adults.

In AppleMgr I separated the problem diagnosis and specimen identification routines into two knowledge bases, DIAGNOSE and IDENTIFY. This format eliminates some redundancy in the rules and questions and is useful when the specimen at hand is not associated with any part of the tree. The PC EASY shell, like EXE, allows the developer to construct rules using parameters whose values are defined

Table 2. Disorders diagnosed from tree and fruit symptoms in decision-tree chart.

Crown and Roots

Vole
Pocker gopher
Crown rot
scale
Crown gall

Trunk and Limbs

Boron deficiency
Manganese tox.
Aerial crown gall
Burr knot
Perennial canker
Fireblight
Sour sap
Sunscald

Branches

Boron deficiency
Winter injury
Fireblight
Manganese tox.
European red mite
Tubercularia

Buds/Blossoms

Dead spur dis.
Boron deficiency
Budmoth

Leafrollers
Bruce spanworm
Green fruitworm
Fireblight
Lygus injury
Apple grain aphid
European red mite
Frost injury
Powdery mildew

Terminal shoots

Deer injury
2,4-D injury
Excess nitrogen
Apple rust mite
Arsenic toxicity
Apple replt. dis.
Crown rot
Fireblight
Apple scab
Iron deficiency
Glyphosate
Powdery mildew
Zinc deficiency

Fruit

Codling moth
European red mite
European fruit

Limb rub
Frost mark
Sunburn
Thrips
Spray burn
Apple maggot
Apple scab
Spring leafroller
Summer leafroller
Leafhopper
San Jose scale
Powdery mildew
Sooty mold
Mechanical injury
Bitter pit
Hail injury
Rosy apple aphid
Fireblight
Mullein bug
Boron deficiency
Spanworm
Green fruitworm
Dock sawfly
Earwig
Bird injury

by other rules or by the user through responses to prompts. Prompts may be constructed to accept single or multiple answers typed in by the user or chosen from a list. A function is included to allow the user to associate degrees of certainty with answers.

Results

The question and answer sequence for identifying an adult codling moth in the EXE version is given below. Answers leading to an identification of the specimen are shown in boldface. At the end of this sequence, EXE uses a graphic display program, GLODER, to present a codling moth picture to the user.

What part of the tree is affected or where is the possible pest or natural enemy found?

1) General tree appearance
2) Crown or roots
3) Buds
4) Blossoms
5) Fruit
6) Leaves
7) Trunk or scaffold limbs
8) Secondary branches or twigs or shoots
9) Ground cover or soil near tree
10) In a pheromone trap

In what kind of pheromone trap did you find the insect?

1) Codling moth

2) Leafroller

3) San Jose scale

Does the insect have wings?

1) Yes, 2 wings only

2) Yes, 4 wings; 2 hindwings may be concealed under forewings

3) No

Are the wings scaly, dusty or powdery?

1) Yes

2) No

How long is the moth from head to wing tips?

1) Less than 1/4 inch long

2) 1/4-3/8 inch long

3) More than 1/2 inch long

Do the forewings appear grayish striped with copper patches at the tips?

1) Yes

2) No

Do the copper patches cover less than 1/3 of the area of the wing?

1) Yes

2) No

Fig. 4 shows the structure of the DIAGNOSE knowledge base in AppleMgr. The goal parameter is **Diagnosis**. To reach a value for **Diagnosis**, the inference engine searches the six rules whose "then" statements read: "**Diagnosis** = . . ." Each of these rules has a premise or "if" statement that sets values for one or more of the 6 other parameters, **Bark**, **Buds**, **Caterpillar**, **Fruit**, **Leaves** and **Location**. When the rules are fired, each parameter in a rule is traced in turn to see whether its value matches the value in the rule's premise. To find values for the parameters, the program asks the user questions such as "What part of the tree or fruit is affected or where is the symptom found?" The answer to this question sets a value for the parameter Location. In this simple knowledge base the program reaches a value for the goal parameter after the user answers only two or three yes/no or multiple choice questions.

The IDENTIFY knowledge base is similar in structure, although larger and more complex. It identifies specimens found in pheromone traps, in or on buds or fruit, on bark or on leaves. Keys are provided for commonly found life stages of codling moth, San Jose scale, scale parasites, European red mite, Panonychus ulmi (Koch), McDaniel spider mite, Tetranychus mcdanieli McGregor and two-spotted mite and Pacific mite (not separated), apple rust mite, Aculus schlectendali (Nalepa), phytoseiid predator mites, Stethorus adult, lacewing larva and egg, adult anthocorids

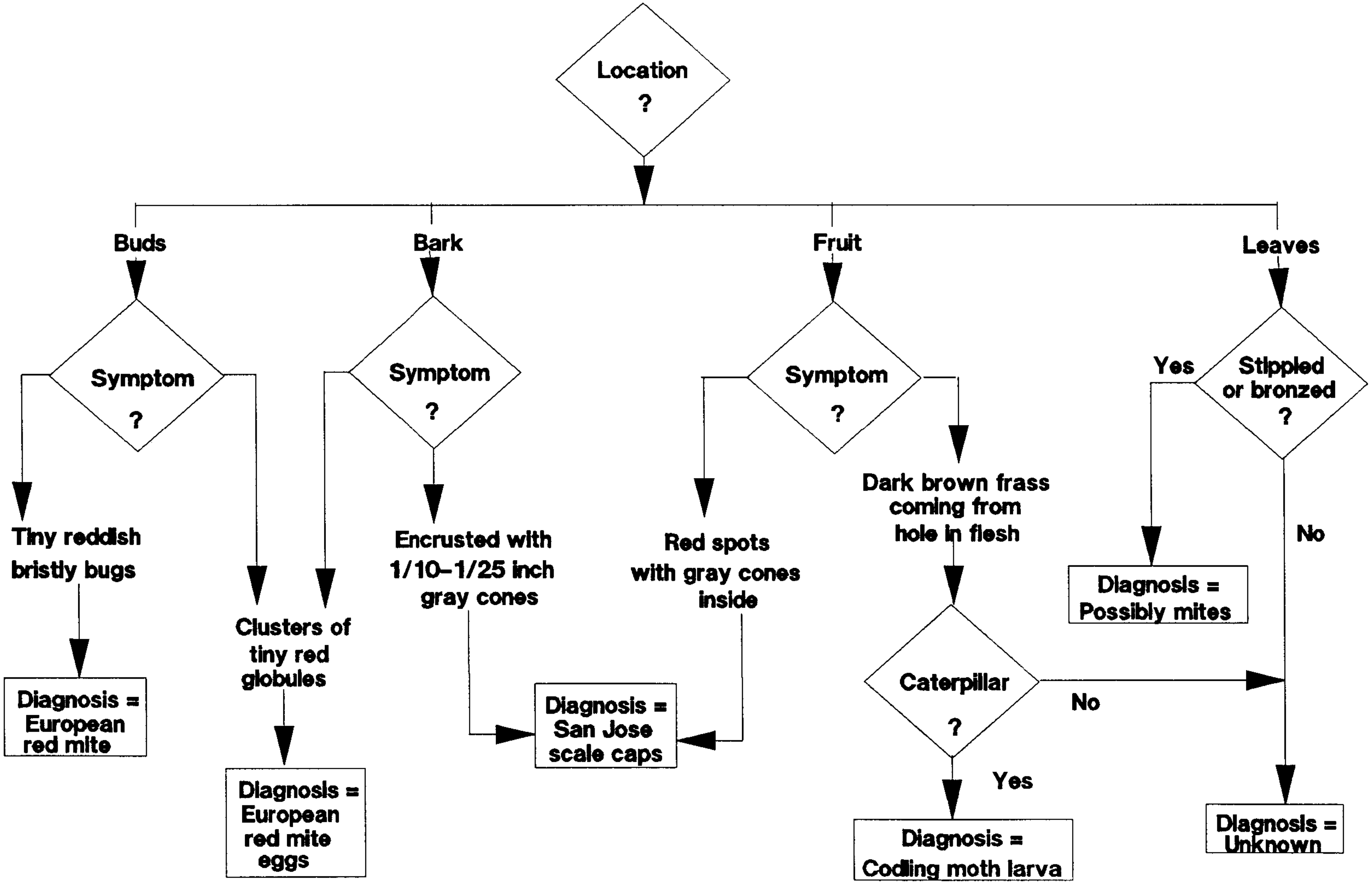


Fig. 4. Structure of AppleMgr diagnosis module.

and adult Deraeocoris. The program reaches a value for the goal parameter **Arthropod** after the user answers four to eight questions. PC EASY's certainty range factor property is used with the parameter **Body_Color** to allow the user to indicate gradations of color by moving the cursor specific distances toward given color choices. For example, yellowish-green may be shown as 30% yellow and 70% green. This idea was adapted from the OSU Hazelnut Expert System (Drapek et al., in press). No graphics are used in the PC EASY version.

Discussion

Since the diagnostic keys in the apple DSS have not been field tested, it is impossible to say how often they would yield correct identifications when used by orchard managers. An evaluation procedure such as that conducted by Schmoldt (1987) in which conclusions produced by the DSS are compared with those reached by pest specialists is needed to answer this question. The decision not to incorporate on-screen graphics in the PC EASY version may make the program less attractive to users. However, I do not believe that the quality of images that can now be produced with reasonably priced hardware justifies the effort involved in their construction. Excellent color photographs of apple pest damage, pests and common natural enemies are readily available through extension services. A booklet of these photos could be inexpensively distributed with a released DSS.

CROP VALUE PREDICTION

Introduction

Research and extension apple IPM literature and computer decision aids do not explicitly consider crop value as a variable. Rather, they use pest detection or fixed economic injury levels and treatment thresholds to determine when control is needed. For example, in their review of the status of biological and IPM research on apple pests, Hoyt et al. (1983) state without elaboration: "With direct pests the economic injury level is generally that pest density that results in 0.5-1% damaged fruit." Advisory schemes in extension bulletins (e.g., Leeper 1980) and computer decision aids (Roach et al. 1987, Rajotte et al. 1989) make control recommendations based on pest detection or static thresholds. Even growers when questioned about the factors they consider in making pest control decisions may not mention the expected return for their crop (Haley 1977). The implicit assumption is that crop value is always many times as high as the grower's costs for pest control.

Yet crop value varies substantially from year to year and orchard to orchard and fluctuates during the fruit growing and storage period as a result of many interrelated weather, management, and market variables. Growers occasionally reduce the number of their pesticide applications because of expectations of a low yield or low grade fruit. To make improved decisions based on cost/benefit analysis of treatment options, accurate predictions of crop value based on current conditions are necessary.

The market value of an apple crop is based on five components--yield, fruit grade, fruit size, price and industry charges (Schotzko & Tukey 1983). The first three components are determined primarily by tree characteristics and density, weather and soil conditions, management practices in the orchard, and fruit handling during storage and packing. Fruit grade is also influenced to some extent by marketing considerations because grading is done during the fall and winter storage and selling period. For the majority of Northwest growers who sell their fruit through private packer-shippers, prices and packing and marketing charges are largely beyond their control.

Fruit yield depends mainly on number of fruit rather than fruit size (Forshey and Elfving 1977). The tendency of many apple cultivars to bear fruit biennially has been largely corrected by the use of chemical thinners in modern apple production (Williams & Edgerton 1982). However, weather conditions such as winter injury to roots and trunks, spring frost damage to buds and blossoms, and unfavorable temperatures, rain, and wind during and after the pollination period still cause severe crop fluctuations. Chemical thinners themselves can overthin the crop if misused or applied during or before unsuitable weather.

Fruit size is influenced by many variables, including tree vigor, weather conditions, pollination and fruit set, horticultural practices, especially pruning and thinning, and pests that attack the crown and roots. High densities of foliage-feeding insects and mites may reduce fruit size under some conditions (Hoyt et al. 1979). Relative prices for fruit of different sizes vary from year to year. For the crop years 1986-1988 smaller Red Delicious apples were favored over the very large sizes that brought top prices in the early 80's (Table 3). Fruit size is generally given in terms of the number of apples that are packed in a standard Northwest apple box weighing approximately 42 lb. Smaller sizes are often packaged in plastic bags or sold loose in boxes (Schotzko 1983).

Fruit grade is determined in the packinghouse according to U.S. standards (Schotzko & Tukey 1983). Larger houses use a presize system in which fruit is graded before being placed into storage and then is packed as orders are received (Schotzko 1983). Electronic machines are often used for sorting by size and color before further grading is done by hand on an assembly line. Fruit grade is based primarily on color, shape, and the presence and severity of defects caused by handling, weather, pests and other problems. Fruit below a minimum size is culled. Because appearance is so important in marketing, surface blemishes usually result in cullage or serious downgrading. The presence of any of certain pests such as San Jose scale

Table 3. Red Delicious fruit sizes bringing top selling price, 1979-1988. Based on data from Washington Growers Clearing House Association, Inc., Wenatchee. Regular refers to regular storage and CA to controlled atmosphere storage.

Crop year	Regular Extra Fancy	CA Extra Fancy
1979	72 and larger	100
1980	100	80/88
1981	72 and larger	72 and larger
1982	72 and larger	72 and larger
1983	138 and smaller	72 and larger
1984	72 and larger	72 and larger
1985	72 and larger	72 and larger
1986	125	125
1987	100	113
1988	80/88	113

in a shipment of fruit prevents export because of a quarantine in several overseas markets (Hoyt et al. 1983).

In orchards in areas with favorable microclimates and excellent management, fruit yield, grade and size are fairly stable from year to year. Price is then the most variable factor. Apple price fluctuations depend on world supply and demand and are increasingly influenced by highly competitive marketing (O'Rourke 1988). An oversupply of 'Red Delicious' resulted in a sharp price decline in 1987 (Fig. 5).

Packing and sales charges are assessed by each packer-shipper according to its own system. It is common to have a presize or in-charge based on the number of boxes delivered plus an additional charge per packed box, which may vary with the type of pack. These charges cover grading, storage, packing, inspection, insurance and marketing. The packer may give a credit per packed box to growers who apply a preharvest fungicide that reduces storage problems.

To predict the potential harm in dollars per acre of pests requires an estimate of crop value based on estimates of each of its five components. Objectives for this part of the DSS were to provide means of estimating yield, fruit size, fruit grade, prices and charges as accurately as possible.

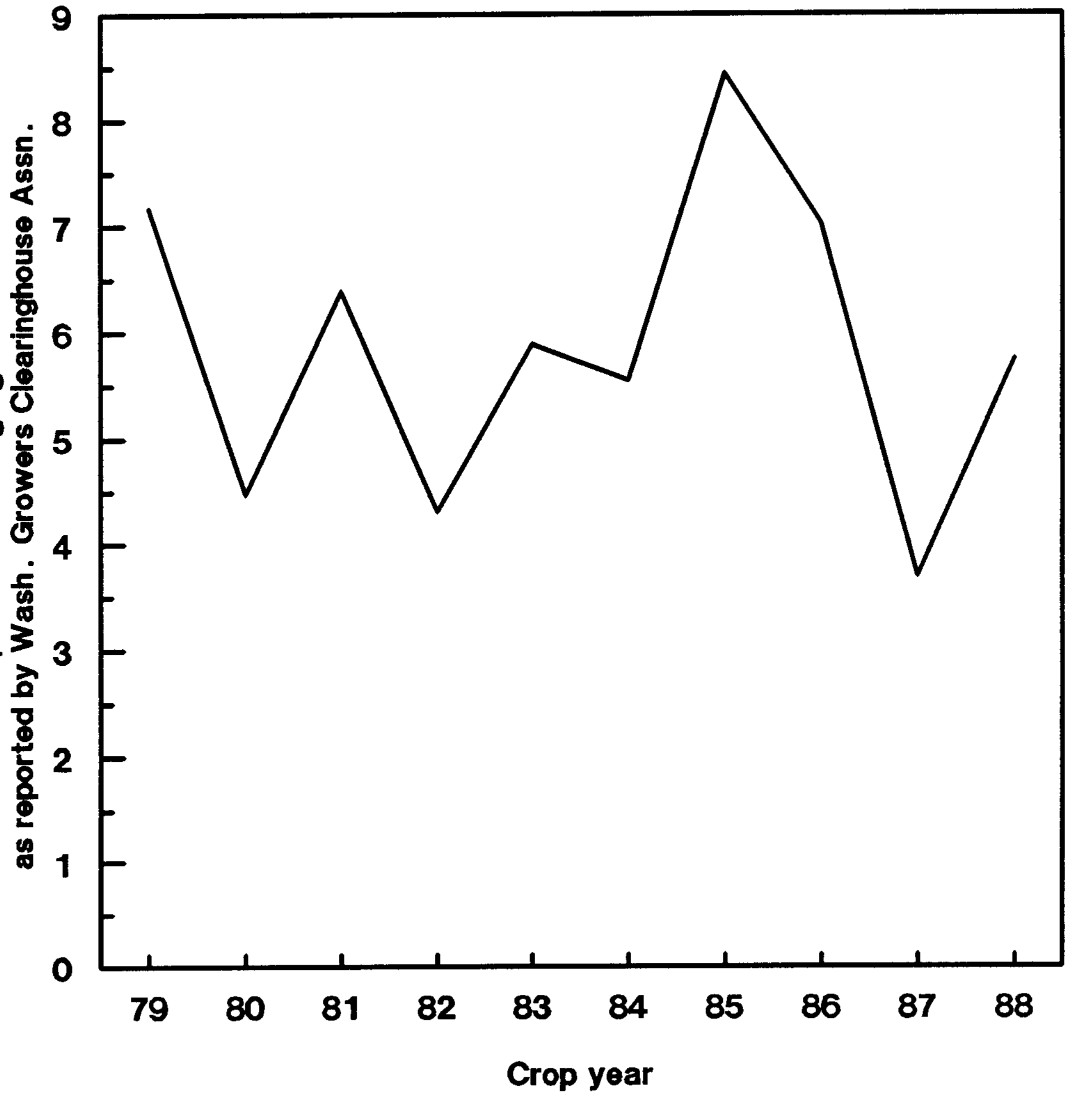


Fig. 5. Weighted average Red Delicious prices, 1979-88.

Methods

Only the AppleMgr version of the decision aid predicts crop value. Two methods are provided for estimation. One assumes that crop samples are available for the current and the previous year, and the other assumes that no samples are available. Both methods require packout records for the previous year's crop.

To enable efficient programming, the DSS structure was laid out using data flow diagrams (DeMarco 1978). These diagrams show the processes needed to transform information ("bubbles" or ovals) and the data inputs and outputs (arrows) linking these processes. Straight lines represent files or databases. Diagrams were constructed at several levels of detail to break down the system into modular units. Upper-level diagrams show the relationships among the components of crop value (Figs. 6 and 7). Both with-sample and without-sample estimation methods use the same way to predict grade, price and presize charges, but different ways to predict yield and fruit size distribution. Fig. 8 shows how fruit size distribution is estimated using crop samples.

The database management program Dbase 3+ (Ashton-Tate, Inc.) was used to construct the databases and in coding the programs and subroutines that calculate crop value with and without the use of crop samples. Results are assigned by means of rules to the PC EASY parameter, **Crop_Value**.

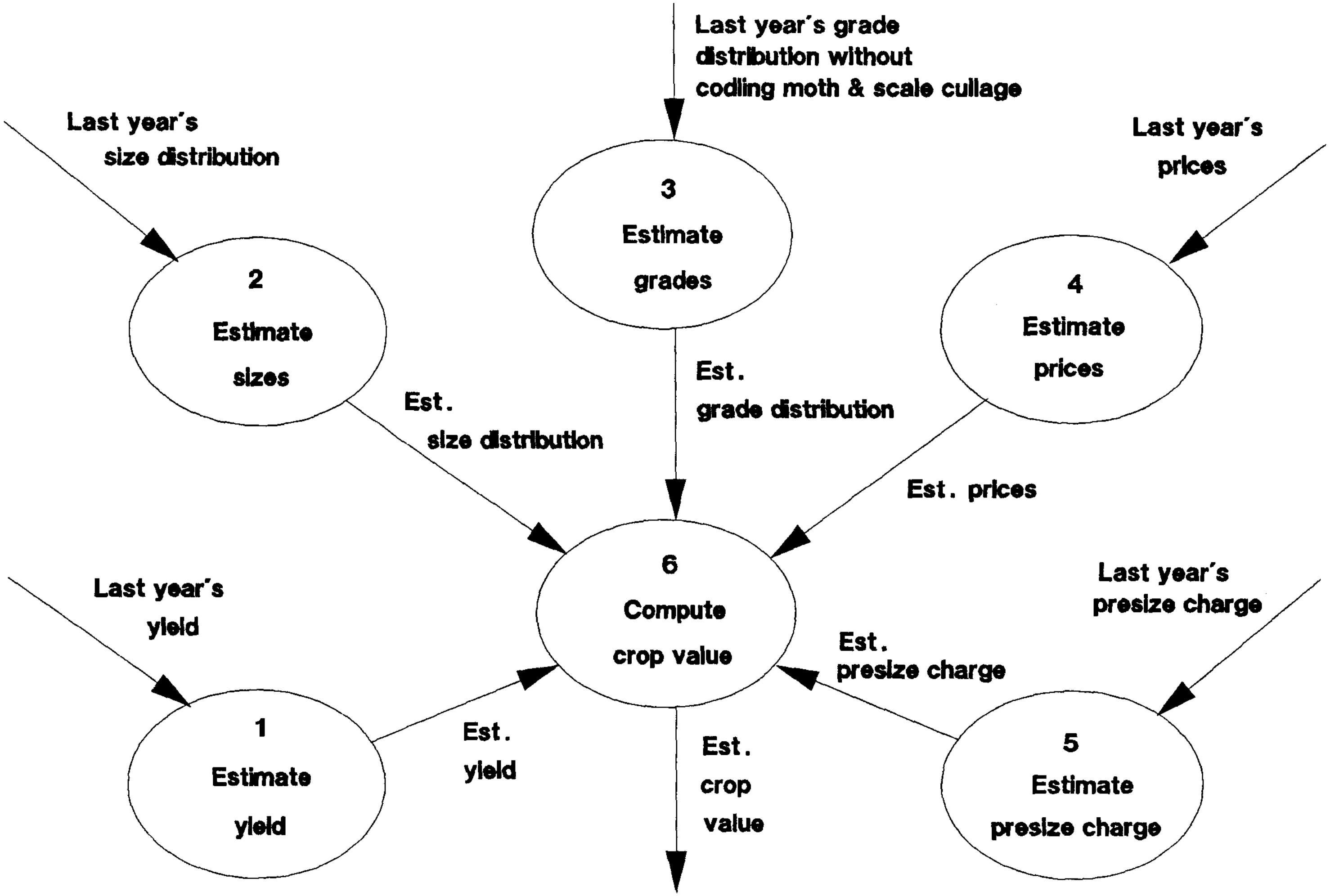


Fig. 6. Estimating crop value with no crop sample.

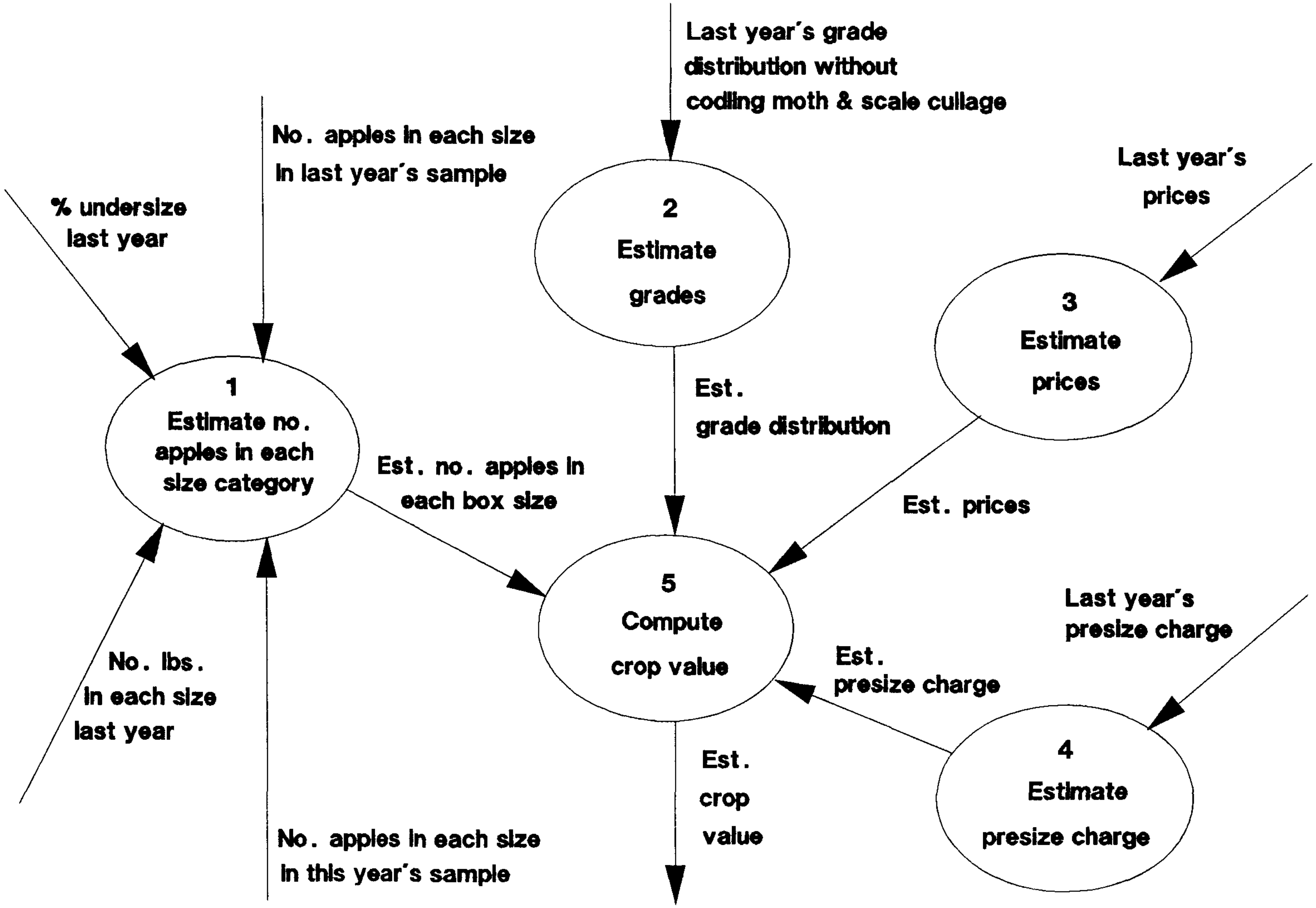


Fig. 7. Estimating crop value with a crop sample.

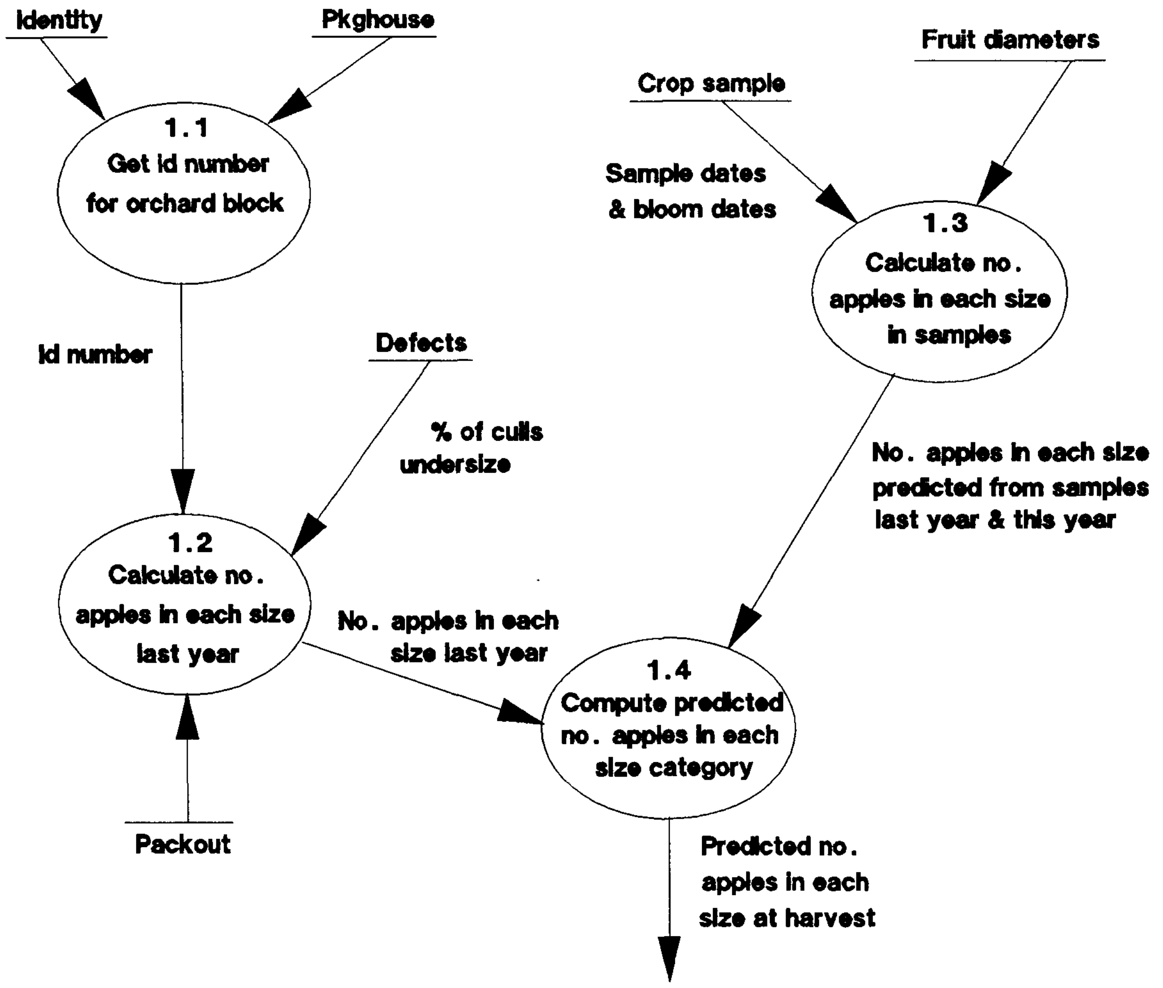


Fig. 8. Predicting fruit size distribution.

To examine the relative importance of each of the components of crop value and their interactions, an analysis of eight packout records was done using 1987 and 1988 prices and packing charges. Packouts, net prices per carton and presize charges were obtained from Duckwall-Pooley Fruit Co., Odell, Oregon (Table 4). Because this packer's presize charges vary widely from one packout to another while other firms use a single presize charge for all growers, average Duckwall-Pooley presize charges per bin for 1987 and 1988 were used in the analysis.

Packout records were chosen to separate the effects of size, percent cullage and percent extra fancy as much as possible within realistic limits (Schotzko 1984). Fruit size and grade distributions of four of the fruit lots used are given in Figs. 9-12. Lot 1 (Fig. 9) has fruit in a desirable size distribution (Bartram 1981) but poor color resulting in a cullage rate of over 50% and less than 20% of the crop in the extra fancy grades. Fruit size is somewhat smaller in Lot 2 (Fig. 10) while grade is much higher, with a cullage rate of only about 5% and over 80% of the fruit grading extra fancy. Lot 3 (Fig. 11) shows both a desirable size range and fairly good grades. Lot 4 (Fig. 12) has over 70% of the crop in the top grade but nearly 14% culls and less than 15% in sizes 80 and larger.

Crop values per acre were computed at three yields--10,000, 40,000 and 70,000 lbs. per acre). The upper and lower limits were suggested by Mike Willett, Yakima Area

Table 4. Net prices per lb. received by growers from Duckwall-Pooley Fruit Co., Odell, Oregon for Red Delicious stripe and blush strains. Net prices include charges per packed box but not presize charges.

1987 Crop

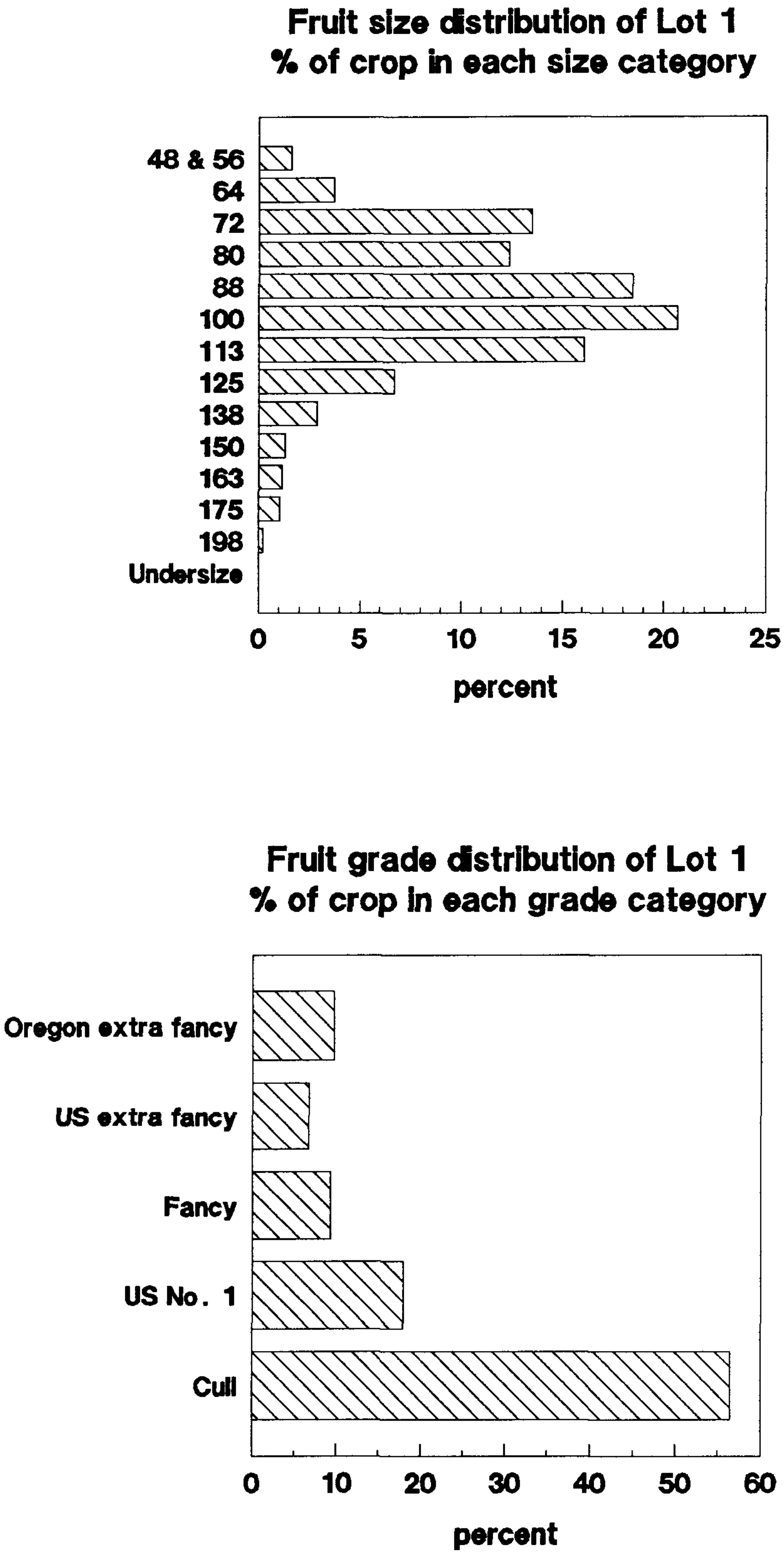
Fruit size	Oregon XF	US XF	Fancy
80 & lrgr	0.13403971	0.07320656	0.01572622
88/100	0.11388502	0.09613120	0.05525578
113	0.06397945	0.07710984	0.05525578
125/138	0.01781243	0.05018956	0.03215706
150 & smlr	-0.01668386	0.06631727	0.00585411
C grade	0.0442285		
Cull	0.01313352		

Average presize charge/bin: 52.42

1988 Crop

Fruit size	Oregon XF	US XF	Fancy
64 & lrgr	0.17396110	0.12564590	0.09543500
72	0.18014790	0.14291840	0.10168110
80	0.18510850	0.14929230	0.09788700
88	0.19327470	0.13856510	0.10740740
100	0.17768750	0.13904560	0.10457370
113	0.16442720	0.13843130	0.07623440
125	0.16337290	0.11162420	0.06570400
138	0.13385420	0.10932310	0.06904620
150	0.12675920	0.10017570	0.06558520
163	0.12255430	0.09479740	0.06547460
175 & smlr	0.11637562	0.08502810	0.02881150
US No. 1	0.11026721		
Cull	0.01500000		

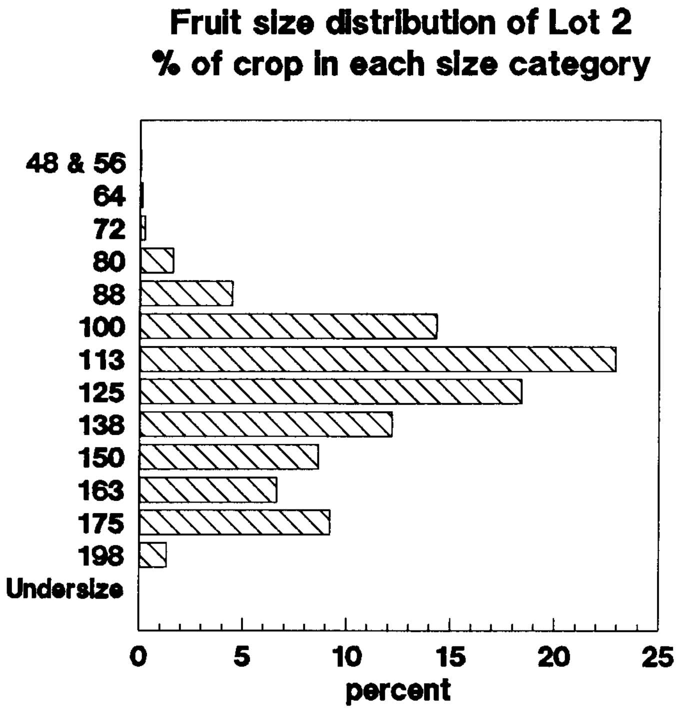
Average presize charge/bin: 50.80



Fruit size distribution of Lot 1
% of crop in each size category

Fruit grade distribution of Lot 1
% of crop in each grade category

Fig. 9. Lot 1 size and grade distribution.



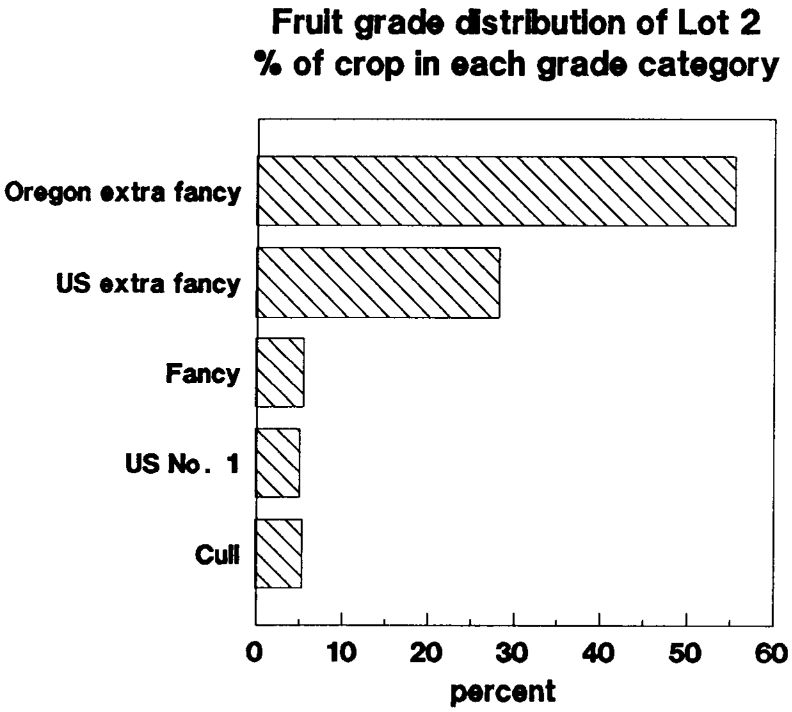
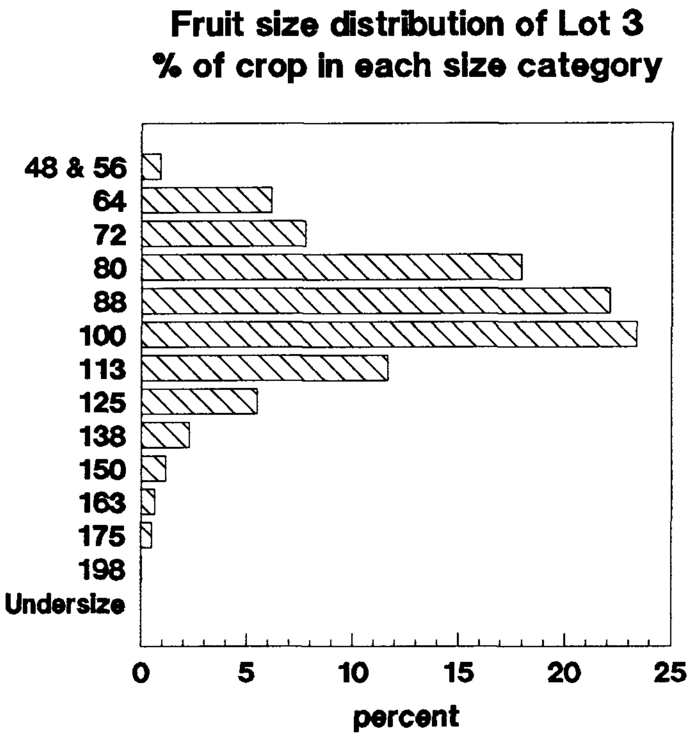


Fig. 10. Lot 2 size and grade distribution.



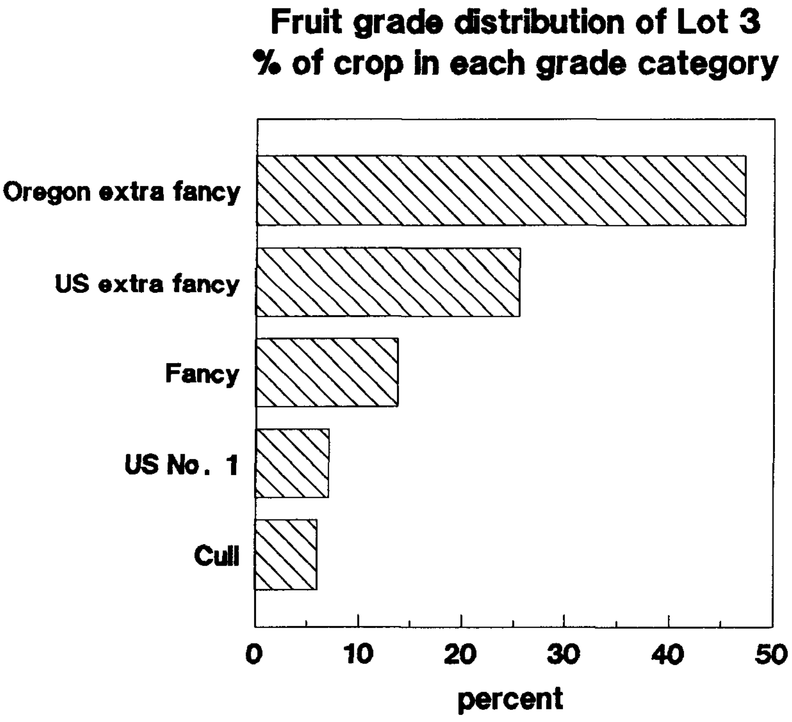
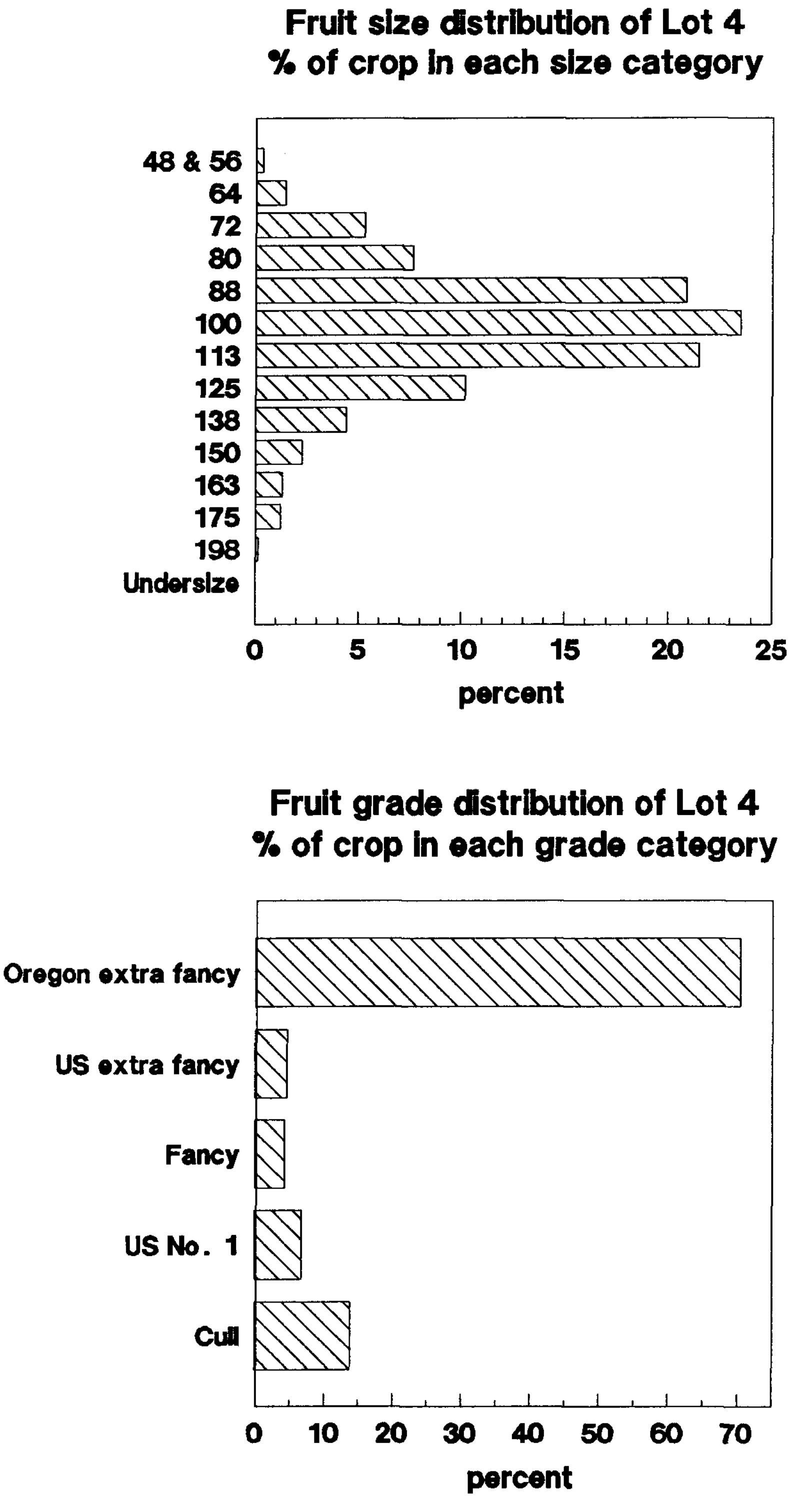


Fig. 11. Lot 3 size and grade distribution.



Fruit size distribution of Lot 4
% of crop in each size category

Fruit grade distribution of Lot 4
% of crop in each grade category

Fig. 12. Lot 4 size and grade distribution.

Extension Agent, as realistic for orchards in Washington. The low yield may occur in an older orchard in a low crop year or a new orchard coming into production, while the high yield represents a sustainable annual level for a high density orchard in full production. The intermediate value is a very good yield for a semi-standard planting (Dickrell et al. 1987).

Results

1) Program structure

Which rule AppleMgr uses to find **Crop_Value** depends on the yes/no parameter **Crop_Sample**. A prompt asks the user if a crop sample was taken and recorded in the databases. An associated help screen gives sampling instructions. These instructions suggest selecting trees and branches according to Forshey (1977), but measuring fruits with a gauge (Batjer et al. 1957) rather than picking and weighing them. This method allows the same fruits to be resampled several times.

If no crop samples are available, the user predicts yield and fruit size distribution. To aid prediction, Dbase programs display last year's yield and fruit sizes to be used as defaults or adjusted to meet current conditions in the orchard (1 & 2 in Fig. 6). Similar programs are used to get user estimates of grades, net prices per packed box and presize charges (3, 4 & 5 in Fig. 6). The five components are then put together to calculate crop value.

If crop samples are available, they are used to predict both yield and fruit sizes (1 in Fig. 7). Fig. 8 shows the calculations in more detail. Process 1.1 indicates a subroutine that retrieves the orchard block identification number from the packinghouse database according to information obtained from the user and stored in the identity database. Records associated with this number and the previous crop year are then located in the packout and defect databases. From the amount of fruit of each size and the percentage culled for small size, another subroutine (1.2) calculates the number of apples in each size category in the previous year. The crop sample database stores sample dates and bloom dates for each orchard block. These dates are linked by numbers to fruit diameter measurements stored in another database. Subroutine 1.3 locates records for the most recent sample in the current year and the corresponding sample (same days past bloom) in the previous year and counts the number of sampled apples assigned to each predicted size class at harvest. Harvest size of each sampled apple is predicted from Table 2 in Batjer et al. (1957), which has been recommended for use in commercial orchards in Washington for many years (Williams & Edgerton 1982). Subroutine 1.4 multiplies ratios of this year's sample to last year's sample by last year's packout size distribution to estimate this year's size distribution.

2) Packout analysis

Fig. 13 shows the results of the calculations of net crop value using 1987 and 1988 prices and packing charges for the four fruit lots illustrated in Figs. 9-12. These values do not include production costs (estimated at $4100/acre for a 218 tree/acre orchard by Dickrell et al. 1987). Net crop values per acre differ by up to $5897 at the high yield, $3370 at the medium yield and $1067 at the low yield for the same lot between the two years. Differences between the highest and lowest value lots due to fruit grade and size within the same year are $3462, $1964 and $495 for 1987 and $5774, $3320 and $825 for 1988 at the high, medium and low yields. Crop value differences due to yield for a given fruit lot ranged from $492 for Lot 4 in 1987 to $5152 for Lot 7 in 1988.

Discussion

The accuracy of crop value prediction using AppleMgr depends on the experience and skill of the user who estimates fruit grades and net prices. These estimates are likely to be most accurate for those situations where the orchard has been under consistent management for several years and good records are available.

Taking crop samples may considerably increase the accuracy of predictions of yield and fruit size, especially when the orchard history is poorly known. Batjer et al. (1957) over an eight-year period predicted harvest size of 'Red Delicious' fruit with a mean accuracy of 75% within a

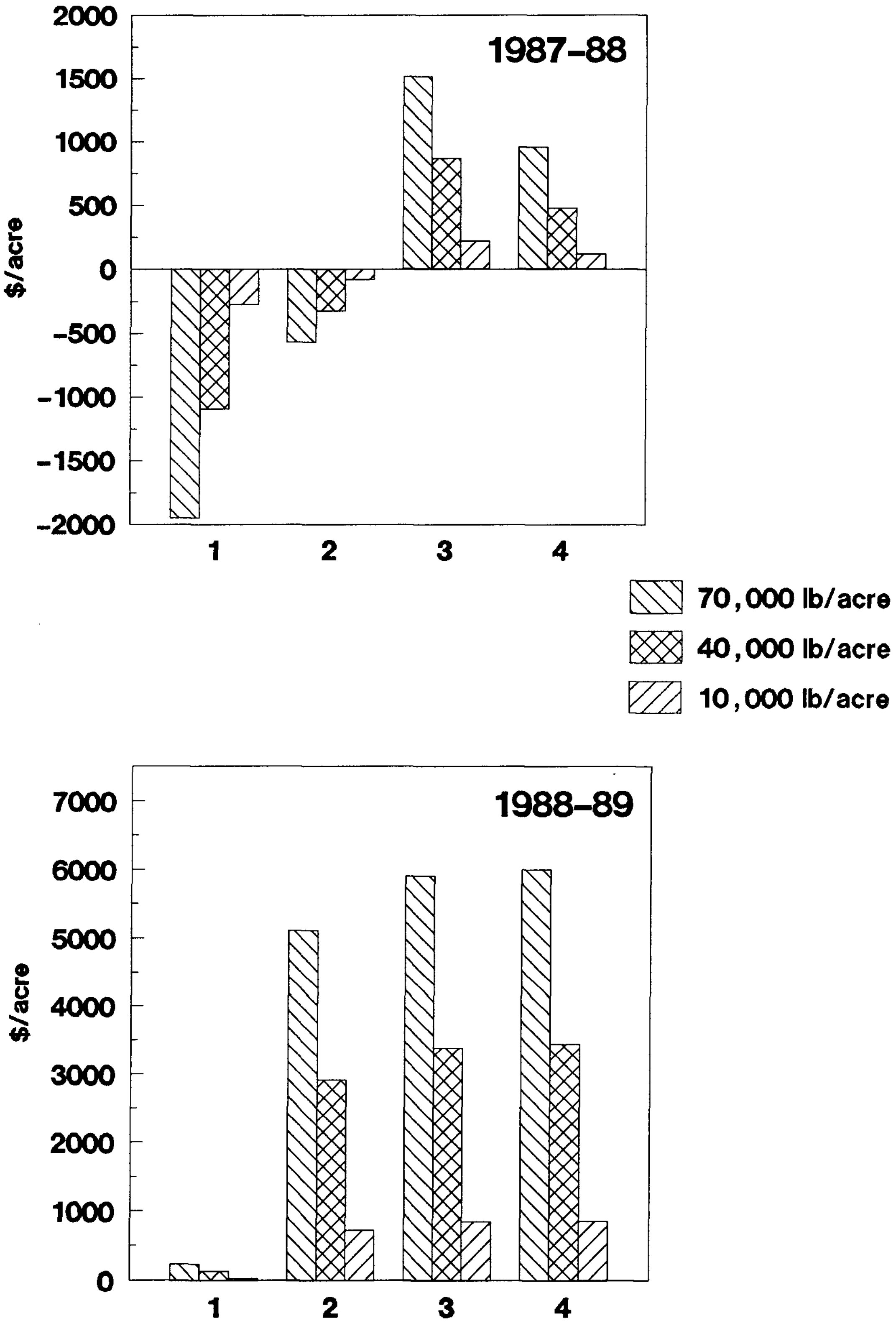


Fig. 13. Net crop value per acre of Lots 1-4.

two-box-size error at 50 days past bloom and found a steady increase in accuracy as harvest approached. However, many pest management decisions must be made early in the growing season before crop samples can predict size and yield very well, if they can be taken at all. Early-season samples would be most useful in cases of fruit set failure or severe overthinning to indicate the extent of yield shortfall below expectations. Because crop value can be calculated in a few seconds using AppleMgr, many scenarios of varying yields, packouts and prices can be quickly explored.

The variations of thousands of dollars per acre in crop values found in the packout analysis indicate that large differences commonly occur between fruit lots and between consecutive crop years. The potential for variation is especially great in crops from high density orchards, which are becoming increasingly common. High-yielding plantings of excellent quality fruit of new varieties appear to offer the best hope of survival for apple growers (Auvil 1988), but only if total acreage is limited and production costs, including those for pest management, can be kept down.

DAMAGE PREDICTION

Introduction

To determine whether a responsive pest control action is worthwhile, an orchard manager needs an accurate prediction of expected crop damage. This prediction must be made sufficiently far in advance so that action may be taken before significant loss occurs. In predicting damage, estimates must be made of crop value, pest phenology in relation to the crop, pest densities and density-injury relationships, pest population dynamics, and expected degree of natural control. Apple entomologists have commonly approached the problem of damage prediction by attempting to arrive at economic injury levels and economic thresholds through field experience, experiment and modeling. Whalon & Croft (1984) summarize thresholds reported for 19 regions in North America.

The generally accepted definitions of economic injury level and economic threshold are those of Stern et al. (1959). They define economic injury level as the "lowest population density that will cause economic damage. Economic damage is the amount of injury which will justify the cost of artificial control measures . . ." Economic threshold is the "density at which control measures should be determined to prevent an increasing pest population from reaching the economic-injury level."

Stern et al. (1959) also state that the "economic threshold and the economic-injury level of a pest species can vary depending upon the crop, season, area, and desire of [the manager] . . ." However, in practice recommended thresholds are generally fixed for a given pest species in a particular region (Leeper 1980; Whalon & Croft 1984), regardless of changing crop values, natural and applied control efficacies, control costs and farmer's goals. Economic optimization models for pest control decision making have been developed for only a few field crops, and combined damage predictions for several pests are rare (Pedigo et al. 1986).

The RECOG and EXE versions contain pest-specific decision making rules based on estimated treatment thresholds. Although these thresholds change for different times in the growing season and include modifications for weather and management stresses on the tree, they are not flexible enough to respond to the many variables involved in a pest management decision. This approach does not explicitly identify the components of an economic threshold so that they may be individually estimated. The system gives the user only an assertion that economic damage is or is not likely to occur and, if appropriate, a pesticide recommendation.

To address some of these deficiencies, an improved system was designed in AppleMgr based on a benefit-cost approach to decision making. The value of the damage that could be prevented by applying a particular control tactic is weighed against the cost of that action. Ideally, a combined damage estimate for all pests is made at each decision point. This strategy separates the estimation of damage, control efficacy and control cost. The benefit of a specific control tactic varies as these estimates change. The user thus receives much more information, and, by choosing a control tactic and examining its potential effects, becomes an active participant throughout the evaluation process.

Methods

The RECOG version consists of a series of modules or chapters for each pest at each different time of the growing season. The user responds to a series of questions in each chapter by selecting from a list of multiple-choice answers. There is no linkage to other programs and no data storage between sessions.

The management part of the EXE version also handles each pest in separate modules and uses the RECOG structure of a series of questions with multiple-choice prompts that must be answered before a rule fires. EXE provides the means to give supporting documentation for each question and rule presented to the user. A user can call up this information from any screen by choosing the "why" alternative. The EXE version expands the management capabilities of the system by adding to the decision making rules (path 4 in Fig. 2) the capacity to run models (path 3) and to manipulate records (path 2) stored in a database management program (Dbase 3+, Ashton-Tate).

When proceeding to damage prediction as a component in benefit-cost analysis, data flow diagrams were constructed as for crop value prediction (Chapter 4). These diagrams show damage prediction for direct pests (Fig. 14) and indirect pests (Fig. 15). In AppleMgr, programs written in Dbase or C calculate values for variables such as last year's scale cullage and accumulated degree-days. Final calculations of predicted damage are done in PC EASY rules.

Results

The RECOG version contains chapters for all major insect and mite pests and powdery mildew (Table 5). These chapters present sampling methods for each pest and integrated control advice based on estimated treatment thresholds and control recommendations from the research and extension literature and my field experience in British Columbia. References are given for each sampling method and recommended treatment. Appendix A contains an example chapter for McDaniel mite.

For the EXE version, the PETE phenology model was modified (Currans & Croft, in press) and used to predict codling moth development. This model and the rules in the treatment decision module both require accumulated degree-day output from the degree-day calculator (Fig. 2), now separate from the model. A database of daily maximum and minimum temperatures supplies input to the degree-day calculator. These temperatures may come from the user's orchard or from the nearest public or private weather

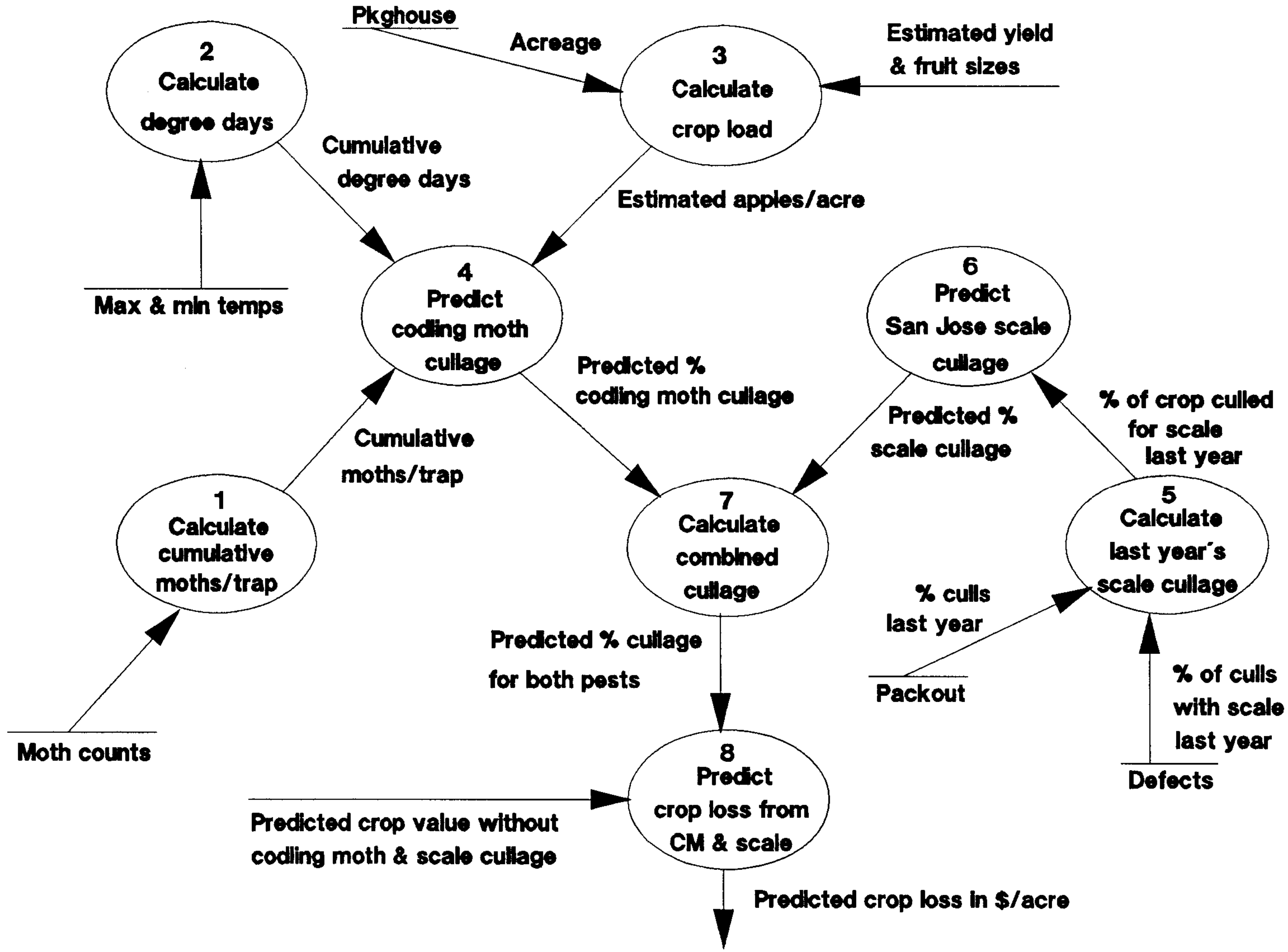


Fig. 14. Predicting crop loss from direct pests.

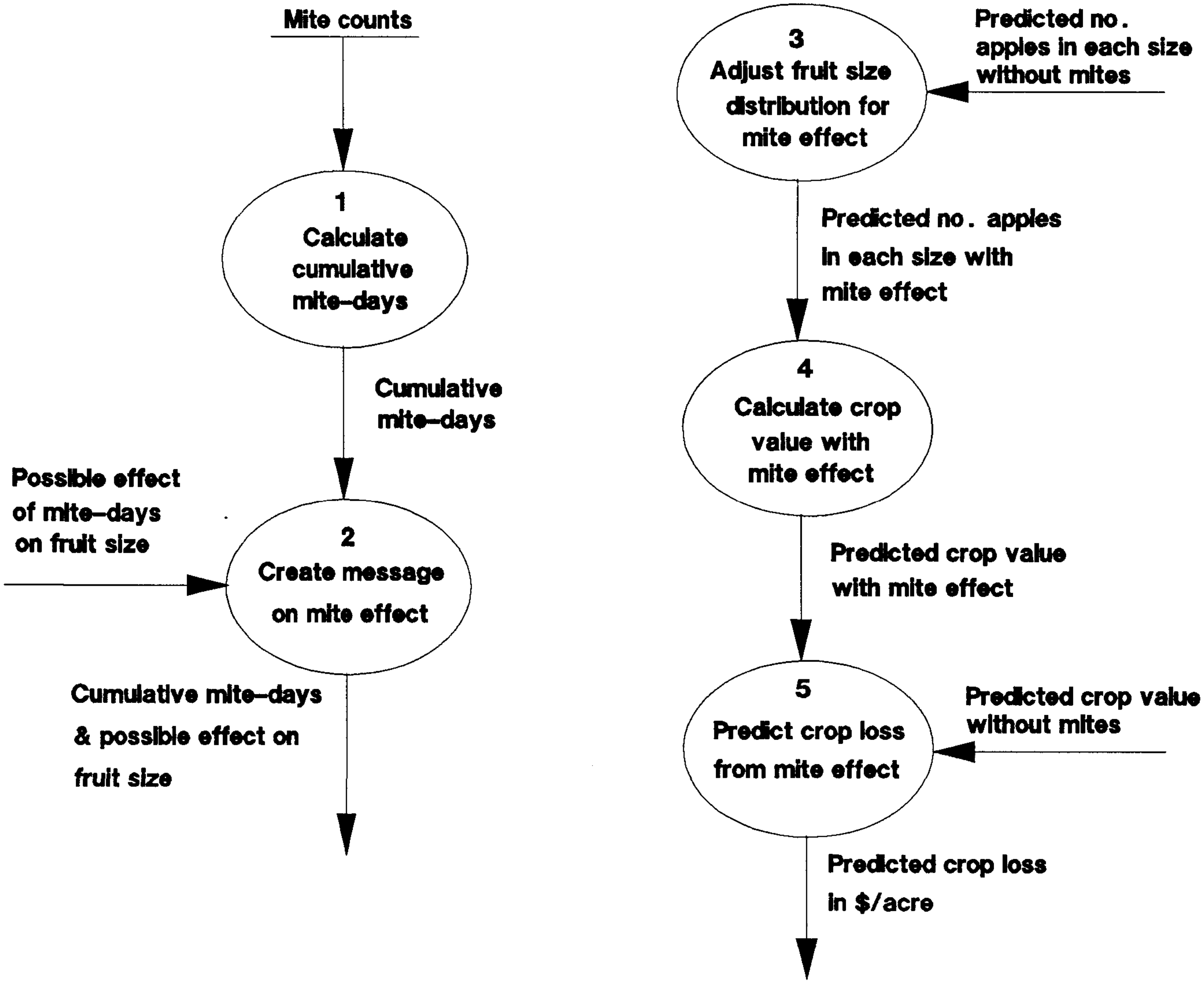


Fig. 15. Predicting crop loss from indirect pests.

Table 5. Pests included in RECOG version.

Apple aphid	*Aphis pomi* DeGeer
Lygus bugs	*Lygus* spp.
San Jose scale	*Quadraspidiotus perniciosus* Comstock
Spring caterpillars	Tortricidae, Noctuidae, Geometridae
Mullein bug	*Campylomma verbasci* (Meyer)
Codling moth	*Cydia pomonella* (L.)
Apple maggot	*Rhagoletis pomonella* (Walsh)
Summer leafrollers	Tortricidae
Apple leafhopper	*Typhlocyba pomaria* McAtee
Spotted tentiform leafminers	*Phyllonorycter* spp.
European red mite	*Panonychus ulmi* (Koch)
Apple rust mite	*Aculus schlectendali* (Nalepa)
McDaniel spider mite	*Tetranychus mcdanieli* McGregor
Powdery mildew	*Podosphaera leucotricha*

station. They are stored in a database and handled through a Dbase program. Paths 2 and 3 (Fig. 2) of the EXE version were built by Currans.

To eliminate redundant questions and use degree-day information, the single codling moth decision making chapter in the RECOG version was expanded into six chapters in the EXE version. The first chapter, "Codling Moth", directs the user to one of the other chapters based on answers to four questions. This chapter also gives a definition of biofix (from Brunner et al. 1982) and advice on how to deal with a lack of temperature data. Two chapters, "Temperature Monitoring" and "Codling Moth Trapping", give information on how to install, use and maintain temperature recording devices and pheromone traps.

The remaining three chapters all begin by calculating accumulated degree-days and then ask a series of questions to determine need for treatment and spray timing. "Pre-Biofix Codling Moth" advises to continue daily trap monitoring until biofix. "Post-Biofix Codling Moth" is intended for users who have temperature data and have reached biofix but are not using pheromone traps to monitor population levels. This chapter recommends spray timing based on degree-days accumulated since biofix or March 1 and on the user's answer to a question about codling moth history of the orchard. These recommendations are taken from Brunner et al. (1982). "Codling Moth Thresholds" recommends whole-orchard, hot-spot or border sprays or no treatment based on accumulated degree-days and the user's answers to questions on trap captures, previous spray timing and fruit damage. This advice is supported with research by Vakenti and Madsen (1976) and Madsen et al. (1974) and my consulting experience in British Columbia. Adjustment of spray thresholds for trap density comes from Riedl et al. (1986).

Fig. 14 shows how AppleMgr predicts combined damage for two direct pests whose injury results in fruit cullage. Codling moth cullage is predicted using a regression model developed in Michigan (Riedl & Croft 1974). This model estimates percent fruit injury at harvest from cumulative captures in pheromone traps (1) at several different times in the growing season given in degree-days (2). Trap captures are adjusted on the basis of the number of fruit in the area surveyed by one trap (3).

Fruit cullage due to the presence of San Jose scale (6) is predicted from a function of last year's cullage (5) estimated by S. C. Hoyt (Wash. State Univ. Tree Fruit Research & Ext. Center, Wenatchee). This function was converted from a hand-drawn curve to a quadratic equation by using the Gauss-Newton method of nonlinear regression (SAS 1985) The equation handles cullage rates of up to 5% of the previous year's crop.

Combined cullage for codling moth and scale (7) is computed according to the rule:

Predicted_%_Cullage_for_CM_&_SJS =

Predicted_%_CM_Cullage + Predicted_%_SJS_Cullage - (Predicted_%_CM_Cullage X Predicted_%_SJS_Cullage).

Finally, crop loss from codling moth and scale (8) is predicted by multiplying combined cullage by the predicted crop value with no damage from these pests (Chapter 3).

Prediction of mite damage is more difficult than for pests such as codling moth and San Jose scale because the effect is indirect. According to research by Hoyt et al. (1979), in the Northwest where orchards are irrigated and heavily thinned, mite leaf injury primarily affects fruit size in the current year. The extent of the effect depends on numbers and species of mites present, the length of time they are feeding, crop load, time of the season and other stresses on the tree. Hoyt feels that this complexity precludes the possibility of making a generalized prediction based on pest density as he did for scale. The models that he and his colleagues have constructed to predict mite effect on fruit size tend to be specific to the particular block and year in which the data were collected.

For these reasons the prediction of crop loss from mite injury shows two separate paths in Fig. 15. Cumulative mite-days (1) are calculated for the orchard block according to the formula:

Total mite-days = MDSM-days + ERM-days + ARM-days/3

where MDSM = McDaniel spider mite, ERM = European red mite and ARM = apple rust mite. Mite-days for each species are computed from mite counts as in Hoyt et al. (1979).

The message displayed to the user (2) gives the combined mite-day accumulation for all three species followed by this interpretation:

> Researchers estimate that 3000 mite-days would be required to reduce the crop by one box size on vigorous trees in mid-season. A portion of the crop could be reduced in size at 2000-2500 mite-days. Where trees are insufficiently thinned or suffering from inadequate irrigation or nutrient deficiencies or winter injury, fruit size reduction may occur at a lower number of mite-days.

To give a benchmark to assess possible economic impact of mites, the value of a reduction of one box size in the crop is calculated. The predicted number of apples in each size class (Chapter 3) is shifted down one box size (3) and crop value is recalculated (4). The difference between the original crop value (Chapter 3) and the crop value with the new size distribution is the predicted crop loss (5).

Discussion

Each of the three different damage prediction methods used in AppleMgr has important limitations. For codling moth the regression model used is not able to predict damage earlier than 600 degree-days. This is somewhat later in the season than the 450 degree-day (or 250 degree-day past biofix) spray timing (3% egg hatch) recommended for most orchards in Washington. However, it is similar to the 560 degree-day timing (20 % egg hatch) recommended in orchards with low codling moth populations (Brunner et al. 1982).

The Riedl and Croft (1974) regression model is based on a single season's data collected in abandoned orchards in Michigan. Riedl and Croft (1978) caution that cumulative trap captures "are crude estimates of population levels since no means of standardization with respect to weather factors, moth dispersal and competition with the native female populations are considered." Nevertheless, were felt sufficiently confident in their model to present it in an extension bulletin for grower use (Riedl & Croft 1978).

Although the Riedl and Croft (1974) model is the only one published relating harvest fruit injury to cumulative pheromone trap captures, thresholds based on cumulative captures are used in many areas of the world to determine the need for sprays (Riedl et al. 1986). Thus, while the regression coefficients may vary from one region to another, the approach is well-established. Because the regression equation occurs in a rule in the PC EASY shell, rather than embedded in program code, it may be adjusted easily to suit local conditions.

The model in AppleMgr to estimate San Jose scale cullage is probably more accurate than the codling moth model because the scale model is based on the many years of research experience of S. C. Hoyt in the Northwest. The scale model is a rough estimate because it generalizes across potentially variable conditions of overwintering mortality and in-season mortality due to natural control by weather and natural enemies.

For mites, the damage prediction calculates the effect on crop value of a standard fruit size reduction (one box size) rather than attempting to predict the effect of the number of mite-days actually accumulated in the user's orchard. This approach recognizes the uncertain situation and at the same time provides a benchmark to estimate potential mite effect.

All three of the damage prediction methods, although faulty, take a step beyond static treatment thresholds toward predicting actual economic damage caused by pests to a particular crop of fluctuating value. They point the way toward a more dynamic and realistic means of damage prediction for apple pests.

CONTROL SELECTION AND EFFICACY

Introduction

Once the potentially significant nature of a pest problem has been established through damage prediction, a manager must consider whether natural control agents are likely be sufficient. If not, additional cultural, biological or chemical control must be applied. In Northwest commercial apple orchards, control by weather and natural enemies is often adequate for many foliage-feeding pests such as mites (Hoyt et al. 1979), but usually inadequate for direct pests such as codling moth and San Jose scale (Hoyt et al. 1983). Conservation of predacious phytoseiid mites, principally western predatory mite, Metaseiulus occidentalis (Nesbitt), is a major control strategy for phytophagous mites (Tanigoshi et al. 1983). Chemical pesticides are the primary control tactic against codling moth and scale. The efficacy of both biological and chemical control must be assessed to estimate how much of the predicted damage (Chapter 5) is likely to be prevented.

To assess the likelihood of biological control of phytophagous mites by a predator mite, Amblyseius fallacis Garman, Croft et al. (1976b) developed a simulation model and also a simplified index based on predator:prey ratios (Croft 1975). This system was used as part of PMEX, an extension delivery system for pest management information in Michigan (Croft et al. 1976a). In the Northwest, assessments of potential biological mite control are also often made on the basis of predator-prey ratios (Downing 1974, Madsen et al. 1975). This is the method used in the RECOG version.

Information on pesticide efficacy is often absent or limited in extension publications and computer expert systems. For example, the 1989 British Columbia Tree Fruit Production Guide (Province of B.C., Ministry of Agric. & Fisheries, Victoria) and POMME (Roach et al. 1987) present apple growers with a list of several recommended pesticides for a specific pest or group of pests with no efficacies given. The 1989 Spray Guide for Tree Fruits in Eastern Washington (Coop. Ext., College of Agric. & Home Econ., Wash. St. Univ., Pullman) and AppleES (Rajotte et al. 1989) shown relative efficacy ratings. None of these presentations provides methods to predict the economic outcome of a spray decision in terms of the value of potential damage likely to be prevented.

The objectives of the efficacy part of the decision aid were to estimate the probability of biological control of spider mites and to provide methods to estimate the percentage of damage likely to be prevented by application of suitable pesticides.

Methods

In the RECOG version, information on biological and chemical control is included in the text of the rule statements and reasons (Appendix A). Once it has been determined that economic damage is likely, the EXE version leads the user by invocation rules (Currans 1988) to a spreadsheet (Lotus 123, Lotus Development Corp.) that compares suitable pesticides. Currans wrote the macros for this spreadsheet. Peter Westigard (OSU, Southern Oregon Exp. Stn., Medford) supplied relative efficacy ratings for the five insecticides against codling moth.

In AppleMgr data collected by S. C. Hoyt from about 25 orchards over 4 years (Fig. 16) was used to construct rules to estimate biological control probability for McDaniel spider mite. Data points were grouped into classes at intervals of 5 spider mites and 0.5 predator mites per leaf. Then the proportion of triangles to total data points was calculated for each class. These proportions were used to create PC EASY rules. Hoyt (pers. comm.) suggested an adjustment to the rules for high predator densities. Rules for European red mite were constructed on the basis of Hoyt's (pers. comm.) estimate that about 0.6 times the McDaniel mite densities with the same predator densities would "compensate for lack of feeding on European red mite eggs and other negative factors."

Hoyt estimated efficacies for miticides and for insecticides against San Jose scale. Helmut Riedl (OSU, Mid-Columbia Agric. Research & Ext. Center, Hood River) provided efficacy estimates for insecticides against codling moth. Hoyt and Riedl were given questionnaires listing several rates for each pesticide where a range of

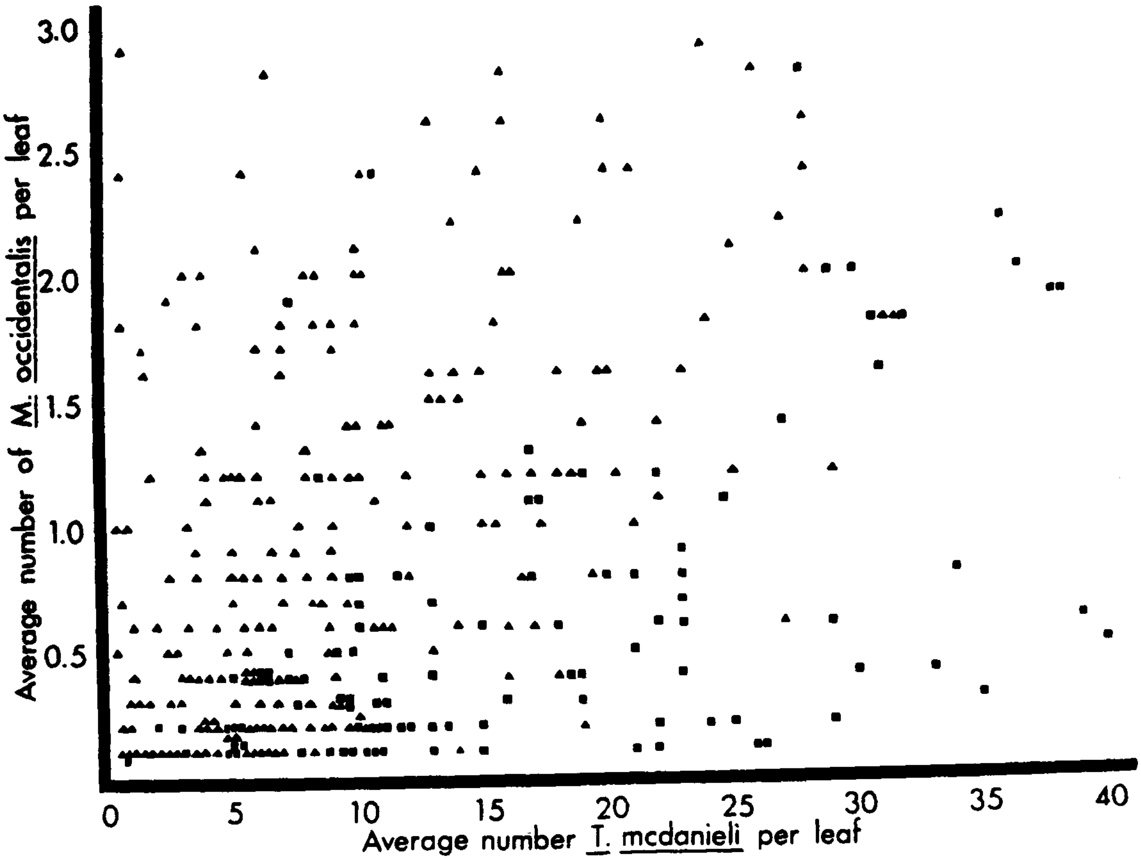


Fig. 16. Data (Hoyt, unpublished) used to formulate rules to predict probability of biological control of McDaniel spider mite in AppleMgr. Triangles indicate successful control and squares unsuccessful control.

rates is given in the WSU Spray Guide (Coop. Ext., College of Agric. & Home Econ., Wash. St. Univ., Pullman). Where efficacy estimates do not differ, the lowest rate is given in the pesticide choice list displayed in AppleMgr. Where estimates differ (e.g., Guthion, Omite), more than one rate is shown. Efficacy estimates are stored in a database and retrieved by PC EASY external access functions.

Relative efficacy ratings for pesticides against secondary pests are stored and displayed in AppleMgr in a spreadsheet similar to the one used in the EXE version. Efficacy ratings for this spreadsheet were taken from the 1989 WSU Spray Guide. Hoyt (pers. comm.), who suggested including this spreadsheet, supplied estimates not given in the WSU Spray Guide.

Results

1) Biological mite control

In the RECOG version, predator-prey ratios are used to assess potential for biological mite control of McDaniel spider mite (Appendix A) and European red mite. If predator densities are low and spider mite densities are below the treatment threshold, the user is advised to wait and resample. AppleMgr uses rules of the form:

If Predator_Mites <1.5 and McDaniel_Mite >= 30,

then Probability_of_Biocontrol < 10%.

Average numbers of predator and spider mites per leaf in the most recent mite count stored in a database are retrieved for testing in the rules.

Probability_of_Biocontrol is the first goal parameter for mites in AppleMgr, thus triggering these rules to fire before any other rules. The probability of biocontrol of mites is displayed before any other results about mites. If the probability is high, the user may then decide to omit damage prediction.

2) Chemical control

In the RECOG version, recommendations for the use of specific pesticides and rates are given in the rule statement (Appendix A). The EXE version presents a spreadsheet (Table 6) showing five suitable pesticides with relative ratings on six factors, including efficacy. The user may assign a weight to each factor depending on its importance in the particular situation. Weights multiplied by normalized ratings for each factor are summed to give a total rating for each pesticide. By selecting "Graph" from a menu, the user may see a stacked bar graph comparing the five pesticides (Fig. 17).

Additional pesticide information is provided to the user of the EXE version who elects to examine the characteristics of control tactics (path 5, Fig. 2). Menus provide choices to see label information or information on use of a pesticide against a certain pest. Dbase programs (written by Currans) give access to databases containing

Table 6. Insecticide comparison spreadsheet in EXE version.

Factors	Wts	Rtg	Insecticides				
	19		Guthion	Imidan	Penncap-M	Pydrin	Zolone EC
Efficacy	5	1	4	4	4	5	4
			1.05	1.05	1.05	1.31	1.05
Appl Hazard	3	1	1	2	2	2	2
			0.15	0.31	0.31	0.31	0.31
Bee toxicity	3	1	0	0	0	1	2
			0	0	0	0.15	0.31
TP Toxicity	2	1	2	1	3	0	4
			0.21	0.10	0.31	0	0.42
MO Toxicity	2	1	3	3	3	0	3
			0.31	0.31	0.31	0	0.31
Spray Cost	4	1	3	2	2	3	3
			0.63	0.42	0.42	0.63	0.63
Totals:	19	6	0.39	0.36	0.40	0.40	0.50

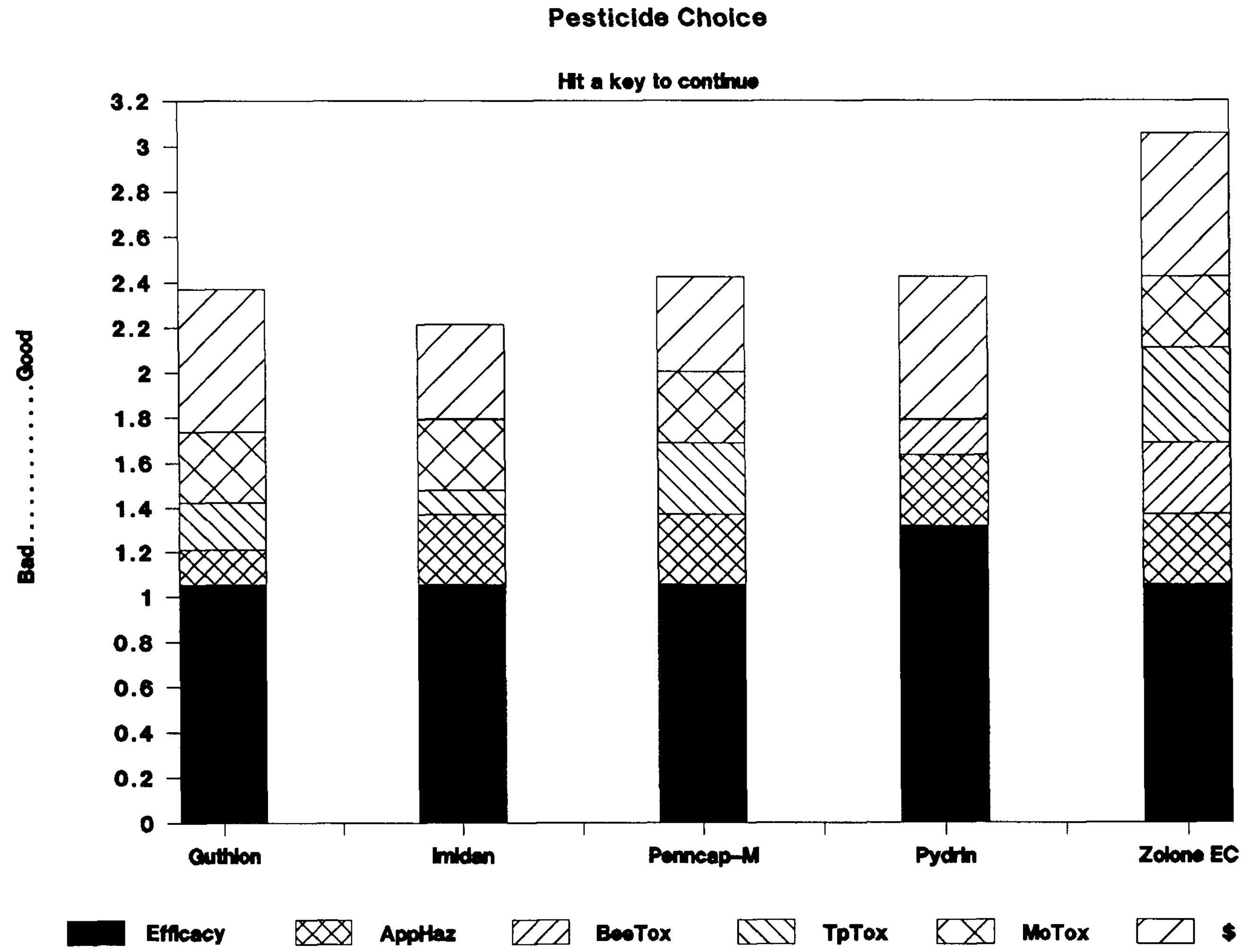


Fig. 17. Pesticide comparison graph in EXE version. AppHaz = hazard to applicator, BeeTox = toxicity to bees, TpTox = toxicity to <u>Typhlodromus pyri</u>, MoTox = toxicity to <u>Metaseiulus occidentalis</u>, $ = cost.

data such as active ingredient, class of pesticide, use restrictions, rates, residue length and cost per acre.

Early in each session, AppleMgr displays a list of suitable pesticides for the time of year and pest(s) selected. There are separate lists of insecticides and miticides. From this list, the user chooses a pesticide to examine in the benefit-cost analysis. Efficacies of each pesticide against each pest (percent of predicted damage preventable) are retrieved from a database and assigned to PC EASY parameters. For codling moth and San Jose scale there are efficacy values for high, moderate and low levels of pest pressure. San Jose scale efficacies for postbloom control also vary depending on which insecticide, if any, was applied before bloom. For codling moth pest pressure ratings depend on the percent of expected fruit injury with no control applied. For San Jose scale, these ratings depend on the percent of the previous year's crop culled for San Jose scale and the age of the trees. Because efficacy of miticides varies considerably from orchard to orchard depending on resistance status, a high and a low value are used to compute high and low values for the predicted benefit of a miticide treatment.

Near the end of a session, the user may choose to examine relative efficacies of pesticides against secondary pests likely to be present. Two spreadsheets are included, one for prebloom pests and one for postbloom pests. Prebloom pests shown are _Pandemis_ spp. leafrollers, aphids, cutworms and Lygus spp. Postbloom pests are Pandemis spp., white apple leafhopper, Typhlocyba pomaria McAtee, green apple aphid, Aphis pomi DeGeer, and woolly apple aphid, Eriosoma lanigerum (Hausmann).

Discussion

AppleMgr supplies more specific and personalized information to the user on control efficacy than previous versions or other apple decision aids. By calculating percent probability of biological control at the start of a session, the DSS reinforces the idea that one should assess the adequacy of natural control before considering a pesticide application. The estimates given are likely to be reliable except where predators are scarce or poorly distributed. Of course, the accuracy of the prediction also depends on the care taken in leaf collection and mite counting. Specific directions are given for leaf sampling in the RECOG version. (Appendix A). These are also available in extension bulletins. Rules to predict biological control probability are based on data and estimates of S.C. Hoyt, the most experienced researcher on Northwest apple mites.

The choices of pesticides shown in the DSS are limited to those commonly recommended for commercial orchards, a small proportion of the registered materials. This is a limitation for those growers and advisors seeking less toxic alternatives. Only oil and possibly Dimilin would fulfill their requirements.

The efficacy estimates given in percent expected damage prevented allow an economic benefit of treatment to be calculated, which is not possible with relative estimates. The precision implied by these percent estimates may be misleading, however. Pest control is highly dependent on spray application equipment and technique and on weather conditions, which are not taken into account in the DSS. Miticide resistance also causes great variability in efficacy from orchard to orchard. The development of pesticide resistance in codling moth and San Jose scale would drastically change the estimates as it has for miticides. The decision to use pesticide efficacy estimates of single rather than multiple experts avoids the problems of weighting components of combined estimates (Ling and Rudd, in press) and does not necessarily produce inferior results. It is finally up to the user to evaluate the predictions given.

The spreadsheets showing relative efficacy values for pesticides against other pests expand the usefulness of AppleMgr. Usually growers have to deal with several pests at a given point in the growing season. Although quantitative estimates for efficacy against these secondary pests are not available, the relative estimates provide additional information needed in making a spray decision.

DIRECT AND INDIRECT COSTS OF PEST CONTROL

Introduction

In predicting the net benefit of a control tactic, both direct and indirect costs must be assessed. As Stern et al. (1959) state, "When chemicals are used, the damage from the pest species must be sufficiently great to cover not only the cost of the insecticidal treatment but also the possible deleterious effects, such as the harmful influence of the chemical on the ecosystem." Later authors (Headley 1972, Norton 1976, Mumford & Norton 1984, Pedigo et al. 1986, Onstad 1987) have narrowed their focus to the direct costs of the chemical and its application in calculating economic injury levels and economic thresholds. The indirect adverse effects of pesticide use may be important but are very difficult to quantify. Therefore, I have included only direct costs in the calculation of net dollar per acre benefit of a pesticide application and have shown relative estimates of four selected indirect costs in a spreadsheet.

Methods

Per acre costs of spray materials (not including application) in the EXE version are based on March 1987 prices from Tualatin Farm Supply, Hillsboro, Oregon and rates from the 1986 WSU Spray Guide. These costs are stored in a database with other pesticide information (Chapter 6). Both chemical and application costs are calculated in AppleMgr. Chemical costs in dollars per container were supplied by Gary Olson of Northwest Chemical Corp., Salem, Oregon in January 1989. Application time and costs per hour for labor and machinery were taken from estimates of a committee of experienced apple growers in the Wenatchee area (Dickrell et al. 1987). Machinery costs are based on a $18,400 50-HP tractor and $9500 airblast sprayer depreciated over 10 years. Pesticide costs and application costs are stored in separate databases and manipulated by a Dbase program which supplies a value to the PC EASY parameter **Control_Cost**.

Relative direct and indirect costs are shown in the pesticide selection spreadsheet in the EXE version (Fig. 17). Estimates of hazard to the applicator and toxicity to bees were taken from the 1986 WSU Spray Guide. Toxicities to two predacious mites (Typhlodromus pyri Scheuten and M. occidentalis) were estimated by B. A. Croft (pers. comm). The AppleMgr spreadsheet has the same format but shows only indirect costs. For AppleMgr estimates of applicator hazard, bee toxicity and toxicity to western predatory mite (WPM), M. occidentalis, were taken from the 1989 WSU Spray Guide. Croft (pers. comm.) estimated risk of resistance.

Results

Fig. 18 shows the procedure used to calculate direct cost of a pesticide application. First, the program extracts the user's choice of pesticide from a database and separates the chemical name from the rate (1). The program can handle either single chemicals or mixtures of two

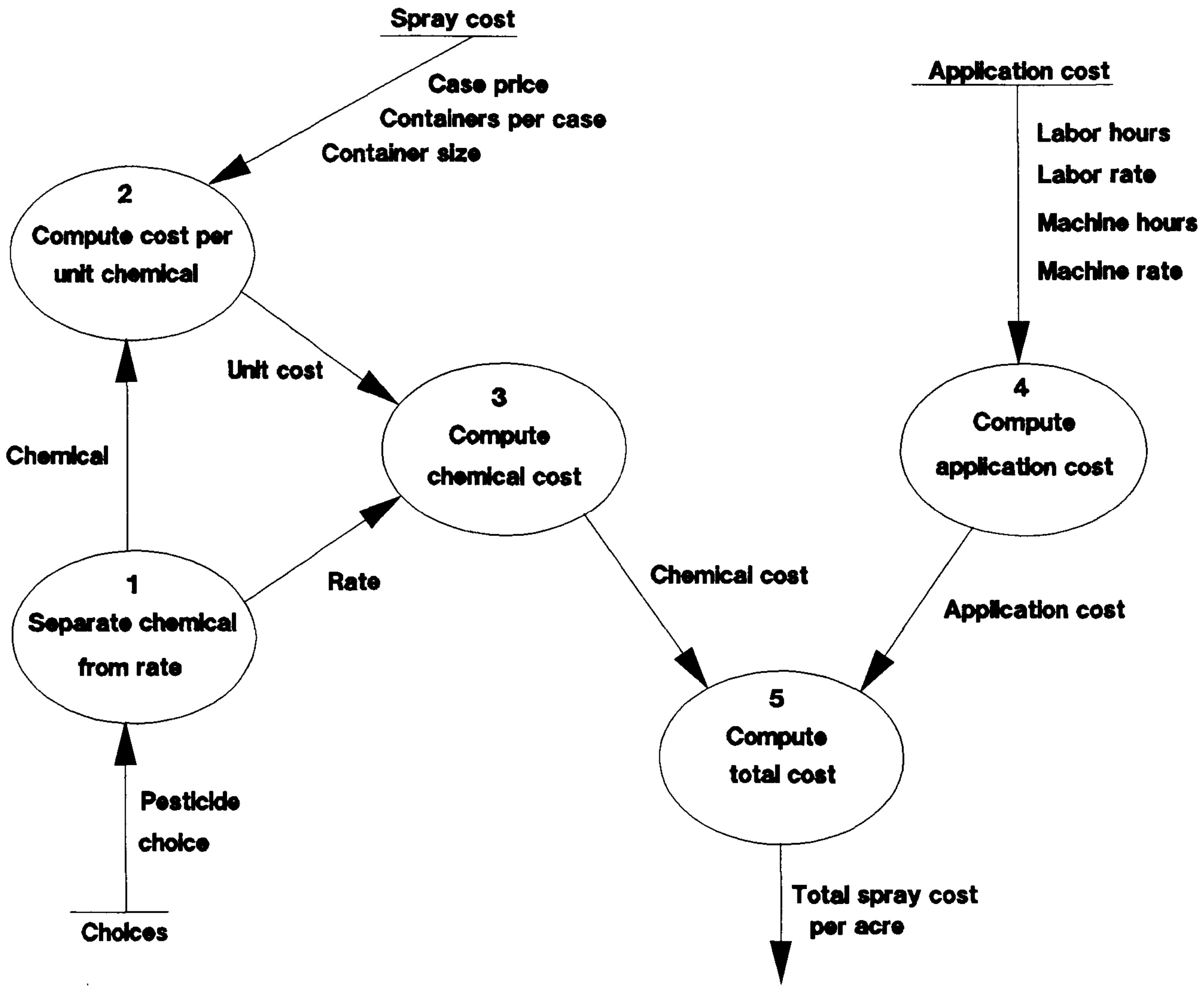


Fig. 18. Computing direct control cost.

chemicals. Then the cost per unit chemical (lb. or gal.) is computed using data from the spray cost database (2). The rate(s) and chemical cost(s) are used to calculate per acre material cost for a single chemical or mixture (3). Application costs are computed from data stored in another database (4) and added to chemical costs to find total spray cost (5).

The four indirect costs selected for the AppleMgr spreadsheet are hazard to the applicator, toxicity to bees, toxicity to WPM and risk of development of resistance. These four variables are rated on a scale of 1 (least hazardous) to 4 (most hazardous). Where the pesticide list applies to control of several species, the resistance risk rating for the species with highest risk is given. Totals for each pesticide depend on both these ratings and on the user's weighting of the four variables. Table 7 shows an example spreadsheet for the comparison of miticides.

Discussion

Information regarding pesticides and control costs is organized in several simple databases to facilitate frequent revision. Chemical costs are divided into fields for price per case, containers per case and amount per container to reflect the way this information is provided by the supplier. Application costs will vary depending on the applicator, machinery and orchard. The default values need to be customized for each situation, but they provide useful estimates for average conditions. Dickrell et al.

Table 7. AppleMgr spreadsheet showing comparison of indirect costs of miticides. App Tox = applicator toxicity, Bee Tox = toxicity to bees, WPM Tox = toxicity to western predatory mite, Res Risk = risk of resistance development.

Weights	3	1	3	2	9
Chemical	App Tox	Bee Tox	WPM Tox	Res Risk	Totals
OMITE	1	1	1	2	11
VENDEX WP	1	1	2	3	16
VENDEX 4L	1	1	3	3	19
CARZOL	3	3	3	4	29

(1987) do not break down their estimates of labor hours per acre for spraying into specific activities. Since their labor time estimates are longer per acre than their machinery time estimates (0.48 hr vs. 0.40 hr), mixing and loading and possibly cleanup appear to be included. There are many other labor and material costs associated with pesticide application that should be taken into account. Some of these are: applicator training, travel to and from the supplier, protective clothing, sprayer calibration, container disposal, recording of the application, notification of orchard workers and public authorities, and disruption of other orchard operations because of re-entry regulations, travel through the orchard and need to avoid overhead irrigation after spraying.

The indirect costs in AppleMgr are only a small selection from many that might be included. Some others that may be equally or more important to consider when comparing pesticides in particular situations are: hazards to orchard workers, family members, neighbors and passers-by; hazards to wildlife; hazards to natural enemies other than WPM; contamination of surface and ground water; and marketing considerations. The ratings given for applicator hazard may be used as an index of general mammalian toxicity. Bee protection plays a vital role in orchard production and is also very important in orchards near alfalfa seed fields. Because of their peculiar foraging habits, bees are uniquely susceptible to Penncap-M (Burgett

& Fisher 1977). Toxicities of pesticides to natural enemies vary considerably with different species and compounds (Croft 1990). Addition to the DSS of selections for apple species from a large database of pesticide effects on natural enemies (Theiling & Croft 1988) might be useful. While there may be a temporary marketing advantage to apple producers who can demonstrate low pesticide use, this advantage is likely to disappear as more controversial compounds are withdrawn.

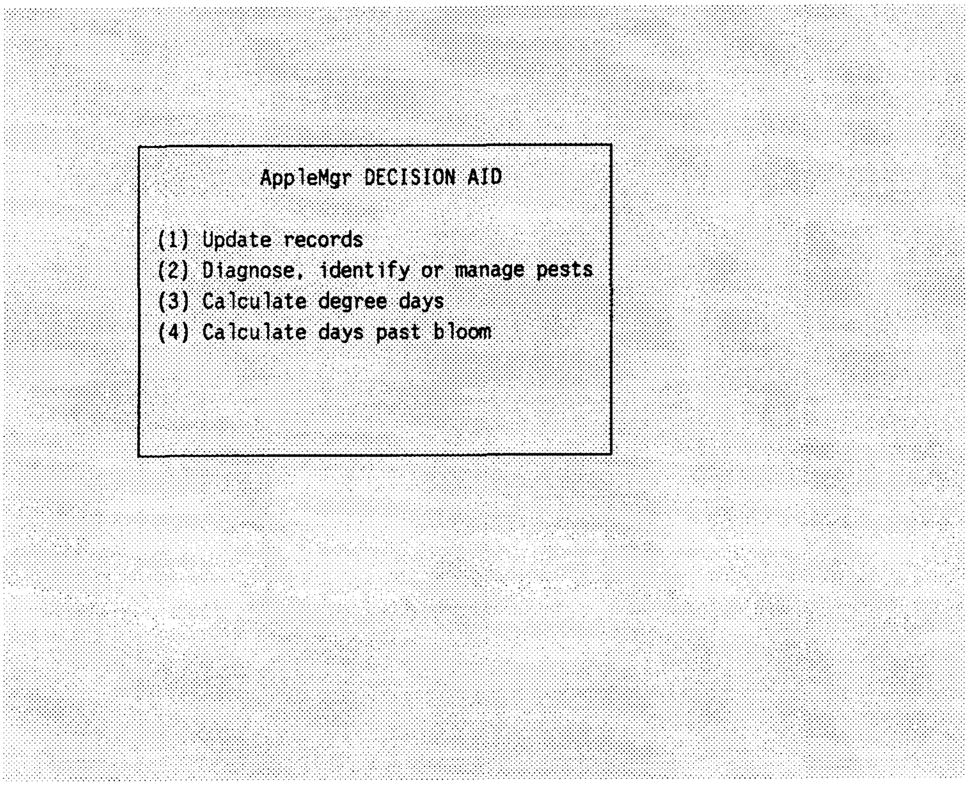
Risk of pesticide resistance is an increasingly important consideration in choosing a pesticide. The estimates shown in AppleMgr are based on historical data and the results of a modeling study on apple species (Tabashnik & Croft 1985). These estimates, like those for efficacy, will change as resistance evolves. Unexplained surprises sometimes occur as with the isolated appearance of codling moth resistance to Dimilin at one site in southern Oregon (Moffitt et al. 1988) and to Guthion at one site in central California (Varela & Welter 1990). The resistance risk estimates in AppleMgr provide important information not available in other pest management decision aids.

AN INTEGRATED SYSTEM

Example Session with AppleMgr

This section shows by means of an example interaction how the parts of AppleMgr discussed in the preceding chapters work together to approach pest management at a particular time of the growing season. Suppose that it is now June 9. We have just taken a crop sample at 35 days past bloom, checked the thermometer and codling moth traps in the orchard block, and taken a mite sample. We are concerned about codling moth and San Jose scale and want to check whether there are likely to be enough predatory mites to handle European red mite.

First we select (1) at the opening menu (Fig. 19) that appears when we type "apple" to run a DOS batch program. This key stroke leads by means of a second batch program to a menu that allows us to choose whether to update temperature records, insect and mite counts, packouts or crop samples. The system also contains default records that may be used to investigate hypothetical scenarios. All of the default records except for the crop sample contain data collected from orchards in the Pacific Northwest. Selections (3) and (4) on the opening menu allow us to run Dbase programs to calculate degree-days or days past bloom without entering the PC EASY shell. This saves time when only a simple calculation is needed to



AppleMgr DECISION AID

(1) Update records
(2) Diagnose, identify or manage pests
(3) Calculate degree days
(4) Calculate days past bloom

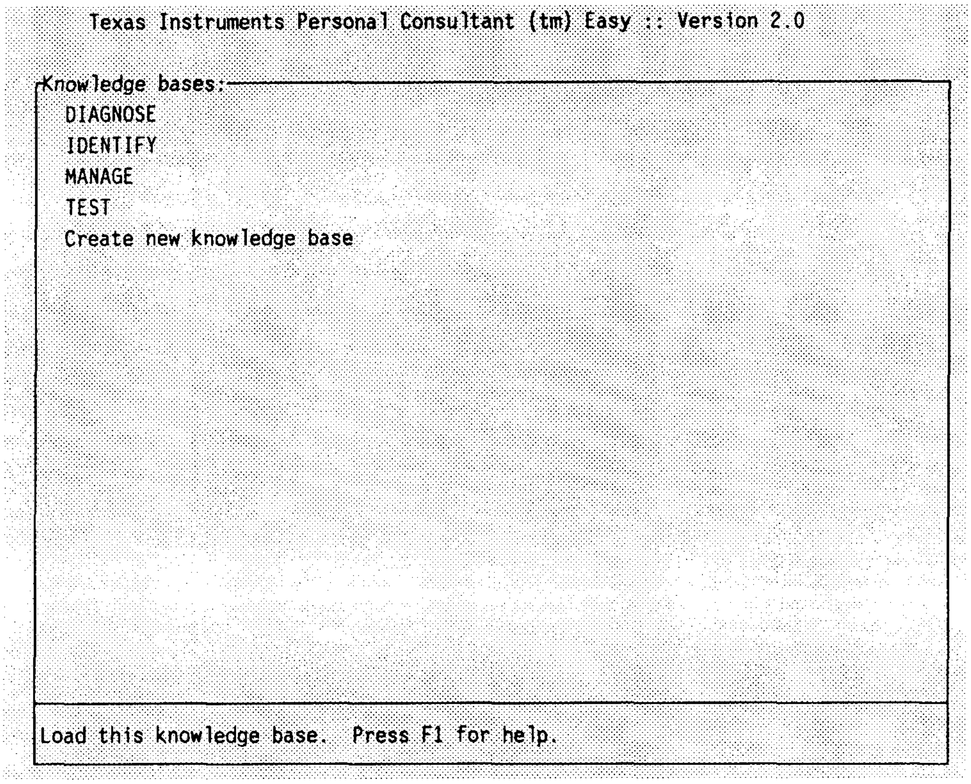
Fig. 19. Opening screen of AppleMgr

determine when to install codling moth traps or to take a crop sample.

After updating our records, we select (2) from the opening menu to load the PCEASY program and display a menu offering a selection of knowledge bases (Fig. 20). DIAGNOSE and IDENTIFY are the programs described in Chapter 3 that troubleshoot orchard problems and identify insect and mite specimens. MANAGE is the one we choose now. After selecting CONSULT at the Activities screen, we see two text screens that describe what the management module does and give the sources of models and expertise used. Then the program evaluates a parameter labeled as INITIALDATA. This designation causes the parameter to be always set first. It is set by running a Dbase program that asks for identifying information (Fig. 21) and stores it in a database for later use by calculation routines.

The MANAGE knowledge base (Fig. 22) has six goal parameters that are evaluated in order during a session. These are:

1) **Benefit_of_Insect_Control**
2) **Insecticide_Side_Effects**
3) **Probability_of_Biocontrol**
4) **Mitedays**
5) **Benefit-of_Mite_Control**
6) **Miticide_Side_Effects**



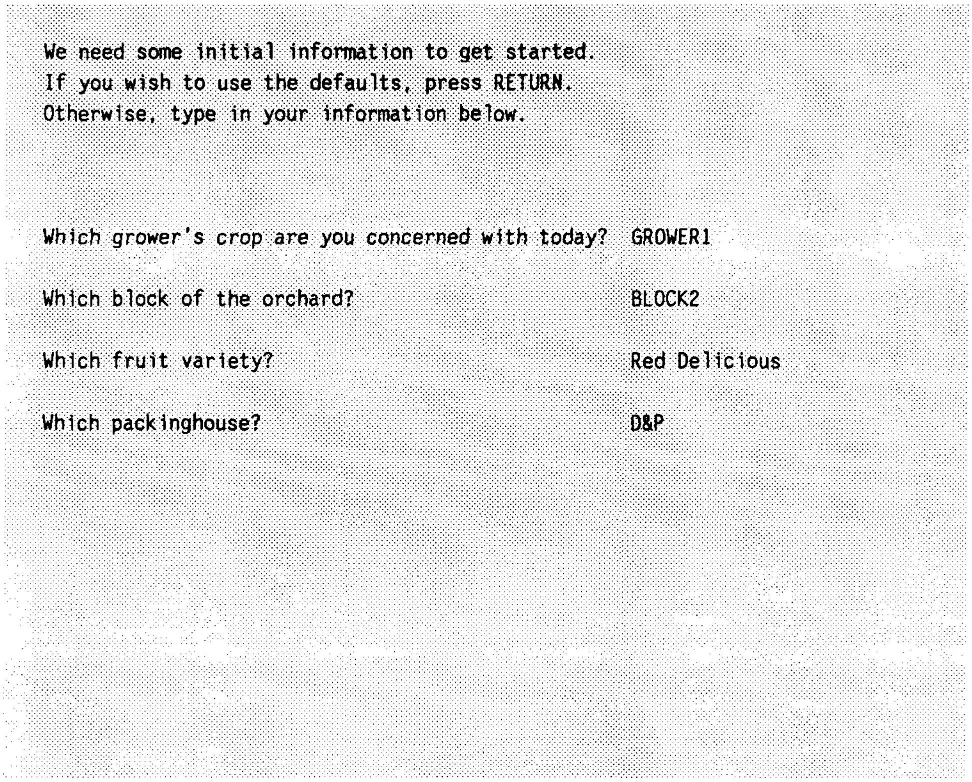
Texas Instruments Personal Consultant (tm) Easy :: Version 2.0

Knowledge bases:

DIAGNOSE
IDENTIFY
MANAGE
TEST
Create new knowledge base

Load this knowledge base. Press F1 for help.

Fig. 20. Knowledge base selection screen in AppleMgr



We need some initial information to get started.
If you wish to use the defaults, press RETURN.
Otherwise, type in your information below.

Which grower's crop are you concerned with today? GROWER1

Which block of the orchard? BLOCK2

Which fruit variety? Red Delicious

Which packinghouse? D&P

Fig. 21. Identity data entry screen of AppleMgr

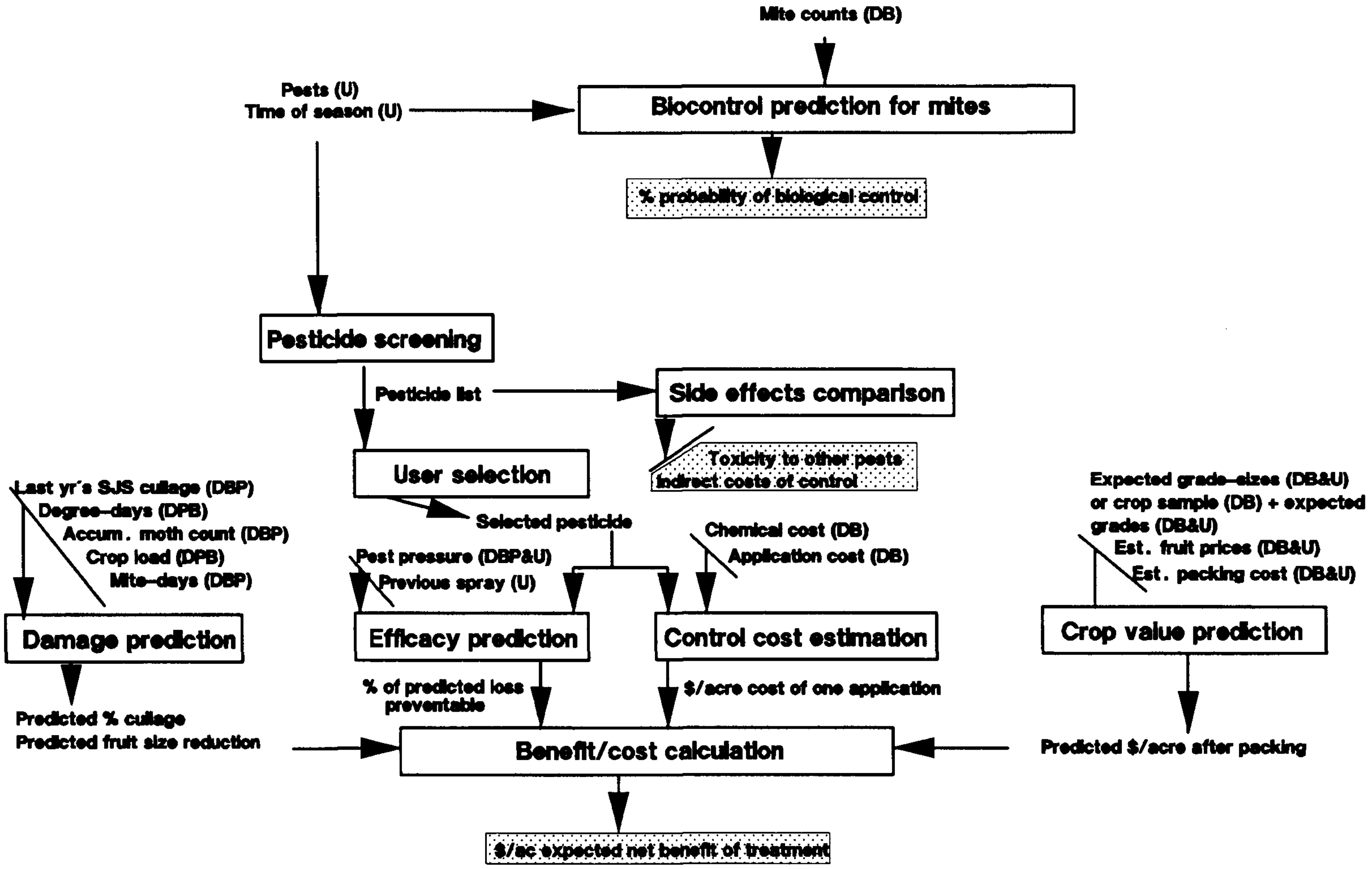


Fig. 22. Structure of AppleMgr management module. Shaded boxes represent results reported to the user. DB = database, DBP = database program, U = user.

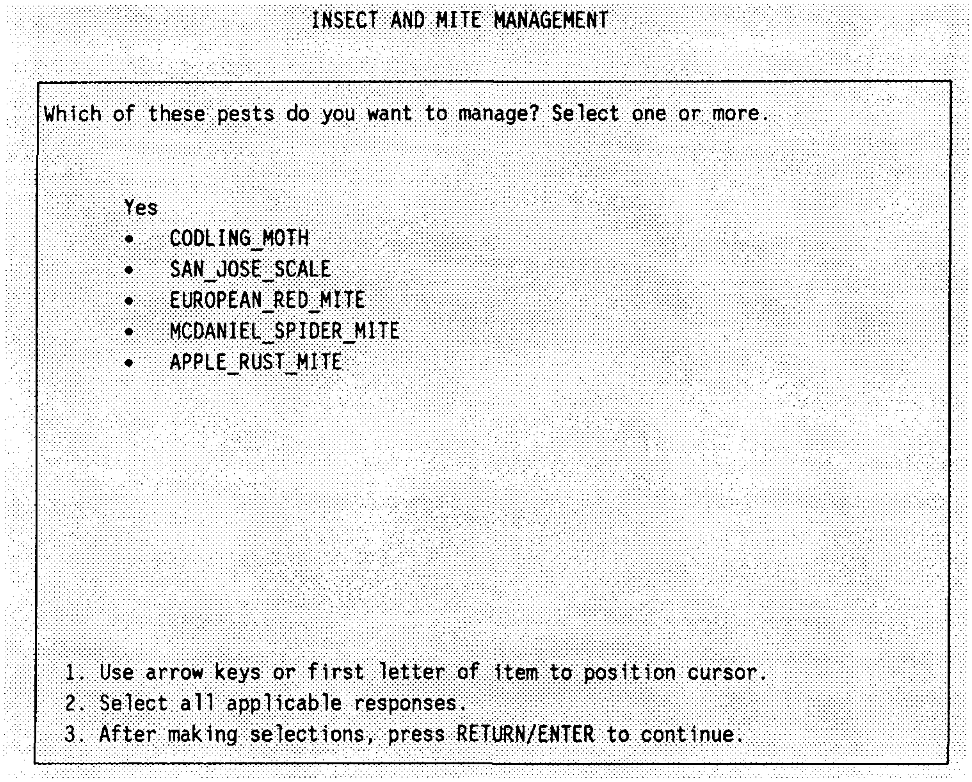
The first goal rules to be evaluated are those that set a value for **Benefit_of_Insect_Control.** The conclusions ("then" clauses) of these rules are of the form:

Benefit = **Predicted Loss** X **Efficacy** - **Control Cost.**

The rule premises ("if" clauses) force evaluation of the parameters **Pest**, **Time**, **Choice**, **Pest_Pressure**, and **Previous_Spray**. Therefore the next three screens that we see (Fig. 23-25) prompt us for choices that determine the course of the session. The pest screen allows up to five pests to be selected by moving the arrow keys to place highlights in the "Yes" column. The other two screens allow only a single choice. The pesticide list displayed depends on which pests and time were previously chosen. We select Codling_Moth, San_Jose_Scale and European_Red_Mite from the first menu and Postbloom from the second. Once we have made our choices for **Pest** and **Time**, only one rule remains whose premise has not failed.

Since we selected both codling moth and scale, the insecticide list we see contains insecticides suitable for both pests. This list is extracted from a database by a Dbase-Retrieve function (Texas Instruments 1986) associated with the choice parameter for codling moth and scale. We select Lorsban since that is what we used last year. Our selection is put into another database by means of a second Dbase external access function.

Evaluation of pest pressure for codling moth requires determination of predicted percent codling moth cullage,



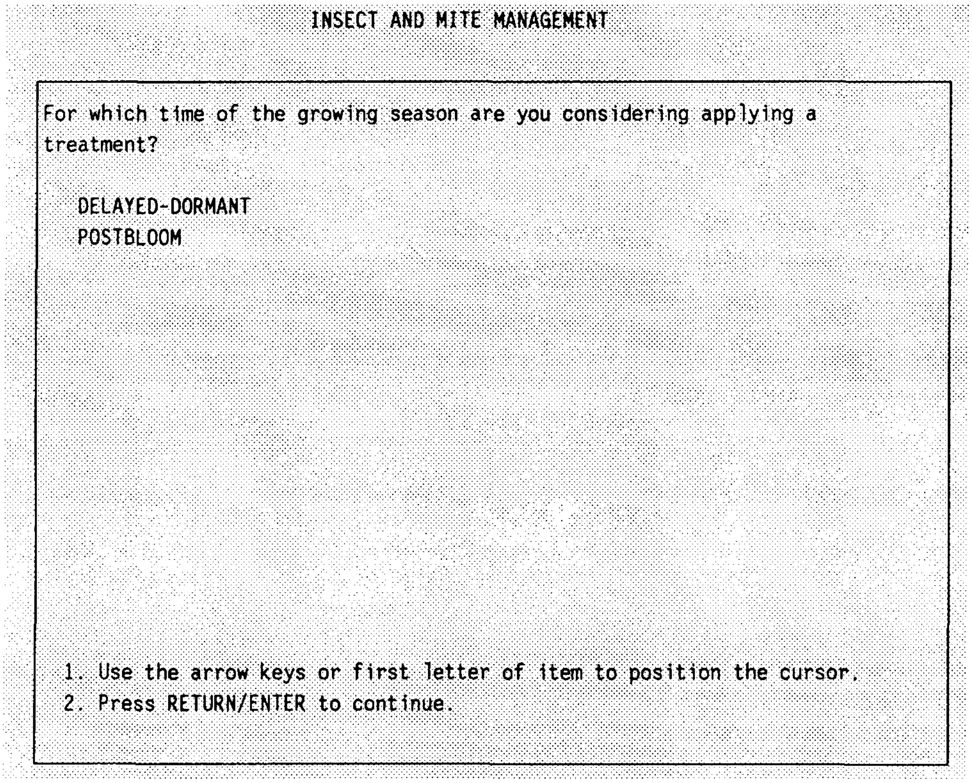
INSECT AND MITE MANAGEMENT

Which of these pests do you want to manage? Select one or more.

Yes
- CODLING_MOTH
- SAN_JOSE_SCALE
- EUROPEAN_RED_MITE
- MCDANIEL_SPIDER_MITE
- APPLE_RUST_MITE

1. Use arrow keys or first letter of item to position cursor.
2. Select all applicable responses.
3. After making selections, press RETURN/ENTER to continue.

Fig. 23. Pest selection screen of AppleMgr



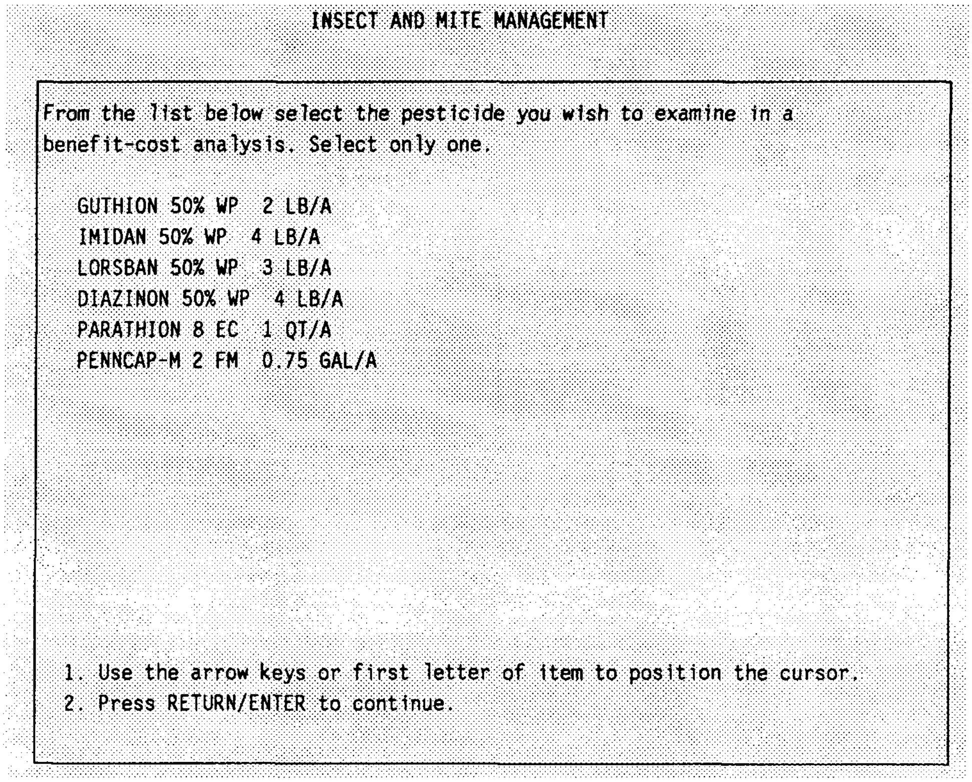
INSECT AND MITE MANAGEMENT

For which time of the growing season are you considering applying a treatment?

DELAYED-DORMANT
POSTBLOOM

1. Use the arrow keys or first letter of item to position the cursor.
2. Press RETURN/ENTER to continue.

Fig. 24. Time selection screen of AppleMgr



INSECT AND MITE MANAGEMENT

From the list below select the pesticide you wish to examine in a benefit-cost analysis. Select only one.

GUTHION 50% WP 2 LB/A
IMIDAN 50% WP 4 LB/A
LORSBAN 50% WP 3 LB/A
DIAZINON 50% WP 4 LB/A
PARATHION 8 EC 1 QT/A
PENNCAP-M 2 FM 0.75 GAL/A

1. Use the arrow keys or first letter of item to position the cursor.
2. Press RETURN/ENTER to continue.

Fig. 25. Pesticide selection screen of AppleMgr

which is set by means of a rule giving the Riedl and Croft (1974) regression equation. Since the equation requires values for the parameters **Degree_Days**, **Moths_Per_Trap** and **Apples_Per_Acre** (1-4, Fig. 14), these are now traced by external Dbase subroutines. Which program is run to find **Apples_Per_Acre** depends on the value of **Crop_Sample**, a yes/no parameter set by our reply to the question "Have you taken a crop sample . .?" (Chapter 4). We answer "Yes".

Evaluation of pest pressure for San Jose scale depends on the parameters **Old_Trees** and **Scale_Cullage_Last_Year.** A prompt screen now appears asking whether most of the fruit from this block comes from old trees with rough bark. We answer "Yes". We also know that the program tracing scale cullage last year (5, Fig. 14) will find that there was about 1% cullage. To set a value for **Previous_Spray**, a prompt screen appears to ask us which spray, if any, was applied for scale before bloom. We see a screen similar to the one in Fig. 25 showing a pesticide list retrieved from a database. We select a spray of oil alone before bloom.

The inference engine now proceeds to evaluate the parameters in the "then" clause of the goal rule. These are **Predicted_Loss_Due_to_CM**, **Predicted_Loss_Due_to_Scale**, efficacy parameters for codling moth and scale, **Predicted_%_CM_Cullage**, **Predicted_%_Scale_Cullage** and **Control_Cost**. **Predicted_Loss_Due_to_CM** depends on **Predicted_%_CM_Cullage**, which has already been evaluated, and **Predicted_Crop_Value**. Like **Apples_Per_Acre**,

Predicted_Crop_Value is evaluated by different Dbase routines depending on the value of **Crop_Sample** (Chapter 4). The efficacy values are retrieved by Dbase-Retrieve functions from a database. **Predicted_Loss_Due_to_Scale** is the product of **Predicted_Crop_Value**, already calculated, and **Predicted_%_Scale_Cullage**, which is a function of **Scale_Cullage_Last_Year**, already calculated. The final parameter, **Control_Cost**, is determined by a Dbase routine.

Having reached a value for the first goal parameter, the inference engine now proceeds to determine **Insecticide_Side_Effects.** This is a dummy parameter used to force firing of a DOS batch program to display two spreadsheets. Which batch program is run and which pesticide list is loaded into the spreadsheet depend on values of the parameters **Pest** and **Time.** First we see a spreadsheet showing the relative toxicity of Lorsban to four additional pests compared with the toxicities of other insecticides in the original list (Chapter 6). Then a second spreadsheet appears showing the relative side effects of this list of insecticides (Chapter 7). We note that Lorsban compares favorably with the other materials in efficacy against other pests except for green apple aphid but has a slightly higher resistance risk and toxicity to western predatory mite. We note the name of another insecticide such as Guthion that has lower ratings for resistance risk and toxicity to western predatory mite to examine next in a second run of the benefit-cost analysis.

To find a value for the third goal parameter, **Probability_of_Biocontrol**, the inference engine searches for rules whose premises set the parameter **Pest** to European_Red_Mite or McDaniel_Spider_Mite and the parameter **Time** to Postbloom. The values of the other two parameters in the rule premise, **Predator_Mites** and **European_Red_Mite** or **McDaniel_Spider_Mite** determine the goal parameter. Dbase programs are called by external access functions associated with the mite parameters to retrieve values from a database of mite count records. While these programs are running, we see messages such as "Finding average predator mites/leaf at latest count . . ." When a conclusion is reached, we see the message: "Probability of biocontrol is at least 90%."

The next goal parameter, **Mitedays**, is set by a rule whose premise requires **Pest** to be one of the three mite species and **Time** to be **Postbloom**. Since these conditions have been met, an external program is run to calculate mite-days from our stored mite counts. The result is read from a file and displayed to us in the message "650 mite-days have been accumulated to your latest count." This is followed by the interpretive statement given in Chapter 6.

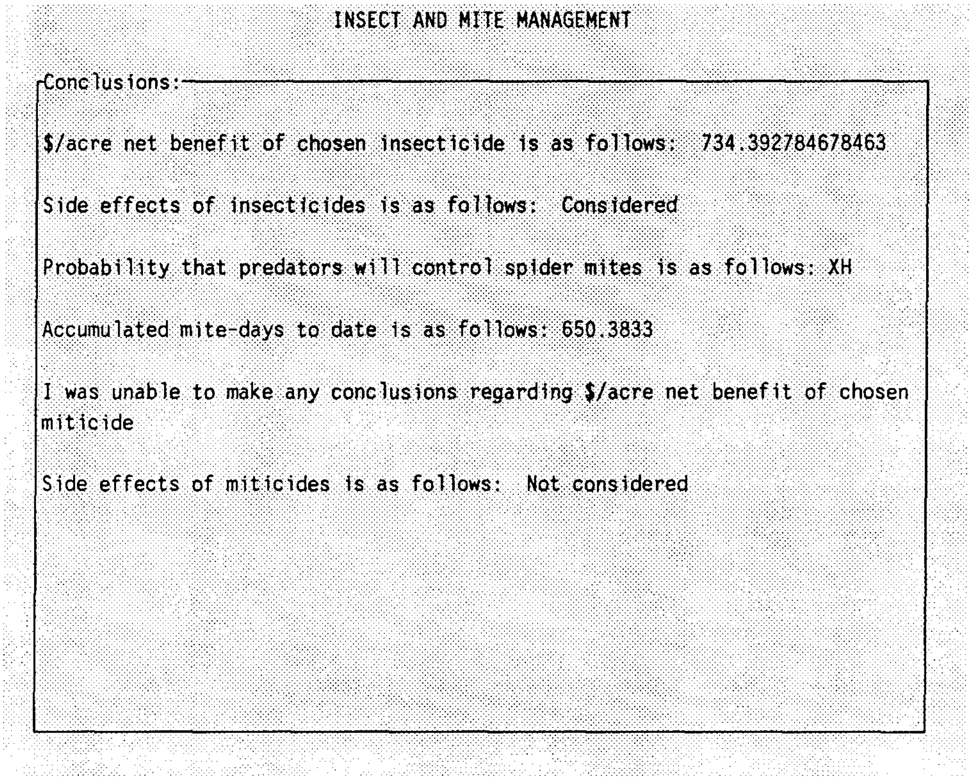
The three rules that set a value for the goal parameter **Benefit_of_Mite_Control** contain the parameters **Pest**, **Time**, **Choice**, **Low_Benefit** and **High_Benefit** in their premises. The low and high benefit parameters are evaluated by rules similar to those for determining

Benefit_of_Insect_Control. **High_Benefit** is calculated using the highest efficacy value for the mite species and miticide, and **Low_Benefit** using the lowest (Chapter 6). Predicted loss is calculated by a rule that takes the difference between **Predicted_Crop_Value** computed assuming no mite effect and crop value predicted with fruit size distribution shifted down one box size.

Since we have such a high probability of biological mite control, we select "NONE" when prompted to choose a miticide for evaluation. Therefore, we do not receive a message regarding the benefit of mite control. If we did select a miticide, we would see the message "Net benefit of mite control is predicted to range from" **Low_Benefit** "to" **High_Benefit** "depending on the level of mite resistance to" **Choice** "in this block."

Because we have not chosen a miticide, we answer "No" when asked whether we want to compare side effects of miticides in evaluation of the last goal parameter. Like **Insecticide_Side_Effects**, **Miticide_Side_Effects** is a dummy parameter that triggers display of spreadsheets showing effects on additional pests and indirect costs (Table 6).

At the end of the session the shell program displays a Conclusions screen giving results for each of the goal parameters (Fig. 26). By pressing F2 and then selecting "Review": from a menu, we may see a listing of intermediate parameters and their values. At the "Review" screens we may indicate which parameter values we wish to change.



```
                    INSECT AND MITE MANAGEMENT

Conclusions:

$/acre net benefit of chosen insecticide is as follows:  734.392784678463

Side effects of insecticides is as follows:  Considered

Probability that predators will control spider mites is as follows: XH

Accumulated mite-days to date is as follows: 650.3833

I was unable to make any conclusions regarding $/acre net benefit of chosen
miticide

Side effects of miticides is as follows:  Not considered
```

Fig. 26. Conclusions screen of AppleMgr

This option provides a way to change the value of one parameter such as the pesticide selected or the age of trees and rerun the analysis quickly.

Software Evaluation

During the course of this project I worked with two student-written noninferencing shell programs, RECOG and EXE, and one commercial backward-chaining shell, PC EASY. Currans and I attempted to integrate commercial database management and spreadsheet software with the latter two shells. Currans (1988) discusses the user interface problems that result from this effort. PC EASY provides a number of external access functions to interact with Dbase. These functions can retrieve values directly from databases already constructed or constructed in running a program. By placing a Dbase access function in the method property (Texas Instruments 1986) of a parameter such as **Crop_Value**, a series of linked programs may be run to calculate a value and assign it directly to the parameter, or a value may be retrieved from a database. Unfortunately, each time one of these external access functions is used, the Dbase licence agreement appears on the screen and remains for several seconds unless the Return key is pressed immediately. This results in a disjointed user interface.

Researchers may tolerate these problems in a prototype, but users require an attractive interface in a released version (R. Kemp et al. 1988). Concern for consistency and ease of use led Drapek to design a new database management interface rather than use a commercial one to be combined with the PC EASY shell in an ES for filbert growers (Drapek et al., in press).

The group at Pennsylvania State University (Saunders et al. 1987, Rajotte et al. 1989) solved the problem of combining data storage with a commercial shell using an internal mechanism that apparently does not allow import or export of data files. Their ESs use the mouse and sliding scales for data entry, pull-down menus and access to help screens by clicking on a term to be explained. These aids help make an ES more interesting and easy to use.

Another aspect of the user interface is how a decision aid explains or justifies its decision process and conclusions to the user. I feel that this capability is essential to make a new decision aid credible to an orchard manager. The RECOG and EXE versions provide "why" functions that explain each step in the decision process. These functions allow supporting information and references to be supplied so that they are easily accessible but do not retard a session if not wanted (Appendix A). Most ES have neglected to adequately explain and justify their reasoning process in a humanlike way, leading to a sense of impotence on the part of the user (R. Kemp et al. 1988). The PC EASY shell provides no means for the domain expert to allow the user to ask "Why?".

Other considerations in using a commercial ES shell are the high cost of licensing and run-time agreements

(Drapek et al., in press) and the lack of access to the source code. As pointed out by Currans (1988) and by Hearn and Brook (1989), a knowledge engineer may distort the decision process of a domain expert by forcing it into forms easiest for computer implementation. This problem is even more acute with a commercial shell whose structure cannot be modified by designers of the ES. For example, both Drapek and I found that the forward-chaining Antecedent Rules in PC EASY did not work properly and had to be avoided in designing our systems. I agree with Hearn and Brook (1989) that "the computer professionals should not engineer our decision support systems." Their role is to supply software appropriate to the objectives and decision processes of the system designers.

Conclusions

AppleMgr provides rapid access to a great deal of information and expertise useful in making pest management decisions. The diagnostic and identification modules give nontechnical keys for determining the nature of common orchard pest problems and arthropods. The management module combines monitoring data and production records with simple models and expert estimates to produce predictions of insect and mite damage, crop value, efficacy of biological and chemical control, direct and indirect control costs, and the net benefit of a control tactic. Effort has been made to assemble the best available information and expertise.

The process of decision making in AppleMgr uses a short-range benefit-cost analysis of a single control application. This approach has the advantage of providing a damage estimate for direct pests that gives their combined effect on value of a particular crop, rather than giving only a spray recommendation triggered by a fixed threshold with an implicit but unstated assumption of crop value. However, once a postbloom application has been made, AppleMgr has no means of evaluating the impact of the spray on pest and predator populations or of predicting the need for additional control later in the season.

Through breaking down the control decision into its components, it is possible to identify the major sources of uncertainty in the benefit-cost equation. These are the predicted percentage loss of fruit grade or size from pest injury and the value of the crop. The great variations in crop value under current conditions of market volatility and high variability in yield due to the wide range of tree densities reveal the inadequacy of simple action thresholds of the sort commonly used (Whalon & Croft 1984, Table 1). There is clearly a need for local or regional models to predict the percentage reduction in fruit grade or size from pest complexes. The "almost total lack of soundly based economic thresholds" for apple pests identified by Hoyt & Burts (1974) still exists (Whalon & Croft 1984).

A limitation of the decision making scheme presented in AppleMgr is that it is a short-range tactical system based on the assumption that apples are grown by the most common commercial practices and that chemical control is the only tactic available when pests reach threatening levels. Changes in the design of an orchard planting to minimize pest problems or use of biological control techniques other than conservation of existing natural enemies are not considered. Another assumption is that pest control decisions are made at the level of individual orchard blocks. This may not be appropriate in the context of a cooperative regional pest management scheme such as a sterile insect release program.

AppleMgr is limited in scope to the narrow domain of integrated chemical control of two major direct insect pests and biological control of mites. Within this domain it has served to focus attention of some entomologists on the application of their research to insect and mite management in commercial orchards. Creation of an integrated ES or DSS for apple orchard management in the Northwest would require long-term cooperation among specialists from many fields with growers and extension workers. A valuable insight from efforts to put ES into the field is "a growing realization that the complex problems faced by growers go beyond the abilities of individual specialists" (Rajotte et al. 1989).

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APPENDICES

APPENDIX A: MCDANIEL MITE CHAPTER IN RECOG

```
frame name is /McDaniel mite/
frame file name is /apple.028/
frame type is e, number of experts is 0
number of questions is 3, number of rules is 5
frame number is 28

question 1
How many active McDaniel mites are found in your leaf sample?

why

answer 1
Average of less than 50 per leaf
answer 2
Average of over 50 per leaf
answer 3
Don't know or have no sample

question 2
What is the ratio of active McDaniel to predator mites in your leaf sample?

why

answer 1
50 or fewer McDaniel mites to 1 predator mite
answer 2
More than 50 McDaniel mites to 1 predator mite
answer 3
Don't know or have no sample
```

Appendix A continued

question 3
Are trees in this block growing poorly or suffering from inadequate irrigation?

why

answer 1
Yes
answer 2
No
answer 3
Don't know

rule # 1
rule type is s , rule orient is 1
expression
$2:1
rule is
McDaniel mite level is below the action threshold. Predator mites are very efficient in quickly destroying populations of McDaniel mites. Avoiding unnecessary summer miticides will help maintain long-term free biological mite control. If no predator mites are present and McDaniel mites are near threshold, resample in 1 week.
why
Action threshold is based on Madsen et al. (1975). See Hoyt (1969) for details on predator mite destruction of McDaniel mite. For dangers of excessive use of miticides, see 1986 Spray Guide for Tree Fruits in Eastern Washington, p. 21-24.

rule # 2
rule type is s , rule orient is 1
expression
$1:1 & $2:2 & $3:1
rule is
Heavily stressed trees suffering from nutrient deficiencies, winter or mechanical injury, lack of water, or inadequate thinning are less tolerant of mite injury than vigorous trees. If substantial leaf injury is occurring, we recommend a spray of Plictran or Vendex 50% WP at 1 lb. per acre if predators are present or 1.5 lb. per acre if no predators are present. Resample in 2 weeks. For good long-term fruit production and mite control, steps must be taken to improve tree vigor. Excessive use of miticides will eliminate predator mites and lead to resistance of McDaniel mite to miticides. If resistance is already a problem, we recommend introducing predator mites.
why
For effects of stress on tree tolerance to mites, see Hoyt et al. (1979). For details on miticide resistance and predator introduction, see 1986 Spray Guide for Tree Fruits in Eastern Washington, p. 21-24.

Appendix A continued

rule # 3
rule type is s , rule orient is 1
expression
`$1:2 & $2:2`
rule is
Predator mite numbers are considered to be too low to reduce McDaniel mites before economic damage to fruit quality or return bloom occurs unless trees are overly vigorous or carrying a very light crop load. We recommend a spray of Plictran or Vendex 50% WP at 1 lb. per acre if predators are present or 1.5 lb. per acre if no predators are present. Resample in 2 weeks. Excessive use of miticides will eliminate predator mites and lead to resistance of McDaniel mite to miticides. If resistance is already a problem, we recommend introducing predator mites.
why
Mite action thresholds are based on Downing (1974), Madsen et al. (1975), and Hoyt et al. (1979). For details on miticide resistance and predator introduction see 1986 Spray Guide for Tree Fruits in Eastern Washington, p. 21-24.

rule # 4
rule type is s , rule orient is 1
expression
`$1:1 & $2:2 & ($3:2 | $3:3)`
rule is
McDaniel mite level is below the action threshold. You may see some leaf injury, but fruit quality and return bloom will not be affected. Excessive use of miticides will eliminate predator mites and lead to resistance of McDaniel mite to miticides. If resistance is already a problem, we recommend introducing predator mites. Resample in 2 weeks to assess population trend and predator-McDaniel mite ratio. If McDaniel mite number is near the threshold, resample in 1 week.
why
Mite action thresholds are based on Downing (1974), Madsen et al. (1975), and Hoyt et al. (1979). For details on miticide resistance and predator introduction see 1986 Spray Guide for Tree Fruits in Eastern Washington, p. 21-24.

Appendix A continued

rule # 5
rule type is s , rule orient is 2
expression
$1:3 | $2:3
rule is

To sample for mites, take 1 sample of 50 leaves from the predominant variety and tree age in a block of up to 5 acres. In low density plantings collect 10 leaves from each of 5 trees, and in high density plantings collect 5 leaves from each of 10 trees. Trees should be preselected and marked so that repeated samples may be taken from the same quarter of each tree. Collect spur leaves from along the entire limb or limbs sampled. Place each 50-leaf sample in a paper bag and transport bags in an ice chest to a mite counting service.

why

Proper collection and handling of leaf samples is essential to obtain accurate mite counts. For more details see Downing and Arrand (1970) or EM 3886 (1974). If you are doing the mite counting yourself, see Morgan et al. (1955).

rule orient # 1
Threshold and control

rule orient # 2
Diagnosis or sampling

APPENDIX B: PESTICIDE NAMES

Trade name	Common name
Carzol	formetanate hydrochoride
Diazinon	diazinon
Dimilin	diflubenzuron
Guthion	azinphosmethyl
Imidan	phosmet
Lorsban	chlorpyrifos
Omite	propargite
Parathion	parathion
Penncap-M	encapsulated methyl parathion
Plictran	cyhexatin
Pydrin	fenvalerate
Vendex	fenbutatin-oxide
Zolone	phosalone