A Bayesian Simulation Approach for Estimating Value of Information:

An Application to Frost Forecasting

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The authors, of course, accept sole responsibility for the content of this document.

PREFACE

Any thrust into the unknown world is fraught with difficulties. So it is with this document. Nevertheless, farmers in the real world make decisions daily with less than perfect knowledge concerning outcomes. In recent years, a number of economists, both agricultural and general, have developed theories which attempt to better explain observed reality in the dynamic, continuous, and uncertain realm of the real world. This is an important and appropriate step away from neoclassical microeconomic theory which assumes the nonexistent utopia of perfect certainty.

Very few applied decision models, however, have incorporated modern decision theory in an attempt to (1) simulate reality and then (2) to empirically estimate economic benefits from information which seeks to improve expectations in an *ex ante* rather than *ex post* context. This empirical study is an effort toward better understanding complex forces which enter the decision process and toward measuring the economic expectations of those forces at the time decisions are made. Nearly all existing economic studies measure the consequence or result of decisions. While hindsight is always perfect, it often does little to aid decision makers in evaluating economic costs and benefits when decisions are made and resources committed.

Although empirical, this study is exploratory in nature. The model has yet to be validated by comparing predicted (model) with actual behavior. The study was confined to one information source used by orchardists in Jackson County, Oregon—nightly frost forecast. A wide variety of information sources need to be evaluated in terms of their expected benefits and costs. While this study was confined to within-year decisions, longer run time dimensions need to be evaluated to measure capital investment and farm expansion decisions within an *ex ante* context also.

Because of its exploratory nature, the study is intended primarily for agricultural economists with some secondary use expected for research horticulturalists, meteorologists, and other scientists concerned with weather effects in agriculture and use of information to improve decision making where weather uncertainty exists.

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ABSTRACT

The economic value of frost forecasts is estimated *ex ante* under various assumptions concerning prior information, accuracy of forecasts, and the shape of the orchard operator's utility functions. The frost protection decision process is simulated in the context of Bayesian decision making under uncertainty. The averaged seasonal values estimated per day per acre were $5.39 for frost forecasts provided by the U.S. Weather Service, $8.57 for perfect frost forecasts, $4.73 for profit maximizers, and $191.39 for completely ignorant decision makers. The methodology used has general application to determination of economic value of information under conditions of uncertainty.

Key words: Bayes, decision making, frost forecasts, information value, risk, uncertainty, weather.

SUMMARY AND CONCLUSIONS

Frost protection is a component of the management process for orchard production. The decisions made by Jackson County, Oregon, pear producers relative to frost protection have a direct and significant economic effect on pear production since, if the crop is lost to frost, the decisions pertinent to orchard production for the rest of the season have little if any effect on current production. Thus frost forecast information appears to have considerable economic value to orchardists. Yet, little effort has been expended to determine the economic value of the frost forecasting service provided on a nightly basis during the frost season from mid-March to mid-May by the U.S. Weather Service advisory. The intent of this study is to provide estimates of the economic value of frost forecast information. In so doing, the study also seeks to model and measure the effect of several variables which influence and condition the forecast value.

A computer simulation was developed to model the frost protection decision process. Components of the simulation include: (1) the nightly frost protection decision structure expressed in monetary terms using a Bayesian strategy, (2) the simulated nightly weather conditions, and (3) an accumulative accounting of the nightly values of the forecast throughout the frost season. The probability distributions were derived from historical weather records for Jackson County. Utility functions were obtained from eight commercial orchardists in Jackson County. Expected prices, expected yields, and costs required for the monetary payoff table also were obtained from the eight orchardists cooperating in the study. Washington State University research provided potential bud loss and resulting crop loss from frost.

The economic model used in the study involves a significant departure from that commonly used in nearly all economic studies which evaluate economic decisions *ex post* or after the fact. Hindsight is always perfect yet real world decisions must be made *ex ante* or before the fact when less than perfect knowledge is available. This study evaluates the role of frost information in that light.

To provide insight into the factors which influence the value of the forecast, a number of runs were made in which the value of the frost forecast is compared against the value of optimal action from each of four alternative assumptions. First, it was assumed that each orchardist is a maximizer of expected utility under the condition where he has no prior information whatever at the time of the nightly forecast. Second, each orchardist again is a maximizer of expected utility but uses the historical prior probability information on frosts in conjunction with the nightly frost forecast. Third, each orchardist is an expected utility maximizer, uses the historical prior probability information, and has available a perfect nightly frost forecast, i.e., the forecast has no error. The fourth assumption is that each orchardist is a profit maximizer and uses the historical prior probability information in conjunction with the nightly frost forecast. This final assumption implies that each orchardist maximizes expected income without regard to the riskiness or variability associated with that income, the assumption implied in budget and linear programming methodologies.

Fifteen runs were made on the model, representing 15 random frost seasons for each orchardist and for each of the four assumptions. The value of frost forecast from each run was added then divided by the number of acres in each orchard, the number of days in the season, and then by the 15 seasons to provide an averaged seasonal per day-per acre value for each orchardist.

The interactive forces treated explicitly by the model which influence the "value" of frost forecast information are:

1. Perceived accuracy of the forecast;

2. Availability and use of information, other than the forecast itself, which condition the value of the forecast;

3. Orchardist utility function;

4. Magnitude of monetary payoff potential;

5. Severity of actual frost season determined by: (a) time of frost occurrence within a season; (b) actual nightly temperature relative to critical bud temperature; and (c) number of critical frosts;

6. Interdependencies between daily frost decisions.

Model results are summarized in Table 1. They express the maximum value which each orchardist places on information under immediate or within-year conditions where only frost protection and harvest costs remain as decision costs.

Table 1. Incremental value of information, per day-per acre, which contributes to frost forecasts for eight orchardists, under an immediate or within-year condition

Orchardist	Risk strategy	Value of historical information only	Value of frost forecast above historical information	Value of frost forecast due to risk adversity component	Value of perfect forecast above existing forecast
		Dollars			
1	Taker	87.07	2.02	–1.03	2.02
2	Mixed	222.80	5.37	1.10	1.95
3	Averse	245.44	8.66	2.74	2.06
4	Mixed	263.79	4.89	–1.82	5.93
5	Averse	212.45	4.98	1.01	1.67
6	Mixed	48.68	0.74	– .76	2.52
7	Averse	167.09	11.21	5.47	3.03
8	Mixed	249.67	5.27	–1.39	5.24
	AVERAGE	186.00	5.39	.66	3.18

Column 1 of Table 1 shows the value of historical prior probability information available to an orchardist at the time a frost forecast is given. The averaged value across orchardists was $186 per day-per acre. This value accumulated over the 62-day frost season exceeds the expected value of the crop. This explains why no orchardist ignorant of historical prior probability data and daily direct use of observed weather behavior could stay in the pear production business. Consequently, it is evident that the economic value of the frost forecasts, shown in column 2, is conditional upon prior information used at the time the frost forecast information also is used. The values in column 2 represent the model's "best" estimate of the value of current frost forecasts in Jackson County, Oregon, provided that the only information, in addition to the forecast itself, is the historical prior probability data.

Column 3 focuses upon the extent to which orchardist attitude toward uncertainty, expressed as a risk adversity component, influences the value of the frost forecast. In the case of orchardist 1, the only risk taker, the average value was a –$1.03. Its implication is that the component of the frost forecast which reduces the variability of outcome, as opposed to generating higher expected gross margin, had a negative value to him. This is because considerable utility is achieved by undertaking risky ventures, particularly as the stakes increase. So, to orchardist 1, that component of the frost forecast which predicted a higher expected gross margin was of positive utility while that component which reduced variability of the outcome had a negative utility. The risk adversity component for orchardists 4, 6, and 8 also averaged out as negative, reflecting their risk-taking attitude in the high expected income ranges. For risk-averse orchardists 3, 5, and 7, both the expected income and risk adversity components of the frost forecast averaged out across frost seasons as a positive value and so the combined value of the forecasts were generally of higher positive value for them than the risk takers. Thus it cannot be concluded that nightly frost forecast information always has a positive value.

The values in column 4 represent the maximum amount that could be expended on improving the accuracy of U.S. Weather Service forecasting services and keep the users of the forecasts at the same level of utility as they would be with the existing service. This assumes the orchardists themselves would be paying for improvement in accuracy of the forecast. It is unlikely, however, that orchardists would bear the full cost of the improved service given that other segments of society would also use and benefit from frost forecasts. Since the result expresses only the benefit of a perfect forecast, cost considerations would need to be evaluated in determining whether the U.S. Weather Service could or should improve the predictability of existing forecasts.

Finally, it must be made explicit that the frost forecast values generated from this study reflect an immediate or within-year condition. A longer run time frame in which total production and capital costs are decision variables will generate lower values for frost forecast information than those shown in this study.

General conclusions from the study are that:

1. The value of the existing forecast is positive. For risk averters the major role of the forecast is in its ability to reduce income variability. For risk takers, the principal value of the forecast is in maintaining high expected income potential.

2. The value of the existing forecast generally is higher for risk averters than for risk takers because of the combined affect of reducing income variability and maintaining high expected income potential.

3. The severity of the frost season contributes to the value of the forecast. The value of the forecast is lower in mild than in severe seasons for risk averters. The value to risk takers is generally higher in mild than

in severe seasons, especially when crop loss potential is 50 percent or more near the end of the season.

4. The value of prior information, other than frost forecast, is very high and conditions the value of the forecast itself.

5. The value of a perfect forecast is positive.

INTRODUCTION

Orchard production in Jackson County, Oregon, can be highly vulnerable to weather effects, particularly from frost damage during a 60-day period of bud development and flowering in the spring. Frost damage varies considerably from year to year and economic assessment of annual crop loss and value of frost protection has not heretofore been undertaken. Some evidence of the yearly variability can be generated, however, by comparing known "bad" frost years such as 1970 with more "normal" years such as 1969. Jackson County pear production in 1969 was 83,000 tons, but in 1970 it was only 31,600 tons, a 61 percent reduction [21].

From mid-March to mid-May, nightly temperatures in Jackson County, Oregon, are likely to fall low enough to cause frost damage in pear orchards. The specific temperature below which frost damage will occur depends on a number of factors including the developmental stage of the crop [25]. Low temperatures are more damaging at open bloom and young fruit stages than at earlier stages, indicating that economics of frost control varies during the frost season.

One method used by Jackson County orchardists to protect against possible frost damage is diversification by orchard location which recognizes climatic differences due to elevation, air drainage, and wind within and between areas. This form of diversification is intended to reduce the potential hazard induced by one particular microclimate. For a specific microclimate three methods used to protect orchards from frost damage are overhead sprinklers, heaters, and wind machines.

With overhead sprinklers, the release of latent heat with freezing of water sprinkled onto the trees gives off some heat, thus providing protection for fruit buds as long as night temperatures do not get more than some 4 to 5 degrees fahrenheit lower than the critical temperature.[1] Sprinklers can warm fruit buds the necessary 4°F. at an estimated capital investment of about $500 per acre, using 1973 costs [15]. Sprinklers also are used during the growing season to provide supplemental irrigation, disseminate chemicals, and cool the trees.

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[1] The critical temperature is the temperature below which frost damage will occur. This temperature varies throughout the frost season as the buds mature.

Orchard heaters are the most common equipment used [14]. Several types are available with each having about the same protection capability of four to five degrees of protection when the standard of 35 heaters per acre is used. Jumbo Cone, Lazy Flame, Return Stack, and Pressurized Oil systems are common, with the latter two having lowest pollution ratings. Capital investment per acre using 35 units ranged from a low of $245 for the Lazy Flame to $550 for a Pressurized Oil system in 1973.

Wind machines are the third mechanical device used to protect orchards. Only a few orchardists currently use them. They work when there is an inversion layer of warmer air above, which can be pulled down by the machines and mixed with cooler air close to the ground. Wind machines are more effective when used in conjunction with orchard heaters than when used alone [1]. Capital investment in wind machines ranged from $500 to $600 per acre in 1973.

During the two-month frost season in Jackson County, daily temperature forecasts are given by the U.S. Weather Service to provide daily dew-point and nightly temperature predictions, along with a subjective prediction of whether or not frost protection will be needed that night [19]. The forecast is first issued at 4 p.m. over local radio and television networks. A revised forecast is given later in the evening. A telephone service is provided also, whereby the orchardist may call an unlisted Medford number for the latest forecast. He then evaluates the forecast and any other information which he may have, including personal observation, to determine whether or not to protect his orchards on any given night, and if so, to what extent.

Although frost protection is but one phase of an orchard management process, the decisions made relative to it can have a direct and significant economic effect on orchard production. If a crop is lost to frost, all other decisions relating to production that year are meaningless. Conversely, nightly frost protection is costly, so if the likelihood of frost damage is low on a given night, then savings can accrue by not protecting, providing of course that no frost occurs.

The daily decision of the orchardist starts with whether or not to adopt a method or system of protection. If not, the decision and action are synonymous, i.e., no investment in frost control facilities is made and frost protection is not initiated. If the decision is to protect, a series of secondary decisions are required. These include the type of control facilities in which to invest, when to initiate protection, for how long, and the number of protection units to use. To carry out the decision to protect on a given night requires activation of work crews to fire heaters and to monitor the system until the danger of frost damage is past. Factors in the decision process are stage of bud development, expected nightly forecast temperature, the stage of bud development and expected accuracy of the forecast to it, all dealing with the physical aspect of the riskiness or variability of potential fruit yield. Further, there is evidence that the orchardist's own feeling as to the forecast accuracy and his aversion to uncertainty of the remainder of the frost season influence the kind of risk strategy he selects [10]. In addition, it appears that risk strategies may also depend upon the orchardist's capital position, debt commitment, alternate income sources, risk philosophy, etc. [11].

STUDY OBJECTIVES

The purpose of this study is to analyze orchard management with special emphasis upon the role of frost protection. In so doing, certain physical and economic factors which appear to influence the uncertainty of orchard production will be treated explicitly. Specific objectives of the study are: (1) to evaluate the effect of frost control upon expected orchard yields and yield variability during the frost season, (2) to identify and measure effects of orchardist risk strategies upon the frost protection decision process and subsequent orchard production, and (3) to estimate the economic contribution of U.S. Weather Service frost forecasts to orchard incomes in Jackson County. Very limited economic research has been conducted to date on determining the value of weather information [4, 12, 23].

The study discusses first the development of the framework used to model and analyze frost protection in Jackson County. This is followed by a presentation of empirical results using a selected number of Jackson County pear orchards.

DYNAMICS OF FROST PROTECTION—A CONCEPTUALIZATION

Orchard production is a dynamic and continuous process over time. The impact of decisions and events at one moment can affect later decisions. The purpose of this section is to conceptualize the role of frost protection decisions within a dynamic economic setting to provide a basis for understanding and hence quantitatively evaluating importance of frost protection decisions.

From a decision making point of view, both income and costs are viewed in an *ex ante* or before the fact sense; thus both are viewed as expectations. Associated with these expectations is some level of variability or dispersion around the expected value, i.e., if an event were repeated many times, such as orchard production over many frost seasons, the long-run average yield would be the expected yield and dispersion of annual outcomes around the expected yield would represent the variability of expected yield.

On the income side of orchard production, both price and yield are variables, each with its own expected value and dispersion characteristics. Expected price and its variability are determined largely by forces beyond the control of the orchardist and perceived as variables of the market which involve the combined characteristics of consumer demand and producer supply within that market. Yield is partly within the control of the orchardist and partly a function of natural conditions, particularly weather. The most important adverse weather effect upon orchard production in Jackson County is frost. Disease, insects, and rainfall are important natural forces; they generally are controlled by irrigation, chemicals, and other orchard management practices so that their impact upon expected yield and its dispersion is minimal. While frost protection is used by orchardists, it has technical limitations which generally preclude increasing the nighttime temperature in orchards by more than 4 or 5 degrees fahrenheit.

Conceptually, the highest level of yield which can occur for a particular orchard without frost is the *maximum crop potential.* This is a function of the natural capability of the cropland, accumulated technology, and management practices. This may increase or decrease over time depending upon the maturity of an orchard, the level and nature of management employed, and adoption of new technology. Whether this technical ceiling is actually reached in a given year is determined by severity of that year's frost season, the orchardist's expectation of income, and his adversity to risk. Severity of frost combined with the technical limitations of particular protection equipment determine *actual crop potential.* This is equal to or less than maximum crop potential since it is possible for frost to be so severe that it exceeds the capability of frost protection equipment to raise orchard temperature above the critical temperature, in which case some crop loss occurs. Knowing this, an orchardist does not base yield expectations upon actual crop potential because he cannot predict perfectly the severity of a frost season. The best he can do is utilize experience and subjective judgment to predict an *expected yield* which reflects a long-run average expectation. Expected yield is unique to each orchardist since it represents an individualized expectation. The same condition is true with expected price since a number of factors may be used by individual orchardists in determining a long-run expected price. Combining expected price and expected yield results in an expected gross income. This represents the normal or usual gross income which can be expected over time. For a given year, the *actual* or *ex poste* gross income may be greater than, equal to, or less than the expected gross income.

Orchard costs, like prices and yield, when viewed *ex ante*, are expectations. While generally being more predictable on an annual basis than prices and yields, they too have dispersion characteristics. These are influenced by such forces as research and technology changes, inflation levels, political forces, world markets, etc. The stronger these forces are the more difficult it is to predict what cost changes will occur, particularly if the projection extends very far into the future. When this occurs, decisions favoring the short rather than the long run occur because of the high discounting for uncertainty which takes place with long-run decisions. This issue is extremely important for capital decisions affecting orchard replacement and machine, irrigation, and frost protection technology which is capital intensive.

Time is an important variable in dictating decision costs. For expository purposes, it is convenient to categorize decision costs for orchard production into:

1. Costs which influence immediate or within-year production.

2. Costs which influence a full (short-run) production year without changing the capital stock.

3. Costs which influence continued production over several production years, hence require replacement or acquisition of capital stock.

These costs are expressed graphically in Figure 1.

As orchardists in Jackson County face a frost season in early spring, their decisions regarding costs are limited to frost protection and harvest costs shown graphically in the lower left hand corner of Figure 1 as the two blocks identified with a 1. It was thought initially that a larger number of expenses would fit into this category. However, survey results showed this to be so only for harvesting expenses. Most of the annual cultural operations which include pruning and thinning; fertilization; irrigation; cultivation; and weed, pest, and disease control are conducted each year regardless of the consequences of that year's frost season. The implication is that trees must be taken care of each spring and summer after a frost season to assure production potential for subsequent years rather than the current year. Because cultural operation costs do not affect current year frost protection decisions, they are viewed in an economic sense as a fixed cost for the current year. The maximum amount which an orchardist will pay for variable production costs is expected gross income, shown as the upper horizontal line in Figure 1, since that is the income stream which the orchardist is attempting to capture. In economic jargon, this means that as long as variable costs are covered by the expected income and/or as long as the opportunity cost of one's capital is not higher elsewhere and risks are comparable, then the variable costs will be increased.

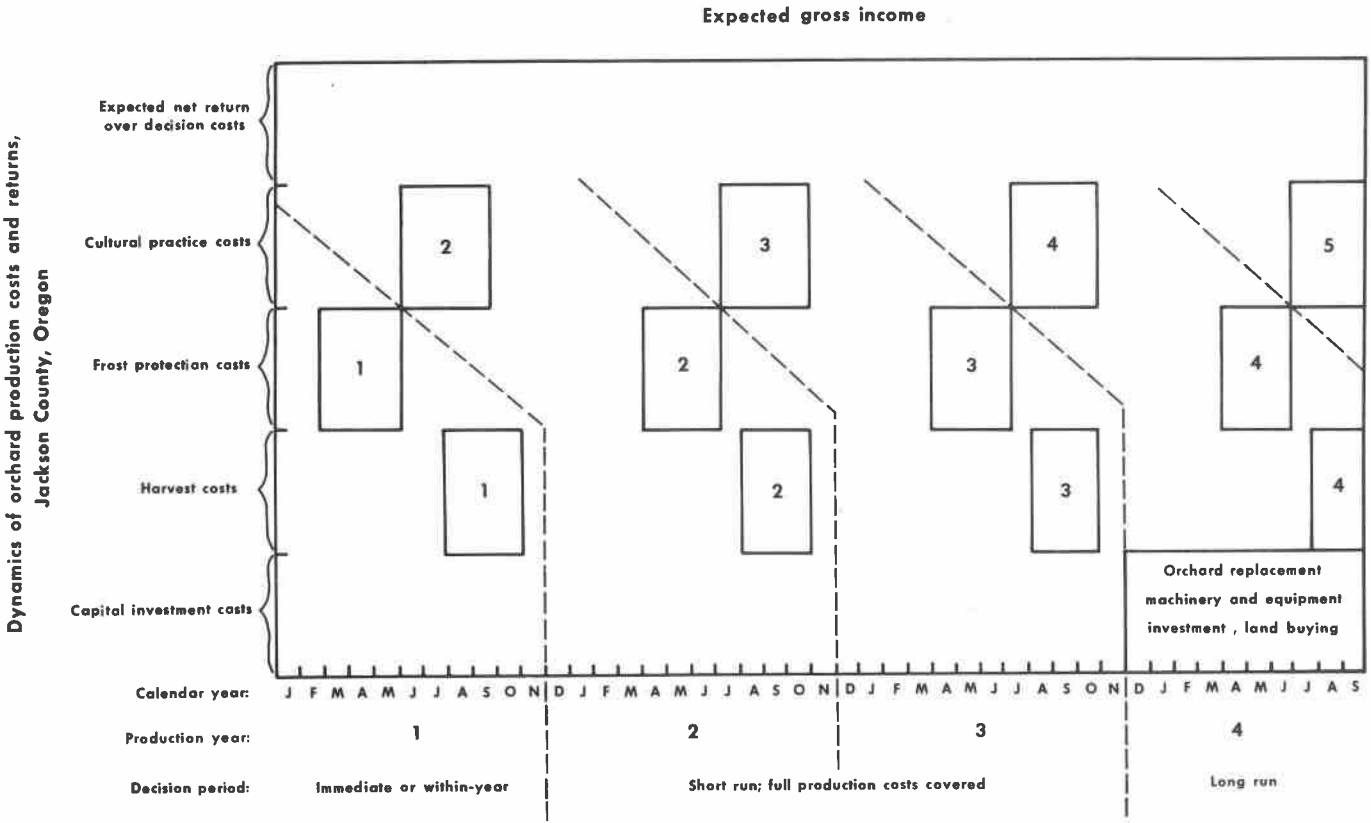

Figure 1. Composition of orchard decision costs by time period.

Once the frost season has occurred, the dimension of decision costs change markedly since the orchardist has entered a new production year within which the crop will be harvested in the next calendar year. Now the costs associated with late spring and summer cultural practices of pruning and thinning, cultivation, irrigation, spraying, and next spring's frost protection and subsequent harvest costs become the relevant decision costs since all of these costs will influence subsequent year crop yield and they may be increased or decreased at the discretion of the orchardist. These costs are shown as the three blocks identified with a 2 in Figure 1. The sum of these decision costs is higher than those associated with the immediate or within-year decision case since they include cultural practice costs. Consequently, the expected net return above decision cost (expected gross income – relevant decision costs) for an entire production year is less than that expected for the immediate or within-year case with the difference being the magnitude of cultural practice costs. The net result, as far as the value of frost protection information is concerned, is lower for the short-run (complete production season) than for the immediate (frost season) period since more variable costs must be covered to assure continued production. Using the same analogy, it is clear that the value of frost protection information is even less in the long run since capital costs must be covered in addition to immediate and short-run costs. This case is shown graphically at the far right portion of Figure 1 and identified as blocks 4 and 5.

For purposes of this research, the conceptual time period is confined to the within-year framework in which only frost protection and harvest costs remain as current year variable costs. The cultural practice costs influencing within-year production are viewed as fixed costs since they are incurred the previous calendar year and cannot be modified to affect or change within-year production at the beginning of a frost season.

THE BAYESIAN MODEL OF FROST PROTECTION DECISIONS

A Bayesian decision framework is used to model and evaluate frost protection at the orchardist level in Jackson County [2, 4, 5, 8, 9, 10, 17]. The process includes (1) modeling of a nightly frost protection decision structure in monetary terms, (2) simulating the actual nightly weather condition, and (3) an accumulative accounting of the value of each nightly forecast throughout the frost season for a selected set of orchardists.

Figure 2 presents a flow diagram of the Bayesian model developed for the frost protection problem in Jackson County, indicating how the information used by the model is evaluated. In the flow diagram the squares

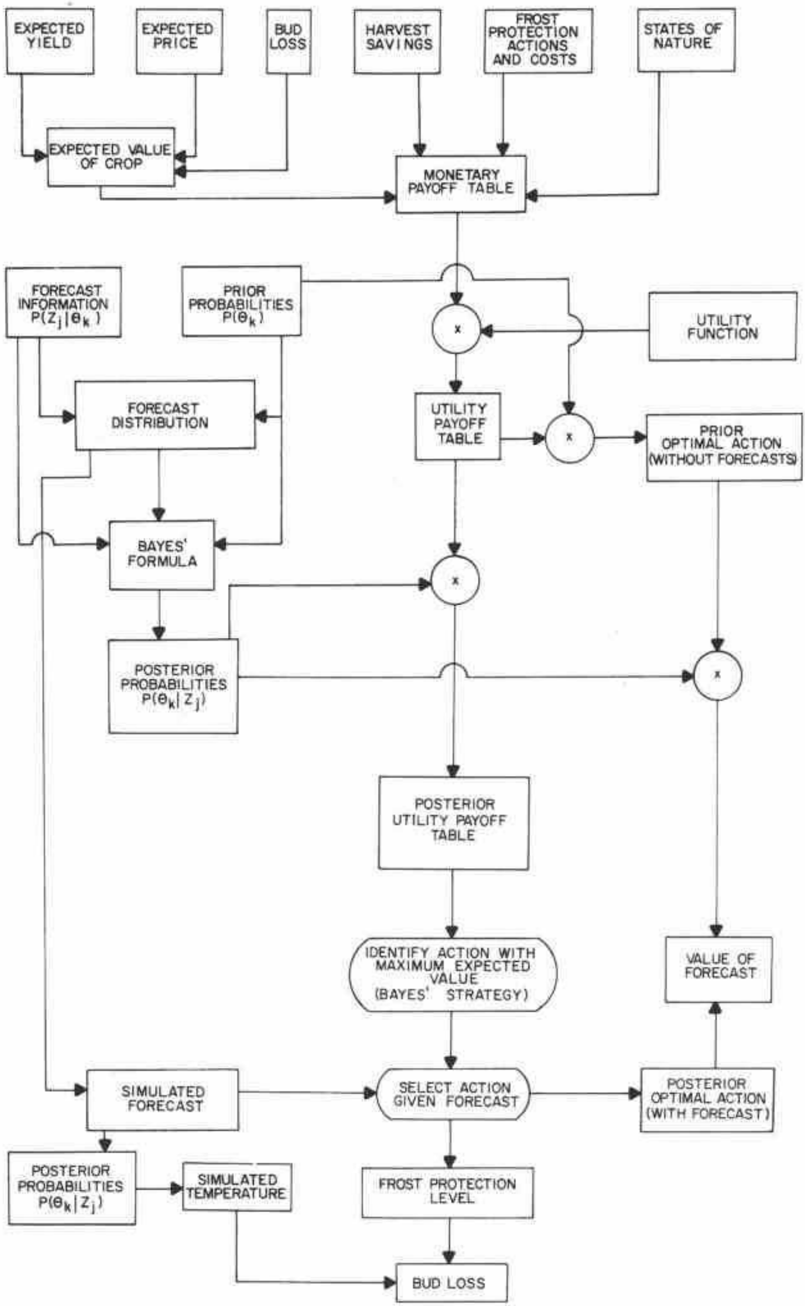

Figure 2. Flow diagram of simulation model used in the valuation of frost forecast information.

represent components of the model and the circles represent calculations made by the model. The three major components are: (1) the nightly frost protection decision process including the monetary payoff table, (2) the nightly weather condition, and (3) the cumulative accounting of the nightly values of each frost forecast for the duration of the frost season. The frost protection decision covers the center of the diagram from the monetary payoff table, and its associated components at the top of the diagram, to the frost protection level. The weather conditions include the eight squares on the left side of the diagram. The three squares on the right side of the diagram, exclusive of the utility function square, embody the cumulative accounting process.

Monetary Payoff Choices

The expected payoff of the pear crop for a given night is a function of (1) expected price, (2) expected yield, (3) nightly crop loss potential, (4) nightly protection cost, and (5) harvest cost reduction. These five elements are combined to calculate a monetary payoff table. The monetary payoff table represents expected payoff for all possible combinations of the 15 states of nature and the three action choices for orchardists in Jackson County for any given night [2, 10, 13, 16]. The action choices are: (1) light no heaters, (2) light one-half of the heaters, (3) light all heaters. The 15 states of nature correspond to the temperatures from 21°F to 35°F. Consequently, the nightly payoff table is a 3 by 16 array unique to each orchardist and to each night during the 62-day frost season. Each element of the array is calculated as:

Expected payoff = [expected gross return per acre for the current crop
-- the value of crop loss – the cost of protection
+ harvest cost reduction] × orchard acres.

The initial expected gross return faced by each orchardist at the beginning of the frost season is presented in Table 3.[2] Expected price and expected yield are combined in that table to obtain expected gross return. Crop loss potential is derived from Table 2 and Figures 3 and 4. Nightly protection cost comes from Table 4. Harvest cost reduction is derived from crop loss in Figure 5 and full harvest costs shown in Table 5.

[2] Monetary payoff choices and orchardist utility functions are calculated on a total orchard rather than per acre basis. This must be done because the marginal utility of a dollar of gain changes with the size of the gain. Hence, the number of acres and the gains per acre determine where the decision maker is on his utility function which in turn affects his choice.

Nightly Frost Protection Decision

The estimated utility function for each orchardist presented in equation form in Table 6 and in graphic form in Figure 6 is used to convert the monetary payoff choices to utility payoff choices. This 3 x 16 array table is then multiplied by the predictive capability of actual frost forecasts (posterior probabilities) to give the utility value for each of the three frost protection actions given the forecast (posterior utility payoff choices). From this posterior utility table, the optimal action for each forecast is selected. The optimal action is that action having the highest utility value for that forecast. The optimization process is carried out using the following criteria [2, 3, 8, 24]:

$$U(A_{ij}) = \underset{i}{\text{Max}}\ U(A_i|Z_j)$$

$$= \underset{i\ \ k}{\text{Max}}[\Sigma U(a_k)P(\Theta_k|Z_j)]$$

where

- $U(A_{ij})$ is the utility value of the optimal action,
- A_i is the set of alternative actions, $i = 1, \ldots, m$,
- Z_j is the set of forecasts, $j = 1, \ldots, n$,
- $U(a_k)$ is the utility of the dollar payoff from an action for each state of nature k, and
- $P(\Theta_k|Z_j)$ is the posterior probability of a state Θ_k and a forecast Z_j, $k = 1, \ldots, 16$, $j = 1, \ldots, 16$.

Selecting the optimal action for each forecast is called the Bayes strategy, named for the mathematician who pioneered probability theory. After the forecast is given, the Bayes strategy is taken which provides a single action to follow. The nightly weather component model then randomly generates the actual nightly temperature. The action taken and the actual nightly temperature determine the actual bud loss for that night. To simulate actual conditions, the nightly frost protection decision is repeated sequentially 62 times to represent each night of the 62-day frost season. The process is iterative with each nightly decision influenced by what has transpired on previous nights which determines existing crop potential. The existing crop potential on any day of the frost season, the utility function of the orchardist, and the nightly frost forecast and its costs then determine what specific frost protection action will be taken.

Actual Nightly Weather Conditions

Actual nightly weather conditions involve the actual weather forecast and the actual nighttime temperature. Both are simulated as a component of the computerized Bayesian model. The actual nightly forecast service, provided by the U.S. Weather Service meteorologist stationed in Jackson County during the frost season, is simulated by random selection of a forecast temperature from the conditional probability distribution of Table 8. The actual low nighttime temperature is simulated by random selection of a temperature from the posterior probability distribution in Table 9 for a given season and frost forecast. Both processes in the model assume independence between temperatures selected and actual temperatures which occurred on previous nights. A review of probability coefficients on the diagonal in Table 8 indicates that the independence assumption is not violated.

Value of Each Nightly Frost Forecast

The third component of the Bayesian model is an accounting process which determines and accumulates the value of the frost forecast each night during the frost season. This value is determined by comparing the expected utility of the optimal action using the forecast against the expected utility of the optimal action from each of four alternative assumptions for an orchardist: (1) availability only of historical nighttime temperature information, (2) availability of a perfect nightly frost forecast service, (3) no prior information available whatever on spring frosts, and (4) maximization of expected income rather than expected utility.

Comparing the frost forecast against having only historical nighttime temperature data measures the incremental value of the frost information assuming that the only two information sources are the historical nighttime temperatures and the frost forecast.[3] The comparison of each optimal action, one with and the other without the forecast, is done in an *ex ante* context. That is, the evaluation is made before the nighttime temperature actually occurs, hence measures the usefulness of the additional information in reducing the uncertainty of making an incorrect decision to protect or not protect. The value of each nightly forecast is accumulated to determine the value of the frost forecast service for the entire frost season. The monetary value of the forecast is the maximum amount of money the orchardist could give up and remain as well off with the forecast as he would have been with just the historical temperature information. The

[3] Independent daily observations by the orchardist involving cloud cover, temperature on the previous night, local wind conditions, etc., provide information to aid the nightly decision, and hence influence the value of the forecast. Because this information is not accounted for explicitly in the model, some overstating of the value of the forecast for that portion actually due to the independent daily observations occurs. The magnitude of this overstating is not known.

computational procedure followed by the Bayesian model to achieve this involves determination of the monetary value which, when subtracted from each cell of the dollar payoff table and converted to utility, yields the same expected utility to an orchardist as did the optimal action with no forecast. The process is repeated for each of the eight orchardists.

Comparing the value of the frost forecast with a perfect frost forecast measures the utility to the orchardists of nightly forecasts that are 100 percent accurate in their prediction. This measures the value to the orchardist of achieving a state of perfect knowledge concerning frost. The condition of perfect knowledge is achieved by modifying the conditional probability table (Table 8) of the model such that there are only 1's in the diagonal.

Comparing the value of the forecast with a state where no information whatever is available concerning frost simulates comparison with a state of perfect ignorance. In this case equal probabilities are attached to each outcome (state of nature). This comparison measures the value of information, other than the nightly forecast, used in determination of nightly frost protection decisions. This includes the collective value of historical temperature information, agronomic knowledge of frost susceptibility, orchardist expertise on ability to interpret daily cloud cover, temperature on the previous night, local wind conditions, etc., as well as any other information which provides capability for improving a nightly frost protection decision beyond that when no information is available. The condition of perfect ignorance is modeled by modifying the historical probability table $P(\Theta_k)$ (Table 7) to a uniform distribution where equal probability is attached to each of the 16 nighttime temperatures.

The fourth and final comparison involves comparing the expected utility of the optimal action using the forecast against the expected utility for risk-neutral orchardists. This case assumes profit maximization without regard to risk adversity of the decision maker. This is achieved by using risk-neutral (linear) utility functions for each orchardist. The comparison measures the value of frost information attributable to the level of risk adversity of each orchardist.

EMPIRICAL ANALYSIS OF FROST PROTECTION DECISION MAKING

In 1972, some 11,500 acres of pears were grown on 100 farms in Jackson County. Approximately 10,350 acres (90%) were frost protected by heaters, sprinklers, or wind machines. Some 9,800 acres (94%) of the protected acres used orchard heaters, leaving 550 acres protected by some other means. The 9,800 acres protected were controlled by 36 commercial orchardists.[4] Because of the overwhelming dominance of orchard heaters as the mechanical device used for frost protection, this study confined its scope to heaters as the protection source. No comparative analysis of mechanical protection systems was made.[5]

Physical and economic data were obtained from 26 of the 36 commercial orchardists. Interviews were conducted in two stages. In the first stage, professional interviewers were used to obtain physical and economic data concerning frost protection on individual orchards. In the second stage, the authors interviewed orchardists to obtain individual attitudes toward uncertainty. Usable information for the second stage was obtained from eight orchardists who control 5,060 acres of pears in Jackson County. Because the Bayesian model is orchard specific, the empirical analysis is confined to the 5,060 acres of Jackson County pears produced by eight orchardists rather than the full 11,500 acres.

Potential Crop Loss From Frost

From mid-March to mid-May, the nightly temperatures in Jackson County, Oregon, may fall low enough to cause frost damage in pear orchards. The specific temperature below which frost damage will occur depends upon several factors, including the development stage of the buds or blossoms.[6] Research done at Washington State University indicates that the blossoms progress through eight stages: (1) Scales separating; (2) blossom buds exposed; (3) tight cluster; (4) first white; (5) full white; (6) first bloom; (7) full bloom; and (8) post bloom.

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[4] A commercial orchardist is defined to be an orchardist who derives his primary source of income from his orchard operation. County Extension agents estimated that 25 acres of orchards would be needed to fit this classification.

[5] It is recognized that the method of protection influences the kind of decisions, e.g., with overhead sprinklers one man turns a valve, but with heating a whole crew is needed. The cash cost penalty for a wrong decision is greater in the latter case but the capital investment also is much less.

[6] Dewpoint influences the rate at which nightly temperature falls. It is the temperature below which moisture held in suspension in the air condenses in the form of dew or frost. For each gram of water condensed as dew, 540 calories of heat are released to the trees and environment providing minimal protection against frost. Meteorologists generally agree that the temperature decline rate attributable to dewpoint is far more important than its heat dissipaton role. Many research horticulturalists view dewpoint as the single most important datum in the late afternoon weather report for deciding if frost will occur that night. However, there is no unanimity among orchardists in Jackson County as to the specific role which dewpoint plays in modifying critical temperature levels. Because it is the responsibility of orchardists rather than research horticulturalists to make nightly frost protection decisions, the dewpoint variable was not included in the model.

Associated with each stage is a different critical temperature below which frost damage may occur [25]. The blossom stages are more susceptible to frost damage than are the early bud stages. So while the riskiness of nightly frost potential diminishes as a season advances toward summer, the susceptibility of pear trees to frost damage increases. For example, a temperature of 15°F. will result in a 90 percent kill in Stage 3, while the same percentage kill will occur at 24°F. in Stage 8, demonstrating the increased sensitivity of trees to frost damage as they advance through bud, blossom, and fruit formation. The lower an actual nightly temperature drops below the critical temperature level, the more severe will be frost damage to an orchard at any stage of development.

The temperature-bud kill relationship used in the study is a linear approximation of research findings from Washington State University. Those research findings are presented in tabular form in Table 2. Because no temperature below 21°F. has ever been recorded in Jackson County during its frost season, this study uses only Stages 3 through 8. Furthermore, at 21°F., no frost damage will occur when the fruit is in Stages 1 and

Table 2. Estimated percentage of buds killed at varying temperature levels for eight stages of bud development

Temperature (°F.)	Stages of development[a, b]							
	1	2	3	4	5	6	7	8
11	30	62	100	100	100	100	100	100
12	27	57	100	100	100	100	100	100
13	20	50	100	100	100	100	100	100
14	15	45	100	100	100	100	100	100
15	10	40	90	100	100	100	100	100
16	5	34	80	100	100	100	100	100
17	0	27	70	100	100	100	100	100
18	0	22	60	100	100	100	100	100
19	0	17	52	90	100	100	100	100
20	0	10	45	75	100	100	100	100
21	0	0	35	65	100	100	100	100
22	0	0	25	52	90	100	100	100
23	0	0	15	40	75	90	100	100
24	0	0	10	25	50	75	90	90
25	0	0	0	10	30	55	70	70
26	0	0	0	0	10	30	50	50
27	0	0	0	0	0	10	30	30
28	0	0	0	0	0	0	10	10
29 & over	0	0	0	0	0	0	0	0

SOURCE: Washington State University, *Pears—Critical Temperatures for Blossom Buds*, Washington State University Research and Extension Center, Prosser.

[a] Stages of bud development and corresponding average dates: 1 = scales separating; 2 = blossom buds exposed; 3 = tight cluster, March 14-19; 4 = first white, March 20-24; 5 = full white, March 25-30; 6 = first bloom, March 31-April 4; 7 = full bloom, April 5-11; and 8 = post bloom, April 12-May 13.

[b] Data base used in the simulation model lies within the rectangle located in the lower right hand corner of the table.

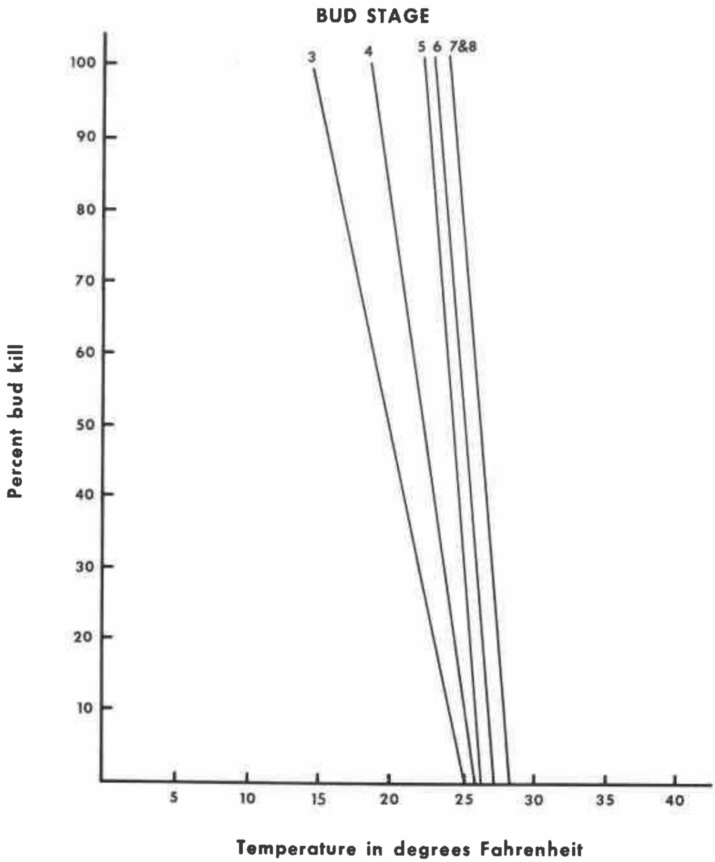

Figure 3. Estimated relationship between temperature and bud kill for stages of bud development (Jackson County, Oregon).

Source: Washington State University, *Pears—Critical Temperature for Blossom Buds,* WSU Research and Extension Center, Prosser.

2. The estimated relationship between temperature and bud kill for the revelant six stages of bud development for Jackson County is presented in Figure 3.

The relationship between bud loss and crop loss is critical in the determination of dollar losses from frost damage in pear orchards. The 26 orchardists interviewed indicated that a full crop can be obtained with as much as a 50 percent bud loss.[7] From this information, a linear relation-

[7] Horticultural research indicates that with a full bloom density an 8 to 10 percent fruit set produces a full crop. This is a much lower fruit set than specified by the 26 orchardists. The difference could perhaps reflect an overt risk aversion strategy by orchardists.

ship between bud loss and crop loss was estimated, with crop losses occurring only with bud losses of greater than 50 percent. The relationship is expressed in graphic and algebraic form in Figure 4.

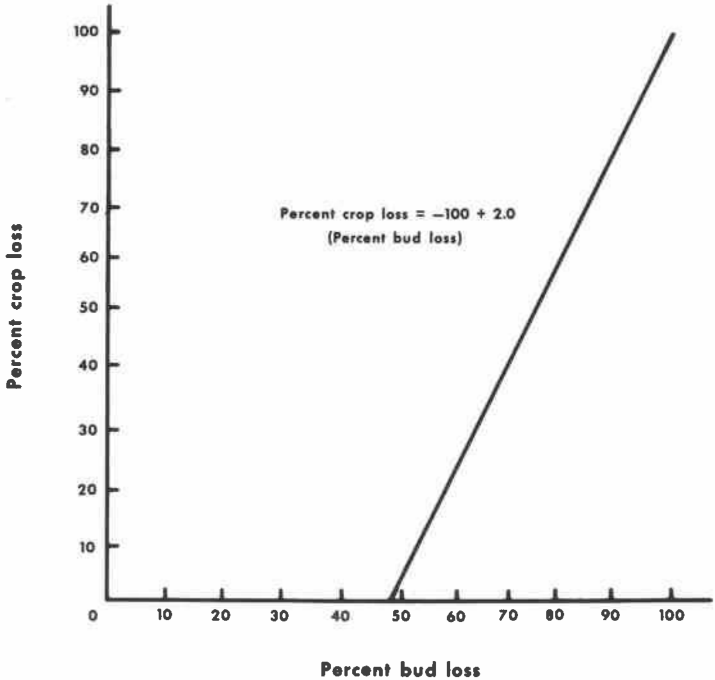

Figure 4. Estimated relationship between bud loss and percent crop loss for pears grown in Jackson County, Oregon.

Potential Economic Value of Crop Saved

Interviews with orchardists indicated that frost protection is thought of in terms of crop saved rather than crop lost. Since no crop exists at the beginning of a frost season, it is *expected* crop yield potential which is perceived in the mind of the orchardist. The *actual* crop yield which develops during the frost season is an *ex post* situation. The portion of a crop actually saved by frost protection is then a gain. An upper limit upon actual production potential is dictated by the technical capability of frost protection to hold orchard temperatures above the nightly critical temperature. Frost protection and resulting production then is a dynamic relationship which develops throughout the frost season and corresponds with the stages of bud and fruit development. Hence, frost protection is an attempt to generate a high production potential at the end of the frost season with minimal costs required to do so.

Expected Gross Returns

Price and yield expectations were obtained from each of the eight orchardists in the study by personal interview. Expected price represents for each orchardist his own best subjective judgment, made prior to the frost season, of the selling price he expects to receive for his crop in the fall after harvest. The expected yield for an orchardist represents his expectation of his orchard's normal yield subsequent to the frost season and using "normal" protection practices. In the course of the interview process, conducted in the early spring of 1973 prior to the frost season, it became apparent that obtaining expected price and yield information directly would be very difficult.

An alternative was selected which involved using historical price and yield averages for each orchardist in recent years. The procedure assumes that, at the beginning of the frost season, the average price and average yield obtained in recent years by the orchardist is his own best estimate of expected price and yield for the current year.

Expected gross returns represent expected price times expected yield. Calculation of expected gross return for each orchardist recognizes the typical production of both Bartletts and winter pears on each farm. Winter pears consist mainly of Anjou, Bosc, and Comice varieties. Jackson County Extension records indicate that, historically, 60.5 percent of the acreage are Bartletts, while 39.5 percent are winter pears [21]. Expected gross return calculations for each of the eight orchardists in the study explicitly weighted the proportion of Bartlett to winter pears using that ratio.[8]

Expected gross returns per acre represent the maximum attainable value of expected production as perceived by each orchardist at the beginning of the frost season. It is from this value that all measures of crop loss are derived and from which the benefits of frost protection information are evaluated by the model. The expected gross returns per acre for each of the eight orchardists are presented in Table 3.

Value of Crop Loss

Each grower goes into the frost season with his assumed expectation of gross return, as discussed in the previous section. As the possibility for a frost occurs, this income potential could change. That is, the possibility exists for crop yield to be lower or higher than the expected yield in actuality. Whether the actual yield turns out to be lower or higher than

[8] To the extent that the proportion of Bartlett to winter pears is used as a strategy against price and yield uncertainty by orchardists, the use of Jackson County averages may bias calculation of frost forecast values. The direction and extent of this bias is not known.

Table 3. Expected price, yield, and gross returns per acre by orchardist

Orchardist	Orchardist expectations: Yield (T/A) Bartlett	Winter	Weighted average[a]	Price ($/T) Bartlett	Winter	Expected gross return ($/acre)[a]
1	11.35	7.76	9.9	66.00	102.67	768
2	11.35	9.08	10.4	112.20	135.96	1258
3	10.50	10.82	10.6	112.20	164.01	1414
4	6.80	9.08	7.7	176.00	242.00	1592
5	7.14	7.01	7.1	193.96	207.39	1409
6	3.40	3.27	3.3	132.00	157.67	475
7	10.95	11.52	11.2	112.20	135.96	1362
8	11.36	10.34	11.0	132.00	161.33	1566

[a] Weighted by historical acreage distribution of 60.5 percent Bartletts and 39.5 percent winter pears in Jackson County.

the expected yield is a function of crop loss. The exact amount of crop loss is a function of bud loss, which in turn is a function of the stage of bud development and the actual nightly temperature. The crop loss-bud loss relationship was discussed in the previous section.

The dollar value of the crop loss is calculated nightly during the frost season as the percentage crop loss from the expected yield for a given minimum nightly temperature attained in the orchard times the expected gross return per acre. Actual crop yield at harvest time often is different from the orchardist's expected yield. This is normal since expected yield is simply a long-run average yield expectation. A probability distribution surrounds that average, and hence, actual yields can be less than, equal to, or greater than the average. In the case of the model, expected yield is used as the ceiling or maximum attainable yield from which all physical crop loss is calculated.[9] Value of crop loss measures any economic loss from the maximum attainable of expected gross return shown in Table 3.

Frost Protection Capability and Costs

Maximum protection capability is achieved using 20 to 45 orchard heaters per acre. The wide variation in heater numbers is determined primarily by unique geographical factors influencing frost hazard on each orchard site. Slope, existence of low spots, and air ventilation are the principal concerns. When all heaters are fired, nighttime temperatures

[9] Because expected or *ex ante* yield is used in the Bayesian model rather than actual or *ex post* yield, some underestimation of the true value of frost information may occur. This may be offset to an unknown degree in the model which uses single valued coefficients instead of distributions for expected yield and expected price.

can be raised some 4 to 5 degrees while lighting one-half of the heaters can raise temperatures 2 to 3 degrees.

The decision of when to fire the heaters is more complex. This decision is influenced by how fast the temperature is dropping, which in turn is a function of dewpoint and possible cloud cover development. In Jackson County, most of the orchardists employ high school boys to light their heaters. Because it takes considerable time to light individual heaters, lighting must commence well in advance of the expected time of the critical temperature.[10]

Interviews with the 26 orchardists, as well as with the county agents, indicated that three protection actions are common with orchardists using heaters. They are: (1) light no heaters; (2) light one-half of total heaters available; and (3) light all heaters available.

While the cost of oil heating varies widely between orchardists, fuel and labor are the major cost components. The costs for each of the three actions with each of the eight orchardists evaluated in the study is summarized in Table 4. The average number of oil heaters used in Jackson County is 34, for a cost of just less than $50/acre/night when all heaters are lit and the heaters are fired for an average of five hours per night. Full protection offered by firing all heaters for a five-hour period ranged from $22 to $73 per acre per night. The wide variation in nightly heating cost between orchardists is due primarily to differences between orchardists in (1) number of heaters per acre, (2) fuel cost, and (3) labor cost. The number of heaters per acre, ranging from a low of 22 to a high of 40, was the major variable.

It is assumed in this study that full protection will increase orchard temperatures five degrees while half protection will raise temperatures three degrees.

Harvest Cost Reduction

The case of harvesting expenses was found to be dependent on the size of the crop. Most of the pears in Jackson County are picked by migrant labor. These migrant laborers are paid on a piece rate per box. In heavy frost damage years, the price paid per box often increases in order to attract laborers whose seasonal earning potential is much higher in other fruit-producing regions known to have good production. In spite of higher labor costs, the total harvesting costs per acre may decline as there are fewer boxes per acre to be picked. Based on the survey results of

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[10] A number of fruit areas in the U.S. have gone to central supply systems for orchard heaters in which the cost of lighting and refilling is only a fraction of the hand operation. Considerably higher capital investment is required with this system, however.

Table 4. Nightly oil heating cost by orchardist, 1973 costs

Orchardist	Heater cost/hour ($)					Full protection		Nightly cost/acre		
	Fuel	Labor	Repair	Other	Total	Number heaters per acre	Number hours per night	Light all heaters	Light half of heaters[a]	Light no heaters
1	.168	.084	.028	......	.28	35	5	$49.00	$24.50	0
2	.132	.044	.022	.022	.22	25	5	27.50	13.75	0
3	.140	.26	......	......	.40	35	5	70.00	35.00	0
4	.337	.03	.008	......	.375	40	5	75.00	37.50	0
5	.15	.05	......	......	.20	22	5	22.00	11.00	0
6	.165	.075	.052	......	.292	35	5	51.15	25.58	0
7	.21	.045	.04	......	.50	22	5	55.00	27.50	0
8	.375	.085	.04	......	.50	22	5	55.00	27.50	0
AVERAGE[b]	.181	.078	.024	......	.283	33.8	5	47.81	23.91	0

[a] Hand lighting of heaters requires a labor crew to go through an entire orchard regardless of the number of heaters fired. Consequently, it is plausible that lighting only half of the heaters results in nightly costs somewhat greater than half of that when all heaters are fired. This study assumes lighting of half the heaters results in halving nightly costs relative to lighting all heaters.

[b] Average of the 23 orchardists which provided heater cost data; 19 used standard oil units and 4 used pressurized oil units.

the 26 growers, it was determined that for crop losses up to 84 percent, harvesting expenses would not be reduced. For crop losses greater than 84 percent, harvesting expenses are reduced. For a crop loss of 100 percent, no harvesting expenses are incurred. These provide two end points from which a linear relationship between crop loss and harvest cost reductions was estimated for use in the study and shown graphically in Figure 5.

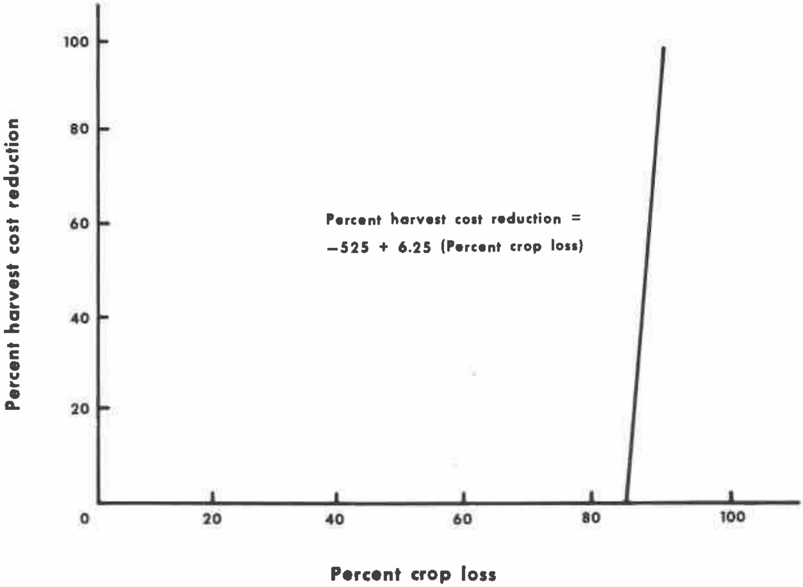

Figure 5. Relationship between crop loss and harvest cost reduction.

The value of the harvest cost reduction is determined as a percentage of full harvest expense. Full harvest expenses were obtained from each of the eight orchardists and reported in Table 5.

Harvest costs were reported initially on a per box basis, then converted to a per ton cost which in turn was converted to cost based on grower yields. Lug box cost was converted to a per ton cost using 45 pounds per box as the standard conversion. Cost per ton was converted to cost per acre with each orchardist using the Jackson County acreage proportion of 60.5 and 39.5 percent Bartlett and winter pears respectively. A harvest cost average of $182 per acre was derived from 17 of the 26 growers sampled who provided harvest cost information. The $182 average was used with three of the eight orchardists in the study who did not report harvest costs. Note in Table 5 that a wide range, from $10 to almost $30 per ton, existed in harvest costs reported on a per ton basis.

Table 5. Full harvest cost per acre by orchardist

Orchardist	Weighted expected yield[a] (tons)	Harvest cost/ton ($)	Full harvest cost/acre[b] ($)
1	9.9	10.10	93
2	10.4	17.20	180
3	10.6	17.10	182
4	7.7	23.60	182
5	7.1	17.20	122
6	3.3	29.80	100
7	11.2	17.30	182
8	11.0	17.50	192

[a] Obtained from Table 3.
[b] Calculated using weighted expected yield.

Orchardist Attitude Toward Risk

A quantitative estimate of orchardist attitude toward risky outcomes, in this case pear production from frost protection, was obtained from the eight orchardists in the study. Each represents an individualized utility function which measures the trade-off between uncertain outcomes at varying income levels, and the variability associated with those outcomes. The authors used a gaming device, called the Ramsey Method, to obtain utility functions in personal interviews with each of the eight orchardists [2, 4, 7, 8, 10, 13, 18, 20, 22]. The Ramsey Method was used repeatedly to determine, over a range of possible expected income levels, the orchardist's attitude toward trade-offs between uncertain outcomes having equal likelihood of occurrence but different ranges of payoff potential. The game was played sequentially four to six times. In providing simplicity, only two states of nature, one with frost and the other without, and two courses of action, protection and nonprotection, were used. Each of the four outcomes in the 2 x 2 matrix is expressed in terms of return over cash expenses for the entire orchard. For each orchardist, the game format was as follows:

	Action	
States of nature	Not protect	Protect
Frost	a	c
No-frost	b	d

Where probability of either weather outcome = .5 and
a = 0
b = return over cash expenses
c is varied
d = 3/4 b

After the game is played at least twice, an ordinal value of the trade-off between expected income and variance of that income is determined and expressed as a utility value for the entire orchard. Playing the game four to six times provides additional data points in deriving an orchardist's utility function. A number of algebraic forms were fitted to the data points. The mathematical forms providing the best statistical fit were used in the model and are presented in Table 6. A graphic presentation of the equations is made in Figure 6 showing the utility of income curve for each of the eight orchardists within an income range of $0 to $900,000. The fitted utility functions showed five orchardists with cubic and three with quadratic equations. Risk adversity depends upon the sign of the second term in a quadratic utility function. If it is less than zero, risk adversity is indicated as is the case with orchardists 3, 5, and 7. This is shown graphically in Figure 6 as the three curves which increase at a decreasing rate throughout. For higher order polynomials, such as a cubic, risk adversity may change with the level of expected income. Orchardist 1 was the only complete risk taker. This is shown graphically as the function which increases at an increasing rate throughout. Orchardists 2, 4, 6, and 8 had mixed risk strategies, represented by cubic functions for which risk adversity changed with the level of expected income. Orchardists 2 and 8 expressed risk aversion from $0 to about $150,000, then risk taking above that. Orchardists 4 and 6 expressed risk aversion from $0 to about $300,000, then risk taking beyond $300,000.

Nightly Weather Conditions During Frost Season

Historical Nightly Temperatures

Frost season temperatures have been recorded at a number of unheated survey station orchards in Jackson County since 1957 [19]. These stations are widely distributed throughout Jackson County and have changed periodically as heating was added or ownership changed [14]. The particular survey station which records temperatures most similar to the majority of orchards in the county is deemed "the average orchard." In recent years, the Beddoe Orchard on Camp Baker Road, about one-half mile south of Phoenix, has been given that designation. Temperatures for the 16-year period, from 1957 through 1972, used in

Table 6. Algebraic form of the utility function used in the model for each orchardist

Orchardist	Utility functions[a]							R^2
1	U(X)	=	$1.637(10^{-3})X$	−	$104.96(10^{-10})X^2$	+	$7.5708(10^{-14})X^3$	.999
			(3.90)		(−1.19)		(1.68)	
2	U(X)	=	$2.4214(10^{-3})X$	−	$147.23(10^{-10})X^2$	+	$3.5388(10^{-14})X^3$	.996
			(6.25)		(−2.88)		(2.20)	
3	U(X)	=	$.12458(10^{-3})X$	−	$.2058(10^{-10})X^2$			.927
			(2.31)		(−1.12)			
4	U(X)	=	$1.1537(10^{-3})X$	−	$29.894(10^{-10})X^2$	+	$.26484(10^{-11})X^3$	.996
			(7.34)		(−3.81)		(3.00)	
5	U(X)	=	$.19532(10^{-3})X$	−	$.4734(10^{-10})X^2$			.887
			(2.18)		(−1.17)			
6	U(X)	=	$1.0288(10^{-3})X$	−	$36.848(10^{-10})X^2$	+	$.44852(10^{-11})X^3$	.999
			(11.78)		(−7.38)		(6.95)	
7	U(X)	=	$.67724(10^{-3})X$	−	$4.3948(10^{-10})X^2$			.889
			(1.24)		(−.969)			
8	U(X)	=	$2.0519(10^{-3})X$	−	$147.2(10^{-10})X^2$	+	$4.7009(10^{-14})X^3$	.993
			(3.54)		(−1.51)		(1.29)	

[a] The numbers in parentheses are the t-values for the coefficients; U(X) = utility of expected net return over cash expenses.

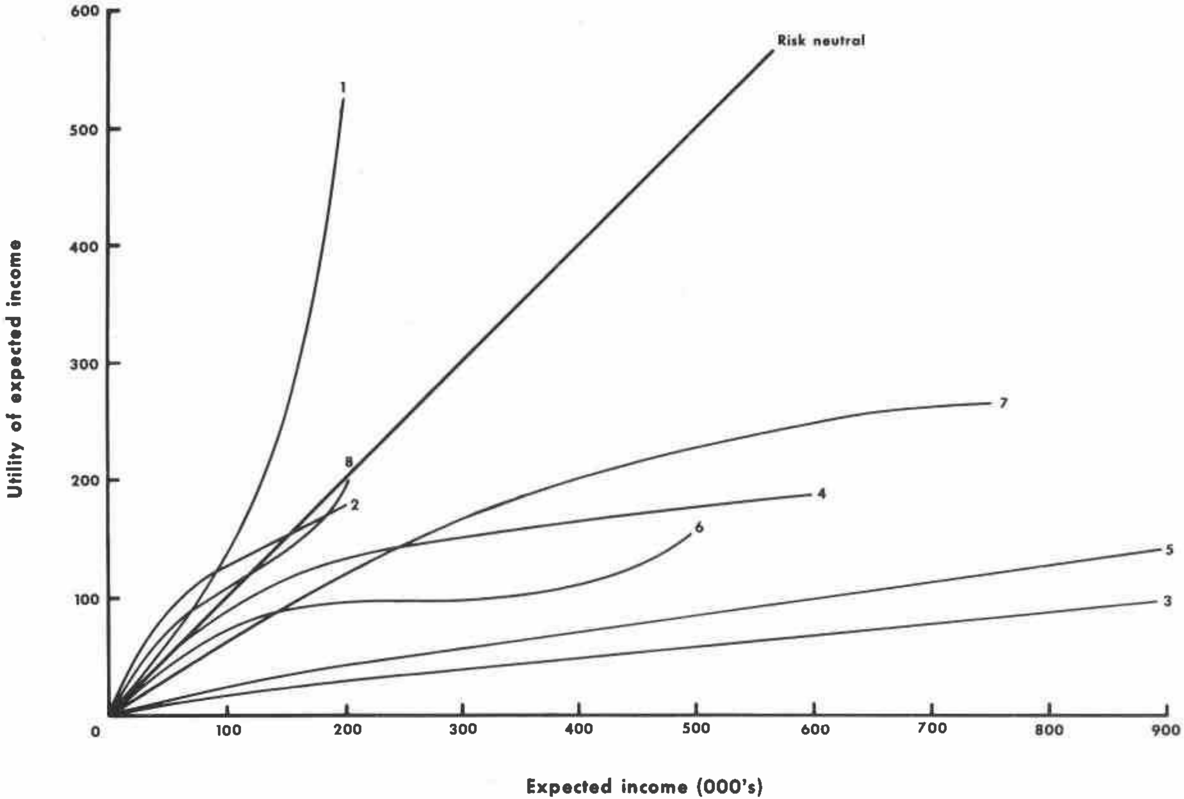

Figure 6. Utility function for eight orchardists, Jackson County, Oregon.

this study were taken from "the average orchard." For the 16-year period, there were a total of 925 days covered by the records, of which 420 days had recorded temperatures of 35°F. or less. Temperatures in excess of 35°F. were not recorded.

Forecasting Nightly Temperatures

Nightly forecasts have been provided by a U.S. Weather Service meteorologist in Jackson County since 1957 [19]. These prognostications of forecast temperature were recorded for the "average orchard" over the 16-year period. The individual orchardist in Jackson County is required to extrapolate the historical temperature recordings and the current temperature forecast from the "average orchard" site to determine historical and expected temperatures for his own orchard.

Probability Distributions

Nightly Low Temperatures (Historical Probabilities)

Low nightly temperatures are more likely to occur early in the frost season rather than late. The frost season in Jackson County starts when the earliest pear variety exhibits bud swelling. While this varies somewhat from year to year, historical records indicate the normal or typical date to be March 14. The season ends in that part of May after which no

Table 7. Historical probability of nightly low temperature readings in Jackson County from March through May

Recorded temperature (°F.)	March 14-31	April 1-15	April 16-30	May 1-13
Above 35	.46108	.5375	.49167	.75899
35	0	.00833	.02083	.03227
34	.02395	.04583	.03333	.02878
33	.041916	.04583	.08333	.06475
32	.08982	.06667	.06667	.02878
31	.04192	.03333	.04583	.02518
30	.04192	.07500	.09167	.02878
29	.07186	.06667	.06667	.02518
28	.07186	.05833	.04167	.00719
27	.05389	.05000	.01667	
26	.04192	.00417	.03333	
25	.03593	.00833	.00417	
24	.01198		.00417	
23	.00599			
22	0			
21	.00599			

SOURCE: *Annual Report of Fruit Frost Activities, Medford District, Jackson County, Oregon.* National Weather Service, U.S. Department of Commerce, Spring 1952 to Spring 1972.

freezing temperatures are recorded with the average ending date being May 13. To account for the decreased probability of frost as the season advances, the historical probability of a particular nighttime temperature occurring is specified for each of four two-week periods during the frost season: March 14-31, April 1-15, April 16-30, and May 1-13. The historical probabilities of occurrence of each of the 16 temperatures in the range from 21°F. to 35°F. for each of the four two-week periods of the frost season are presented in Table 7.

Accuracy of Frost Forecasts Historically (Conditional Probabilities)

The accuracy, in an *ex post* sense, of the nightly frost forecast service provided by meteorologists of the U.S. Weather Service in Jackson County from 1957 through 1972 is a vital component in determining the usefulness of forecasts to orchardists. This refers to the historical conditional probability of a forecast temperature given the actual temperature that occurred. Since a forecaster has no control over weather conditions, his ability to predict a temperature condition is independent of the absolute value of an actual temperature. The conditional probability of a correct forecast then, is not dependent upon the week or the month during the frost season when the prediction is made. Consequently, all temperature observations made during each frost season since 1957 are included in the study to derive conditional probability values of a correct forecast, regardless of when they occurred during a particular season [6].

The relationship between a specific occurring nightly temperature and the conditional probability of the forecast being made is presented in Table 8. Each cell in Table 8 is calculated by dividing the number of times a given temperature was forecasted and actually occurred during the 16-year period by the total number of times the specific actual temperature occurred. The probability of the forecast being exactly correct or predicting some other temperature is determined by reading down the historical nighttime temperature column. For example, on nights when the actual temperature was 26°F., the forecaster predicted that outcome in 35 percent of his forecasts. In other words, his prediction was exactly correct about one-third of the time. In the remainder of his forecasts in which 26°F. actually occurred, he had forecasted 29°F. 12 percent of the time, 28°F. 24 percent of the time, 27°F. 18 percent of the time, and 25°F. 12 percent of the time. Blanks within the table indicate that for a given nightly actual temperature, a particular forecast temperature was never observed in the historical period. For purposes of this study, the conditional probability distribution in Table 8 was smoothed to fill in the missing cells.

It is important to note that the forecaster's range of accuracy is narrower when the lower temperature occurred. That is, the dispersion

Table 8. Conditional probability table of forecast temperature outcomes for 16 recorded temperatures (Jackson County, 1957 to 1972)

Forecasted temperature	Recorded temperature (°F)															
	ND[a]	35°	34°	33°	32°	31°	30°	29°	28°	27°	26°	25°	24°	23°	22°	21°
ND	.9778	.625	.5455	.30357	.25926	.11765	.05455									
35°	.00185		.0303	.01786	.01852	.02941										
34°	.00370		.0606	.01786	.01852	.02941										
33°	.00555			.01786		.05882	.01818	.02273								
32°	.00370	.1875	.2121	.21429	.22222	.17647	.05455	.13636	.15385	.04167						
31°	.00185		.0606	.19643	.18519	.17647	.20	.02273	.02564	.04167						
30°	.00185	.125	.0606	.10714	.18519	.05882	.25459	.250	.17999	.08333						
29°	.00185	.0625		.01786	.05555	.20588	.16369	.34091	.15385	.33333	.11765					
28°				.05357	.03705	.08824	.18182	.09091	.25641	.29167	.23539					
27°			.0303	.03571	.01852	.08824	.05455	.11364	.15385	.125	.17647	.44444				
26°								.02273	.05128	.04107	.35294	.22222	.33333			
25°							.01818		.02564	.04167	.11765	.3333	.66667			
24°			.01786											1.0		1.0
23°																
22°																
21°																

SOURCE: *Annual Report of Fruit Frost Activities, Medford District, Jackson County, Oregon.* National Weather Service, U.S. Department of Commerce, Spring 1957 to Spring 1972.

[a] ND represents "No Danger," and all temperatures above 35° are in this category.

of a forecast is greater when a mild temperature is forecast than when lower temperatures are forecast. On nights when the actual recorded temperatures were very near the freezing point (between 31°F. and 33°F.), the dispersion of the forecast was somewhat higher than for lower temperatures.

About half the time the forecasted temperature was lower than the actual with the forecast ranging as low as 27°F. While this provided a positive margin of error for orchardists, it also resulted in heater firing on some nights in which frost protection was not needed. It should be kept in mind that comparison of the historical forecast data with the actual temperature was averaged over the 16-year period for which data was available. No basis exists in the analysis for evaluating whether the accuracy of forecasts has changed, either improved or deteriorated, during that period. There is reason to hypothesize, however, that some improvement has occurred concurrent with availability of more sophisticated prognostication technology in recent years.

Predictive Accuracy of Actual Forecast (Posterior Probabilities)

On any given night, a forecast is made as to what the nightly temperature will be. The accuracy of a nightly prediction, and the accumulated set of nightly predictions for the entire season, are important in determining the value of the seasonal forecasting service. To do so requires calculation of the predictive or *ex ante* capability of actual forecasts rather than *ex post* capability discussed in the previous section. This is done by use of a formula in which posterior probabilities are calculated. The posterior probability for each temperature from 21°F. to 35°F. is simply the probability of its actually occurring on any night, given the temperature forecasted for that night. The formula, called the Bayes Formula [2, 10, 17], revises historical temperature probabilities by explicitly accounting for the accuracy of historical forecasts as follows:

$$P(\Theta_k|Z_j) = \frac{P(\Theta_k)P(Z_j|\Theta k)}{\sum_k P(\Theta_k)P(Z_j|\Theta_k)}$$

where

$P(\Theta_k|Z_j)$ = the posterior probability of a nightly temperature (Θ_k) actually occurring on any night for a given nightly forecast (Z_j), representing a measurement of the *ex ante* or predictive accuracy of forecasts,

$P(\Theta_k)$ = probability of a historical recorded temperature,

$P(Z_j|\Theta_k)$ = conditional probability of a forecast temperature for a given historical recorded temperature representing an *ex poste* measurement of the accuracy of forecasts historically, and

$\sum_k P(\Theta_k)P(Z_j|\Theta_k)$ = sum of the historical recorded temperatures weighted by their conditional probabilities.

Posterior probability distributions are calculated for each of the four periods within the frost season and reported in Table 9. These distributions are the revised estimates of nightly temperatures which are apt to occur given the forecast. Note, that as the frost season progresses, the range of error potential decreases for the forecasted temperature. This is not due to any improvement in the quality of the forecast, but rather to a truncating of the range of weather variability at the lower temperature levels as the frost season advances. The distributions in Table 9 were derived from Tables 7 and 8, using the Bayes Formula and some smoothing of the data to account for missing data points.

RESULTS FROM BAYESIAN MODEL OF FROST PROTECTION DECISIONS

The actual nightly temperatures in the model are simulated by using a random process which, like reality, provides potential for an infinite number of seasonal weather outcomes. To be manageable, 15 runs of the model were made, each representing a different but commonly experienced frost season. Characteristics of the 15 frost seasons are shown in Table 10.

The value of the frost forecast is determined by comparison against three alternative states of knowledge: (1) availability of historical nightly temperature information, (2) availability of a perfect nightly frost forecast service, and (3) no prior information available whatever on spring forecasts. In each of the three situations, the value derived represents the assumed maximum amount the orchardist would be willing to pay to receive the weather forecast within a production year framework where only frost protection and harvest costs remain as current year variable costs. The results are presented for each case in a similar format. The percentage of the crop remaining and the assumed maximum value of the forecast is expressed for each orchardist over the 15 frost seasons and across orchardists for a given season. A fourth situation is evaluated which compares the value of frost information where orchardists maximize expected income rather than expected utility so as to identify that portion of value attributable to orchardist risk adversity.

Table 9. Predictive capability of frost forecasts relative to historcial prior distribution

	Forecasted temperatures (°F)							
	> 35	35	34	33	32	31	30	29
	Probability of outcome of actual temperatures							
MARCH 14-31								
> 35	.735611	.188114	.116279	.045781	.017820	.007394	.007103	.007355
35	.085671	.455240	.281422	.129248	.064693	.044721	.034368	.017792
34	.078960	.075924	.176005	.184763	.125877	.096960	.064484	.044511
33	.042174	.074050	.085832	.150173	.210468	.160039	.104822	.072357
32	.034380	.073077	.112937	.207472	.207697	.157931	.124130	.071403
31	.014198	.047779	.073844	.096897	.135803	.168976	.144289	.130724
30	.005089	.034257	.026471	.027787	.048679	.134601	.181023	.180741
29	.002727	.027535	.042556	.055842	.071740	.086560	.129926	.161434
28	.001190	.024024	.055695	.058466	.068285	.070804	.086155	.103292
27	0	0	.028959	.030399	.026628	.044177	.077803	.139146
26	0	0	0	.013173	.015385	.012762	.030649	.038082
25	0	0	0	0	.006923	.011486	.011034	.022849
24	0	0	0	0	0	.003589	.003448	.007141
23	0	0	0	0	0	0	.000766	.002380
22	0	0	0	0	0	0	0	.000793
21	0	0	0	0	0	0	0	0

	28	27	26	25	24	23	22	21
MARCH 14-31								
> 35	.008701	0	0	0	0	0	0	0
35	.021049	.029119	0	0	0	0	0	0
34	.035105	.024283	.036180	0	0	0	0	0
33	.051359	.047368	.052932	.077060	.079357	0	0	0
32	.033789	.023372	.034824	.050697	.078315	0	0	0
31	.110464	.091690	.068307	.066297	.102413	.093938	0	0
30	.158385	.109557	.048971	.047529	.036712	.067352	0	0
29	.159150	.096875	.039365	.038207	.029508	.054135	.089679	0

(*continued next page*)

Table 9—Continued

	Forecasted temperatures (°F)							
	28	27	26	25	24	23	22	21
MARCH 14-31								
28	.133305	.169049	.137386	.066670	.051496	.047234	.078246	0
27	.129957	.107872	.089291	.077997	.080323	.073682	.122060	0
26	.075086	.135038	.247631	.225320	.139226	.127711	.105782	0
25	.067577	.130881	.153220	.162228	.125302	.114937	.095204	.232648
24	.008447	.017530	.052236	.101397	.097896	.071839	.059504	.145409
23	.003754	.007790	.019344	.039427	.069606	.095773	.052886	.064618
22	.002815	.005193	.011607	.028162	.060905	.127697	.158656	.193852
21	.001056	.004382	.008705	.019009	.048941	.125702	.237983	.363473

	> 35	35	34	33	32	31	30	29
APRIL 1-15								
> 35	.891895	.400847	.278849	.125308	.051747	.021905	.020848	.021483
35	.037257	.347939	.242065	.126890	.067380	.047520	.036181	.018641
34	.031202	.052729	.137565	.164827	.119132	.093619	.061685	.042375
33	.016745	.051674	.067407	.134610	.200143	.155264	.100752	.069213
32	.013723	.051265	.089164	.186958	.198557	.154033	.119944	.068663
31	.005400	.031940	.055556	.083206	.123714	.157046	.132859	.119790
30	.002072	.024512	.021317	.025540	.047467	.133902	.178416	.177280
29	.001206	.021396	.037217	.055739	.075969	.093515	.139065	.171958
28	.000499	.017696	.046169	.055318	.068542	.072507	.087410	.104292
27	0	0	.024692	.029585	.027493	.046533	.081193	.144511
26	0	0	0	.012019	.014892	.012603	.029985	.037078
25	0	0	0	0	.004964	.008401	.007996	.016479
24	0	0	0	0	0	.003150	.002998	.006179
23	0	0	0	0	0	0	.000666	.002060
22	0	0	0	0	0	0	0	0
21	0	0	0	0	0	0	0	0

	28	27	26	25	24	23	22	21
APRIL 1-15								
> 35	.025656	0	0	0	0	0	0	0
35	.022262	.032229	0	0	0	0	0	0
34	.033738	.024422	.037597	0	0	0	0	0
33	.049595	.047867	.055268	.084041	.092708	0	0	0
32	.032802	.023744	.036553	.055584	.091976	0	0	0
31	.102188	.088763	.068325	.069265	.114615	.125425	0	0
30	.156831	.113523	.052431	.053151	.043978	.096257	0	0
29	.171137	.109014	.045770	.046401	.038388	.084021	.167527	0
28	.135877	.180318	.151417	.076748	.063501	.069489	.138552	0
27	.136252	.118353	.101224	.092355	.101880	.111499	.222315	0
26	.073802	.138899	.263178	.250121	.165555	.181178	.180623	0
25	.049201	.099720	.120622	.133396	.110368	.120782	.120415	.480031
24	.007379	.016025	.049340	.100036	.103459	.090578	.090300	.359978
23	.003280	.007122	.018274	.038903	.073571	.120771	.080267	.159991
22	0	0	0	0	0	0	0	0
21	0	0	0	0	0	0	0	0

	> 35	35	34	33	32	31	30	29
APRIL 16-30								
> 35	.888781	.394450	.280164	.128430	.053876	.023266	.022973	.024787
35	.039612	.365302	.259483	.138756	.074848	.053850	.042537	.022947
34	.032582	.054371	.144829	.177020	.129971	.104194	.071226	.051233
33	.017136	.052219	.069549	.141680	.213992	.169350	.114012	.082009
32	.013221	.048769	.086604	.185241	.199849	.158157	.127772	.076588
31	.005336	.031164	.055345	.084557	.127714	.165389	.145161	.137044
30	.001987	.023213	.020611	.025191	.047560	.136867	.189200	.196849
29	.000949	.016636	.029544	.045138	.062494	.078477	.121077	.156764
28	.000396	.013875	.036959	.045174	.056859	.061360	.076744	.095877
27	0	0	.016911	.020669	.019512	.033690	.060988	.113660
26	0	0	0	.008143	.010249	.008848	.021841	.028279
25	0	0	0	0	.003075	.005309	.005242	.011312
24	0	0	0	0	0	.001244	.001229	.002651
23	0	0	0	0	0	0	0	0
22	0	0	0	0	0	0	0	0
21	0	0	0	0	0	0	0	0

(continued next page)

Table 9—Continued

	Forecasted temperatures (°F)							
	28	27	26	25	24	23	22	21
APRIL 16-30								
> 35	.030659	0	0	0	0	0	0	0
35	.028384	.043148	0	0	0	0	0	0
34	.042247	.032111	.053269	0	0	0	0	0
33	.060863	.061682	.076742	.122848	.135229	0	0	0
32	.037894	.028803	.047780	.076487	.126295	0	0	0
31	.121081	.110437	.091601	.097758	.161419	.194300	0	0
30	.180360	.137089	.068225	.072809	.060115	.144728	0	0
29	.161587	.108081	.048898	.052185	.043081	.103719	.213866	0
28	.129375	.180281	.163126	.087043	.071866	.086503	.178366	0
27	.110991	.101235	.093298	.089612	.098644	.118748	.244855	0
26	.058298	.115210	.235223	.235342	.155440	.187112	.192910	0
25	.034979	.074443	.097029	.112964	.093264	.112265	.115747	.680855
24	.003279	.007478	.024809	.052952	.054647	.052625	.054256	.319145
23	0	0	0	0	0	0	0	0
22	0	0	0	0	0	0	0	0
21	0	0	0	0	0	0	0	0

	> 35	35	34	33	32	31	30	29
MAY 1-13								
> 35	.947822	.598151	.488730	.275953	.133896	.065353	.071146	.085525
35	.020376	.267205	.218343	.143811	.089728	.072963	.063544	.038192
34	.015514	.036814	.112806	.169827	.144224	.130679	.098490	.078930
33	.007850	.034016	.052118	.130771	.228457	.204346	.151678	.121556
32	.005629	.029528	.060320	.158918	.198309	.177379	.157994	.105513
31	.001969	.016353	.033409	.062871	.109836	.160762	.155567	.163632
30	.000533	.008859	.009049	.013622	.029748	.096758	.147470	.170943
29	.000247	.006162	.012589	.023690	.037938	.053846	.091593	.132125
28	.000058	.002912	.008923	.013434	.019557	.023854	.032894	.045785
27	0	0	.003713	.005589	.006103	.011910	.023770	.049356
26	0	0	0	.001514	.002204	.002150	.005853	.808442

25	0	0	0	0	0	0	0	0
24	0	0	0	0	0	0	0	0
23	0	0	0	0	0	0	0	0
22	0	0	0	0	0	0	0	0
21	0	0	0	0	0	0	0	0

	28	27	26	25	24	23	22	21
MAY 1-13								
> 35	.114328	0	0	0	0	0	0	0
35	.051055	.094636	0	0	0	0	0	0
34	.070341	.065193	.124323	0	0	0	0	0
33	.097495	.120481	.172317	.275001	.257222	0	0	0
32	.056420	.052291	.099718	.159141	.223285	0	0	0
31	.156243	.173768	.165688	.176285	.247338	.390677	0	0
30	.169268	.156880	.089753	.095490	.066993	.211646	0	0
29	.147185	.120043	.062433	.066427	.046597	.147210	.419829	0
28	.066769	.113451	.118010	.062777	.044041	.069563	.198387	0
27	.052088	.057931	.061375	.058769	.054971	.086835	.247646	0
26	.018809	.045326	.106382	.106110	.059552	.094069	.134138	0
25	0	0	0	0	0	0	0	0
24	0	0	0	0	0	0	0	0
23	0	0	0	0	0	0	0	0
22	0	0	0	0	0	0	0	0
21	0	0	0	0	0	0	0	0

Table 10. Computer simulated frost seasons showing resulting bud and crop loss when no frost protection is used

Season	Date of frost	Night temperature (°F.)	Percent bud loss	Buds remaining (%)	Crop remaining (%)
1	March 25	22	52	48	96
	April 13	28	10	43	86
	April 17	28	10	39	78
	April 30	28	10	35	70
	May 2	25	70	10	20
2	March 22	22	25	75	100
	March 31	25	30	53	100
	April 14	28	10	47	94
	April 15	28	10	43	86
	April 28	27	30	30	60
3	April 14	25	70	30	60
	April 29	27	30	21	42
4	March 22	25	10	90	100
	March 29	25	30	63	100
5	March 30	26	10	90	100
	April 21	26	50	45	90
6	March 25	24	50	50	100
	March 30	27	10	45	90
7	April 7	25	30	70	100
	April 10	24	75	18	36
8	March 22	22	52	48	96
	April 15	23	100	0	0
9	April 1	26	10	90	100
	April 6	27	10	81	100
	April 8	27	30	57	100
	April 16	28	10	51	100
10	....	....	....	....	....
11	April 13	28	10	90	100
	April 15	28	10	81	100
12	March 29	26	30	70	100
	April 16	25	70	21	42
13	March 29	25	55	45	90
	March 30	27	10	41	82
	March 31	27	30	28	56
	April 1	26	50	14	28
	April 10	27	30	10	20
	April 14	28	10	9	18
14	April 7	28	10	90	100
15	March 29	27	10	90	100
	April 20	27	30	63	100
	April 22	26	50	32	64

Value of the Nightly Frost Forecast

The value of nightly frost forecast information is compared against the value of having only historical nightly temperature data. The results are presented in Table 11, with the values representing the maximum amount each orchardist is willing to pay to receive the weather forecast. It measures the difference in value of information in a decision process where no nightly forecast is given, so that only prior probabilities are available to assess the likelihood of temperature occurrence, against the value of information where the nightly weather forecast is available, so that revised probabilities are used to assess the likelihood of temperature occurrences.

The annual value of the frost forecast averaged across 15 frost seasons and the eight orchardists sampled was $337.50 per acre or $5.39 per acre per day. The range was from a low of $1.59 per acre for orchardist 6 to a high of $1,097.80 per acre for orchardist 3. While the results are specific only to the eight orchardists in the study, it is apparent that the average immediate value of nightly frost forecasting in Jackson County is high when compared to the alternative choice of each orchardist becoming his own daily forecaster using only historical nightly temperature data and without personal interpretation of daily weather conditions.[11]

It should be observed that the value of nightly frost forecasts varies widely between orchardists for a given season and between seasons for a given orchardist. This is because the "value" of the forecast is determined by a number of interrelated factors. At the inception of the study it was thought that the value of the forecast would be determined, among other things, by the percentage of crop saved. Intuitively it seemed that an orchardist would be willing to pay more for a weather forecast as his percentage of crop saved increased. Comparison in Table 11 of the percent of crop remaining where no frost protection is used against percent crop remaining with protection indicated that this is not the case. Rather, the "value" of the forecast is determined by:

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[11] The frost forecast value is overstated since it includes the value of personal interpretation of daily weather conditions. Furthermore, as stated in the conceptualization section, the results represent the maximum value of the forecast expressed in an immediate or current year setting. The necessity for orchardists to cover annual cultural practice costs as a short-run practice to assure production potential throughout the useful life of the existing orchard and capital investment costs to assure the long-run existence of orchard production as a viable economic activity are recognized as being important decision costs. Inclusion of these components in a study of this type will reduce the value of frost forecast service when expressed in these short- and long-run settings.

Table 11. Summary of crop remaining and the maximum value per acre of frost forecast against having only historical prior probability distribution as the information source (for 8 orchardists and 15 random seasons, assuming orchardists are utility maximizers)

Frost season	No protection	With protection							
		Percent crop remaining and value of forecasts, by orchardist							
	Percent of crop remaining	%	Or. 1	%	Or. 2	%	Or. 3	%	Or. 4
1	20	90	$210.26	100	$437.62	86	$969.08	78	$459.06
2	60	100	159.29	100	400.09	100	854.37	94	301.76
3	42	60	85.54	100	313.75	100	380.69	60	619.58
4	100	100	117.01	100	288.78	100	363.24	100	212.80
5	90	90	84.68	100	333.23	90	488.13	90	166.40
6	90	90	278.85	100	369.34	100	1,097.80	90	743.34
7	82	100	72.33	100	317.83	100	421.27	100	114.21
8	0	44	222.51	82	456.68	44	724.09	44	675.11
9	100	100	149.01	100	340.81	100	463.75	100	248.26
10	100	100	11.46	100	104.00	100	125.69	100	18.67
11	100	100	52.26	100	246.59	100	281.44	100	99.37
12	42	100	152.02	100	392.75	100	530.29	100	298.00
13	18	100	176.68	100	381.22	100	531.21	100	352.34
14	100	100	42.91	100	302.17	100	373.13	100	96.69
15	64	100	80.26	100	354.59	100	527.31	100	184.34
Avg. across seasons			126.47		335.96		542.10		306.00
Avg. per day			2.02		5.37		8.66		4.89

Table 11—Continued

Frost season	No protection: Percent of crop remaining	With protection: Percent crop remaining and value of forecasts, by orchardist: %	Or. 5	%	Or. 6	%	Or. 7	%	Or. 8	Average across orchardist
1	20	86	$391.92	26	$ 48.88	86	$740.90	78	$602.38	$482.51
2	60	100	374.42	66	57.20	100	861.45	100	429.86	429.81
3	42	100	305.79	60	155.82	100	668.95	60	351.98	360.26
4	100	100	311.40	100	25.56	100	742.04	100	326.19	298.38
5	90	100	316.93	90	18.17	100	632.98	90	255.37	286.99
6	90	100	322.19	90	84.13	100	760.25	100	717.51	546.68
7	82	100	234.35	100	13.30	100	528.96	100	198.02	237.53
8	0	90	387.79	44	81.76	82	816.16	44	651.18	501.91
9	100	100	324.36	100	30.27	100	652.03	100	207.98	302.06
10	100	100	155.57	100	1.59	100	471.57	100	41.43	116.25
11	100	100	252.50	100	9.84	100	646.26	100	133.51	215.22
12	42	100	363.54	42	48.44	100	774.90	100	400.97	370.11
13	18	100	345.28	90	81.17	100	809.41	100	246.05	365.42
14	100	100	285.67	100	12.63	100	694.94	100	139.36	243.44
15	64	100	307.94	100	22.48	100	728.19	100	242.43	306.19
Avg. across seasons			311.98		46.08		701.67		329.61	337.50
Avg. per day			4.98		0.74		11.21		5.27	5.39

1. Perceived accuracy of the forecast.

2. Severity of frost season determined by: (a) time of frost occurrence within a season; (b) nightly temperature relative to critical temperature; and (c) number of critical frosts.

3. Magnitude of monetary payoff potential.

4. Degree of risk aversion.

5. Interdependencies between daily frost decisions.

Perceived accuracy of the forecast by individual orchardists will influence the degree to which the forecast information will be "discounted" as being useful in application to the nightly frost protection decision. The degree of belief of forecast accuracy is evaluated in the next section.

Severity of the frost season contributed to the "value" of the forecast. In "mild" years, such as seasons 4, 9, 10, 11, and 14, the average benefit from nightly frost forecasts was low relative to the average benefit across seasons. This is because the risk of frost in those years was low relative to the high frost risk seasons. In years where one or more frosty nights could cause severe loss, such as in seasons 1, 8, and 13, the "value" of the forecast tends to be high relative to the average.

Timing of nightly frosts during the season is a factor. Early frosts generally are not as critical as late frosts in terms of potential crop loss. Three factors contribute to this. First, the orchard is less vulnerable to low nighttime temperatures in the early stages of bud development. Secondly, no crop loss occurs until at least 50 percent bud loss exists, and thirdly, crop loss is a cumulative factor. Table 2 shows that any frost occurring after April 5 with nightly temperatures of 28 or below results in high crop losses without frost protection. Seasons 1, 2, 3, 7, 8, 12, 13, and 15 in Table 10 are representative of this situation. The intensity of a particular nightly frost contributes to the severity of a frost season, particularly when previous frosts in the season have reduced buds remaining to less than 50 percent. A further aggravating force is the number of critical frosts within a season. Seasons 1, 2, and 13 reflect the compounding effects of these two conditions. It should be noted, however, that model results show the severity of the frost season by itself does not assure that a high value is placed upon frost protection, as noted by results for orchardist 6 in season 1 and orchardist 8 in season 13. Obviously other factors play a role.

The magnitude of potential monetary gain, which can be translated as the opportunity cost of financial gain foregone when initial frost occurs and frost protection is not implemented, is a factor. Orchardists 1 and 6 had the lowest expected gross return per acre (Table 3) of the eight orchardists upon entering the frost season. Also, by model results, they quite consistently placed the lowest value per acre on the frost forecasts on the average as well as with most of the separate weather seasons. The consistency is attributed primarily to the markedly lower gross return expectation relative to the other six orchardists upon entering the frost season, especially in the case of orchardist 6. Six orchardists had expected gross returns at the beginning of the frost season which ranged between approximately $1,250 and $1,600 per acre. The value of the forecast for these orchardists ranged from about $340 to $900 per acre with no consistent pattern relative to the expected gross return.

Degree of risk aversion is a factor influencing the "value" of the forecast. The role of this factor can be shown in a cursory fashion by comparing results in Table 11 with the utility functions in Table 6 or Figure 6. Note that orchardist 1 is a strong risk taker relative to the other orchardists. This factor contributes to the low value he places upon frost forecast. A philosophy of risk taking discounts the value of frost forecasting since the degree of riskiness of crop loss is viewed by a risk taker as a desired attribute rather than something to minimize. The potential of greater gain, regardless of the degree of risk associated with its attainment, is viewed by the risk-taking orchardists as being the central issue.[12] Strong risk aversion had the opposite effect of risk taking. Orchardists 3, 5, and 7 were risk averters throughout the entire range of their utility functions and, generally speaking, reflected the highest "values" for frost forecasts. However, the combined effect of all variables used in the model is apparent since operator 7 had the highest average value for frost forecast but was not the most risk averse. Utility functions of orchardists 2, 4, 6, and 8 were mixed: at low income levels they were risk averters while at higher levels they were risk takers. The impact of having a mixed utility function is not obvious from analysis of Table 11 and so is treated specifically in the section on risk adversity. The interdependencies between daily frost decisions also are treated in that section.

Value of a Perfect Frost Forecast

The value of a perfect frost forecast is compared against the value of having only historical nighttime temperature data. Results are presented in Table 12. Values in the table represent the maximum amount each orchardist is willing to pay to receive a perfect forecast relative to

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[12] An additional factor complicates the results. It was noted earlier that historical or *ex post* average gross returns were used as an estimation of *ex ante* expected gross returns. To the degree that the input is really an *ex post* reflection of the consequences of being a risk taker, the gross incomes will understate the true value of the frost forecast to the risk takers.

Table 12. Summary of crop remaining and value per acre of a *perfect* frost forecast relative to having only historical prior probability distributions (for 8 orchardists and 15 random seasons, assuming orchardists are utility maximizers)

Frost season	With protection							
	Percent crop remaining and value of forecasts, by orchardist							
	%	Or. 1	%	Or. 2	%	Or. 3	%	Or. 4
1	100	$240.41	100	$426.30	100	$ 466.90	100	$ 511.85
2	100	420.57	100	528.79	100	1,021.70	100	904.39
3	100	206.26	100	378.42	100	403.58	100	439.06
4	100	339.62	100	524.22	100	711.79	100	726.06
5	100	170.57	100	321.48	100	321.57	100	364.45
6	100	736.12	100	671.79	100	1,413.27	100	1,575.78
7	100	223.45	100	387.58	100	439.31	100	477.27
8	100	286.21	100	491.86	100	591.29	100	609.48
9	100	408.25	100	509.87	100	985.37	100	871.81
10	100	74.95	100	133.95	100	140.89	100	159.31
11	100	185.32	100	339.44	100	347.85	100	393.93
12	100	424.16	100	599.03	100	1,023.69	100	901.25
13	100	520.44	100	634.88	100	1,126.64	100	1,108.61
14	100	208.70	100	384.90	100	425.18	100	445.52
15	100	315.52	100	539.99	100	651.33	100	673.78
Avg. across seasons		317.35		458.17		671.36		677.50
Avg. per day		5.07		7.32		10.72		10.82

Table 12—Continued

Frost season	With protection								Average across orchardist
	Percent crop remaining and value of forecasts, by orchardist								
	%	Or. 5	%	Or. 6	%	Or. 7	%	Or. 8	
1	100	$421.73	96	$299.56	100	$ 852.97	100	$ 512.09	$466.44
2	100	467.48	100	235.04	100	995.92	100	911.52	685.68
3	100	362.75	100	117.92	100	850.05	100	438.87	399.61
4	100	443.42	100	192.64	100	944.44	100	728.54	576.34
5	100	326.59	100	96.80	100	818.05	100	365.42	348.12
6	100	597.84	100	415.47	100	1,129.64	100	1,376.34	989.53
7	100	331.99	100	127.69	100	655.04	100	479.02	390.17
8	100	454.90	86	357.67	100	1,015.46	100	609.28	552.02
9	100	458.39	100	232.73	100	857.45	100	874.34	649.78
10	100	146.88	100	43.68	100	539.49	100	159.42	174.82
11	100	366.32	100	106.79	100	798.82	100	393.60	366.51
12	100	506.48	100	243.54	100	1,021.05	100	855.05	696.78
13	100	545.02	100	296.84	100	1,047.31	100	1,044.50	790.53
14	100	354.22	100	118.14	100	864.23	100	446.09	405.87
15	100	456.77	100	178.45	100	978.44	100	674.85	558.64
Avg. across seasons		416.05		204.20		891.22		657.93	536.72
Avg. per day		6.65		3.26		14.24		10.51	8.57

having only the historical temperature data. The difference between cells in Table 11 and Table 12 for each orchardist represents the maximum amount each orchardist is willing to pay to receive a perfect forecast in lieu of the existing forecast. This average value was $3.18 per day per acre ($8.57 – $5.39) or $199.22 per acre ($536.72 – $337.50) averaged across 15 seasons. The range was from a low of $42.09 ($43.68 – $1.59) per acre for orchardist 6 to a high of $832.44 ($1,575.78 – $743.34) per acre for orchardist 4. This represents the maximum immediate or within-year amount that could be expended on improving the U.S. Weather Service frost forecasting services and keep the orchardists at the same level of utility as they would be without the forecast information. As stated earlier, the short- and long-run benefits would be less than the immediate or within-year amount. Consequently the results must not be construed to imply that the U.S. Weather Service could or should provide perfect forecasts for that expenditure. It does reflect, however, that the eight orchardists place a positive economic value upon a forecast which has less error than the current one.

Value of Other Information

The value of nightly frost forecast information is compared against the hypothetical case of each orchardist being completely ignorant of the historical prior probability distribution which assumes a uniform prior distribution. Results are presented in Table 13. Values in the table represent the maximum value of the forecast in a hypothetical case where no other information whatever is available upon which to judge nightly frosts. The difference between cells in Table 11 and Table 13 for each orchardist represents the maximum value of information other than the frost forecast (historical prior probability distributions, daily orchardist weather observations, knowledge of cultural practices affecting future crop production, etc.) in making frost protection decisions. The average value for the eight orchardists was $186 per day per acre ($191.39 in Table 12 – $5.39 from Table 10). Comparison of the value with the expected gross returns per acre in Table 13 shows that an accumulation of this value across the 62-day frost season would soon exceed the value of the crop. It is clear that no orchardist would pay such amounts for forecast information. It should also be clear that the assumption used is naive and that no orchardist is that ignorant of the prior historical probability distributions. If he were, he would not be in the pear production business for long. What is important here is a recognition that: (1) frost forecast information is only one component of a larger body of knowledge necessary to make pear production a successful venture, and (2) the value of frost forecasts is conditional upon the level or extent of that body of prior

Table 13. Summary of crop remaining and value of frost forecast, relative to having no prior information whatever (for 8 orchardists and 15 random seasons, assuming orchardists are utility maximizers)

Frost season	With protection							
	Percent crop remaining and value of forecasts, by orchardist							
	%	Or. 1	%	Or. 2	%	Or. 3	%	Or. 4
1	96	$6,051.66	100	$13,077.07	100	$10,418.61	96	$16,383.37
2	100	6,039.55	100	9,704.94	100	12,299.28	100	15,866.67
3	100	5,542.91	100	15,189.77	100	16,821.84	100	17,076.55
4	100	5,518.94	100	14,867.04	100	16,998.04	100	16,839.54
5	100	5,528.42	100	14,725.41	100	16,342.43	100	15,418.82
6	100	5,839.60	100	15,752.44	100	17,026.22	100	18,575.71
7	100	4,728.34	100	14,123.16	100	15,105.99	100	14,774.18
8	90	5,854.23	100	12,539.62	100	17,339.48	90	17,297.58
9	100	5,589.12	100	13,048.82	100	16,946.29	100	16,793.97
10	100	4,501.68	100	13,839.90	100	14,399.21	100	14,060.93
11	100	5,192.29	100	14,861.46	100	16,477.18	100	16,250.61
12	100	6,035.98	100	15,758.01	100	17,244.86	100	18,658.69
13	100	6,012.33	100	15,880.52	100	17,375.37	100	18,860.05
14	100	5,488.98	100	15,258.05	100	16,907.20	100	17,198.70
15	100	5,726.28	100	15,629.94	100	16,895.70	100	18,235.58
Avg. across seasons		5,576.69		14,283.74		15,906.51		16,819.40
Avg. per day		89.08		228.17		254.10		268.68

(*continued next page*)

Table 13—Continued

Frost season season	With protection								Average across orchardist
	Percent crop remaining and value of forecasts, by orchardist								
	%	Or. 5	%	Or. 6	%	Or. 7	%	Or. 8	
1	100	$13,228.18	78	$3,034.58	100	$10,934.67	98	$15,712.28	$11,105.05
2	100	10,549.89	94	2,952.49	100	10,794.54	100	15,582.70	10,473.76
3	100	13,859.21	60	2,232.51	100	10,964.93	100	15,492.90	12,160.08
4	100	14,516.54	100	3,344.47	100	10,837.29	100	15,398.62	12,290.06
5	100	14,611.36	90	2,956.54	100	10,930.37	100	14,429.52	11,867.86
6	100	13,740.05	90	3,187.54	100	11,490.03	100	16,395.75	12,750.92
7	100	15,210.21	100	2,985.18	100	11,277.44	100	13,278.47	11,435.37
8	100	10,172.34	78	3,219.37	100	11,367.93	100	16,724.55	11,814.39
9	100	13,185.06	100	3,180.31	100	10,941.97	100	15,450.69	11,892.03
10	100	15,399.86	100	2,435.73	100	11,463.60	100	12,642.10	11,092.88
11	100	14,512.54	100	3,188.40	100	10,829.02	100	14,579.76	11,986.41
12	100	13,744.05	100	3,558.97	100	11,498.31	100	16,882.85	12,922.72
13	100	13,873.58	100	3,466.24	100	11,513.82	100	16,881.87	12,982.97
14	100	13,951.35	100	2,939.87	100	11,101.61	100	15,412.64	12,282.30
15	100	13,610.52	100	3,625.16	100	11,474.51	100	16,077.57	12,659.41
Avg. across seasons		13,610.98		3,093.82		11,161.34		15,396.15	11,981.08
Avg. per day		217.43		49.42		178.30		245.94	191.39

information. In other words, the economic value assigned to frost forecasts is determined in part by the level and quality of prior information that one has and uses with the frost forecast at the time each nightly frost protection decision is made. Consequently, the values shown in Table 11 represent the study's "best" estimate of immediate value for the U.S. Weather Service frost forecast in Jackson County given that the only previous information each orchardist has is the historical prior probabilities for each night of the frost season. To the extent that each orchardist has more information than this implies some overstating of actual forecast value.

Influences of Risk Adversity

To this point in the analysis it was assumed that each orchardist is a utility maximizer. This assumption recognizes that because the future is uncertain, each orchardist is concerned about expected income and the variability associated with that income. This is measured in the analysis by a unique utility function for each orchardist which measures his aversion from or preference for risky ventures. To measure the precise influence which orchardist risk adversity has upon determining the value of a frost forecast, it was necessary to establish the value of a frost forecast under the assumption of profit maximization. This is a commonly used assumption in economic research, especially in the cases where budgeting and linear programming methodologies are employed. Use of that assumption in this study implies maximization of expected income, or that each orchardist has a risk-neutral (linear) utility function, as shown in Figure 6.

Results are presented in Table 14. Values in the table represent the maximum amount each orchardist would be willing to pay to receive a forecast relative to having only the historical temperature data. The averaged value across all eight orchardists was $4.73 per day per acre. The difference between cells in Table 11 and Table 14, for each orchardist, represents the contribution of risk adversity to the value of frost forecast information. This result is shown in Table 15. This value averaged $0.66 ($5.39 – $4.73) per day-per acre. Of far greater importance is the value of risk adversity on an individual orchardist basis, however. Orchardists 3, 5, and 7 showed positive values for frost protection because of risk adversity. This comes as no surprise since each of these orchardists had utility functions which showed risk adversity at all levels of expected income as shown in Figure 6. Note that orchardist 7 had the most curved or concave from below function of the three. This factor along with his high gross income expectation accounts for his value of risk adversity being the highest. Orchardist 1 was the only orchardist with a risk-

Table 14. Summary of crop remaining and value per acre of frost forecast relative to having only historical prior probability distribution (for 8 orchardists and 15 random seasons, assuming orchardists are *profit* maximizers)

Frost season	With protection							
	Percent crop remaining and value of forecasts, by orchardist							
	%	Or. 1	%	Or. 2	%	Or. 3	%	Or. 4
1	78	337.06	86	407.57	78	679.54	86	768.54
2	100	262.99	100	371.93	100	536.92	100	608.21
3	60	134.14	100	221.27	100	193.43	100	224.26
4	100	197.58	100	223.50	100	405.98	100	467.20
5	90	144.06	100	257.17	90	298.79	90	344.41
6	100	468.03	100	308.76	100	854.04	100	941.46
7	100	118.42	100	264.23	100	246.62	100	284.01
8	44	336.02	82	409.57	44	638.49	44	703.08
9	100	128.48	100	272.48	100	262.71	100	302.15
10	100	15.83	100	61.92	100	40.10	100	47.39
11	100	78.37	100	159.34	100	132.01	100	153.41
12	100	261.37	100	281.78	100	509.53	100	581.98
13	100	151.56	100	271.92	100	281.67	100	326.35
14	100	85.37	100	203.72	100	179.09	100	207.85
15	100	145.05	100	296.20	100	295.88	100	340.26
Avg. across seasons		190.96		267.42		370.32		420.04
Avg. per day		3.05		4.27		5.92		6.71

Table 14—Continued

Frost season	With protection								Average across orchardists
	Percent crop remaining and value of forecasts, by orchardist								
	%	Or. 5	%	Or. 6	%	Or. 7	%	Or. 8	
1	86	346.22	78	154.33	86	625.02	86	728.06	505.79
2	100	322.14	94	122.71	100	521.33	100	600.76	418.37
3	100	240.86	60	53.44	100	217.48	100	246.97	191.48
4	100	229.43	100	89.74	100	425.05	100	492.44	316.37
5	100	258.30	90	62.08	90	333.01	90	377.53	259.42
6	100	262.51	90	203.53	100	697.41	100	822.57	569.79
7	100	147.60	100	51.93	100	268.77	100	306.81	211.05
8	90	348.72	44	151.02	82	481.07	44	600.18	458.52
9	100	254.32	100	115.95	100	286.42	100	325.81	243.54
10	100	78.34	100	1.63	100	52.53	100	58.65	44.55
11	100	184.25	100	38.21	100	150.63	100	170.89	133.39
12	100	298.87	100	122.05	100	523.14	100	599.19	397.24
13	100	282.78	100	140.81	100	294.62	100	339.15	261.11
14	100	224.63	100	33.89	100	200.60	100	228.17	170.42
15	100	250.89	100	80.25	100	314.81	100	358.92	260.28
Avg. across seasons		248.66		94.77		359.46		417.07	296.09
Avg. per day		3.97		1.50		5.74		6.66	4.73

Table 15. Summary of the value of risk adversity for 8 orchardists and 15 random seasons[a]

Frost season	With protection							
	Percent crop remaining and value of risk adversity							
	%	Or. 1	%	Or. 2	%	Or. 3	%	Or. 4
1	78	–126.80	86	30.05	78	289.54	86	–309.48
2	100	–103.70	100	28.16	100	317.45	100	–306.45
3	60	–48.60	100	92.48	100	187.26	100	395.32
4	100	–80.57	100	65.28	100	–42.74	100	–254.40
5	90	–59.38	100	76.06	90	189.34	90	–178.01
6	100	–189.18	100	60.58	100	243.76	100	–198.12
7	100	–46.09	100	53.60	100	174.65	100	–169.80
8	44	–113.51	82	47.11	44	85.60	44	–27.97
9	100	20.53	100	68.33	100	201.04	100	–53.89
10	100	–4.37	100	42.08	100	85.59	100	–28.72
11	100	–26.11	100	87.25	100	149.43	100	–54.04
12	100	–109.35	100	110.97	100	20.76	100	–283.98
13	100	25.12	100	109.30	100	249.54	100	25.99
14	100	–42.46	100	98.45	100	194.04	100	–111.16
15	100	–64.79	100	58.39	100	231.43	100	–155.92
Avg. across seasons		–64.49		68.54		171.78		–114.04
Value of risk adversity per day		–1.03		1.10		2.74		–1.82
Type utility function		Risk taker		Mixed		Risk averse		Mixed

Table 15—Continued

Frost season	With protection								Average across orchardists
	Percent crop remaining and value of risk adversity								
	%	Or. 5	%	Or. 6	%	Or. 7	%	Or. 8	
1	86	45.70	78	–105.45	86	115.88	86	–125.68	–23.28
2	100	52.28	94	–65.51	100	340.12	100	–170.90	11.44
3	100	64.93	60	102.38	100	451.47	100	105.01	168.78
4	100	81.97	100	–64.18	100	316.99	100	–166.25	–17.99
5	100	58.63	90	–43.91	90	299.97	90	–122.16	27.57
6	100	59.68	90	–199.40	100	62.84	100	–105.06	–23.11
7	100	86.75	100	–65.23	100	260.19	100	–108.79	26.48
8	90	39.07	44	–69.26	82	335.09	44	51.00	43.39
9	100	70.04	100	–85.68	100	365.61	100	–117.83	58.52
10	100	77.23	100	–.04	100	419.04	100	–17.22	71.70
11	100	68.25	100	–28.37	100	495.63	100	–37.38	81.83
12	100	64.67	100	–73.61	100	251.76	100	–198.22	–27.13
13	100	62.50	100	–59.64	100	514.79	100	–93.10	104.31
14	100	61.04	100	–21.26	100	494.34	100	–88.81	73.02
15	100	57.05	100	–57.77	100	413.38	100	–116.49	45.91
Avg. across seasons		63.32		–48.69		342.21		–87.46	41.41
Value of risk adversity per day		1.01		–.76		5.47		–1.39	.66
Type utility function		Risk averse		Mixed		Risk averse		Mixed	

[a] Measures the difference in average value between a utility maximizer and a profit maximizer. Each cell in the table is obtained by subtracting the value in Table 13 from the value shown in Table 10.

preferring utility function throughout its entire range. This accounts for his average value for risk adversity being negative. For the remaining orchardists 2, 4, 6, and 8, the value of risk adversity cannot be determined *a priori*. It may be positive or negative depending upon the nature of an actual frost season. This is because, over the lower portion of each orchardist utility function, he is risk averse, while at higher expected income levels, he is a risk taker. Orchardist 2 averaged out to be a risk averter across the 15 seasons. Orchardists 4, 6, and 8, on the other hand, averaged out as risk takers with a negative value for risk adversity. For a given frost season, the result is a function of actual frost severity. Each of these three orchardists had a positive value for risk adversity in season 3 because the first frost on April 14 was so severe that the crop remaining was reduced to 60 percent. Thus, when the frost forecast for April 29 showed a strong loss potential, if no frost protection were used, the value of the forecast was positive as a means for averting potential reduction of expected income. The same situation occurred again for orchardist 4 in season 13, and for orchardist 8 in season 8.

Analysis in this section makes it apparent that while the value of nightly frost protection information has a positive value for each orchardist, as shown in Table 11, it is of greatest economic value in cases where risk adversity is of concern to the orchardists. In that situation, the positive value of the frost forecast information lies both in its ability to predict expected outcome (yield and price effects) *and* to reduce the variability or riskiness associated with the expected outcome. For the risk-taking orchardist, the value of the forecast is confined only to its ability to predict the expected value of the outcome. To a risk taker, that component of the forecast which reduces variability of outcomes has a negative value. While the average situation is clear, it does not explain the positive values for risk adversity by a risk taker and a negative value for a risk averter in certain instances. This issue is treated in the next section.

Interdependencies Between Daily Frost Decisions

There were several atypical cases in which the value of risk adversity was positive for risk takers and negative for risk averters. This situation occurred for risk-taking orchardist 1 in seasons 9 and 13 and risk-averting orchardist 3 in season 4, as shown in Table 15. To determine the basis for this, a full season profile is required.

For risk-taking orchardist 1, a case of having a positive risk adversity value is presented in graphic form in Figure 7 using frost season 13 as the example. The value of risk adversity is measured by the vertical distance between orchardist 1's cumulative utility function and the

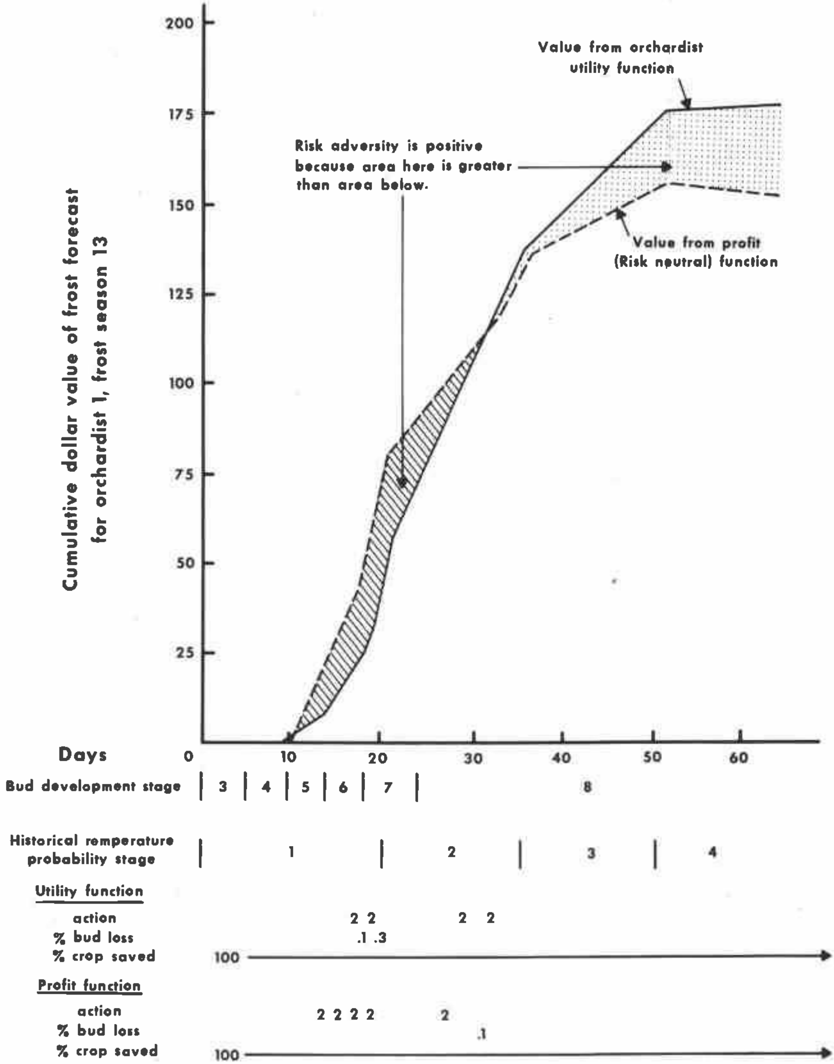

Figure 7. Comparison of cumulative value of frost forecast over frost season 3 using orchardist 1, a risk taker, and risk-neutral utility functions.

profit (risk neutral) utility function. In the first 32 days of the frost season, the profit function exceeded the risk taker's utility function. This is the usual or normal case and simply expresses the dollar value of the frost forecast being higher for the profit maximizing case. But note the bottom of the graph which shows that after day 20, risk taker orchardist 1 has suffered 40 percent bud loss and he still has yet to go through historical weather stage 2 in which frost risk is the highest.[13] Even in weather stage 3, the value stays high. This is due to two factors. One, each time some frost protection occurs, expected gross margin declines, making orchardist 1 a somewhat less strong risk taker than previously since he is being forced down his utility function where the slope is flatter, and hence, the degree of risk taking is less. Of greater importance is that the risk-neutral case involves a much more conservative decision posture and hence after day 30 has incurred only 10 percent bud loss, an excellent "risk cushion" for the last 30 days. Up to 40 percent more bud loss can occur without incurring crop loss. In weather stage 4, the value is negative since the risk of a killing frost which would kill more than 40 percent of the buds has almost zero probability of occurring. Consequently, the frost forecast value becomes small in weather stage 3 and negative in stage 4. All orchardists have a 50 percent bud loss cushion going into a frost season on which to gamble without it affecting income. The risk taker takes advantage of that cushion right from the first day of the frost season, but if the season turns bad he then places high reliance on the forecast relative to the risk-neutral case so as to avoid erosion of his expected gross margin. Thus, in a frost season in which risk-taking orchardist 1 suffers up to 50 percent bud loss in weather stage 2 and 3, and the season turns mild for bud development stage 6, the value of risk adversity can become positive relative to the risk-neutral situation.

The full season profile for orchardist 3 is shown in Figure 8 and presents the case where the value of risk adversity can be negative for a risk averter. The value of risk adversity is again measured by the vertical distance between orchardist 3's cumulative utility function and the profit (risk-neutral utility) function. During the first 32 days of the frost season, the value of the utility function exceeded the profit function reflecting the normal case where the dollar value of the forecast is greater for a risk averter than for the risk-neutral case. Also note that up to that point, the risk averter has suffered only a 10 percent bud loss so goes into the remainder of the season with a 40 percent bud loss "cushion" to protect against actual crop loss. The risk-neutral case, however, has a 40 percent bud loss, leaving only a 10 percent bud loss "cushion" before actual crop loss would occur. Thus, as weather stages 3 and 4 are entered, the probability of an actual crop loss for orchardist 3 becomes very small and hence, the value of frost information, relative to the risk-neutral case, drops markedly. The net result is a situation where risk adversity becomes negative for the season. This is shown graphically by the area between the two curves up to day 32, a positive value, which is more than offset

[13] This can be achieved visually by combining the historical weather probabilities in Table 7 with bud kill in Table 2.

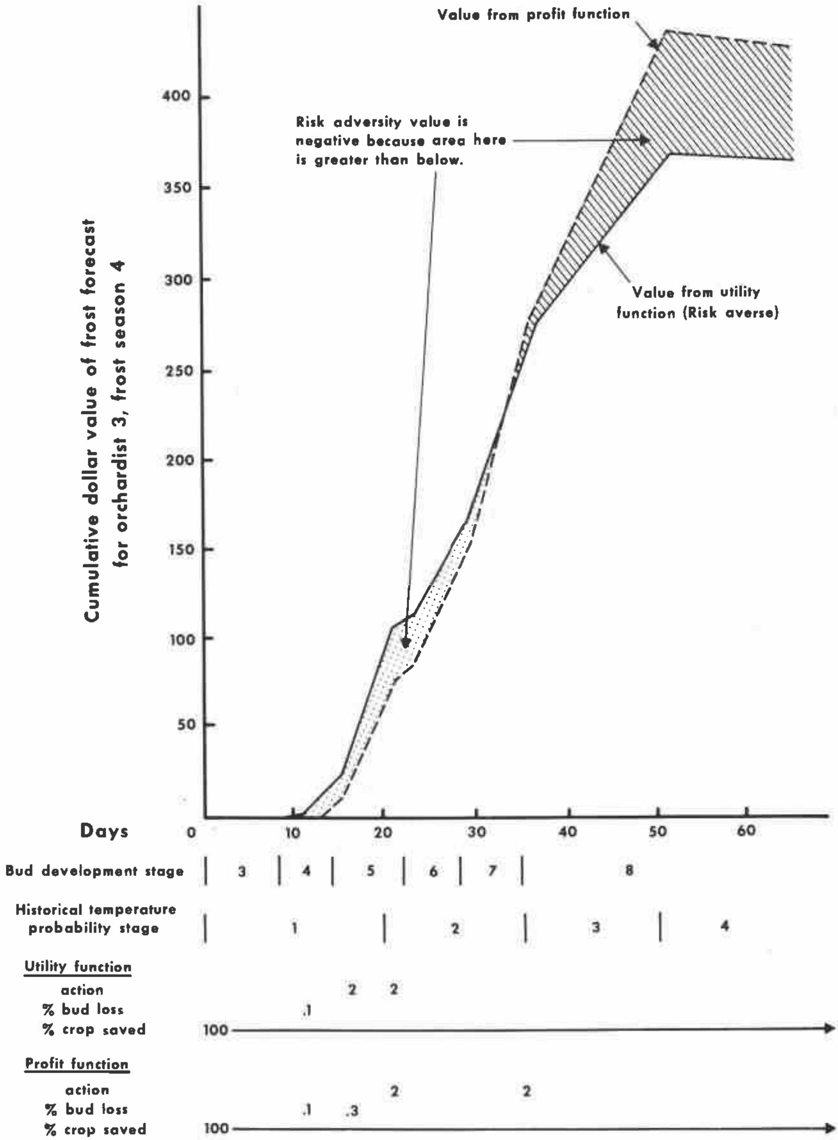

Figure 8. Comparison of cumulative value of frost forecast over frost season 4 using orchardist 3, a risk averter, and risk-neutral utility functions.

by the area between the two curves from day 32 through day 64, which has a negative value.

In both of the atypical cases, the net result is not only a function of the nature of the frost season, but the kind of frost protection strategy taken and the resulting bud losses which in turn influence the importance or value of frost forecasts in subsequent nights.

Study Uses and Limitations

This study was designed as an exploratory quantitative probe into the complex processes of decision making under uncertainty. Its intent is to provide a better understanding of several facets of that process, particularly the role of information to improve the decision process. While the study was confined to an evaluation of nightly frost forecast information for Jackson County, Oregon, orchardists, the Bayesian simulation model developed here can be used in a wide variety of instances where determination of the economic value of information designed to reduce uncertainty is sought. The approach used involves a significant departure from that used in most economic studies where evaluation of information is made *ex post* or after the fact. Hindsight is always perfect, yet real world decisions must be made *ex ante,* or before the fact when less than perfect knowledge is available. Consequently, the value of information needs also to be measured *ex ante* to determine its real economic benefit, if any, to farm decision makers. This study does that. In addition, it provides insights into how certain decision variables interact to influence the value of information.

Because the study is designed primarily to do a better job of explaining observed reality, it does not provide a set of prescriptions for telling orchardists how to improve their decision making. An implied but fundamental proposition expressed here is that they are already doing a good job of that. Any educational thrust intended is directly primarily toward economists as social scientists and physical and biological scientists concerned with meteorology and horticultural practices. For them, this study hopefully will provide a better understanding of why some research and Extension recommendations are not utilized by orchardists, even though it appears to the researcher that his recommendations would "clearly" improve orchardists' well-being. It is not that the orchardist is irrational in his decisions, but rather that his economic incentives, given resource constraints and risk aversion, simply do not warrant implementation.

The value of frost forecasts generated from the model are orchardist specific. That is, the results show the daily and seasonal value of the forecast under a number of simulated frost seasons. These results cannot automatically be summed to determine an "average" value for frost forecast service for the entire Jackson County pear-producing region. To do so requires an assumption that the eight orchardists evaluated are representative of all orchardists. The wide diversity between the eight orchardists in risk aversion strategies does not warrant use of that assumpton. If regional rather than individual grower values are to be estimated, a substitution of utility functions with a regional demand function for information is suggested as being more appropriate.

As stated earlier, hindsight is always perfect in vision. Conducting research is no exception. If afforded an opportunity to reinitiate the project, knowing *ex post* what we did not know *ex ante*, two modifications would have been made.

Historical, or *ex post*, average gross returns were used as an approximation of *ex ante* expected gross returns. To a degree that variable is an *ex post* reflection of the consequence of specific risk-aversion strategies which vary among orchardists. Further, historical returns may not accurately reflect new technology influences which orchardists include in their current frost decision process. A procedure for obtaining estimations of the *ex ante* expected gross returns from individual growers would appear worthwhile, which in turn could lead to more accurate frost forecast values.

The proportion of Bartlett to winter pears (Anjou, Bosc, and Comice) selected by individual orchardists is a means for diversifying orchard operations as a risk-aversion strategy against price and yield variability. Their susceptibility to frost are different and they enter different markets at different times of the year at different market prices. Incorporation into the model of individual grower crop proportions would be more accurate than to use constant proportions as assumed in this study.

Recommendations for Future Research

A number of recommendations are suggested for further research conducted in using a Bayesian simulation model to explain decision processes and then to use it as a predictive tool. The first requirement involves model validation. At this moment, we do not know how good the model predictions are to approximating actual behavior. Two choices appear plausible for validating the model. One is to have each of the eight orchardists in the study make frost protection decisions with the 15 simulated weather seasons and compare their decisions against those of the model. Since the data base and circumstances were for 1973, an accounting for possible changes in risk philosophy, capital position, debt commitment, and alternate income sources would need to be incorporated into the model. A second choice would be to observe grower decisions over several actual seasons, incorporate the actual season data into the model, run the model, and then compare model prediction against actual behavior. Incorporation of grower changes in risk philosophy, debt commitment, etc., into the model also would be required.

Analysis of the study was limited to within-year decisions where only frost protection and harvest costs serve as decision costs. A full year and multiple year time horizons should also be analyzed to evaluate the short- and long-run benefits from the frost forecasting as well as capital investment strategies designed to reduce uncertainty in orchard production.

The specific roles which capital position, debt commitment, and alternative income sources play in determining the nature of grower utility functions at a specific moment in time and over time is not fully understood. Evaluation of these factors and identification of other variables which affect grower utility functions is recommended.

A number of additional refinements could be made in the model which might improve its predictive accuracy. These include (1) a more complete identification of the prior information knowledge base of each orchardist since that base conditions the value of frost forecasts as added information, (2) a comparative analysis of different frost protection systems to permit comparison of their capital costs and frost protection capability trade-offs, (3) inclusion of dewpoint data into the model when orchardists begin using it as a decision variable, and (4) a more accurate specification of the relationship between bud loss and crop loss and its role as a risk-aversion strategy.

Computer Program

A copy of the computer program is available upon request from the authors. It is written in Fortran language for use on a CDC 3600 computer. The program contains four modes:

Mode 1. Value of current frost forecast relative to having only historical nightly temperature information for orchardists maximizing expected utility.

Mode 2. Value of current frost forecast relative to having no prior information (uniform distribution) whatever on spring frosts for orchardists maximizing expected utility.

Mode 3. Value of current frost forecast relative to a perfect nightly frost forecast for orchardists maximizing expected utility.

Mode 4. Value of current frost forecast relative to having only historical nightly temperature information for orchardists maximizing expected income.

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