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An Economic Analysis of Sprinkling for Bloom Delay and Freeze Protection of Apples in Farmington, Utah

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AN ECONOMIC ANALYSIS OF SPRINKLING FOR BLOOM DELAY AND FREEZE PROTECTION OF APPLES IN FARMINGTON, UTAH

by

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Jay Val Anderson

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ABSTRACT

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by

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The major purpose of this study is to analyze the economic feasibility of bloom delay by sprinkling as a means of protecting delicious apples from frost. The framework of this study is based on decision making theory under uncertainty. It demonstrates the usefulness of the Bayesian approach to determine optimum action to take in face of uncertain climatic conditions. The economic analysis was conducted for Farmington, Utah, where significant relationships were found between the end of winter rest (end of chill-unit accumulation) and time of full bloom of red delicious apples.

A posteriori probabilities for the state of nature were determined using accumulated data of end of winter rest of the apple trees. Applying the Bayesian approach, optimal strategies were determined by use of *a posteriori* probabilities and knowledge of time of end of winter rest.

It was concluded from the analysis that the installation of solid set sprinklers and use of sprinkling to delay bloom is an effective means of frost protection. Sprinkling provides two methods of freeze

protection. Bud development can be delayed increasing the hardiness of the bud to colder temperatures. Sprinkling can also be used during periods of freezing temperatures to protect the buds from freezing. It was found that a combination of protection by delay and by sprinkling for freeze protection would result in increased net returns over any other alternative. An important finding of this study is that with the dual protection afforded by sprinkling, extended amounts of delay are not necessary to obtain the desired results.

(68 pages)

INTRODUCTION

Production of fruit in Utah is characterized by high loss due to freezing temperatures occurring during sensitive stages of bud development. Losses also occur from frost during later stages of development. During the last 15 years, fruit losses have reached major proportions in Utah.

The problems of risk and uncertainty go hand in hand with apple production in Utah. Climatic conditions become the key factor in determining the success or failure of crop production. No factor is as variable or independent of prediction as are the weather patterns typical of each location. The climatic conditions cannot be controlled, thus it is necessary to have phenological knowledge about the fruit to enable us to plan in advance for adverse weather conditions.

The introduction of water application to control the temperature of fruit buds and subsequent bud development has aided the fruit grower in combating variable weather conditions. It has been empirically shown that bloom delay by sprinkling will reduce the vulnerability of the blossoms to freezing temperatures and is very effective for protection from frost damage during later stages of development.

Fruit growers can improve their success by use of the new water management technique. The decision of fruit growers to incur the extra cost of this technique can be aided by putting the decision in the correct framework and by use of a systematic approach to the decision problem. The approach to be used in this analysis is Bayesian decision theory.

Major fruit production in Utah is concentrated in a narrow band along the Wasatch front, ranging from Box Elder County on the north to Utah County on the south. The growing season is quite long providing a favorable climate for fruit production. It is hampered by early spring frosts during time of bloom. With the application of the new techniques of fruit production, some of the risk can be reduced or eliminated. Since each area and type of fruit require independent action, this study will deal only with the production of red delicious apples in the Farmington area. Decision theory will not provide any sure answers. Due to uncertain conditions, we can only hope to improve the success of the fruit grower.

To enhance the production of apples and to overcome damage due to frost, the operator must first determine a desired bloom date. With this date in mind, the operator, via decision theory, will be able to determine the correct action to be taken to achieve the desired bloom date. There are two routes possible in determining the actions to be taken. If data can be gathered to predict what the state of nature will be, then *a posteriori* probabilities will be used; but if prediction of the state of nature is not possible, then it is a "no data" problem and *a priori* probabilities are applied.

OBJECTIVES

1. To determine the projected cost of installation of solid set sprinklers, and cost of use.
2. To determine the marginal (extra) cost and revenue accrued by sprinkling for bloom delay.
3. To calculate the profit from sprinkling for freeze protection versus other alternative methods.
4. To determine the method to achieve various alternative levels of delay.
5. To develop a decision-making model that will demonstrate optimal use of alternatives based on risk and uncertainty of probable climatic conditions.
6. To determine the adverse affects of use of water application for bloom delay.

REVIEW OF LITERATURE

Prior to this study, no studies have been published using a Bayesian decision theory approach to determine optimum use of water to control frost damage in apple production. Literature in agricultural economics has not caught up with the Bayesians and few good pieces of literature can be found.

This review will briefly discuss sources of decision theory and studies involving application of decision theory within the decision making process. Bayesian statistics, other than the initial contribution of Bayes in 1762, was begun in 1959 with the publication of Probability and Statistics for Business Decisions by Robert Schlaifer (19). This book introduced the key ideas of Bayesian statistics, namely that probability is orderly opinion and that inference from data is nothing more than the revision of such opinion in the light of relevant new information.

Since that time, several significant books and articles have been written. Two of these books are very helpful in gaining an understanding of decision theory. The first is Decision Under Uncertainty written by Albert N. Halter and Gerald W. Dean (10). This book outlined the fundamentals of decision theory in a step by step approach. The main thrust of this book is the implementation and application of decision theory. The second book is Elementary Decision Theory by Chernoff and Moses (5). This book presents the general decision making formulation using a theoretical approach to Bayesian Decision Theory. Chernoff and Moses move through the theory of the "no data" problem and the use of *a priori*

probabilities; with the addition of a posteriori probabilities, they turn to a discussion of the optimal Bayes' strategy in a simple tabular calculation. This expansion to the "data" problem shows the contrast of situations when data may or may not be available in making decisions under uncertainty. The Bayesian strategy, it should be noted, is that action or combination of actions that will maximize gain or minimize loss.

An early study using decision theory was done by McConnen (13). He considered a problem of stocking rates which were determined by the five levels of range productivity in terms of animal unit days. There are three actions: heavy, medium, and light stocking rates. He presented a table of gross ranch profits for each action given a particular state of nature. He then presented a table of a posteriori probabilities which he uses to calculate expected gross ranch profits for each strategy taken. This yields an optimal stocking rate, taking into account the state of nature, using the predicted level of range productivity based on observations of the different rates of precipitation.

T. A. Walther (25) used McConnen's analysis in his approach to statistical decision theory applied to western range problems and ranch management. He clarifies some of the concepts that have prevailed in trying to apply decision-making theory and points out that the use of a choice criterion such as the minimax makes sense only if he feels that nature is going to do the worst she can by him. The minimax is that strategy which minimizes the maximum average loss. He felt that the possible criteria for selecting alternatives did not fit the situation. He states that the crux of the problem is that these criteria would fit

in a war game situation or perhaps for rival store owners in a community where the opponent is intelligent and realizes that his gain is the other's loss and acts accordingly. However, to say that nature realizes that her gain is the decision-maker's loss is going somewhat far afield and means that this type of model is not readily applicable to most range management decisions. He then demonstrates a decision model which utilizes any relevant information which is available to the decision maker.

Gerald W. Dean (6) employed the Bayesian theorem to evaluate the alternative stocking rates of cattle ranches in the foothills range area of Northern California, where stocker cattle are purchased in fall or early winter and sold in late spring or early summer. Two critical sources of uncertainty are range feed supply and cattle prices. He succeeded in obtaining reasonable appearing estimates of the *a priori* and *a posteriori* probabilities of various range conditions. Net returns for alternative action were calculated using *a posteriori* probabilities and a calculated payoff matrix for stocking rates under various conditions, given observed January 1 range conditions. He noted that even if devices for perfectly predicting range conditions were available, the possibility of increasing expected income would be slight within the scope of production possibilities presented.

Vernon R. Eidman, Gerald W. Dean, and Harold O. Carter (7) presented empirical results of a study using Bayesian theory to solve a problem involving choices between contract and independent production for California turkey producers. Their study demonstrates that several well-known quantitative tools used previously in dealing with risk and

uncertainty-probability distribution, price-forecasting equations, and simulation techniques can be employed in developing the component of the decision problem.

Harold H. Hiskey and Darwin B. Nielsen (11) employed decision theory to select optimum rotation crops for farmers in Cache Valley. The state of nature was the stream flow of the Logan River which is dependent on snowpack of the surrounding area. This can be described as an a priori probability distribution. A conditional probability distribution was constructed from snowpack observations on April 1. It is only a computational task to develop the a posteriori probabilities, and applying the Bayes' theory gives us the optimal crop rotation. The study demonstrated the importance of Bayesian theory in agriculture in measuring the magnitude of the differences between alternative actions and provides an array of estimates for consideration.

Lackawathana (12) did a similar study on crop rotations for Sevier County farmers. He employed reservoir storage and observed snowpack as the predictors of states of nature to determine water availability for irrigation purposes during late summer. Optimal action was first determined where only the knowledge of the a priori probabilities of the states of nature was available. Optimal strategies were then determined from runoff observations where available, and the a posteriori probabilities of the states of nature were determined. The study results indicated that the expected value of the additional information is substantial and came out very close to a perfect predictor and higher than the expected value of the "no data" problem.

Anderson (1) employed Bayesian theory to select optimal planting date and variety of corn to plant in the Cache Valley area. In this study, the states of nature were the damage that would occur due to various frost intensities. From this, _a priori_ probabilities were obtained. _A posteriori_ probabilities were calculated from the observed growing degree days. Using these probabilities, the optimum strategy was found that would yield maximum profit.

Bayesian theory will not remove the uncertainty characteristic of agriculture production. But it may be recognized for its importance as a tool for decision making as these studies have demonstrated.

CLIMATE OF AREA UNDER DISCUSSION

Farmington is located in northern Utah on a narrow, flat plain between the Great Salt Lake and the Wasatch Mountains. The Great Salt Lake, which has an average maximum length of 75 miles and an average maximum width of 50 miles, lies three miles to the west. This large body of water which never freezes over due to its high salt content provides a moderating effect on temperatures, particularly during the summer and winter seasons. About two miles to the east, the Wasatch Range rises abruptly to over 5,000 feet above the area. Due to the proximity of these mountains, several inches more precipitation per year falls along the eastern edge of the city than over the valley a few miles to the west.

Farmington has a semi-arid continental climate with four well defined seasons. Summers are characterized by hot, dry weather; but the high temperatures are not oppressive since the relative humidity is generally low. Afternoon and evening thundershowers occasionally bring some relief from the heat during this season. The average daily temperature range is about 32 degrees in summer; and even after the hottest days, nights are usually cool. Temperatures above 100 degrees fahrenheit in summer are likely to occur in about one season out of four.

Winters are cold, but usually not severe. The Rocky Mountains to the east and northeast act as a barrier to invasions of cold continental air masses. Thus, extended periods of extremely cold weather at Farmington are rare. The average annual snowfall is 62 inches, but as much as 152 inches have fallen in a single winter season.

Precipitation, relatively light during the summer and early fall, reaches a maximum in spring when storms from the Pacific Ocean moving into the area are more intense than at other seasons of the year. Precipitation in July, the driest month, averages one-half inch; but it averages about one inch or more for the other 11 months.

Winds are generally light to moderate in all seasons, normally ranging below 20 miles per hour. The strong, damaging winds that do occasionally occur are usually associated with easterly winds blowing out of the canyons of the Wasatch Mountains or with local thundershowers. Hail, although normally small in size, occasionally causes some damage to crops and property during the spring and summer months.

The growing season, or freeze-free period, averages about 5-1/2 months in length and extends from late April to mid-October. The foregoing description was taken from the U.S. Department of Commerce, National Oceanic and Atmospheric Administration, Environmental Data Service, Climatological Summary (22).

Some of the limiting factors of apple production are the early freezing temperatures which destroy blossoms or buds and occasional irrigation water shortages. The length of growing season and cool fall temperatures serve to produce a high quality apple.

THEORETICAL FRAMEWORK AND STUDY ASSUMPTIONS

Decision model

This section will illustrate, in a theoretical sense, the components of the decision theory process. It will be applied in a later section of this thesis. This will follow the seven general steps outlined by Halter and Dean (10, p. 9).

The first step is a listing of all the actions available to the fruit producer.

$$a_1, a_2, a_3, \ldots a_i$$

The actions to be included would include doing nothing or following tradition or those actions more responsive to the state of nature. However, to avoid complication of the problem and for simplicity, some of the vast array of possible actions need to be excluded.

Step two is much like step one. It is a listing of the states of nature that could occur. This, too, should include only the most important ones to avoid over complication of the problem.

$$\theta_1, \theta_2, \theta_3, \ldots \theta_j$$

In step three, a loss or gain table is generated from the consequences of each possible combination of actions and states of nature. This can be measured in utility or dollars. Let U signify utility (the gain or loss from each combination of actions and states of nature) in Table 1.

Table 1. Loss-gain table

States of nature	Available actions			
	a_1	a_2	. . .	a_i
θ_1	$U(\theta_1,a_1)$	$U(\theta_1,a_2)$	. . .	$U(\theta_1,a_i)$
θ_2	$U(\theta_2,a_1)$	$U(\theta_2,a_2)$	. . .	$U(\theta_2,a_i)$
.	.	.	. . .	.
.	.	.	. . .	.
.	.	.	. . .	.
θ_j	$U(\theta_j,a_1)$	$U(\theta_j,a_2)$	. . .	$U(\theta_j,a_i)$

This table indicates the gain or loss that will occur in each possible situation.

Step four is an experiment or other device for obtaining knowledge about the state of nature. Observations are made that are related to the state of nature. It should be possible to make those same observations at the time the decision is made. An estimation of an actual relationship between the observation and the state of nature is made in probabilistic terms. This makes it possible to draw some conclusions about what the state of nature will be by the observations made and probability of success.

It is at this point that the "data" problem is separated from the "no data" problem as mentioned by Chernoff and Moses (5, p. 167). If it is not possible to make any observations prior to the decision, then we can only treat the situation as a "no data" problem. After we conduct

the experiment and the observations are made, we can generate the following probability table (Table 2).

Table 2. Probability of observing Z_k when θ_j is the state of nature

	Observations					
States of nature	Z_1	Z_2	.	.	.	Z_k
θ_1	$P(Z_1,\theta_1)$	$P(Z_2,\theta_1)$	.	.	.	$P(Z_k,\theta_1)$
θ_2	$P(Z_1,\theta_2)$	$P(Z_2,\theta_2)$	.	.	.	$P(Z_k,\theta_2)$
.	.	.	.	.	.	.
.	.	.	.	.	.	.
.	.	.	.	.	.	.
θ_j	$P(Z_1,\theta_j)$	$P(Z_2,\theta_2)$	.	.	.	$P(Z_k,\theta_2)$

This table is then used to calculate the optimum strategy in the steps to follow. Any new or additional information can be used to make the data more reliable before the decision is made.

"No data" decision problem

The "no data" situation is not as detailed as the "data" situation. Of course, the ability to make a meaningful decision is considerably less. The lack of knowledge and information about the states of nature is the cause of this. Where it is not possible to make an observation that predicts the state of nature, it is possible to improve the ability of making decisions by using *a priori* probabilities. This is the "no data"

problem. *A priori* probabilities are formulated for each state of nature by using the data of all past periods. An example of *a priori* probabilities (Table 3) is the probability of frost before a certain date such as is published in *Freezing Temperature Probabilities in Utah* by Gaylen L. Ashcroft and W. J. Derksen (3). This was based on 30 or more years of accumulated data.

Table 3. Table of *a priori* probabilities

$P(\theta_j)$
$P(\theta_1)$
$P(\theta_2)$
.
.
.
$P(\theta_j)$

By using the loss or gain table and the *a priori* probabilities, it is possible to arrive at the best available action or best decision considering there is no additional information. This is accomplished by multiplying the loss or gain by the corresponding *a priori* probability. By taking the total sum of the loss or gain for each action, the best alternative can be selected. This is demonstrated in Table 4.

Table 4. Tabular calculation of the "no data" problem

States of nature	Loss-gain table Available actions				Probability table *A priori* probabilities
	a_1	a_2	. . .	a_i	$P(\theta_j)$
θ_1	$U(\theta_1,a_1)$	$U(\theta_1,a_1)$	. . .	$U(\theta_1,a_i)$	$P(\theta_1)$
θ_2	$U(\theta_2,a_1)$	$U(\theta_2,a_2)$	. . .	$U(\theta_2,a_i)$	$P(\theta_2)$
.	.	.	. . .	.	.
.	.	.	. . .	.	.
.	.	.	. . .	.	.
θ_j	$U(\theta_j,a_1)$	$U(\theta_j,a_2)$	. . .	$U(\theta_j,a_i)$	$P(\theta_j)$

Loss-gain table with probabilities considered

Available actions

a_1	a_2	. . .	a_i
$[U(\theta_1,a_1)][P(\theta_1)]$	$[U(\theta_1,a_2)][P(\theta_1)]$	. . .	$[U(\theta_1,a_i)][P(\theta_1)]$
$[U(\theta_2,a_1)][P(\theta_2)]$	$[U(\theta_2,a_2)][P(\theta_2)]$	. . .	$[U(\theta_2,a_i)][P(\theta_2)]$
.	.	. . .	.
.	.	. . .	.
.	.	. . .	.
$[U(\theta_j,a_1)][P(\theta_j)]$	$[U(\theta_j,a_2)][P(\theta_j)]$	. . .	$[U(\theta_j,a_i)][P(\theta_j)]$
$\sum_{\theta=1}^{j}[U(\theta_j,a_1)][P(\theta_j)]$	$\sum_{\theta=1}^{j}[U(\theta_j,a_2)][P(\theta_j)]$	. . .	$\sum_{\theta=1}^{j}[U(\theta_j,a_i)][P(\theta_j)]$

After the previous calculation of Table 4, the optimal available action can be readily distinguished. If it is a loss table, the best action will be the minimum of the sums from a_1 to a_i.

$$\sum_{\theta=1}^{j} [U(\theta_j, a_i)][P(\theta_j)]$$

If it is a gain table, optimal action will be the sum with the maximum value.

"Data" decision problem

We can resume consideration of the "data" situation now that the "no data" situation has been briefly explained. Proceeding with step five, the decision maker lists the possible strategies that are available in any given situation. A strategy is a rule for decision making which indicates which action to take for each kind of observation. Table 5 lists all the possible combination of actions for each given observation of Z_1 to Z_k.

Table 5. List of all possible strategies

	Actions taken with given observations					
Strategies	Z_1	Z_2	.	.	.	Z_k
s_1	a_1	a_1	.	.	.	a_i
s_2	a_1	a_3	.	.	.	a_i
s_3	a_3	a_1	.	.	.	a_i
.	.	.	.	.	.	.
.	.	.	.	.	.	.
.	.	.	.	.	.	.
s_m	a_2	a_3	.	.	.	a_i

The sixth step determines the consequences of each strategy for each state of nature as determined by the probabilities in Table 2. This step yields the average gain or loss for each strategy given the corresponding state of nature (Table 6).

Table 6. Average utility for each strategy and corresponding state of nature

States of nature	Strategies s_1	..... s_m
θ_1	$P(\theta_1,Z_1)\cdot U(\theta_1,a_i)+P(\theta_1,Z_2)\cdot U(\theta_1,a_i)+......P(\theta_1,Z_k)\cdot U(\theta_1,a_i)$	.....
θ_2	$P(\theta_2,Z_1)\cdot U(\theta_2,a_i)+P(\theta_2,Z_2)\cdot U(\theta_2,a_i)+......P(\theta_2,Z_k)\cdot U(\theta_2,a_i)$	.....
.	.	.....
.	.	.....
.	.	.....
θ_j	$P(\theta_j,Z_1)\cdot U(\theta_j,a_i)+P(\theta_j,Z_2)\cdot U(\theta_j,a_i)+......P(\theta_j,Z_k)\cdot U(\theta_j,a_i)$	.....

The last step is multiplying the average gain or loss of each state of nature, in the previous step, by its respective a priori probability. By summing the results, we arrive at one gain or loss figure for each strategy. The decision maker can then choose the optimal strategy yielding the maximum gain or the minimum loss. This approach can be quite time consuming inasmuch as it includes all possible strategies. If only the optimal strategy is desired, one may go the route using a posteriori probabilities. A complete review of the above method can be found in Decision Under Uncertainty by Halter and Dean (10).

To calculate the a posteriori probabilities when no new information is available, the states of nature corresponding to the observation $(P(\theta_j,Z_k))$ are multiplied by the corresponding a priori probabilities (Table 7). The sum of the products relative to each observation is

Table 7. Computation of the *a posteriori* probabilities

States of nature	Observations Z_1	Z_2	. . .	Z_k	*A priori* probabilities $P(\theta_j)$
θ_1	$P(\theta_1,Z_1)$	$P(\theta_1,Z_2)$	. . .	$P(\theta_1,Z_k)$	$P(\theta_1)$
θ_2	$P(\theta_2,Z_1)$	$P(\theta_2,Z_2)$	. . .	$P(\theta_2,Z_k)$	$P(\theta_2)$
.	.	.	. . .	.	.
.	.	.	. . .	.	.
.	.	.	. . .	.	.
θ_j	$P(\theta_j,Z_1)$	$P(\theta_j,Z_2)$	. . .	$P(\theta_j,Z_k)$	$P(\theta_j)$

Joint probabilities $P(\theta_j)\ P(\theta_j,Z_k)$

Z_1	Z_2	. . .	Z_k
$P(\theta_1)\ P(\theta_1,Z_1)$	$P(\theta_1)\ P(\theta_1,Z_2)$	. . .	$P(\theta_1)\ P(\theta_1,Z_k)$
$P(\theta_2)\ P(\theta_2,Z_1)$	$P(\theta_2)\ P(\theta_2,Z_2)$	. . .	$P(\theta_2)\ P(\theta_2,Z_k)$
.	.	. . .	.
.	.	. . .	.
.	.	. . .	.
$P(\theta_j)\ P(\theta_j,Z_1)$	$P(\theta_j)\ P(\theta_j,Z_2)$	. . .	$P(\theta_j)\ P(\theta_j,Z_k)$
$\sum_{\theta=1}^{j} P(\theta_j)\ P(\theta_j,Z_1)$	$\sum_{\theta=1}^{j} P(\theta_j)\ P(\theta_j,Z_2)$.	. .	$\sum_{\theta=1}^{j} P(\theta_j)\ P(\theta_j,Z_k)$

divided by the sums corresponding to Z_k for relative members of the joint probability matrix as in Table 8. This gives the a posteriori probabilities corresponding to each state of nature (θ_j) and each observation (Z_k) denoted by the letter w_1 through w_j. Next, multiply the a posteriori probabilities by the corresponding figures in the loss-gain table and sum the values for each available action as shown in Table 9. When all calculations have been accomplished, the Bayesian strategy ($B(\bar{w},a)$) for each observation is self-evident. If you are using a loss table, it is that strategy with the minimum loss. If using a gain table, it is that strategy with the maximum gain. This can be done for any number of possible actions. The most important property of this scheme is that it yields the optimal strategy or Bayes' Strategy.

Table 8. A posteriori probability table

A posteriori probabilities	Observations			
	Z_1	Z_2	. . .	Z_k
w_1	$\frac{P(\theta_1)\ P(\theta_1,Z_1)}{\sum_{\theta=1}^{j} P(\theta_j)\ P(\theta_j,Z_1)}$	$\frac{P(\theta_1)\ P(\theta_1,Z_2)}{\sum_{\theta=1}^{j} P(\theta_j)\ P(\theta_j,Z_2)}$	. . .	$\frac{P(\theta_1)\ P(\theta_1,Z_k)}{\sum_{\theta=1}^{j} P(\theta_j)\ P(\theta_j,Z_k)}$
w_2	$\frac{P(\theta_2)\ P(\theta_2,Z_1)}{\sum_{\theta=1}^{j} P(\theta_j)\ P(\theta_j,Z_1)}$	$\frac{P(\theta_2)\ P(\theta_2,Z_2)}{\sum_{\theta=1}^{j} P(\theta_j)\ P(\theta_j,Z_2)}$	. . .	$\frac{P(\theta_2)\ P(\theta_2,Z_k)}{\sum_{\theta=1}^{j} P(\theta_2)\ P(\theta_2,Z_k)}$
.	.	.	. . .	.
.	.	.	. . .	.
.	.	.	. . .	.
w_j	$\frac{P(\theta_j)\ P(\theta_j,Z_1)}{\sum_{\theta=1}^{j} P(\theta_j)\ P(\theta_j,Z_1)}$	$\frac{P(\theta_j)\ P(\theta_j,Z_2)}{\sum_{\theta=1}^{j} P(\theta_j)\ P(\theta_j,Z_k)}$	. . .	$\frac{P(\theta_j)\ P(\theta_j,Z_k)}{\sum_{\theta=1}^{j} P(\theta_j)\ P(\theta_j,Z_k)}$

Table 9. Bayes' strategy

	Observation Z_1					
	Z_1	Z_2	.	.	.	Z_j
$B(\bar{w},a)$	$\sum_{w=1}^{j} w_j\ U(\theta_j, a_1)$	$\sum_{w=1}^{j} w_j\ U(\theta_j, a_2)$	.	.	.	$\sum_{w=1}^{j} w_j\ U(\theta_j, a_i)$

Chill-unit model

Deciduous fruit trees will not grow noticeably during a period in the winter, even if temperature and soil moisture conditions are favorable. This physiological condition is termed "rest". This rest condition is broken by sufficient exposure to cold temperatures. At the end of this period, any warm climatic condition causes a beginning of development.

In the past, the standard method of determining the time of rest completion was to bring shoots into a greenhouse and expose them to growing temperatures (18-24° C.). If the shoots develop within a two to three week period, rest is considered completed. This approach was very time consuming and, for many purposes, the delay in obtaining results was too long. With this in mind, a chill-unit model equating temperatures to effective chill-units, such that rest completion can be predicted with a high degree of accuracy, was developed by Richardson, Seeley, and Walker (17). This model is based on the accumulation of chill-units where one chill-unit equals one hour exposure at 43° F. (6° C.). The chilling contribution becomes less than one as temperatures drop below or rise above this optimum value. A negative contribution to the chill-unit accumulation occurs at temperatures above 60° F. (15° C.) and zero unit contribution occurs below 32° F. (0° C.). Table 10 lists specific temperature values and their equivalent chill-unit contributions as used in the model.

The conversion of ambient air temperatures to chill-units is accomplished by use of a computer. It converts each hourly temperature to

the equivalent chill-unit value as determined by Table 10. These values are accumulated for an entire 24 hour period.

Table 10. Conversion of selected ambient air temperatures to chill-units

Ambient air temperatures		Chill-units contributed
°C.	°F.	
<1.4	<34	0.0
1.5 - 2.4	35 - 36	0.5
2.5 - 9.1	37 - 48	1.0
9.2 - 12.4	49 - 54	0.5
12.5 - 15.9	55 - 60	0.0
16.0 - 18.0	61 - 65	-0.5
>18	>65	-1.0

To determine when accumulated chill-units become effective in meeting rest requirements, chill-unit accumulators beginning in late summer are plotted as a function of time. During the late summer, the temperature is usually above 60° F. (15.6° C.), hence chill-units are negative. Positive chill-unit accumulation begins just after the day in the fall when the largest negative accumulation takes place (18, p. 49).

Chill-units required to break the rest period can vary greatly among different fruits and among different cultivars of a given species. The requirement of the red delicious apple, necessary to complete rest, is

1,234 accumulated chill-units. The chill-unit concept is used to predict the time when trees have completed winter rest. It is also used to determine the progress of trees during their dormant period and allows an estimation of intensity of rest (18).

Growing degree hour model

By use of the previously discussed chill-unit model, the date a tree completes winter rest can be estimated quite accurately (18). After the time of rest completion, any energy in the form of temperatures above a base temperature will result in some bud development. The amount of growth that occurs in a given day increases as temperatures rise above the base temperature. The growing degree hour model expresses this growth-heat relationship. Under this concept, it is assumed that there is no growth or development of a given plant species while the plant is held below some base temperature.

The linear increase in rate of growth with increase in temperature cannot continue indefinitely. At high temperatures, the increase in rate of growth may cease; and at even higher temperatures, proteins are denatured and damage to plant cells may occur. Thus, an upper limit of 77° F. (25° C.), beyond which there is no increase in plant development, is included within the model.

A growing degree hour (GDH) is defined as one hour at a temperature one degree Celsius above the base temperature of 4.5° C. (40° F.). GDHs are calculated by subtracting 4.5° C. from each hourly temperature between 4.5° C. and 25° C. All temperatures above 25° C. (77° F.) are assumed to equal to 25° C.; thus, the greatest accumulation for any one hour is 20.5 GDHs. Use of this method enables us to predict phenological

stages of development; also prediction of bud hardiness such as T-10, T-50, T-90 temperatures and indicated harvest date is possible from this method. The amount of GDHs necessary for full bloom in red delicious apples is 12,480.

Fruit bud delay design and cost

Application of the previous two models enables us to consider overhead sprinkling for bloom delay. After the completion of rest, sprinkling is begun whenever the temperatures of the apple buds rise above 45° F. The cooling effect of evaporating water will delay the development of the bud (2). This will continue as long as sprinkling occurs. It should be noted that the amount of water necessary for bloom delay increases considerably during the later stages of bud development because of higher ambient air temperature. This delayed development of the buds will result in significantly later bloom dates.

Limited amounts of research have been done in the area of bloom delay by sprinkling. The design and cost of any sprinkler installation will vary according to topography of the area, source and availability of water, and other economic factors such as cost and type of equipment installed. Because of these variable factors, we have assumed a 40 acre orchard on reasonably level ground. Tree spacing is a moderately high density planting, (200 trees/acre) reflecting the new methods of cultivation currently being used to increase efficiency of orchard operation. Orchard design is found in Figure 1. The cost attached to components of the system came from Olsen, Snyder, and Bullens (4, 14, 20) in 1975. They are as follows:

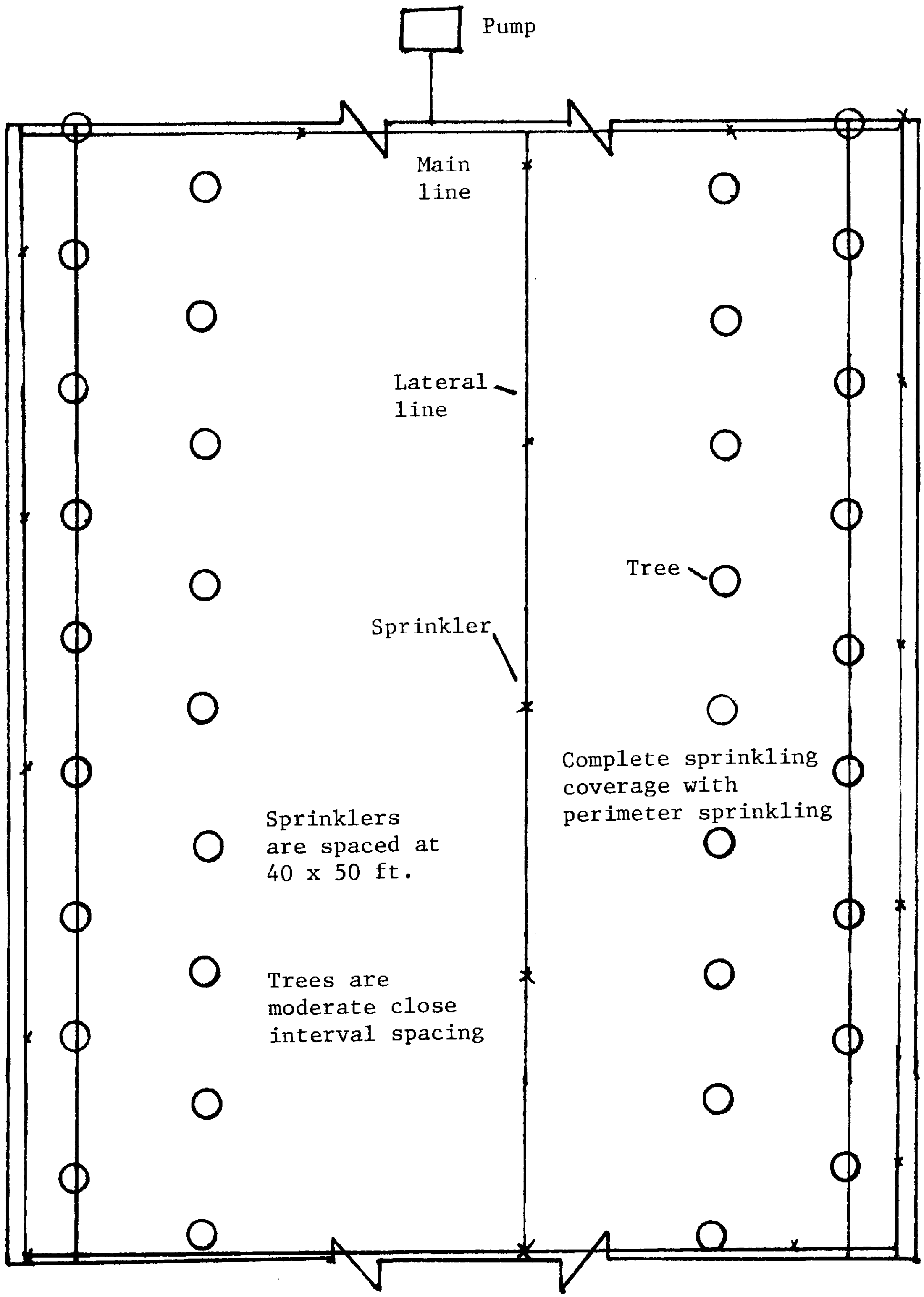

Figure 1. Sprinkler layout for a 40-acre orchard.

Source: Richard Griffin, Department of Agricultural and Irrigation Engineering, Utah State University.

Cost estimate - 40 x 50

Pump 165 BHP, 3332 GPM		$6,622.00
Panel		1,594.00
Laterals 3 inch PVC 27 x 1320 = 35,640 ft. 160 PSI $59.00/100 ft.		21,038.00
Risers (anchors may be necessary) 3/4 inch riser 13 ft. x 918 = 11,934 ft. $41.00/100 ft.		4,892.00
Tees 3 inch x 3 inch x 3/4 inch = 918 $6.70/each		6,150.00
Sprinklers 918 $6.00/each		5,508.00
Main lines - 660 ft. 8 inch IPS $159.00/100 ft.		1,113.00
660 ft. 6 inch IPS 91.00/100 ft.		637.00
Tees (main lines) 13 8 inch x 8 inch x 3 inch $22.00/each		286.00
14 6 inch x 6 inch x 3 inch 13.50/each		189.00
Automatic equipment		500.00
Drain line		660.00
	Total	$49,189.00
	Per acre	$ 1,229.00
Cost per year @ 8% for 15 years		$ 5,847.00
Cost per ac/yr	$144.00	

Fruit bud delay - design and cost

40 acre tree spacing 20 x 20 ft.

Rainbird No. 30

40 PSI 9/64 nozzle 3.63 GPM

40 x 50 spacing pr 0.13 in/hr

Continuous operation 918 sprinklers

918 x 3.63 = 3332 GPM

Main line

660 ft. 8 inch IPS	10.56 PSI loss
660 ft. 6 inch IPS	6.27 PSI loss

Laterals

34 x 3.63 = 123 GPM

3 inch PVC 6 PSI loss

Total friction loss

Sprinklers	40.00 PSI
Mains	10.56 PSI
	6.27 PSI
Laterals	6.00 PSI
Miscellaneous	5.00 PSI
	67.83

Pump

$$BHP = \frac{3332 \times 67.83}{3960 \times .433 \times .80} = 165$$

This system is assumed to be an ideal situation. The water is assumed to be available and the source is near the center. Some additional factors may be necessary such as support for risers and adaptors for low level sprinkling as the season progresses. One should take notice that the designed system provides for wetting of the trees on the periphery. The sprinklers are spaced close enough together to insure adequate wetting of the buds. The sprinkling system should be designed for adequate output of water and should conform to the requirements set forth by Griffin (8).

ANALYSIS AND APPLICATION OF THE MODEL

Desired bloom date

An optimum bloom date that will reduce fruit loss is desired. The actual bloom date will depend on the actions taken by the producer. The actions chosen will be based on the following considerations: (1) the spring weather typical for each area; (2) the normal bloom data of past years; and (3) the degree of risk of possible T-10, T-50, and T-90 temperatures (Appendix, Table 21). These temperatures refer to the amount of blossom loss if subjected to those temperatures at time of bloom. An ideal situation is one where the degree of risk is as low as possible for the minimum amount of loss. Consider, however, that if we delay bloom until all chance of frost damage is over, there may be ill effects at the time of harvest.

It has been suggested that an acceptable decision for time of full bloom is after day 252 or May 10. This is a fruit tree date where day 1 begins on September 1 and continues through day 365 or August 31. At this time, there is a 25 percent chance of T-50 frost damage. One must realize that a 50 percent loss of blossoms may result in no loss of total crop. However, succeeding freezing temperature after time of bloom can result in significant crop loss.

Alternative actions

Actions to achieve an optimal bloom date must be considered. Since each year's climate is different, so might be the action taken each year.

The action taken would depend on the state of nature we predict at the end of chill-unit accumulation. Whichever action leads us to the greatest reward will be taken.

Analysis of the 31 years of data leads us to several conclusions. On the average, if apple blossom development was delayed one week, significant gains in production would be attained. The amount of delay necessary would vary according to the states of nature. Extended delay could be harmful to the crop at time of harvest or marketing as could delay only with no other action during prolonged frost periods. Thus, actions including delay and freeze protection by sprinkling are necessary. Also, during certain years, freeze protection only would be necessary. A control action of no action at all would also be useful in projection of gains and losses.

With this in mind, the following actions were selected. These are as follows:

A_1. Delay to produce full bloom on May 4, no further action.

A_2. Delay to produce full bloom on May 9, no further action.

A_3. Delay to produce full bloom on May 17, no further action.

A_4. Do nothing.

A_5. Freeze protection by sprinkling only.

A_6. Delay to produce full bloom on May 4, then application of freeze protection by sprinkling.

A_7. Delay to produce full bloom on May 9, then application of freeze protection by sprinkling.

A_8. Delay to produce full bloom on May 17, then application of freeze protection by sprinkling.

There could be many different actions taken but these differences would not be significant. Those actions that would not be applicable have not been considered. It must be kept in mind that the decision as to which action to apply must be made at the time of end of chill-unit accumulation. The success of each action corresponding to the state of nature will be shown in the corresponding tables (Tables 11 to 14). The states of nature correspond to different bloom dates of the apple trees.

To derive a profit or loss table, first calculate the cost of each action. This cost includes the cost of installation of the sprinklers, cost of operation, and the freeze loss associated with each action for the given state of nature.

The cost of the sprinkling system was shown in the previous section. For a 40 acre orchard, the amortized cost of installation will be $144.00 per acre for 15 years.

The number of growing degree hours required to delay bloom for each action was determined using a method devised by Richardson (16). This method makes use of the growing degree hour concept where temperatures above 40° F. contribute to the development of the bud. A model was devised to calculate the number of growing degree hours needed in past years to obtain the desired bloom date. This was done by use of recorded maximum and minimum temperatures for the Farmington area (23). Since hourly temperatures have not been recorded, a reliable means of estimating these temperatures was necessary.

Maximum and minimum temperatures are recorded every 24 hours. Thus, by following the procedure of dividing the range by 11, and adding the

fractional part to the minimum temperature and following temperatures in succession, hourly temperatures can be estimated. By assuming that the minimum temperature is approximately equal to the dew point (actual difference in Farmington is not significant) and the maximum temperature is equal to the dry bulb temperature, we can estimate maximum wet bulb temperature (21). Hourly wet bulb temperatures are estimated by using the previously explained procedure. The range of maximum and minimum wet bulb temperatures are divided by 11. The fractional part is added to the minimum temperature and following temperatures in succession to estimate hourly wet bulb temperatures. This can vary significantly from the ambient air temperature. Since we begin sprinkling when the ambient air temperature is 45° F. and continue until it is below, we can estimate the accumulation of growing degree hours in the sprinkled orchard. This enables us to determine the protection achieved by sprinkling for bloom delay. Growing degree hours are calculated by subtracting 40° F. from the estimated hourly wet bulb temperature. The difference, if positive, constitutes the number of growing degree hours accumulated for that hour. A normal growing degree hour accumulation curve for sprinkled fruit can be drawn using normal maximum and minimum temperatures. Comparing this curve with the actual growing degree hour accumulation curve for any particular year, and with the assumption that commencement of growing degree hour accumulation is the same for the normal data and for the particular year, the number of days delay necessary each year to achieve the desired bloom date was determined. The number of hours of sprinkling was estimated by use of the normal temperatures and normal phenological dates of red delicious apples in the Farmington area. The

past procedure of estimating the hourly temperatures for each day was repeated. Thus, the number of hours with a temperature greater than 45° F. can be calculated. Once the needed number of days of delay is calculated, then the hours of sprinkling for those days was calculated quite readily.

The number of hours of sprinkling for freeze protection only was calculated in the following manner. Recorded maximum and minimum temperatures during the stages of bloom were employed to construct a temperature trace. Sprinkling for freeze protection begins four degrees above the lethal temperature and continues until the temperature is four degrees above. By using the temperature trace, the number of hours of sprinkling required to protect against the lethal temperatures was estimated. The number of hours of required sprinkling for each action and the respective state of nature are listed in Table 11.

With the knowledge of the needed amount of hours of sprinkling, we can calculate the cost incurred. This is done using the current cost schedule of Utah Power and Light for 1975 (24). Pumping costs were calculated on the basis of two and three months as required by the different actions (Table 12).

The amount of crop loss for the 31 years of record was determined in the following manner. Recorded maximum and minimum temperatures during the stages of bloom was compared to the T-10, T-50, and T-90 temperatures. These temperatures refer to the amount of blossom loss the tree will suffer if exposed to those temperatures. By keeping record of the amount of T-10, T-50, or T-90 temperatures the tree was exposed to, it was possible to estimate the percent of blossom loss due

Table 11. Number of hours of required sprinkling for each action and the respective state of nature

State of nature	A_1	A_2	A_3	A_4	A_5	A_6	A_7	A_8
θ_1	150	300	500		65	185	315	510
θ_2	25	110	260		60	25	110	260
θ_3	0	13	50		25	20	20	54
θ_4	0	10	50		10	10	15	54

Note: A_1 = Delay to produce full bloom on May 4, no further action.

A_2 = Delay to produce full bloom on May 9, no further action.

A_3 = Delay to produce full bloom on May 17, no further action.

A_4 = Do nothing, no sprinkling involved.

A_5 = Freeze protection by sprinkling only.

A_6 = Delay to produce full bloom on May 4, then application of freeze protection by sprinkling.

A_7 = Delay to produce full bloom on May 9, then application of freeze protection by sprinkling.

A_8 = Delay to produce full bloom on May 17, then application of freeze protection by sprinkling.

Table 12. Cost of sprinkling ($) per acre plus amortized cost of installation of sprinkler system

State of nature	A_1	A_2	A_3	A_4	A_5	A_6	A_7	A_8
θ_1	177	177	194		170	178	185	195
θ_2	167	166	184		169	167	174	184
θ_3	144	159	169		167	166	166	169
θ_4	144	159	169		166	166	166	169

Note: All costs were rounded to the nearest dollar.

to freezing temperatures for each year. It was assumed that 50 percent of the blossoms would constitute a full crop of apples. In this case, that would mean four bushels per tree. If the orchard manager used the correct cultural practices of chemical thinning, etc., this estimate would be somewhat pessimistic.

After the calculations for each year were made, average losses were determined for the years corresponding to the respective states of nature. Average losses are shown in Table 13.

Profit and loss tables were constructed by using the data from the previous tables and from an estimated receipts, costs, and net returns for 1975 (Appendix, Table 22 and 23). All calculations were based on costs and returns for a mature orchard. All fixed costs were the same. Changes in variable costs occurred only with those costs involving harvesting of the crop and interest on operating capital. Any additional costs incurred are in the form of sprinkler installation and operation.

Table 13. Crop loss due to frost only, calculated in percent for each action taken

State of nature	A_1	A_2	A_3	A_4	A_5	A_6	A_7	A_8
θ_1	45	15	9	86	20	0	0	0
θ_2	63	55	10	61	10	0	0	0
θ_3	47	17	0	48	0	0	0	0
θ_4	3	3	0	5	0	0	0	0

The estimated costs and net returns table assumes a miscellaneous crop loss of ten percent. This increased amount of crop loss must be taken into consideration before a net return or loss can be calculated.

Application of the costs and receipts to the corresponding actions permit development of the profit or loss per acre as shown in Table 14.

States of nature

An experiment was performed using the chill-unit model and the growing degree hour model. This provided information as to the time of end of winter rest (end of chill-unit accumulation) and the several stages of bloom for red delicious apples in Farmington, Utah for 31 years shown in Appendix, Table 24. Analysis of the 31 years of data provided a basis for a selection of states of nature. The state of nature is an exogenous factor that directly affects the outcome of a particular action, but cannot be controlled with certainty by the decision maker. The states of nature in this study correspond to the

Table 14. Profit or loss for each action taken according to the true state of nature in dollars per acre

State of nature	A_1	A_2	A_3	A_4	A_5	A_6	A_7	A_8
θ_1	(171)	241	304	(556)	179	445	438	428
θ_2	(408)	(297)	301	(213)	317	454	449	439
θ_3	(165)	231	455	(35)	456	457	457	452
θ_4	439	424	455	555	457	457	457	452

θ_j = actual bloom date.

A_i = alternative actions available to the producer at time of ECA.

All profit or loss was rounded to the nearest dollar.

full bloom dates of red delicious apples in Farmington. Four states of nature have been considered and are as follows:

θ_1 Poor full bloom before day 242.

θ_2 Fair full bloom between day 242 and day 249.

θ_3 Good full bloom between day 250 and day 254.

θ_4 Excellent full bloom after day 254.

The data also provided information as to observations made of end of chill-unit accumulation (ECA). These observations serve as predictors as to what the state of nature will be. Four classifications of observations (Z_k) were considered. They are as follows:

Z_1 Poor ECA on or before day 180.

Z_2 Fair ECA between day 181 and day 190.

Z_3 Good ECA between day 191 and day 200.

Z_4 Excellent ECA after day 220.

The selection of class intervals for the states of nature and observations was made on the basis of logical breakpoints after inspection of the calculated data.

<u>Conditional probability</u>

θ_j is an independent variable which the orchard operator needs to know more about to select the correct action in advance. The observation of ECA serves as a useful predictor in estimation of the value of θ_j, or the state of nature. Significant relationship has been seen between ECA and time of full bloom. The results of the observed frequencies which served as a predictor of the states of nature (θ_j) are shown in Table 15.

Table 15. Frequency of four observations at time of ECA given the state of nature

State of nature		Z_1	Z_2	Z_3	Z_4	Total θ_j
θ_1	Poor	4	3	0	0	7
θ_2	Fair	4	6	2	1	13
θ_3	Good	2	1	2	1	6
θ_4	Excellent	0	0	2	3	5
Total Z_k		10	10	6	5	31

θ_j = the state of nature (actual bloom date).

Z_k = the observation of ECA date.

If θ_1 is the state of nature (full bloom before day 242), four of the seven years will be expected to have a poor ECA date; three of the seven years will be expected to have a fair ECA date; no year is expected to have a good or excellent ECA date. The rest of the table can be interpreted in a similar manner.

From the _a priori_ experience (observation of bloom date for 31 years for each θ_j), the conditional probability distribution can be computed.

$$P\ (Z_k/\theta_j)$$

where Z_k is the observation of date of ECA (Table 16).

Table 16. The conditional probability of observing Z_k when θ_j is the state of nature

State of nature		Z_1	Z_2	Z_3	Z_4
θ_1	Poor	0.571	0.429	0.0	0.0
θ_2	Fair	0.308	0.462	0.154	0.077
θ_3	Good	0.333	0.167	0.333	0.167
θ_4	Excellent	0.0	0.0	0.4	0.6

This table shows the conditional probabilities of four observations of ECA given the state of nature θ_j. The value of 0.571 in column one means that 57.1 percent of the time, if ECA occurs on or before day 181, apple growers can expect an early bloom year when, in fact, it will be an early bloom. The remaining conditional probabilities can be derived similarly. It is the ECA date that is observed, not the θ_j. The state of nature is unknown at the time of the decision.

As discussed previously in the "no data" problem, a priori probabilities are formulated by use of data of all past periods. After examination of the data, the observed number of occurrences for the state of nature θ_1 to θ_4 are 7, 13, 6, and 5, respectively. Thus, the a priori probabilities based on the 31 year period analyzed are as shown in Table 17.

Table 17. *A priori* probabilities for the 31 year period

$P(\theta_j)$
$P(\theta_1) = 0.226$
$P(\theta_2) = 0.419$
$P(\theta_3) = 0.193$
$P(\theta_4) = 0.161$

If this was a "no data" problem, we could now apply the *a priori* probabilities to determine the best available action. However, we are dealing with a "data" problem and are seeking the Bayesian strategy. Therefore, we will continue with the calculation of the *a posteriori* probabilities without regressing to the "no data" problem for the remainder of this thesis.

A posteriori probabilities

Using the conditional and *a priori* probabilities, one can calculate the joint probabilities. This is done by multiplying the conditional probability corresponding to the state of nature by the corresponding *a priori* probability, $P(\theta_j, Z_k)\ P(\theta_j)$. This will yield Table 18.

The probability of observing Z_1 through Z_4 is given by $P(Z_k)$. It is obtained by summing the $P(Z_k/\theta_j)$ over all θ_j for a particular Z_k. These are shown in Table 18.

The 0.129 (0.571 x 0.226) in column one of Table 18 is the probability of an observed poor ECA date and a poor blossom date. Similar interpretation can be derived from the remaining probabilities.

Table 18. Joint probability of observing Z_k when θ_j is the true state of nature

State of nature		Z_1	Z_2	Z_3	Z_4
θ_1	Poor	0.129	0.097	0.0	0.0
θ_2	Fair	0.129	0.193	0.064	0.032
θ_3	Good	0.064	0.032	0.064	0.032
θ_4	Excellent	0.0	0.0	0.064	0.097
Total P (Z_k)		0.322	0.322	0.192	0.161

To calculate the *a posteriori* probabilities corresponding to each state of nature, the sums corresponding to Z_k are divided into the relative numbers of the above probability matrix. This yields:

$$\frac{P\ (\theta_j)\ P\ (Z_k/\theta_j)}{P\ (Z_k)}$$

the *a posteriori* probability table (Table 19).

Table 19. *A posteriori* probability of θ_j after observing Z_k

State of nature		Z_1	Z_2	Z_3	Z_4
θ_1	Poor	0.40	0.301	0.0	0.0
θ_2	Fair	0.40	0.599	0.333	0.2
θ_3	Good	0.2	0.1	0.333	0.2
θ_4	Excellent	0.0	0.0	0.333	0.60

Bayes' strategy

It is now possible to calculate from the foregoing data the Bayes' strategy that corresponds to each observation Z_k and alternative actions a_i. Multiplying the corresponding figures in the profit or loss table and summing the values for each action will give us the information shown in Table 20.

From this table, the Bayesian strategy can now be obtained. It is composed of those actions that maximize the gain of the orchard manager. In this case, action six would yield the greatest profit per acre for all observations Z_k. This is the action which combines a short term sprinkling for delay and sprinkling for freeze protection.

Sprinkling versus
alternative methods

The sprinkling of fruit as a means of freeze protection is not new to orchard managers. This practice is currently being used in Washington, New Mexico, parts of Utah, and other fruit producing states. It is a very effective and economical means of protecting from frost. Evidence now shows that sprinkling where possible is more economical to operate than any other conventional type of protection, namely gas or oil heaters.

The difference between sprinkling for bloom delay and sprinkling for freeze protection should be recognized. The former is the delayed development of the bud by lowering the temperature by sprinkling. The latter is the protecting of the bud from freezing temperatures by increasing the temperature of the bud above the lethal temperature.

Table 20. Bayes' strategy for all actions a_i

	A_1	A_2	A_3	A_4	A_5	A_6	A_7	A_8
Z_1	-264.4	23.56	332.54	-130.23	289.30	450.54	445.74	436.74
Z_2	-312.19	-82.49	316.84	-291.47	289.02	451.13	446.03	436.53
Z_3	- 44.62	119.21	403.26	102.23	409.59	455.54	453.87	447.21
Z_4	149.37	241.26	423.40	283.64	428.02	455.48	454.49	448.50

In 1974, the county agent in Wenatche, Washington calculated that the average cost of protection with oil heaters was $11.50 per acre per hour. Sprinkling for protection including cost of equipment was $1.45 per acre per hour (15).

In 1974, a grower in Utah County, Utah, sprinkled three acres at a cost of $60.00 for water. This was a gravity flow system. They estimated that pumping the water would have cost an additional $16.00 an acre, an average of $36.00 per acre to protect by sprinkling. They also heated seven nights using propane heaters. The cost for fuel alone was $90.00 an acre (15).

In 1976 at Macho Springs, New Mexico, two orchards 20 miles apart applied means of frost protection. Both orchards contained approximately five and a half acres. The one sprinkled for bloom delay for about six weeks at a cost of $300.00. The other grower heated three nights with oil. The cost of oil alone was $2,000.00 (15).

This period of growing energy shortages and rising fuel costs make conventional methods of protection quite unattractive. Sprinkling will become more attractive as time goes on because of its dual method of protecting from frost damage.

Sprinkling for freeze protection, however, does have its drawbacks. Sprinkling of water during decreasing temperatures is only effective as the amount of water applied increases. Colder temperatures require greater amounts of water. The 13 hundredths of an inch per hour used in this study is effective only at temperatures of 25° F. or greater. The water output requirement dictated by local climate will influence the design of the sprinkler system.

The use of overhead sprinklers for freeze protection requires several decisions that need to be made well in advance of installation or use. The most important is whether or not the trees can withstand the potential ice load. This will depend on the pruning of the trees, the duration of time the trees must be sprinkled, the amount of water that must be applied to maintain a mixture of ice and water on the buds, and the amount of wind and the depression of the wet bulb below the expected minimum temperature. New orchards that can withstand potential ice loads are necessary before sprinkling for freeze protection can be used extensively in the Farmington area.

Adverse effects of sprinkling

During the years of trial at Utah State University, no evidence of adverse effects upon the fruit or the trees has been seen (15). These trials have been run over a short period of time. There may be ill effects in the long run, but to date there is no evidence to prove it.

If sprinklers are used for irrigation purposes, a film of calcium could develop on the apple if hard water is used. This film of calcium is not harmful to the fruit itself. The film cannot be washed off and, thus, decreases the appeal of the apple color.

If the bloom of the apple is delayed significantly, prices received for fresh apples could be effected considerably. This would be due to the later marketability of the product. However, as shown by the decision model, the optimum action would not delay bloom significantly. Also, in the Farmington area, most apples are sold at roadside stands,

canned, or stored. Thus, the national fresh apple market does not effect them to any great extent.

It must be noted, however, that if sprinkling for bloom delay becomes widespread, the apple crop will increase considerably. This will tend to have a stabilizing effect on the prices received by producers. Prices could stabilize at a much lower level and some producers could be forced out of business. This could only be a very long term effect. As one assesses the data contained in this thesis, the effect of sprinkling will greatly enhance the production of apples in Farmington, Utah.

SUMMARY AND CONCLUSIONS

This thesis involves the derivation of *a posteriori* probabilities of the state of nature by weighting of *a priori* probabilities by conditional probabilities. These conditional probabilities are the probability of observing a particular end of chill-unit accumulation date (Z_k) when θ_j is the state of nature. There was found to be a significant relationship between the two variables. The *a posteriori* probabilities were used in this study to determine the Bayes' strategy for an orchard operator of red delicious apples. The information provided should prove very useful in the continued production of this fruit.

The study, using Bayesian decision theory, proved useful in determining the optimum action in event of any observation Z_k. The optimal strategy was to delay bloom until May 4, then freeze protection by sprinkling until all danger of frost was past, (a_6) for all observations Z_k. This action gave the greatest reward in all cases. It should be noted that there was not considerable difference in gains between action a_6, a_7, or a_8. However, there was considerable difference between those actions and all others.

Results presented in this thesis are for the Farmington, Utah area. Other areas might have similar or entirely different results; thus, decisions effecting other areas would have to be made independently.

Sprinkling for freeze protection would have great merit during many years, but it would necessitate considerable changes in orchards and sprinkler design.

An important conclusion found in this study is that of the dual protection afforded by sprinkling. In previous research at Utah State University, some studies have placed emphasis upon bloom delay only while others have only considered freeze protection. This study demonstrates the importance of protection achieved through use of both methods.

With the dual protection, producers do not have to delay bloom as long as was expected to achieve the desired protection. Increased production of apples can be achieved without extended delay of bloom or harvest at a cost much lower than incurred by conventional methods of protection, such as heating or by simply letting it freeze.

If water is available and correct pruning methods used, sprinkling to delay bloom and for freeze protection is an economical and feasible method of increasing returns to producers of delicious apples in Farmington, Utah. It will become increasingly important in this area as housing development forces orchards into less desirable locations, thus, requiring greater protection from the environment.

In conclusion, it is recommended that further study of application of this model be considered. The incompleteness of data and, hence, many assumptions made are the basis for this recommendation. The ideas used in this thesis should open the door and assist in the further development of additional research.

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APPENDIX

Table 21. Pheno-climatography of red delicious apples

	% of full bloom energy requirements	Requirement: Chill-units or GDH° C. / GDH° F.	Requirement: T_{10} ° C. / ° F.	Requirement: T_{50} ° C. / ° F.	Requirement: T_{90} ° C. / ° F.	Logan USU	Brigham City	Farmington	SLC Airport
Begin chill-unit accumulation		0				9/25	10/1	10/6	10/6
End chill-unit accumulation		1,234				4/6	3/13	2/23	3/11
1. Silver tip	30	2,061	-9.4	-12.8	-16.7	4/27	4/11	4/4	4/12
		3,710	15	9	2				
2. Green tip	37	2,544	-7.8	-10.0	-12.2	5/1	4/15	4/9	4/16
		4,580	18	14	10				
3. Half-inch green	45	3,100	-5.0	-7.2	-9.4	5/5	4/19	4/14	4/21
		5,580	23	19	15				
4. Tight cluster	57	3,939	-2.8	-4.4	-6.1	5/10	4/25	4/20	4/26
		7,090	27	24	21				
5. First pink	70	4,856	-2.2	-3.3	-4.4	5/15	4/30	4/25	4/1
		8,740	28	26	24				
6. Full pink	78	5,394	-2.2	-2.8	-3.9	5/18	5/2	4/28	5/4
		9,710	28	27	25				
7. First bloom	89	6,172	-2.2	-2.8	-3.9	5/21	5/6	5/2	5/7
		11,110	28	27	25				
8. Full bloom	100	6,933	-2.2	-2.8	-3.9	5/25	5/9	5/6	5/11
		12,480	28	27	25				
9. Post bloom			-2.2	-2.8	-3.9				
			28	27	25				

Table 22. Apple orchard establishment: Estimated costs per acre, Utah, 1975

Item	Year 1	Year 2	Year 3	Year 4	Total
			$/acre		
Variable costs:					
Plowing	11.00				11.00
Disking & harrowing	7.00				7.00
Marking holes	9.00				9.00
Digging holes	33.00				33.00
Planting	33.00				33.00
Trees, 200 @ $2.25	450.00				450.00
Tree loss, 10%	45.00				45.00
Fertilizing	20.00	20.00	25.00	25.00	90.00
Hand watering	17.00				17.00
Furrowing	5.50	5.50	5.50	5.50	22.00
Cultivating	22.00	22.00	22.00	22.00	88.00
Weeding	33.00	22.00	22.00	22.00	99.00
Sod establishment		50.00			50.00
Irrigating	40.00	40.00	40.00	40.00	160.00
Water cost	12.00	12.00	12.00	12.00	48.00
Rodent control	15.00	15.00	15.00	15.00	60.00
Spreading		45.00	25.00	20.00	90.00
Spraying	40.00	40.00	70.00	100.00	250.00
Pruning	5.00	25.00	35.00	35.00	100.00
Removing brush	5.00	5.00	10.00	15.00	35.00
Total	802.50	301.50	281.00	311.00	1,697.00
Fixed costs:					
Interest on investment 8.5%/year		69.57	102.47	136.47	308.51
Land tax	4.45	4.45	4.45	4.45	17.80
Other	11.55	11.55	11.55	11.55	46.20
Total	16.00	85.57	118.47	152.42	312.51
Total costs (investment)	818.50	387.07	399.97	463.97	2,069.51

Table 23. Apples, bearing orchard: Estimated receipts, costs, and net returns per acre, Utah, 1975

Item	Year 5	Year 6	Year 7	Year 8	Year 9	Years 10-30
Production:						
Trees/acre	200	200	200	200	200	200
Yield/tree bu	.50	2.0	2.5	3.0	3.5	4.0
Total bu/acre	100	400	500	600	700	800
Discount 10%*	10	40	50	60	70	80
Net bu/acre	90	360	450	540	630	720
	$/acre					
Receipts @ $3.30/bu	297.00	1188.00	1485.00	1782.00	2079.00	2376.00
Variable costs:						
Fertilizing	30.00	35.00	40.00	45.00	45.00	45.00
Furrowing	5.00	5.00	5.00	5.00	5.00	5.00
Cultivating	22.00	22.00	22.00	22.00	22.00	22.00
Weeding	22.00	22.00	22.00	22.00	22.00	22.00
Irrigating	40.00	40.00	40.00	40.00	40.00	40.00
Water costs	12.00	12.00	12.00	12.00	12.00	12.00
Rodent control	15.00	15.00	15.00	15.00	15.00	15.00
Spreading & thinning	20.00	60.00	50.00	50.00	50.00	50.00
Spraying	90.00	90.00	100.00	120.00	120.00	120.00
Removing brush	15.00	21.00	27.00	27.00	27.00	27.00
Picking & hauling @ $.50/bu	45.00	180.00	225.00	270.00	315.00	360.00
Grading & boxing, @ $.50/bu	45.00	180.00	225.00	270.00	315.00	360.00
Containers, @ $.52/bu	46.80	187.20	234.00	280.80	327.60	374.40
Interest on operating capital, 8.5%/½ yr	17.33	36.94	43.22	50.09	55.88	61.71
Total	425.13	906.14	1060.22	1228.89	1370.88	1513.71
Fixed costs:						
Interest on investment @ 8.5%/yr	175.90	169.14	162.37	155.61	148.47	142.08
Depreciation, establishment costs	79.59	79.59	79.59	79.59	79.59	79.59
Land tax	4.45	4.45	4.45	4.45	4.45	4.45
Other	11.55	11.55	11.55	11.55	11.55	11.55
Total	271.49	264.73	257.96	251.70	244.06	237.67
Total costs	696.62	1170.87	1318.18	1480.59	1614.94	1751.38
Net return to land and management	(399.62)	(17.13)	166.82	301.41	464.06	624.62

*Discount, loss other than that attributed to frost.

Table 24. Accumulated development of red delicious apples for 31 years by fruit tree date*

Year	BCA	ECA	Stage of development 1	2	3	4	5	6	7	8
1942	19	191	220	222	224	228	233	237	247	250
1943	41	175	210	213	215	219	226	228	231	234
1944	40	175	225	234	239	244	249	251	253	255
1945	43	181	219	230	232	238	242	244	247	249
1946	46	188	210	216	221	226	229	231	234	237
1947	30	157	191	196	199	205	212	220	227	232
1948	39	212	230	232	235	240	246	249	254	258
1949	43	220	232	234	236	238	242	244	249	251
1950	35	176	202	212	216	222	228	232	235	243
1951	61	188	217	220	224	228	233	235	240	246
1952	32	188	223	228	231	235	238	240	243	246
1953	42	179	206	209	212	228	233	236	239	246
1954	41	186	215	217	221	226	230	233	236	239
1955	40	212	233	236	241	244	248	250	253	255
1956	19	174	204	206	211	220	227	230	234	236
1957	41	184	211	216	221	226	230	235	242	244
1958	33	176	225	227	230	235	244	246	249	252
1959	49	172	204	208	214	217	223	226	234	237
1960	21	208	221	222	226	232	236	241	245	249
1961	37	171	206	213	215	224	230	234	240	243
1962	17	187	217	222	225	228	231	233	237	241
1963	43	193	214	219	224	235	242	244	247	249
1964	50	237	254	256	257	260	263	265	267	269
1967	30	182	206	210	217	224	232	239	249	252
1968	34	192	213	221	224	237	243	245	249	253
1969	19	183	216	220	224	231	235	240	244	247
1970	31	158	197	207	218	225	238	245	248	252
1971	19	149	206	210	216	222	227	232	241	244
1972	14	183	199	202	209	217	223	229	236	242
1973	46	198	227	235	238	244	249	251	254	256
1974	22	195	219	225	230	235	238	243	246	249

*Fruit tree date: Day 1 begins September 1 and continues through day 365 on August 31.

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