AN ECONOMIC ANALYSIS OF THE SEQUENTIAL DECISION PROBLEM FOR IRRIGATED COTTON PRODUCTION IN SOUTHWEST OKLAHOMA

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CHAPTER I

INTRODUCTION

Description of the Research Problem

Cotton (Gossypium hirsutum L.) is the principal natural fiber crop of the world. Lint from the plant is an important source of natural fiber in clothing, home furnishings, and industrial products. Oil and protein meal (from its seed) yield important food products for both man and livestock. Cotton has woven a culture and tradition throughout recorded human experience that transcends its status as a commodity. It has been closely tied to many historical events including the Industrial Revolution and the U.S. Civil War.[1]

U.S. Cotton Production Trends

The cotton species raised in the United States and elsewhere is upland cotton. It is grown throughout the 17 Southern states comprising the U.S. Cotton Belt and accounts for about 98 percent of total U.S. production.[2]

Cotton became a major Southern cash crop after the invention of the cotton gin in 1794. Strong European demand coupled with cheap land and

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[1] For a review of the origins of cotton and of its past and current role in the world, see Munro (1987, pp. 1-40), Lee (1984, pp. 1-25), Bowling (1984, pp. 571-587), and Lewis and Richmond (1968, pp. 1-21).

[2] Upland cotton has a staple (fiber) length from 3/4 to 1-1/4 inches within an average of 1-3/32 inches. American Pima (Gossypium barbadense L.) is an extra/long-staple cotton (1-3/8 inches or more) that is primarily grown in the irrigated valleys of Arizona, New Mexico, and west Texas. It represents about two percent of the total U.S. crop and is used for thread and high-valued fabrics and apparel (Stults et al., 1989, p. 53).

slave labor stimulated production. The U.S. was the dominant producer in the 19th century with three-quarters of the world output. Per acre yields averaged about 180 pounds and seldom exceeded 200 pounds between 1866 and 1930 (Stults et al., 1989, p. 2).

World cotton production has steadily risen since 1900 with China, the U.S.S.R., India, Pakistan, and Brazil becoming major producers along with the U.S. (Munro, 1987). However, during the 20th century, U.S. production has reached a plateau with acreage declining and yields per acre increasing. Acreage declined from a high of 44 million in the mid-1920's to less than 20 million by the early 1950's. Planted acres has hovered around 10 to 12 million with production between 7.4- and 14.5-million bales per year since 1965 (Stults et al., 1989, p. 66). U.S. yields have exhibited a strong and statistically significant upward trend throughout the 20th century (Figure 1.1).[3] Yields have increased from less than 200 pounds before the mid-1930's to about 700 pounds at present.

Government programs and market prices have been the fundamental influences on acreage. Weather and pests have been the foremost influence on yield variability and quality.

Production has gradually shifted westward over time. Lower costs and the elimination of marketing quotas and restrictive acreage allotments tied to historical production helped foster this trend. This westward migration of

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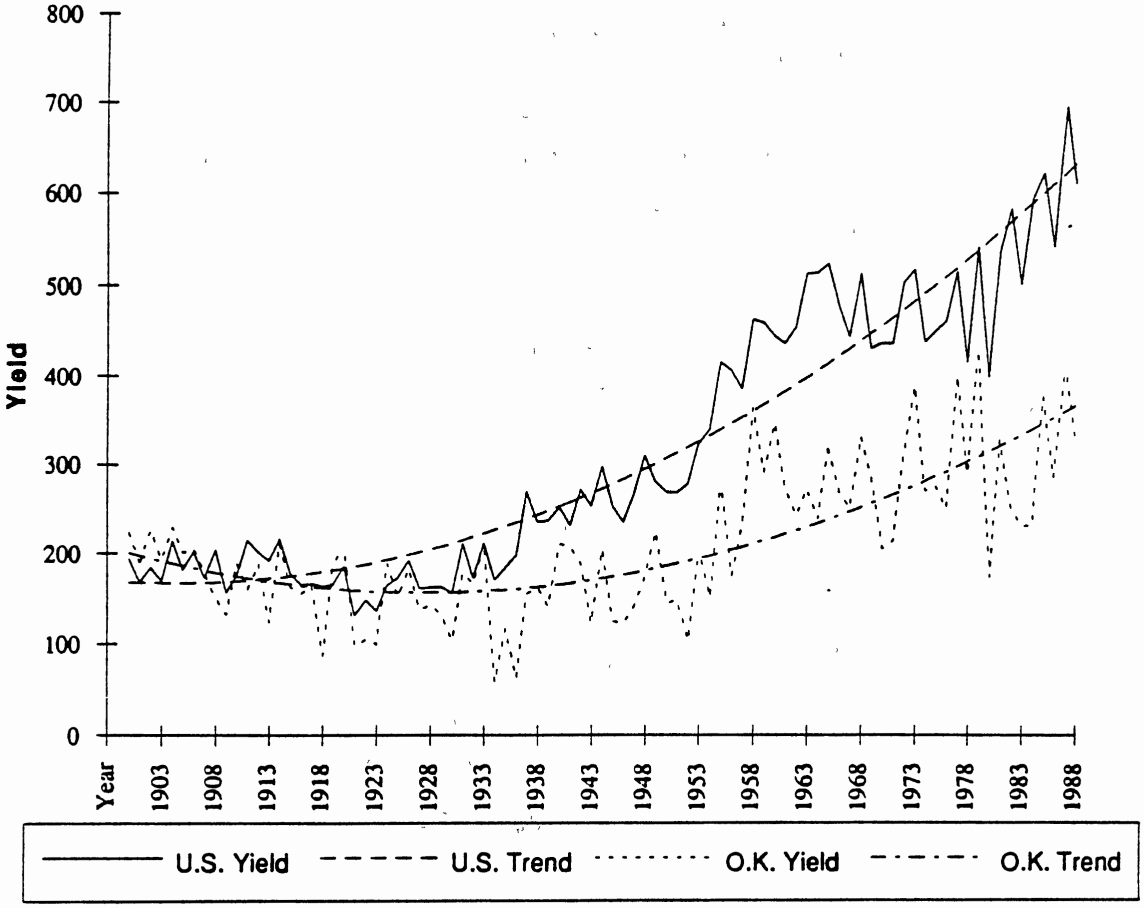
[3] A simple quadratic time-trend was fitted to U.S. and Oklahoma cotton lint yield data (1900-1988):

$$\text{U.S.:} \quad \text{Yield}_{\text{u.s.}} = 243{,}745 - \underset{(-7.27)}{255.82} \bullet \text{Year} + \underset{(7.42)}{0.07} \bullet \text{Year}^2 \qquad R^2 = 0.89$$

$$\text{Oklahoma:} \quad \text{Yield}_{\text{Okla.}} = 214{,}872 - \underset{(-6.72)}{222.81} \bullet \text{Year} + \underset{(6.76)}{0.06} \bullet \text{Year}^2 \qquad R^2 = 0.53$$

The t-values for the time coefficients are in parenthesis. The time-trend lines are shown along with the actual data in Figure 1.1.



Source: U.S. Dept. Agri., Econ. Res. Ser., *Agricultural Statistics*, and Okla. Dept. Ag., *Oklahoma Agricultural Statistics*, Various Issues.

Figure 1.1. U.S. and Oklahoma Cotton Lint Yield Trends, 1900 through 1988

acreage ceased during the 1980's with output again increasing in the Mississippi Delta and the Southeast. Nearly two-thirds of all U.S. cotton production is in Texas, California and Mississippi.[4]

Oklahoma Cotton Production Trends

Oklahoma cotton acreage and production reached a pinnacle during the 1920's (Table 1.1). Jackson county in southwest Oklahoma produced more cotton than any other county in the U.S. during the early 1920's (Bailey and Graft, 1961, p. 62). Cotton was grown throughout the southern three-quarters of Oklahoma. Lint yields averaged 157 pounds per harvested acre.

Acreage and total production in Oklahoma have shown a marked and steady decline since the 1920's (Table 1.1). Harvested per acre yields also deteriorated between 1900 and the mid-1930's (Figure 1.1). Government programs and market prices have been the primary influences on declining acreage and production in Oklahoma. Harsh weather, particularly four years of drought in the 1930's, and the inability to control the boll weevil (Anthonomus grandis Boheman) and other pests were the foremost influences on this downward trend in harvested yield (Verhalen et al., 1984).

Yields have moved upward since the mid-1930's, but at a much slower rate than for the U.S. (Figure 1.1). The probable reason for this difference is the severe, short-season environment for cotton production in the state. Average yield during the 1980's was 314 pounds compared to 564 pounds at the national level. Planted acreage averaged 399,167 acres between 1980 and

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[4] The top ten cotton producing states and their proportion of total U.S. production for 1984-1988 were: 1) Texas (30.6%), 2) California (21.6%), 3) Mississippi (12.4%), 4) Arizona (6.8%), 5) Louisiana (6.7%), 6) Arkansas (5.9%), 7) Tennessee (3.6%), 8) Alabama (3.2%), 9) Georgia (2.4%), and 10) Oklahoma (2.0%) (U.S. Department of Agriculture, Economic Research Service, 1989, p. 31).

TABLE 1.1

OKLAHOMA COTTON ACREAGE, LINT YIELD, AND BALE PRODUCTION STATISTICS, 1894 TO 1988

Period	Planted	Harvested	Planted Acres Harvested	Yield Per Harvested Acre	Production 480-Pound Net Bales
	---Acres---		Percent	Pounds	Bales
1894-99	---[a]	415,667	---[a]	227	189,280
1900-09	---[a]	1,979,333	---[a]	183	716,320
1910-19	2,739,000	2,631,000	96.10	162	844,480
1920-29	4,418,500	4,237,333	95.75	157	1,337,600
1930-39	2,316,000	2,171,333	94.04	116	486,400
1940-49	1,255,000	1,171,667	93.25	166	399,200
1950-59	716,000	668,333	93.52	250	315,840
1960-69	498,667	454,167	90.64	283	257,120
1970-79	503,333	477,000	94.03	321	328,000
1980-88	399,167	370,000	91.98	314	245,333

Source: Oklahoma Department of Agriculture, Oklahoma Agricultural Statistics Service, Oklahoma Agricultural Statistics, Various Issues.

[a] Planted acres were not published before 1908.

1988 (Table 1.1). Cotton production averaged 245,333 bales per year during this period.

Cotton is usually third in value among Oklahoma agronomic crops (Oklahoma Agricultural Statistics Service data). Acreage and production are now concentrated in the southwest and west-central sections of Oklahoma. Four of the top five cotton producing counties in 1990 are in the southwest crop reporting district: Jackson, Tillman, Harmon, and Kiowa Counties (Figure 1.2).[5] Farmers in the eight counties of the district grew 75 percent of all the cotton in

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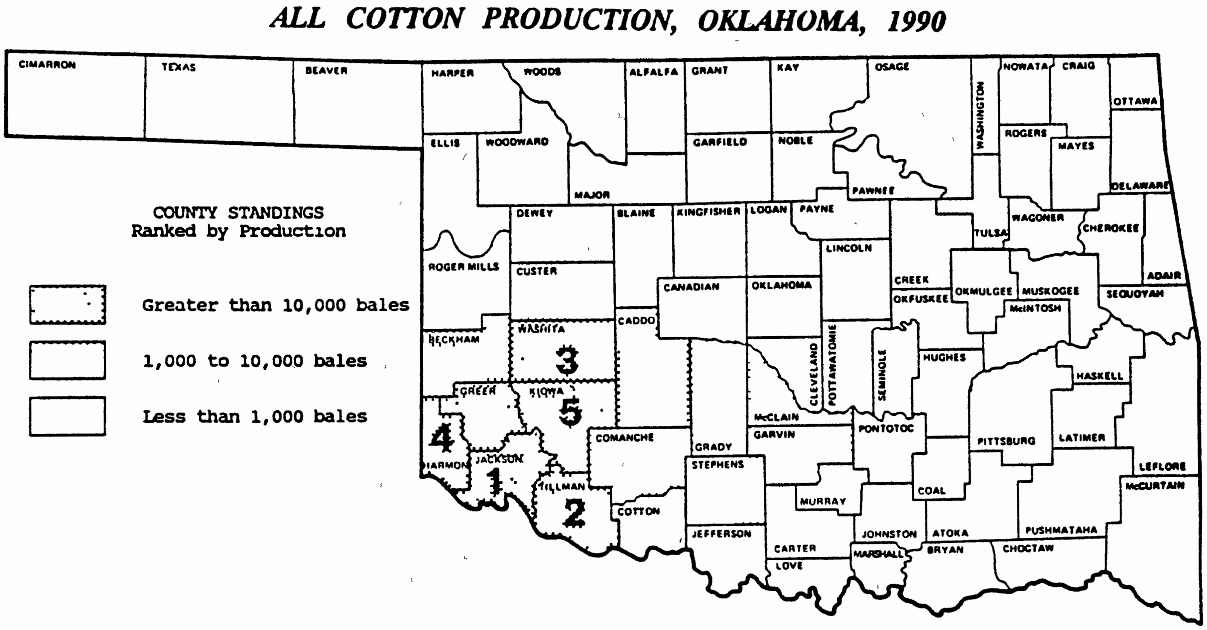
[5] Counties in the southwest crop reporting district are Harmon, Greer, Jackson, Kiowa, Tillman, Caddo, Comanche, and Cotton. Counties in the west-central crop reporting district are: Roger Mills, Beckham, Washita, Custer, Blaine, and Dewey.



Adapted from: Oklahoma Department of Agriculture, Oklahoma Agricultural Statistics Service. "Oklahoma Agricultural Statistics 1990." p. 32.

Figure 1.2. Cotton Production in Oklahoma, 1990

the state, including the majority of the irrigated cotton (Oklahoma Agricultural Statistics Service data). Another 20 percent of Oklahoma's cotton production is located in the west-central crop reporting district; primarily in Washita, Beckham, and Custer Counties. Approximately 21 percent of the crop acres harvested and 44 percent of total crop market value in the southwest district come from cotton. Its production is especially important in three southwest Oklahoma counties. Two-thirds of the total crop market value in Jackson, Tillman, and Harmon counties originates from cotton production (U.S. Department of Commerce, Bureau of the Census data, 1989).

The Cotton Production Decision Problem

The growth and development of the cotton plant is dynamic and complex. Yet, its development is highly structured and very predictable. Cotton is cultivated as an annual plant in the U.S. It is, however, essentially a perennial (indeterminant) shrub adapted to survive in a warm semi-arid environment. The indeterminate and warm-climate attributes of the plant present several unique problems for cotton farmers in Oklahoma.

First, the life cycle pattern of the cotton plant is similar to other perennials such as trees. Cotton, under the right growing conditions, will first develop a root, stem, and branch structure. Only after the plant has this basic structure will it then begin to attempt to reproduce. Consequently, the cotton plant must be placed under a limited managed stress to encourage reproductive, rather than vegetative growth. However, the plant can easily be returned to vegetative growth by changes in the environment. One management challenge is to maintain a vegetative-reproductive balance throughout the growing season that will optimize both lint yield and quality (Banks, 1990).

The second management challenge is Oklahoma's often harsh, short-season environment for cotton. Major climatic hazards in Oklahoma include short seasons, cool temperatures in late spring and/or early fall, recurrent drought and erratic rainfall, high winds, and stress induced by pests (Verhalen et al., 1984).

Oklahoma production occurs in a shorter season environment than is witnessed in most areas of the Cotton Belt. Cool spring temperatures cause poor plant stands and encourage seedling diseases, weed competition, and herbicide injury problems. Establishment of a viable stand that will mature in a short season environment is a critical management problem in Oklahoma (Verhalen et al., 1984).

Summers, by contrast, are characterized by prolonged hot temperatures. The summer of 1980, for example, had 28 consecutive and a total of 47 days where temperatures were above 100°F. In 1985 there were 45 days where the temperature was above 100°F (Anonymous, 1989).

Early cool fall temperatures and early frosts are common in southwest Oklahoma. Early frosts on October 19th and 20th caused considerable damage to the cotton crop in 1989 (Banks et al., 1990). Cool fall temperatures also slow growth and encourage verticillium wilt and immature lint, reducing both lint yield and quality.

The uncertain and bimodal rainfall pattern of southwest Oklahoma presents another management problem to cotton producers. Average yearly rainfall is about 24 inches. Precipitation is heaviest between April and June. Frequent and intense spring planting time-early growth stage rainfalls cause considerable problems in establishing an acceptable stand of plants.

Summer precipitation is spotty and undependable. Dry periods of four to six weeks with frequent hot winds are common. The July-August time-period is especially critical in the growth of the cotton plant. Water consumption by cotton is heaviest during the reproductive (fruiting) stage of plant development. High temperatures and hot, dry winds remove moisture from the plant faster than it can be replenished through the roots. This period of stress can result in large yield and fiber quality losses.

Frequent and substantial rainfall is not uncommon during September and October. Moist and cool conditions at this time of year coincide with cotton boll maturation and can substantially affect lint yield and quality. These conditions can encourage verticillium wilt and boll rot problems and also interfere with harvest.

The last (but certainly not least) environmental hazard that presents management problems to cotton producers is pest damage, that is, damage due to diseases, insects, and weeds. The seedling disease complex, fleahoppers, [Pseudatomoscelis seriatus (Reuter)], boll weevils, and the bollworm-tobacco budworm complex (Heliothis spp.) are persistent cotton production management problems in Oklahoma. Pest control management is integrally related to the cotton plant growth habit, seasonal climatic conditions, and cultural practices.

Rationale for the Study

Cotton production in southwest Oklahoma occurs in a dynamic and stochastic agricultural ecosystem.[6] The important elements of this field ecosystem are: 1) the plant, 2) uncertain growing conditions (climate, soil, and

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[6] El-Zik and Frisbie (1985, p. 22) define an agricultural ecosystem as "a highly complex and interactive system in which man attempts to produce acceptable agricultural commodities while maximizing economic returns." Webster's Ninth New Collegiate Dictionary (1988) definition of an ecosystem is "the complex of a community and its environment functioning as an ecological unit in nature."

pests), and 3) management inputs injected into the process (El-Zik and Frisbie, 1985, p. 24). Thus a producer is confronted with an exceedingly complex decision problem involving a sequence of input choices using imperfect information about input-output consequences. Various inputs, such as labor, equipment, seed, irrigation, pesticides, etc., are sequentially injected into the production process. A farmer must understand the linkages between the cotton plant, service flows into production, and environmental inputs that condition those relationships.

A farmer's management stratagem--both tactical (within a year) and strategic (across more than one year)--is shaped by behavioral patterns and information about uncertain input-output relationships. Considerable evidence exists that a farmer operates, as do most businesses, to earn the highest possible return to their invested resources (Antle, 1988, p. 10). However, producer actions are conditioned by: 1) the amount of and the accuracy of information about uncertain input-output relationships, 2) how the decision maker processes information and forms expectations, 3) attitudes towards uncertainty and risk, and 4) institutional and societal constraints on decision making.[7]

A study of the economics of the sequential decision problem for cotton production in southwest Oklahoma is appropriate for three reasons. First, cotton is an important crop alternative and source of income for many farmers in southwest Oklahoma. However, average Oklahoma lint yields for both dryland

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[7] Uncertainty can be defined in terms of an action where there is more than one possible consequence. This uncertain event is considered to be important to a decision maker if it affects his or her material well-being. Thus, a risky event can be defined as an uncertain event whose outcome alters the decision maker's well-being. The producer is indifferent to an uncertain nonrisky event, but not to an uncertain risky event. A farmer confronted with a set of risky choices learns to order them from least to most risky. This ranking does not depend solely on the level of risk associated with the decision alternative, but also on the farmer's attitude towards risk (Robison and Barry, 1987, pp. 13-14).

and irrigated production have lagged behind the rest of the U.S. (Figure 1.1). Additional information about the complex interactions that influence the economics of input choices and yield potential could enhance producer welfare by improving efficiency and profitability.

Second, cotton production, especially under irrigation, is an intensely managed and complex system. Basic knowledge is needed regarding how cotton ecosystem components and linkages interact with the climate and with the economic behavioral responses of farm producers.

Finally, few agricultural economic studies have considered the complex interactions that occur during a crop production cycle (e.g., Mjelde, 1985). Neoclassic production economic theory assumes that the relationship between inputs and outputs is deterministic. This abstraction is often inappropriate in a biological production process that is influenced by both time and random factors such as weather, pests, etc. A study that adds to the knowledge base of dynamic and stochastic interactions in an agricultural production economics problem is indeed an appropriate undertaking.

Objectives of the Study

This study develops a farm level sequential decision framework to examine the economics of a multifaceted biological production process. Salient dynamic and stochastic features of the growing environment are incorporated into the economic model. The framework is used to evaluate the influence of alternative choices and information levels on enterprise net revenue and risk.

Specific objectives are:

1. To identify and synthesize into a coherent sequential decision framework the salient features and relationships of the cotton production problem in southwest Oklahoma.

2. To generate yield and net enterprise incomes that reflect the growth habit of the cotton plant, uncertain environmental conditions, and the management choices actually witnessed in southwest Oklahoma.

3. To analyze the economic consequences of alternative information level assumptions on optimal decision strategies.

4. To assess the influence of uncertain information in developing decision rules on farmer profit and risk.

5. To develop management decision information and risk reduction strategies useful to southwest Oklahoma cotton farmers.

Methods, Data, and Limitations of the Study

The conceptual framework for this analysis draws from sequential decision-making theory and concepts (Antle, 1983, 1988; Antle and Hatchett, 1986) and value of information theory and concepts (Gould, 1974; Hirshleifer and Riley, 1979; Hess, 1982; Byerlee and Anderson, 1982; Bosch and Eidman, 1987). This analysis examines three parts of the sequential decision problem: planting, irrigation and insect management. The outcomes from these three decisions have the greatest impact on cotton lint yields and profitability under Oklahoma growing conditions (Verhalen et al., 1984). Other important aspects of the decision problem such as weed, fertilizer, and harvest-aid management are not examined in this study.

Two daily time-step simulation models were used to represent the cotton field ecosystem and to generate outcome distributions. COTTAM simulates the physiological growth and development of the cotton plant in response to management and environmental inputs (Jackson et al., 1990). TEXCIM simulates the principal cotton plant-pest-beneficial predator relationships in response to management and environmental inputs (Hartstack et al., 1990).

Alternative inflexible and flexible calendar date and timed strategies under various information assumptions are simulated for each part of the decision problem. Stochastic dominance and value of information criteria are then used to identify and evaluate risk efficient strategies for each part of the decision problem. Interactions between the three components of the sequential problem are examined where possible, e.g., the interaction between planting and irrigation management.

This study uses 43-years (1948 through 1990) of daily climate data, representative soil profile data, and six years of cotton insect pheromene trap data to represent alternative environmental conditions in the field ecosystem (data from the Oklahoma State University Irrigation Research Station, Altus).

Three basic cotton production schemes occur in the state: 1) high input irrigated--both furrow (e.g., Lugert-Altus Irrigation District) and sprinkler applied, 2) low input dryland, and 3) river bottom land semi-irrigated production. Each type of production involves a unique set of management problems (Banks, 1990).

This study investigated furrow irrigated cotton production as found in the Lugert-Altus Irrigation District of Jackson and Greer Counties. The reasons for this limitation are two-fold. First, the detailed production data required for a study of this type are more readily available for irrigated production. Second, irrigated production occurs in a more complicated decision-making environment where the decision maker has more opportunities to influence the input-output relationships.

This area of investigation affords the opportunity to study the economics of sequential decisions in an intensely managed production situation. The results of this study should be transferable to other types of irrigated or river bottom cotton production in the Rolling Plains region of southwest Oklahoma and Texas.

Organization of this Dissertation

This dissertation includes six chapters. Chapter I is the introduction to this study. Chapter II presents a review of the literature and develops the theoretical basis for the study. A description of the dynamic and stochastic elements in the southwest Oklahoma irrigated cotton field ecosystem is the subject of Chapter III. Chapter IV develops the empirical framework for conducting the economic analysis of the sequencial decision problem. The economic analysis of the problem is the subject of Chapter V. Finally, the summary and conclusions are presented in Chapter VI.

CHAPTER II

REVIEW OF THE THEORY AND LITERATURE

This chapter develops the theoretical and methodological foundation for the cotton field ecosystem simulation framework assembled in Chapter IV and the economic analysis conducted in Chapter V. Topics include the economic theory of the sequential decision problem, the role of information in developing sequential decision rules, the methods of decision analysis employed in the study, pest management concepts, and a review of selected empirical studies.

Economics of the Sequential Decision Problem

The essence of the short-run production decision problem at the farm level involves answering three questions by the decision maker; that is, what should be produced, how should one produce it, and how much of it should be produced (Nelson, 1984, pp. 2-6). What combination of farm enterprises requires information on the various production technologies (input-output relationships), input-output price relationships, and the quantity of inputs available. The "how to produce" question involves finding the optimum mix of a set of inputs to use in the production process. The "how much to produce" problem considers the optimum output level from a given set of variable and fixed inputs. This study specifically examines questions two and three for a southwest Oklahoma irrigated cotton producer.

The respective solutions to these two decision problems from the neoclassical theory of production economics for a single output, n-variable input production process are:

$$MPP_1/MFC_1 = MPP_2/MFC_2,\ldots,MPP_n/MFC_n \tag{2.01}$$

$$P_yMPP_1 = MFC_1,\ P_yMPP_2 = MFC_2,\ldots,P_yMPP_n = MFC_n \tag{2.02}$$

where

MPP_n = marginal physical product of input n, i.e, the change in output, y, resulting from using an additional unit of input n in production.

MFC_n = marginal factor cost, i.e., increase in cost of input n associated with the purchase of an additional unit of the input;

P_y = constant output price; and

P_yMPP_n = value of the marginal product, .i.e., the value of the additional output resulting from another unit of input n at constant output price P_y.

The assumptions associated with these two neoclassical results are (Beattie and Taylor, 1985, pp. 5-6):

1. Input-output transformation product price and factor price relationships are known with certainty. This assumption signifies static, instantaneous production. The elements of time and uncertainty are not considered in the decision making (optimization) process. Thus the sequence of events and their unknown outcomes are not considered. Furthermore, the farmer is assumed to know all pertinent information with 100 percent (probability=1) certainty when making the optimal input choice.

2. The objective of the farm firm decision maker is to maximize profits.

3. The production function is given by a single, twice differentiable function.

4. The production process is monoperiodic. A firm's production activity is so arranged that production in one time period is separate or independent of production in preceding and subsequent time periods. This assumption precludes the influence of such factors as soil moisture carry over, overwintering insect populations, and soil nitrogen carry over on the decision problem.

5. All inputs and outputs of the farm firm are homogeneous in the sense that there are no quality differences for different levels of a particular input or output.

6. Funds available for the purchase of variable factors of production do not limit such purchases.

Relaxing assumptions one and two can change the results of the theory in an essential way. Consider the situation where assumption one is relaxed to introduce uncertainty--and thus the elements of time, information, and risk--into the production process.[1] An illustration originating from Antle and Hatchett (1986, pp. 940-941) and Antle (1988, pp. 48-52) eloquently demonstrates the economic implications of a sequence of input decisions made by a farmer in a biological (uncertain) production process.

Assume a simplified version of the decision problem for a single crop such as cotton. It consists of three input decision stages paralleling critical junctures in crop growth and development. Presume that the objective function of a profit maximizing farmer who wants to optimize a single input (e.g., successive applications of irrigation water) applied in response to these critical points is mathematically represented by:

$$\underset{\{x_1, x_2, x_3\}}{\text{Max}}\ E_t[\pi \mid \Omega_t] = E_t[p \bullet y_3 \mid \Omega_t] - \sum_{t=1}^{3} E_t[r_t x_t \mid \Omega_t] - rz \qquad (2.03)$$

where

E_t = expectation operator taken with respect to the random variable at time t;

---

[1] Robison and Barry (1987, pp. 13-14) define uncertainty as an action where there is more than one possible consequence. The consequences associated with this action are considered to be important to the decision maker if it influences the agent's material well-being. Thus, risk can be defined as an uncertain event whose outcome alters the decision maker's well-being. An agent is indifferent to an uncertain non-risky event, but not to an uncertain risky event. A decision maker confronted with a set of risky choices learns to order them from least to most risky. This ranking does not depend solely on the level of risk associated with the choice, but also on the agent's preferences (risk attitude) towards risk.

Y_3 = final composite cotton lint and seed yield;
π = farmer's expected profit function
Ω_t = information set at time t on which the timed input decision is based;
p = composite price of cotton lint and seed;
r_t = price of the timed input x_t;
x_t = units of timed input;
r = price of non-timed or fixed input z; and
z = non-timed or fixed input.

Associated with the decision problem is a multi-stage production function of the general form

$$y_1 = f_1 (x_1, z, \theta_1) \text{ for } t=1, \text{ and} \quad (2.04)$$

$$y_t = f_t (x_t, y_{t-1}, \theta_t) \text{ for } t=2, 3, \quad (2.05)$$

where

θ_t = random event of production, e.g., weather, pests, etc., generated from probability distribution $h(\theta_t)$ that influences the outcome of the input decision at time t on crop yield and profit;
y_t = current state of the crop; and
y_{t-1} = previous state of the crop as a result of past input choices and random events of production.

Recursive substitution of y_1 and y_2 into y_3 produces

$$y_3 = F_3 (x_1, x_2, x_3, z, \theta_1, \theta_2, \theta_3), \quad (2.06)$$

the final composite cotton lint and seed yield production function. The composite production function is assumed to be strictly concave.

At the first decision point, t_1, the variable input x_1 and the non-timed input z are determined using initial knowledge of expected prices, yield, and the decision rule for future optimal inputs. The farmer formulates an initial expectation for the decision rule for optimal inputs x_2^* and x_3^* at stages two and three. This is represented by

$$x_2^* = x_2^* (r_2, y_1, \omega_2) \text{ and} \quad (2.07)$$

$$x_3^* = x_3^* (r_3, y_2, \omega_3)$$

where w_t symbolizes the farmer's subjective distribution at time t of future input and output prices and the outcomes of future input decisions. The information set at stage 1, Ω_1, incorporates all a priori knowledge before production begins Ω_0, plus initial expectation for x_2^* and x_3^* at stages two and three, i.e., $\Omega_1 = \Omega_1 (\Omega_0, x_2^*, x_3^*)$. Ω_0 embodies the decision maker's knowledge, experience, and judgement about past events influencing yield, input-output price ratios, and profit outcomes in the form of a joint subjective conditional prior probability distribution. Given these initial expectations, the farmer solves subject to the multi-stage production function (equations 2.04 and 2.05).

$$\text{Max } E_1 \{[py_3 - r_1x_1 - rz - r_2x_2^* - r_3x_3^*] \mid \omega_1\}, \tag{2.08}$$

Using the composite production function, $y_3 = F_3 (x_1, x_2, x_3, z, \theta_1, \theta_2, \theta_3)$, and the concept of total derivatives (Chiang, 1984, pp. 198-204), totally differentiate y_3 with respect to x_1 to yield

$$dy_3 = f_1dx_1 + f_2dx_2^* + f_3dx_3^* + d_z + d_{\theta 1} + d_{\theta 2} + d_{\theta 3}. \tag{2.09}$$

Assume that $d_{\theta t}=0$ and $d_z=0$ and let $f_t = dy_3/dx_t$ for t=1, 2, and 3 then divide through by dx_1 to obtain the first order condition of y_3 with respect to x_1 is:

$$\frac{dy_3}{dx_1} = \frac{dy_3}{dx_1}\frac{dx_1}{dx_1} + \frac{dy_3}{dx_2}\frac{dx_2^*}{dx_1} + \frac{dy_3}{dx_3}\frac{dx_3^*}{dx_1} \tag{2.10}$$

Thus the first order condition for π with respect to x_1 is:

$$E_1 [p \mid \Omega_1]\left[\frac{dy_3}{dx_1} + \frac{dy_3}{dx_2}\,\frac{dx_2^*}{dx_1} + \frac{dy_3}{dx_3}\,\frac{dx_3^*}{dx_1} \mid \Omega_1\right] = \tag{2.11}$$

$$E_1\left[r_1 + r_2\,\frac{dx_2^*}{dx_1} + r_3\,\frac{dx_3^*}{dx_1} \mid \Omega_1\right]$$

In words this result states that the expected value of the marginal product of x_1 ($EVMP_1$) is equal to the expected marginal factor cost of x_1 (MFC_1). $EVMP_1$ encompasses the direct influence of input x_1 on stage one of production plus the indirect carry over effect of x_1 on stages two and three of the decision process. $EMFC_1$ includes the current marginal factor cost plus the opportunity cost of the input in the two future stages. The carry over effects and opportunity cost occur because input use in stage one influences the crop state and therefore optimal input use in stage two and three.

Once x_1 is selected, production commences and the first random production event θ_1 occurs and the first state of the crop y_1 occurs.

At the next decision juncture, t_2, the farmer uses information, embodied in crop state y_1, about what has happened so far regarding yield potential plus expectations of prices and x_3^* to choose x_2 and solve

$$\text{Max } E_2 \{[py_3 - r_1x_1^0 - r_2x_2 - r_3x_3^*] \mid \omega_2\}, \tag{2.12}$$

subject to the multi-stage production function (equations 2.04 and 2.05). The information set at this stage is represented by $\Omega_2 = \Omega_2(\Omega_1, y_1, x_3^*)$.

The first order condition for π with respect to x_2 is:

$$E_2[p \mid \Omega_2]\left[\frac{dy_3}{dx_1}\frac{dx_1^0}{dx_2} + \frac{dy_3}{dx_2} + \frac{dy_3}{dx_3}\frac{dx_3^*}{dx_2} \mid \Omega_2\right] = \tag{2.13}$$

$$E_2\left[r_1\frac{dx_1^0}{dx_2} + r_2 + r_3\frac{dx_3^*}{dx_2} \mid \Omega_2\right]$$

$EVMP_2$ encompasses three consequences of input choice two: 1) the indirect carry over effect between the previous input decision x_1 and the current choice x_2, 2) the direct influence of input x_2 on stage two of production, 3) and expected indirect influence between x_2 and future choice x_3 at stage three. Once x_2 is chosen, the production process continues and random event θ_2 and crop state y_2 are realized.

In the final stage, the farmer exploits the information about the state of the crop y_2 plus his expectation ω_3 to select x_3 to solve

$$\text{Max } E_3 \{[py_3 - r_1x_1^0 - r_2x_2^0 - r_3x_3] \mid \omega_3\}, \tag{2.14}$$

subject to the mult-stage production function (equations 2.04 and 2.05). The information set at stage three is represented by $\Omega_3 = \Omega_3 (\Omega_2, y_1, y_2)$. Thus, the first order condition for π with respect to x_3 is:

$$E_3 [p \mid \Omega_3] - \left[\frac{dy_3}{dx_1} \frac{dx_1^0}{dx_3} + \frac{dy_3}{dx_2} \frac{dx_2^0}{dx_3} + \frac{dy_3}{dx_2} \mid \Omega_3 \right] = \tag{2.15}$$

$$E_3 \left[r_1 \frac{dx_1^0}{dx_3} + r_2 \frac{dx_2^0}{dx_2} + r_3 \mid \Omega_3 \right]$$

If assumption two is changed from the objective of profit maximization to expected utility maximization, then equation (2.03) becomes:

$$\text{Max } E_tU [\pi \mid \Omega t] = E_tU\left[[py_3 \mid \Omega_t] - \sum_{t=1}^{3} [r_tx_t \mid \Omega_t] - rz\right] \tag{2.16}$$

where utility is a function of profit. The consequences of utility and non-neutral risk preferences on decision making is presented in the section on decision analysis methods used in the study.

This illustration of farm decision making under risk clearly demonstrates the dependence among current, previous, and future choices resulting from uncertainty. It also portrays the role of information in developing decision strategies.

Role of Information in Developing Sequential Decision Strategies

As suggested in the conceptual model by Antle and Hatchett, the farmer must formulate a subjective probability assessment using available information about the uncertain outcomes associated with these timed input choices. The subjective assessment incorporates all the (data) information known by the decision maker in each time period about the influence of the input decision on profit. This information set is augmented by new data as time progresses, thus logically this knowledge base can only grow and never decline.

If Ω_t is the information set used by the farmer to make the input choice at time t, then let f $[\pi (x_t, h(\theta_t)) \mid \Omega_t]$ be the continuous conditional probability density for the random outcome distribution, $\pi(x_t \mid \Omega_t)$, given information set Ω_t. An intuitive description of a conditional probability states that it represents a re-evaluation of the probability of event A occurring given information about event B which has already occurred (Malliaris and Brock, 1981, p. 12). Corresponding to the conditional density is the conditional expectation:

$$E_t [\pi (x_t, \theta_t) \mid \Omega_t] = \int \pi (x_t, \theta_t) f(\pi (x_t, \theta_t) \mid \Omega t) dx_t \qquad (2.17)$$

The conditional expectation of the random variable is the expected value of the variable formed by the conditional density. Intuitively, this conditional expectation is a forecast by the decision maker of the uncertain profit outcome resulting from the input choice at time t.

The decision process described by Antle and Hatchett can be characterized as a martingale stochastic process. Martingale is a French word that describes a certain gambling strategy.[2] The martingale process is defined as (Gardner, 1986, pp. 90-91):

An independent incremental process with zero mean has the property:

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[2] Martingale theory has it origins in gambling. This is illustrated by an example. Let $X_1, X_2, ..., X_n$ be a sequence of gambler winnings associated with n random trials in a succession of games. The gambler's expected fortune after n+1 trials, given the gambler has played n games, is represented by $E[X_{n+1} \mid X_1,.., X_n]$. This sequence contains all of the information about the gambler's fortune up to and including the nth trial. If the game is fair, then the gambler will not expect to be either wealthier or poorer after the n+1 trial, i.e., $E[X_{n+1} \mid X_1,.., X_n]=X_n$.

$$E\{X(t_n) - X(t_{n-1}) \mid X(t_1), X(t_2), \ldots, X(t_{n-1})\} = 0, \qquad \text{or} \qquad (2.18)$$

$$\text{or } E\{X(t_n) \mid X(t_1), X(t_2), \ldots, X(t_{n-1})\} = X(t_{n-1})\}.$$

An important attribute of a martingale is the monotoneity property. This property implies that the amount of information in this incremental process is increasing over time. It incorporates the concept "that the past to time n+1 includes more events, information or history than the past to time n. The overall informational structure represented by the monotonically increasing sequence (equation 2.18) captures the concept of *learning without forgetting* (Malliaris and Brock, 1981, pp. 16-19)."

Associated with the conditional expectation is a forecast error term, $\in_t$, defined as

$$\in_t = \pi(x_t) - E[\pi(x_t) \mid \Omega_t] \qquad (2.19)$$

with the following properties:

$$E[\pi(x_t) \mid \Omega_t] = E[\pi(x_t) \mid \Omega_t] - E[\pi(x_t) \mid \Omega_t] = 0 \qquad \text{and} \qquad (2.20)$$

$$E[\in_t \Omega_t \mid \Omega_t] = 0. \qquad (2.21)$$

The first property says that the expected value of the forecast error is zero. At time t, the conditional expectation or forecast is known so that its conditional expectation is the forecast itself. The second property says that the forecast error is uncorrelated with any information that is available to the farmer. It would be possible to improve the forecast if this is not so. Thus the farmer's forecast will be correct on average and is not subject to systematic error. This does not imply that there will not be a large error in the decision makers' expectation of a decision outcome.

Let the decision maker's subjective, psychological expectation for the random event, $\pi(x_t, \theta_i)$, be represented by $E_t[\pi(x_t)]$. If the farmer's subjective expectations are, on average, equal to the true values of the variable, then the

$$\begin{array}{l}\text{farmer's}\\ \text{subjective}\\ \text{expectation}\end{array}\left\{ E_t\,[\pi\,(xt)] = E\,[\pi\,(x_t) \mid \Omega_t] \right\}\begin{array}{l}\text{mathematical}\\ \text{conditional}\\ \text{expectation}\end{array} \tag{2.22}$$

Thus there is a linkage between the beliefs of the farmer and the actual stochastic behavior of the crop ecosystem.

Taylor and Chavas (1980, pp. 675-680) and Antle (1983, pp. 286-290) have investigated the properties of information sets and how they influence alternative optimization decision rules. Taylor and Chavas contend that farmers must "rely on their own experience in choosing optimal input rates (p. 675)." This implies that any input decision may have two roles. First, input choices are used to control the mean and higher moments of profit. Second, current input choices produce new outcomes and consequently new information. This updated knowledge base is used by the farmer to improve input choices in the future. They outlined three decision rules based on the types of knowledge used:

1. **Certainty Equivalence (CE) Strategy**: The optimal input choice based on the current estimates of the parameters of the response function is used throughout the planning horizon. This means that no new information is used as additional data become available.

2. **Updated Certainty Equivalence (UCE) Strategy**: Parameter estimates are updated and optimal rates revised each time a new observation becomes available. Current decisions are made without acknowledging how these choices will influence the learning process.

3. **Actively Adaptive Control Strategy**: This "wide sense" approach explicitly recognizes how current decisions will influence future knowledge. "Current and future uncertainty are introduced into the decision rules, thus increasing information for improved performance in the future (p. 677)."

Antle provides a more comprehensive examination of the properties of information and their relation to alternative sequential decision rule schemes.

Antle (1983, p. 284) suggests that there are three properties of information used by farmers in sequential optimization, and thus should be considered in developing economic production models:

1. Property A: **Sequential dependence of decisions.** Previous input choices may influence subsequent input decisions. For example, the decision of when to plant, x_1, may depend on how this choice, based on a priori knowledge, is expected to affect a future management choice x_2 such as a pest management decision. Thus, the optimal choice of x_2 may be a function $x_2(x_1)$.

2. Property B: **Information feedback on input choices.** Outcome data that become available from preceding production stages are incorporated into subsequent choices. The decision maker uses the current expectation of final yield, $E_t\ (y_t \mid \Omega_t)$, rather than the original expectation to determine the current input choice, x_t.

3. Property C: **Anticipated revision of input decisions.** Earlier input decisions may be revised later as new information becomes available. A farmer anticipates that additional information about yield potential will become available in subsequent periods.

These three properties of information sets used to model decision making are the basis for four decision rules: the open loop, sequential updating, open loop with feedback, and closed loop solutions.

1. **Open loop (OL) solution.** The OL solution exploits property A, the sequential dependence characteristic. The decision rule is selected using all available a priori knowledge of the behavior of the system, i.e., input choices are based only on information available before production begins. This rule is in no way influenced by the current state of the system during production. It implies that the decision maker does not use what is learned about production outcomes at future stages of the decision making process. This rule is identical to the certainty equivalence (CE) strategy of Chavas and Taylor.

2. **Sequential updating (SU) solution**: The SU solution employs property B, the information feedback feature. The information set is updated at each decision stage, but knowledge about the influence of the current choice on future decisions in not accounted for in the decision rule. This rule is analogous to the

updated certainty equivalence (UCE) strategy of Chavas and Taylor.

3. **Open loop with feedback (OLF) solution**: The OLF solution combines the sequential dependence (property A) and information feedback (property B) characteristics. The decision rule is developed using: 1) all available a priori knowledge of the behavior of the system before production begins, and 2) additional information received at each decision stage during production. The influence of the current choice on future decisions is still not accounted for in the decision rule.

4. **Closed loop (CL) solution**. The CL solution combines properties A, B, and C in the formulation of a decision rule. Thus the decision rule is developed using: 1) all available a priori knowledge of the behavior of the system before production begins, 2) additional information received at each decision stage during production, and 3) knowledge about the influence of the current choice on future decisions is also accounted for in the decision rule. This rule is comparable to the actively adaptive control strategy of Chavas and Taylor.

Decision Analysis Methods used in the Study

This section describes the decision analysis methods employed for the economic analysis conducted in Chapter V. An outline of the components of the decision problem under risk is presented first, followed by a brief review of utility theory. These two elements form the foundation for the stochastic dominance and information valuation criteria presented in the final two parts of this section.

Components of the Decision Problem

The elements of the decision problem involving uncertainty or risk, their nomenclature, and their definitions are (Anderson, Dillon, and Hardaker 1977, pp. 4-6; Hirshleifer and Riley 1979, pp. 1,377-1,381):

1. **Act a_j**: represents the j_{th} decision among $a_1, a_2, \ldots, a_j, \ldots$ mutually exclusive and exhaustive choices among which a decision maker must pick.

2. **State** θ_i: represents the $_{jth}$ state of nature or random event among $\theta_1, \theta_2, \ldots, \theta_j, ..$ mutually exclusive and exhaustive uncertain events generated from probability distribution $f(\theta_i)$.

3. **Prior Probability** $p(\theta_i)$: represents the conditional prior probability of the ith state of nature. It embodies the decision maker's initial subjective assessment about the state's chance of occurrence, i.e., all a priori knowledge, experience, and judgement about past events influencing yield, input-output ratios, and profit outcomes.

4. **Consequence function** $U(a_j \mid \theta_i)$: represents the utility derived from a particular consequence, outcome, or payoff resulting from the $_i$th state when the $_{jth}$ act is chosen.

5. **Message** z_k: represents the $_k$th possible message or forecast among a distribution of $z_1, z_2, \ldots, z_j, ..$ predictions. Messages are derived through experiments, e.g., a predictive device, buying a forecast, etc., which gives additional information about the probabilities of the states.

6. **Likelihood Function** $p(z_k \mid \theta_i)$: represents the vehicle for transmitting information in the form of a conditional probability distribution that is also called a likelihood function. It represents the likelihood of z_k given θ_i

7. **Posterior Probability Function** $p(\theta_i \mid z_k)$: Revised probability belief of the agent for state θ_i given the message z_k.

8. **Strategy** s_l: represents the $_{lth}$ strategy or decision rule chosen by the agent. It specifies in advance the act or schedule of acts that will be implemented in response to any information signal or message when particular earlier acts have been chosen and preceding events have become known, e.g., s_l is defined as implementing the $_{jth}$ act when the $_{kth}$ message is received.

There are two types of acts. **Terminal actions** involve the decision maker's use of the existing combination of information and ignorance in devising a strategy. In statistical parlance, the terminal action is symbolized by the balancing of Type I (reject the null hypothesis when the null is true) and Type II (accept the null when the null is false) errors in coming to a decision on the basis of the evidence or data now in hand. **Informational**

actions are non-terminal in that the final decision is deferred while awaiting or actively seeking new evidence which is anticipated to reduce the uncertainty resulting from the choice. In statistical terminology, informational actions imply running experiments designed to provide additional evidence in coming to a decision of rejecting or accepting the null hypothesis.

An important feature of the decision problem that is not elaborated above is the agent's choice criterion or objective function. This study assumes the criterion of maximizing decision maker expected utility in the evaluation of decision alternatives. An outline of the theory is next.

Utility and the Decision Problem

The expected utility theorem (EU) is the theoretical basis of the stochastic dominance criteria used to order uncertain choices and to value information regarding those alternatives. Daniel Bernoulli in 1730 first postulated the expected utility theorem which recognizes that one additional dollar "is worth more to a poor man than to a rich man (Anderson et al., 1977, p. 66)." John Von Neumann and Oskar Morgenstern (1947) extended the observation of Bernoulli by rigorously developing a set of axioms for the EU. These axioms are based on assumptions about decision maker behavior; that is, economic agents are rational and consistent in choosing among risky choices. Let a_1, a_2, and a_3 represent choices confronting an agent, then the most important of these axioms are (Robison and Barry, 1987, p. 18):

1. **Ordering of choices**: If a_1 is preferred to a_2 the decision maker either prefers a_1 to a_2, prefers a_2 to a_1, or is indifferent.

2. **Transitivity among choices**: If a_1 is preferred to a_2 and a_2 is preferred to a_3, then a_1 must be preferred to a_3.

3. **Substitution of choices**: If a_1 is preferred to a_2, and a_3 is some other choice, then a risky choice $pa_1+(1-p)a_3$ is preferred to another risky choice $pa_2+(1-p)a_3$, where p is the probability of occurrence of a_1 and a_2.

4. **Certainty equivalent of choice**: If a_1 is preferred to a_2, and a_2 is preferred to a_3, then some probability p exists that the decision maker is indifferent to having a_2 for certain or receiving a_1 with the probability p and a_3 with probability 1-p. Thus a_2 is the certainty equivalent of $pa_1+(1-p)a_3$.

The expected utility theorem states that a decision maker, whose preferences are consistent with these axioms, can be quantitatively represented by a single value utility function, U=U(•). This function relates a single real number or utility value with each uncertain outcome. It has the following properties (Anderson, Dillon, and Hardaker, 1977, p. 68):

1. If a_1 is preferred to a_2, then $U(a_1)>U(a_2)$ and vice versa. An economic agent whose preferences are consistent with the axioms will choose between the uncertain alternates to maximize expected utility.

2. The utility associated with an uncertain outcome is its expected utility value, i.e,

$$U(a_j) = E[U(a_j)] = \int U(a_j \mid \omega)\, h\,(w)\, d\omega \tag{2.23}$$

where h(w) is the agent's subjective expectation distribution of uncertain outcomes. The higher moments of utility such as its variance are not relevant to decision making.

3. The numerical scale used to describe utility is arbitrary. The properties of a utility function that are relevant to decision analysis are not changed under a positive linear transformation of that function. Moreover, a comparison of utility values among individuals is meaningless since it is a unique measure of preferences.

The risk attitude of the decision maker can be inferred from the shape of the agent's utility function. Let U'(•) represent the first derivative and U"(•) the second derivative of the utility function, then:

1. Linear implies risk neutral, i.e., U'(•)>0 and U"(•)=0, thus utility always increases with income but at a constant rate.

2. Concave implies risk averse, i.e., U'(•)>0 and U"(•)<0, thus utility always increases with income but at a decreasing rate.

3. Convex implies risk preferring, i.e., U'(•)>0 and U"(•)>0, thus utility always increases with income but at an increasing rate.

A risk averse agent will always prefer a certain outcome (certain income) to an uncertain consequence with the same expected monetary value. The decrease in utility from a monetary loss exceeds the rise in utility from a monetary gain when both the potential loss and gain are of equal size and probability (Robison, Barry, Kliebenstein, and Patrick, 1984, p. 15).

This consequence is illustrated in Figure 2.1. Any point on the concave utility curve U(x) will lie above any vertically aligned point along any line segment connecting two points on the curve. The point on the curve represents the utility of a sure income. This sure income, called the certainty equivalent (CE), is defined as "the amount exchanged with certainty that makes the decision maker indifferent between this exchange and some particularly risk prospect (Anderson, Dillon, and Hardaker, 1977, p. 70)." The vertically aligned point on any line segment represents the utility of the uncertain consequence (risky prospect) with an expected value equal to the sure income.

The diagram specifically shows a decision problem with two equally likely outcomes. Let x_1=\$0 and x2=\$1,000 represent the outcomes of an uncertain choice with probabilities p=0.50 and 1-p=0.50, respectively.

The expected utility of a certain consequence, as depicted by the expected monetary value [EMV = 0.50•\$0 + 0.50•\$1,000 = \$500] of x_1 and x_2, surpasses the utility of the uncertain outcome [EU(X) = 0.50•U(\$0) + 0.50•U (\$1,000)]. A risk averse decision maker would not buy the uncertain

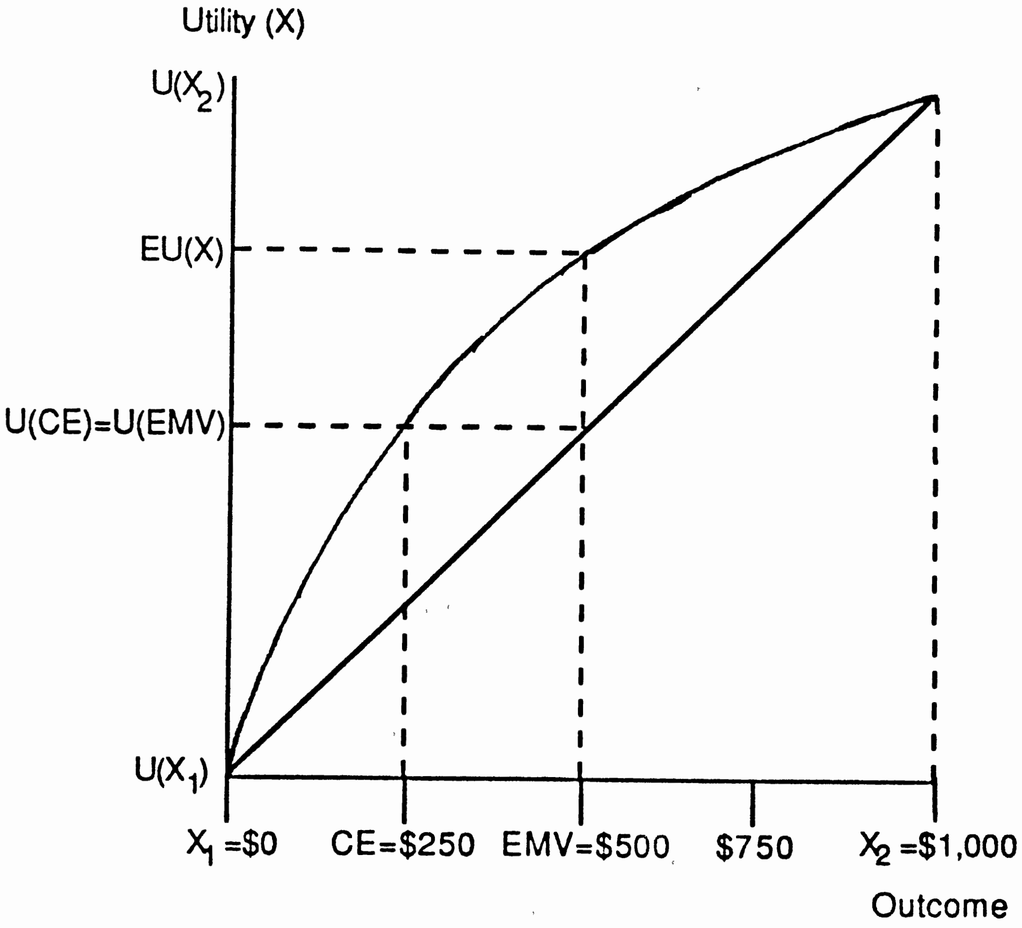


Figure 2.1. Utility and the Risk Averse Economic Agent

consequence at a price equal to its expected monetary value. This occurs because the zero monetary gain translates into a utility loss for the agent as shown in Figure 2.1. Stated differently, the uncertain consequence is the utility equivalent of a sure income represented by the certainty equivalent (CE) of only $250. Since the CE is less than the EMV, the decision maker displays risk aversion. The difference between the CE and EMV is the risk premium. It represents the amount of compensation in terms of utility for the agent to accept the risky choice.

This rudimentary treatise of utility and risk provides the foundation for the discussion of stochastic dominance efficiency criteria and valuing information under risk techniques used in this study. These two topics are presented in the next two sections.

Stochastic Dominance Efficiency Criteria

Various methods to order risky choices for expected utility maximizing decision makers have been formulated in the literature. This section reviews these techniques and their applications in the literature.

These methods, called either "efficiency (e.g., Hanoch and Levey)" or "stochastic dominance (e.g., Hadar and Russell; Myer)" criteria in the literature, allow either a partial or total ordering of the uncertain outcomes associated with management choices for a class of economic agents. This is accomplished by placing certain restrictions on the preferences of the decision maker(s) under consideration. Risk efficiency criterion divides the decision alternatives into two mutually exclusive groups, the efficient and inefficient set. The efficient set contains the preferred choice(s) for every individual whose preferences conform to the restrictions placed on those choices. Conversely, the inefficient set contains the choice(s) not preferred by every individual whose preferences conform to the restrictions. Thus, the criterion narrows the set of risky choices to a manageable level.

Stochastic dominance efficiency criterion are used to order uncertain outcomes that can be specified as discrete or continuous cumulative probability distributions. Myers (1977, pp. 326-336) developed the generalized stochastic dominance (GSD) procedure, the most powerful and flexible of the risk efficiency ranking criteria. GSD ranks uncertain choices for classes of decision makers defined by specified lower and upper bounds on the absolute risk aversion function $r(y)=-U''(y)/U'(y)$. Pratt (1964, pp. 122-136) demonstrated that $r(y)$, defined as the negative ratio of the second and first derivatives of the utility function with respect to income (y), is a measure of risk preference. This simple measure of curvature along the utility function is not changed by an arbitrary positive linear transformation of the utility function. Thus it is a pure number that allow interpersonal comparisons of the risk preference at different income levels: $r(y)>0$ implies risk aversion, $r(y)<0$ implies risk seeking behavior, and $r(y)=0$ implies risk neutrality.

Assume that an agent is confronted with the problem of choosing between two cumulative probability distributions, F(x) and G(x), associated with probability distributions f(x) and g(x). F(x) and G(x) have a bounded interval [0,1] such that $F(0)=G(0)=0$ and $F(1)=G(1)=1$. GSD establishes the necessary and sufficient conditions for F(x) to be preferred to G(x) by all decision makers with absolute risk aversion functions that lie everywhere between lower and upper bounds $r_1(y)$ and $r_2(y)$ (King 1979, pp. 98-99).

Let

$$\int_0^1 [G(x) - F(x)]u'(x)dx \qquad (2.24)$$

represent the difference in the expected utilities associated with the two cumulative probability distributions G(x) and F(x). This expression is then minimized subject to the constraint $r_1(y) \leq -u''(y)/u'(y) \leq r_2(y)$ and $u'(0)=1$ to ascertain if G(x) is unanimously preferred to F(x) (King, 1979, p. 99).

In applying this procedure for a given class of decision makers (defined by $r_1(x)$, $r_2(x)$), if the minimum of the difference in expected utility between F(x) and G(x) is:

1. positive, then F(x) is unanimously preferred to G(x);
2. zero, then the agent is indifferent between F(x) and G(x); or
3. negative, then F(x) cannot be said to be unanimously preferred to G(x).

If the minimum of the utility difference is negative, then G(x) and F(x) are switched and equation

$$\int_0^1 [F(x) - G(x)]u'(x)dx \tag{2.25}$$

is minimized subject to $r_1(y) \leq -u''(y)/u'(y) \leq r_2(y)$ and $u'(0)=1$ to determine if F(x) is unanimously preferred to G(x). If the minimum of both comparisons is negative, then both distributions are not preferred by agents in the bounded interval $r_1(y)$, $r_2(y)$ (Myer, 1977, p. 333).

First-degree stochastic dominance (FSD), second-degree stochastic dominance (SSD), and mean-variance (EV) efficiency criterion are special cases of generalized stochastic dominance.

First-degree stochastic dominance (Quirk and Saposnik, 1962; Fishburn, 1964) places the single restriction of a monotonically increasing utility function on decision maker preferences. Expressed another way, FSD assumes that the economic agent has positive marginal utility for money; that is, the first derivative of the utility function is positive ($U'(x)>0$). This restriction of rising utility with increasing income holds regardless of risk preference. In terms of absolute risk aversion space, it represents the class of agents whose absolute risk aversion function lies everywhere between lower and upper bounds r1(y)= -∞ and r2(y)=+∞

FSD is often not satisfactory in empirical analysis since few distributions can be eliminated using this method. Furthermore, many distributions cross each other precluding the chance of finding the efficient set using this criterion.

Second-Degree Stochastic Dominance (Fishburn, 1964; Hanoch and Levey, 1969; Hadar and Russell, 1969; Hammond, 1969) places the additional restriction of risk aversion. The utility function is not only monotonically increasing but is also strictly concave. That is, the first derivative of the utility function is positive (U'(x)>0) and the second derivative is negative (U"(x)<0). In terms of absolute risk aversion space, it represents the class of agents whose absolute risk aversion function lies everywhere between lower and upper bounds $r_1(y)=0$ and $r_2(y)=+\infty$.

SSD is a more discriminating than FSD. However, the assumption of risk aversion may not always be valid. Thus the preferred choice may be excluded from the efficient set if this assumption is violated. Furthermore, SSD may not effectively reduce the number of alternatives in the set of possible outcomes to be considered by the decision maker.

Mean-variance (Tobin, 1958; Markowitz, 1959) is a special case of second-degree stochastic dominance. Mean-variance (EV) and SSD yield identical results when the decision maker is considered risk averse and the outcomes are normally distributed. The criterion has the advantage of being easy to use and understand. However, there are several potential problems associated with EV the criterion. First, the decision maker is assumed to be risk averse. Second, EV is used under the assumption that outcomes are normally distributed. Using EV to order non-normal distributions, commonly found in agriculture, may result in an efficient set that differs from second-degree stochastic dominance. Third, EV only considers mean and variance; other higher moments of the distribution may need to be considered. Finally, the EV method frequently fails to reduce the number of decision making alternatives to a manageable level.

<u>Review of Selected Studies Using Stochastic Dominance</u>. Myer (1977, pp. 334-335) suggests several possible applications of generalized stochastic dominance (GSD): 1) to determine if F(x) is preferred or indifferent to G(x) by all agents in the set $u(r_1(x), r_2(x))$; 2) as an efficiency criterion method of reducing the preferred set by eliminating all distributions that are dominated by other distributions in the set; and 3) for evaluating the sensitivity of the preferred set to changes in the bounded interval $u(r_1(x), r_2(x))$.

Bosch and Eidman (1987, pp. 658-668) proposed a fourth application for GSD. They investigated the value of different strategies based on the level of information. This application of GSD is discussed further in the section on valuing economic information under risk.

Stochastic dominance criteria have been extensively applied to decision problems in agricultural economics. These studies include: Musser, Tew, and Epperson (1981, pp. 119-124) evaluating integrated pest management (IPM) strategies; Cochran, Lodwick, Jones, and Robison (1982) applying stochastic dominance techniques to the analysis of apple scab pest management strategies; McGuckin (1983, pp. 43-50) examining IPM and harvest management strategies for alfalfa on a Wisconsin dairy farm; Rister, Skees, and Black (1984, pp.151-158) comparing outlook information and grain sorghum marketing alternatives using GSD and certainty equivalents; and Harris and Mapp (1986, pp. 298-305) using biophysical simulation techniques and stochastic dominance to evaluate water conserving and intensive irrigation strategies at each decision stage and for a sequence of stages for sorghum.

Valuing Economic Information Under Risk

This section outlines the theory of valuing information under uncertainty. A conceptual model of valuing information under uncertainty modified from Hirshleifer and Riley (1979, pp. 1,375-1,421) is presented. Next, several approaches to valuing information under risk that have been developed in the literature are discussed. Finally some selected studies of the problem of valuing economic information under risk for the farm decision maker and their various methodologies are reviewed.

A Conceptual Model of Information Valuation. This section presents a conceptual model of informtion value as described by Hirshleifer and Riley (1979, pp. 1,375-1,421). Assume that a utility maximizing economic agent is confronted with a decision problem consisting of a_1, a_2, ...,a_j,.. actions associated with θ_1, θ_2 ,..., θ_i,.. possible states and $U(a_j \mid \theta_i)$ consequences. The decision maker has a prior probability distribution of initial expectations $f(\theta_i)$ regarding the uncertain consequence of each action-state combination. Assume that the agent has the ability to acquire information in the form of a set of messages z_1, z_2,..., z_k,.. (e.g., by forecasting or experimentation). These messages can lead to a modification of the agent's prior probability belief $p(\theta_i)$ and thus to a revision of act a_j. The revised likelihood probability $p(z_k \mid \theta_i)$ contains new information about state i given message k. This new information is processed via Bayes' theorem

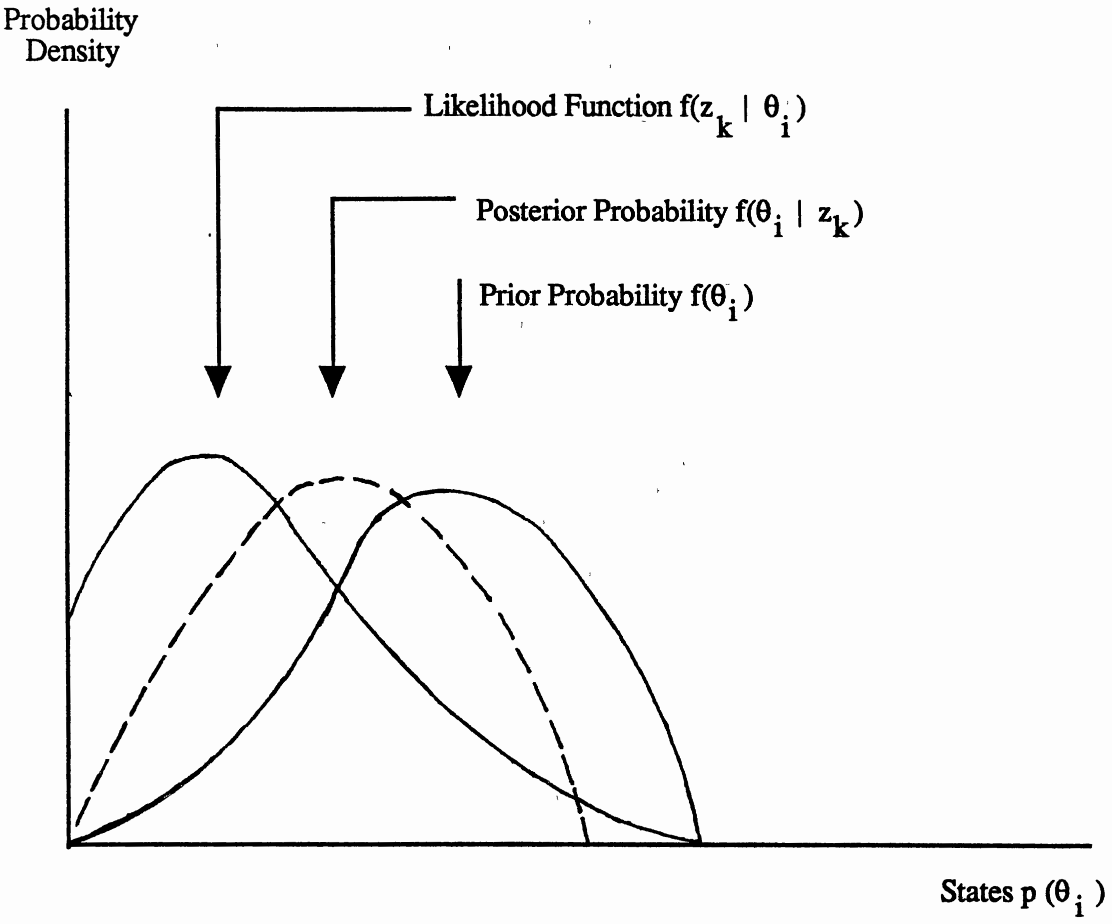
$$p(\theta_i \mid z_k) = \frac{p(\theta_i)\, p(z_k \mid \theta_i)}{\Sigma i\ p(\theta_i)\, p(z_k \mid \theta_i)} = \frac{p(\theta_i, z_k)}{p(z_k)} \qquad (2.26)$$

where $p(\theta_i, z_k)$ is the joint probability of state i and message k and $p(z_k)$ is the marginal or unconditional probability of receiving message k. Jefferies (1961, p. 29) states that Bayes' theorem is the fundamental rule entailed in the process of learning from experience.

An illustration of Bayesian probability recalculation given message z_k in continuous probability space is presented in Figure 2.2. The posterior probability distribution is essentially an average of the likelihood and prior probability functions. This is derived by multiplying the prior probability by the likelihood probability in the numerator for each state. The numerator is then rescaled using a proportionality factor, the products of the prior and likelihood probabilities summed over all states, in the denominator so that the revised probabilities lie between zero and one.

In the diagram, the bulk of the agent's prior probability distribution is assumed to lie towards the right, i.e., states having a larger rather than smaller value. The likelihood function generates messages (evidence) of states having a smaller rather than a larger value. The decision maker's degree of confidence in his or her initial beliefs is indicated by how close the posterior distribution resembles the prior distribution. This diagram illustrates that the higher (lower) the agent's prior confidence, the more (less) the posterior will look like the prior for any given weight of the evidence. This suggests that the degree of prior confidence is inversely related to the value of acquiring evidence and thus to the value of information.

The value of information for the terminal action decision problem is determined by the expected utility gain from shifting to the more preferred choice among the set of terminal acts. It is an *ex post* valuation since the message z_k is known with certainty when revising probabilities, i.e, $p(z_k)=1.0$.



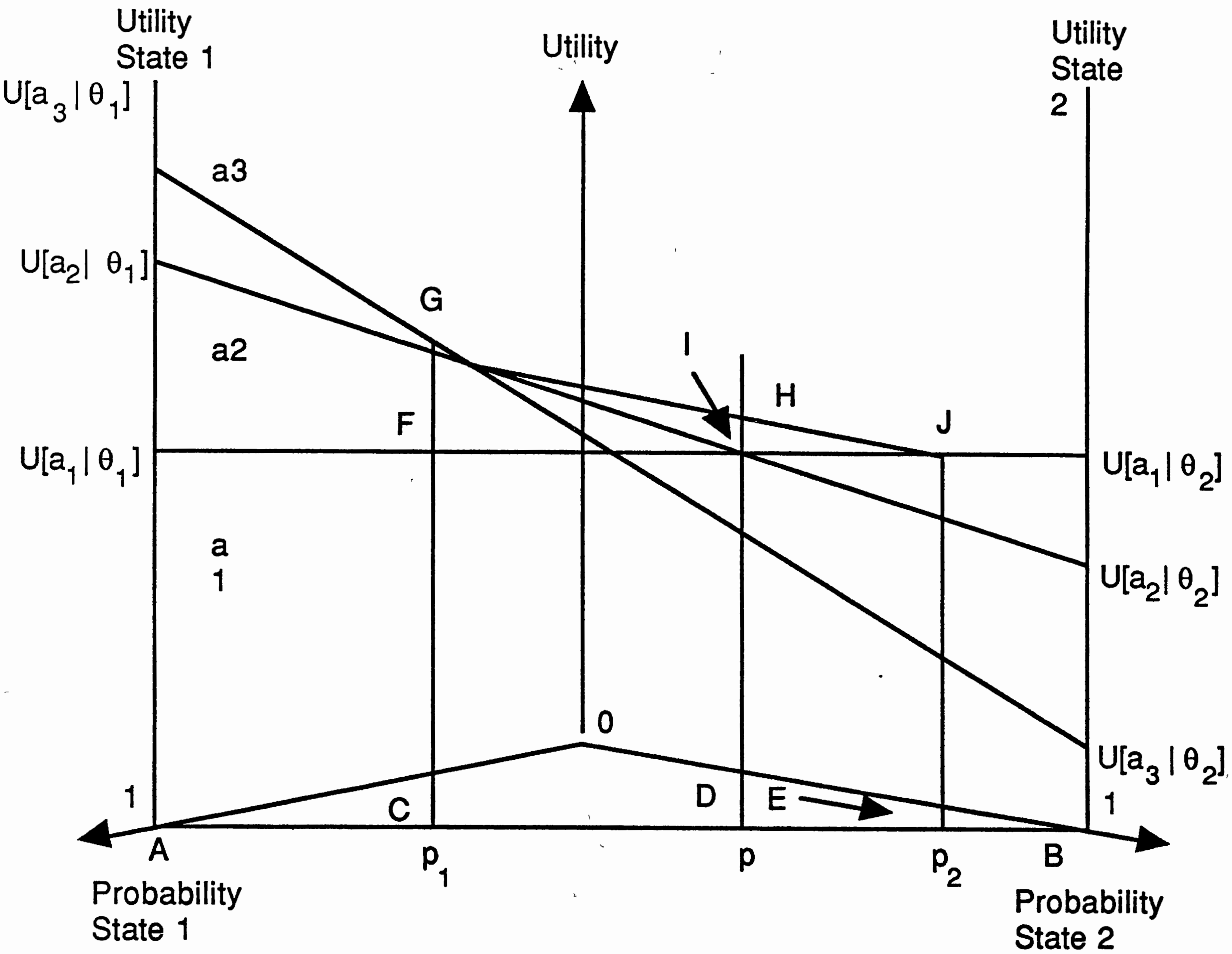
Adapted from: Hirshleifer, J. and John G. Riley. 1979. "The Analytics of Uncertainty and Information--An Expository Review." Journal of Economic Literature, Vol. 17, No. 4, p. 1,394.

Figure 2.2. Illustration of Probability Revision Via Bayes' Theorem

Derivation of the value of information for the non-terminal action (informational) decision problem is an *ex ante* analysis. Value is determined by the expected utility gain from shifting to the more preferred choice given new information in the form of a message or forecast about the occurrence of state i. The agent is uncertain of what message z_k will be received out of the set of possible messages $z_1, z_2, \ldots, z_k, \ldots$ Thus the decision maker cannot purchase a single message, but an information service, i.e., a forecast, generating a distribution of possible messages. This information service can never lower the decision maker's expected utility before considering the cost of acquiring the information. Thus the decision maker is uncertain about the actual prediction as well as uncertain about the estimate of the true value of the random variable given by the prediction.

The concepts associated with information valuation by a utility maximizing agent are illustrated in Figure 2.3. Assume that the decision maker is confronted with a terminal action decision problem consisting of three alternative actions with two possible states and six consequences, that is,

	States of Nature	
Actions	State θ_1	State θ_2
a_1	$U(a_1 \mid \theta_1)$	$U(a_1 \mid \theta_2)$
a_2	$U(a_2 \mid \theta_1)$	$U(a_2 \mid \theta_2)$
a_3	$U(a_3 \mid \theta_1)$	$U(a_3 \mid \theta_2)$
Beliefs	p_1	$p_2=(1-p_1)$



Adapted from: Hirshleifer, J. and John G. Riley. 1979. "The Analytics of Uncertainty and Information--An Expository Review." Journal of Economic Literature, Vol. 17, No. 4, p. 1,396.

Figure 2.3. Diagram Outlining Value of Information of Information Concepts

Further, assume that there is a costless information service with two messages, z_1 and z_2. Finally, let p_1 and p_2 represent the decision maker's beliefs (posterior probability) regarding action-state-consequence interactions.

Expected utility in Figure 2.3 is measured along the three vertical axes. The probabilities associated with the two states are scaled on the two horizontal axis. Each possible set of probabilities associated with the states one and two is portrayed as a point on the line segment AB, i.e., $p_1 + p_2 = 1.0$. The expected utility of any act a_j and belief vector (p_1, p_2) is the vertical aligned distance from a point on the line segment AB up to point on the line joining $U(a_j \mid \theta_1)$ and $U(a_j \mid \theta_2)$ for action a_j.

Consider the terminal action decision problem case in Figure 2.3. If p represents the agent's prior probability vector, then act a_1 is the utility maximizing choice with utility represented by DI. Now assume that a message is received indicating that state one will occur. The revised optimal action is a_2 which is represented by point G. The *ex post* utility gain is represented by the vertical distance GF. If a message is received that indicates state two will occur, then the best action remains a_1 with a zero *ex post* gain in utility. Weighting the utility gains for each message by their probability of occurrence yields the value of the information service. This is represented by the vertical distance HI.

Figure 2.3 also shows how higher prior confidence by the agent signifies a lower value of information. A posterior distribution that is close to the prior distribution means that the posterior, p_1 and p_2, would lie closer to the prior, p. The result is to lessen the distance HI, thus the expected value of information.

Hirshleifer (1973, pp. 31-39) outlines five economic attributes that influence the value of information to potential users: 1) certainty, i.e., the degree of confidence that the agent exhibits through the prior probability distribution; 2) diffusion, which influences the scarcity value of information; 3) applicability of the information to the particular decision problem; 4) content, i.e., information about the physical environment (exogenous variables) versus information about how other agents act (endogenous variables); and 5) the relevance of the information to the decision problem. Alternatively, Hilton (1979, pp. 411-435) recounts five determinants of information value: 1) the agent's technology and environment, 2) the decision maker's perception of the nature of the information system, 3) the agent's degree of uncertainty about the prior probability distribution, 4) the flexibility of the structure of the decision maker's action set, and 5) the timing of the information signal received by the agent.

Hilton (1981, pp. 59-61) also presents several general results regarding information value:

> 1. There is no general monotonic relationship between action flexibility and information value;
>
> 2. There is no general monotonic relationship between the degree of absolute or relative risk aversion and the value of information;
>
> 3. There is no general monotonic relationship between wealth and information value;
>
> 4. Information value is invariant with respect to wealth if and only if the utility function is linear or negative exponential; and
>
> 5. There is no monotonic relationship between information value and RS (Rothschild-Stiglitz) degree of uncertainty in the prior (probability distribution).[3]

Review of Selected Information Valuation Approaches and Studies. Many approaches to the valuation of information have been advanced in the literature. Several are reviewed below.

---

[3] Rothschild and Stiglitz (1970, pp.225-243) present a definition of risk that is not the same as using variance as a measure of risk. They provide three equivalent definitions: 1) random variable Y is riskier than random variable X if Y is X plus some uncorrelated random noise; 2) Y is riskier than X if Y and X have the same mean and $E[U(X)] \geq E[U(Y)]$ for all concave U; and 3) Y is riskier than X if they have the same mean but Y has more weight in the tail than X.

Gould (1974, pp. 64-84) and Hess (1982, pp. 231-238) both define the value of information as the difference in expected utility between an optimally chosen act a_j when the state of nature is known with perfect certainty and an optimally chosen act a_j when the state of nature is not known with certainty. This definition measures the difference in expected utility value between perfect information about the outcome and when information about the distribution of the state of nature is known. Using the notation defined previously, this measure is mathematically represented by

$$E[\max_{a_j} u(a_j \mid \theta_1) - \max_{a_j} E[u(a_j \mid \theta_1)] = \tag{2.27}$$

$$\int \max_{a_j} u(a_j \mid \theta_1)h(\theta_1)d\theta_1 - \max_{a_j} \int u\,(a_j \mid \theta_1)h(\theta_1)d\theta_1$$

The Gould-Hess measure of information value contrasts with the concept developed by Hirshleifer and Riley and presented in the previous section. Hirschleifer and Riley define the value of information in terms of using new information to revise the prior probability employing Bayes' theorem to formulate a posterior probability, i.e., compare the difference in utilities of less informed and more informed distributions. This is mathematically represented by

$$\max_{a_j} \int\int u_0(a_j \mid \theta_1)f_0(\theta_1 \mid z_k)d\theta_1 dz_k \quad \text{and} \tag{2.28}$$

$$\max_{a_j} \int\int u_m(a_j \mid \theta_1)f_m(\theta_1 \mid z_k)d\theta_1 dz_k$$

where $f_0(\theta_i \mid z_k)$ and $f_m(\theta_i \mid z_k)$ represent the less informed and more informed posterior distributions, respectively. Thus the value of information in the sense of knowing a better estimate of the true distribution is mathematically represented by

$$\int\int u_0(a_j^* \mid \theta_1) f_m(\theta_1 \mid z_k) d\theta_1 dz_k - \tag{2.29}$$
$$\int\int u_m(a_j^* \mid \theta_1) f_0(\theta_1 \mid z_k) d\theta_1 dz_k$$

where a_j^* represents the optimal act for the less and more informed posterior distributions, respectively. This expression represents the difference in the expected utilities associated with the two probability distributions.

The Gould-Hess and Hirshleifer and Riley valuation measures are in terms of utility. Unfortunately, a utility valuation measure is unique only up to some positive linear transformation. Thus a utility valuation measure is of limited use since a comparison of information value from different sources and to different decision makers is not possible (Byerlee and Anderson, 1982, p. 233; Preckel, Loehman, and Kaylen, 1987, p. 194). Several researchers have suggested methods to overcome the problem with direct utility measurements.

Roe and Antonovitz (1985, pp. 382-391) defined a measure of information value in terms of monetary units rather than utility. This so called "money metric" approach has two alternative measures of information: 1) willingness to accept (WTA) and 2) willingness to pay (WTP). WTA represents the dollar amount that must be received in every state of nature to exactly compensate the agent for not having information about the posterior probability distribution. Conversely, WTP is defined as the dollar amount the agent would be willing to pay for the information contained in the posterior probability distribution. The WTA and WTP measures are mathematically represented by

$$\int\int u_0[\pi\,(a_j^* \mid \theta_1) - WTA] f_0(\theta_1 \mid z_k) d\theta_1 dz_k - \tag{2.30}$$
$$\int\int u_m[\pi\,(a_j^* \mid \theta_1)] f_m(\theta_1 \mid z_k) d\theta_1 dz_k = 0$$

and

$$\int\int u_0[\pi\,(a_j^* \mid \theta_1) - WTP]f_0(\theta_1 \mid z_k)d\theta_1 dz_k - \int\int u_m[\pi\,(a_j^* \mid \theta_1)]f_m(\theta_1 \mid z_k)d\theta_1 dz_k = 0 \tag{2.31}$$

where utility is a function of profit π.

Byerlee and Anderson (1982, pp. 231-246) developed an information valuation model for evaluating probabilistic information for a utility maximizing economic agent with non-neutral risk preferences. They developed a value of information definition for prediction z_k of state θ_i that is subject to error. Information value is defined as the monetary amount V_z which the decision maker could pay for that prediction (information) and remain as well off in utility terms as when the agent did not have the information. This definition is represented by

$$\int\int U_0[\pi\,(\theta_1 \mid a_j^*) - V_z]\, f_0(\theta_1 \mid z_k)f(z_k)d\theta_1 dz_k - \int\int u_m[\pi\,(\theta_1 \mid a_j^*)]f_m(\theta_1 \mid z_k)f(z_k)d\theta_1 dz_k = 0 \tag{2.32}$$

where $f(z_k)$ represents the probability of generating prediction z_k. Equation (2.32) is subject to the constraint that a_j^* is chosen to maximize expected utility for every z_k for which $f(z_k)>0$. This is mathematically represented by

$$d\left[\int U_0[\pi(\theta_1 \mid a_j^*)] - V_z\ f_0(\theta_1 \mid z_k)\ d\theta_1\right] / da_j = 0. \tag{2.33}$$

The profit function is reduced by amount V_z until maximum expected utility is equal to the expected utility of the prior optimal action. V_z is an *ex ante* measure of information since it incorporates uncertainty about the actual prediction and uncertainty about the true value of the random variable given the prediction.

This definition appears to be analogous to the Roe and Antonovitz willingness to pay (WTP) definition, except that the predictor is subject to error in the Byerlee and Anderson approach. Byerlee and Anderson assume that agents have quadratic utility functions in order to solve for V_z analytically.

Bosch and Eidman (1987, pp. 658-668) extended the Byerlee and Anderson non-neutral risk preference approach by using Generalized Stochastic Dominance (GSD) to value information under uncertainty. Consequently the valuation of information under non-neutral risk preferences is not dependent on the form of the utility function. They define information value as "that amount by which each element of a net income distribution generated with information can be lowered before it no longer dominates a net income distribution generated without information (p. 659)." The value of a strategy s_I generated with information is dollar amount V_I such that inequalities

$$\begin{aligned} &{}_0\int^1 [G_0(x) - F_m(x-v_1)]u'(x)dx > 0, \text{ and} \\ &{}_0\int^1 [G_0(x) - F_m(x-v_1-Y)]u'(x)dx \leq 0 \end{aligned} \tag{2.34}$$

are simultaneously satisfied subject to $r_1(x) \leq -u''(x)/u'(x) \leq r_2(x)$ where

x = net income;
$G_0(x)$ = cumulative net income distribution generated without information;
$F_m(x)$ = cumulative net income distribution generated with information; and
Y = a small positive amount.

V_I^* represents the lower bound estimate of the value of information for decision makers within the specified absolute risk aversion interval $[r_1(x), r_2(x)]$. Information value can be higher than the lower bound estimate for some decision makers in the interval.

Bosch and Eidman applied their methodology to a representative Minnesota farm irrigation decision problem. They used biophysical simulation techniques to construct net income distributions based on different information level assumptions. GSD was used to value the alternative information level strategies.

Mjelde and Cochran (1988, pp. 285-293) also used GSD to estimate the value of seasonal climate forecasts for the Illinois corn production problem. Their approach appears identical to Bosch and Eidman, except that they reported both the lower and upper bound values, i.e., they reported upper bound estimates which would include at least one agent in the interval.

Massey and Williams (1991, pp. 227-236) used stochastic simulation methods and GSD to value alternative swine breeding schemes. They analyzed decision maker willingness to pay for information on improved swine breeding technologies.

There are other information valuation approaches such as entropy that are presented in the literature. However, there is no established general relationship between entropy and the value of information to a decision maker (Chavas and Pope, 1984, p. 706). For more information (pun intended) about entropy and other valuation measures start with Chavas and Pope (1984, pp. 705-710) and Gould (1974, pp. 64-84).

Review of Pest Management Concepts

Pests have been a recurring problem for farmers over the millennia. Early attempts at pest control were often based on superstition, mysticism, or religion. For example, "in Berne, Switzerland [1476 A.D.], cutworms were taken to court, pronounced guilty, excommunicated by the archbishop, and banished (Flint and van den bosch, 1981, p. 55)."

Fortunately better techniques of pest control gradually evolved through the process of observation and experimentation. By the early part of the Twentieth Century, six major approaches to controlling pests were well established and being commonly used: 1) biological control: the use of natural enemies to hold the pest in check; 2) mechanical and physical control: tillage, plant material destruction, etc; 3) cultural control: crop rotation, time of planting, etc; 4) chemical control; 5) pest resistant varieties, and 6) legal control: inspections and quarantines to prevent entry and spread of pest-infested materials (Flint and van den Bosch, 1981, p. 64).

The emphasis placed on these pest control management approaches changed appreciably with the adoption of synthetic organic pesticide technology during the post World War II era. A chemist with J.R. Geigy Co. in Switzerland, Paul Mueller, discovered the insecticidal properties of dichloro-diphenyl-trichloroethane (DDT) in 1939 (Perkins, 1985, p. 299). The success of DDT as a cheap and effective way to control pests changed the emphasis placed on various pest management technologies in several ways: 1) it prompted development of other synthetic organic pesticides, 2) old pesticides were abandoned in favor of new ones, 3) chemical control acquired much greater prominence as a pest control alternative, 4) the development of new biological control technologies was disrupted, 5) habitat sanitation and cultural practice control technologies were abandoned, 6) pest eradication proposals became more popular, and 7) entomology research shifted from biological towards insecticide studies (Perkins, 1985, p. 299).

After World War II, the use of synthetic organic pesticides on farms became a commonplace management practice alongside such practices as planting and tillage. Farmers frequently followed a pesticide spray schedule without counting insects during the growing season. This strategy was seen as "an uncomplicated, easy-to-follow procedure, and growers regarded it as inexpensive and foolproof insurance against pest damage (Flint and van den Bosch, 1981, p. 70)."

Spiralling usage and increased dependence on synthetic pesticide controls spawned several mostly unforeseen problems. First, pests developed increasing resistance to pesticides resulting in fewer insects being destroyed. This rising resistance phenomena "is a common and logical evolutionary response to [environmental] stress" by the pest species (Fint and van den Bosch, 1981, p. 73). The second problem was the phenomena of target pest resurgence after spraying. This meant that the target pest population would initially decline after spraying and then rebound to higher levels than before spraying. Broad-spectrum pesticides killed pest predators along the target pest. Consequently, no natural enemies existed to prevent target pest population regrowth. Another unintended consequence was inducing secondary pest outbreaks. This results when a plant-feeding species that was not previously a pest suddenly increases its population density to damaging levels. Again this is caused by the destruction of natural predators by the pesticide that had previously kept the now new pest under control. The cotton bollworm and tobacco budworm, once minor pests, have become major problems because of this phenomena (Flint and van den Bosch, 1981, pp. 68-77).

Farmers initially combated these problems with more pesticide applications, thus exacerbating the problem. This "pesticide treadmill" dilemma caused by these unintended consequences, along with growing evidence of environmental contamination, prompted a gradual re-evaluation of the pest management problem by the agricultural entomology community. This process of re-thinking over a period of decades resulted in the development of the philosophy and theory of what is now called the Integrated Pest Management (IPM) Paradigm (Perkins, 1985, p. 307).

Integrated Pest Management (IPM)

Integrated Pest Management is defined by Flint and van den Bosch (1981, p. 6) as:

> an ecologically based pest control strategy that relies heavily on natural mortality factors such as natural enemies and weather and seeks out control tactics that disrupt these factors as little as possible. IPM uses pesticides, but only after systematic monitoring of pest populations and natural control factors indicate a need. Ideally, an integrated pest management program considers all available pest control actions, including no action, and evaluates the potential interaction among various control tactics, cultural practices, weather, other pests, and the crop to be protected.

According to Flint and van den Bosch (1981, pp. 108 -109), there are three philosophical elements associated with IPM:

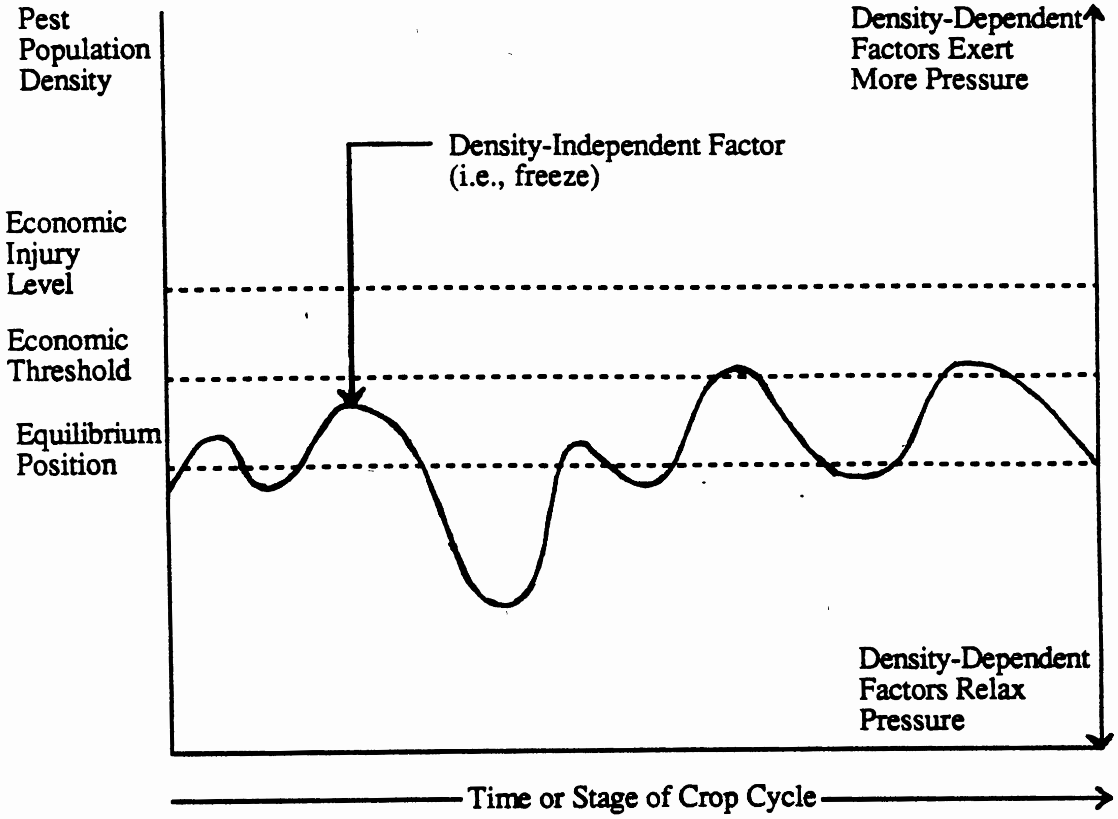
> 1. *A conception of the managed resource as a component of a functioning ecosystem.* Actions are taken to restore, preserve, or augment checks and balances in the system, not eliminate species. Surveys must be made to evaluate and avoid or diminish disruption of already existing natural controls of both the target pest and other potential pests. IPM programs do not include eradication methods, although it is recognized that in a very few instances eradication and not integrated pest management may be the best management strategy.
>
> 2. *An understanding that the presence of an organism of pestiferous capacity does not necessarily constitute a pest problem.* It must be ascertained, before a potentially disruptive control method is employed, that a pest problem actually exists. This requires the implementation of economic injury levels or some suitable decision-making criterion.
>
> 3. *An automatic consideration of all possible pest control options before any action is taken.* The integrated pest management strategy utilizes all combinations of all suitable techniques in as compatible a manner as possible; in other words, it is important that one technique not antagonize another.

The concept of an equilibrium for a pest population or a "characteristic abundance" is central to the IPM philosophy. According to Flint and van den Bosch, the economic loss due to pests is predominately a function of its population density, i.e., the pest becomes a problem when its population density, for whatever reason, rises above its normal level.

Two types of environmental constraints keep the pest population fluctuating around an average level or characteristic abundance (Flint and van den Bosch, 1981, pp. 33-34). The first type of constraint is density-dependent factors such as predation, parasitism, intra-species competition for food, available nesting sites, and territoriality. These factors influence the pest population more when the pest density is high rather than low (Figure 2.4). Changing one of these density-dependent factors, either purposefully or accidentally, can shift this equilibrium level up or down.

Other natural pest control elements, called density-independent factors, are divided into two components: 1) physical, e.g., temperature, humidity, wind movement, exposure, soil pH; and 2) biological, e.g., host suitability and food quality (Figure 2.4). These independent factors restrict the pest population in ways that are independent of their density. Thus these factors are not as important in maintaining the natural equilibrium level.

Pest control practices can either raise or lower this equilibrium level. For example, biological control, such as introducing a new predator, can be used to lower the target pests equilibrium level below economically damaging levels. On the other hand, the equilibrium level can be inadvertently raised through indiscriminate use of chemical controls.



Adapted from: Flint, Mary Louise and Robert van den Bosch. 1981. Introduction to Integrated Pest Management. Plenum Press, New York, pp. 33, 36.

Figure 2.4. Influence of Density-Independent and Density- Dependent Factors on an Equilibrium Position of a Pest Population

Economic Threshold

Integral to IPM are the concepts of an *economic injury level* and the *economic threshold* (Stern et al., 1959, pp. 81-101; Stern, 1973, pp. 260-261; Flint and van den Bosch, 1981, pp. 37-38). The *economic injury level* is defined as the number of pests per unit area at which the cost of artificial control measures is less than the value of damage caused by the pest. This definition indicates the number of pests and damage that a crop can tolerate, but not when to do something about the problem. The *economic threshold* or *control action threshold* is defined as the pest population density at which the decision maker must take some action to prevent an impending pest outbreak. Both of these concepts are illustrated in Figure 2.4.

Stern (1973, pp. 264-265) contends that economic thresholds "need to be quantified in terms of local climate conditions, time of year, stage of plant development, the crop involved, plant variety, cropping practices, the purpose for which the crop is to be used, the desire of man, and economic variables." An additional consideration in quantifying an economic threshold is that "pesticides are often most effective at a certain stage of a pest's life-cycle. Insecticides are sometimes most destructive of young larvae and in some cases do not give satisfactory control of older larvae, pupae, adults, or eggs... Thus the susceptibility of the prevalent stage of the pest insect should be known before insecticide application is made (Flint and van den Bosch, 1981, p. 115)

Headley (1972, pp. 100-108) was the first economist to develop a rigorous conceptual economic framework for evaluating the pest management decision problem. He defines the economic threshold as the pest population level where the marginal dollar benefit of preventing crop damage equals the incremental cost of maintaining that population threshold through a control program.

The Headley model considers three components of the pest decision problem: the dollar value of crop damage due to pests, the pest population, and time. The model has five parts: 1) a pest population growth function, 2) a pest damage function, 3) a product yield function, 4) a pest control cost function, and 5) a profit function. The equations associated with the five components are:

$$P_t = P_{t-n}(1+r)^n \tag{2.35}$$

$$D_t = b\,P_t^2 - A \tag{2.36}$$

$$Y = N - c\,D_t \tag{2.37}$$

$$O = \frac{L}{P_{t-n}} \tag{2.38}$$

$$\pi = R\,Y - 0 \tag{2.39}$$

where

t = time period;
P_t = pest population unit at time t;
P_{t-n} = pest population units n-periods before time t;
r = growth rate of the pest population per time period;
$(1+r)^n$ = pest population compound growth factor;
D_t = damage caused by the pest at time t;
b = constant parameter relating units of pest population to units of crop damage;
A = constant to define the damage tolerance level;
Y = units of product yield;
N = constant reflecting units of product yield with no pest damage;
c = constant parameter relating units of pest damage to units of product yield;
O = total cost in dollars to reduce the pest population to P_{t-n} at time t-n;
L = parameter relating the inverse of pest population units to the total control cost in dollars;
π = net return from pest control; and
R = constant product yield price per unit.

Combining the pest population growth (2.35) and the pest damage (2.36) functions into the product yield function (2.37) yields:

$$Y = N - c\{b[P_{t-n}(1 + r)^{n2}] - A\} \tag{2.40}$$

Substituting the product yield (2.40) and pest control functions (2.38) into the profit function (2.39) produces:

$$\pi = R[N - c\{b[P_{t-n}(1 + r)^{n}]^{2} - A\}] \frac{L}{P_{t-n}} \tag{2.41}$$

Differentiating π with respect to P_{t-n} yields:

$$\frac{d\pi}{dp_{t-n}} = -2Rcb(1 + r)^{2n}\frac{P_{t-n}}{(P_{t-n})^{2}} - L = 0 \tag{2.42}$$

Solving for P_{t-n} produces:

$$P_{t-n} = \left[\frac{L}{2Rcb(1+r)^{2n}}\right]^{1/3} \tag{2.43}$$

This expression is the Headley economic threshold, i.e., the pest density level where the marginal dollar benefit of preventing crop damage equals the incremental cost of maintaining that population threshold through a control program.

Hall and Norgaard (1973, pp. 198-201; 1974, pp. 644-645) contributed to the Headley model by: 1) providing a critique and 2) extending it to simultaneously consider the timing and quantity of pesticide applied.

They present three criticisms of the Headley model. First, they state that pest damage prior to t-n is not considered in the Headley model. Furthermore, they argue that the Headley economic threshold determines the level, P_{t-n}, to which the pest population should be reduced, not the point, P_{t-n}, at which control should be initiated. Thus, the Headley threshold is consistent with the *economic injury level* definition, but not the *economic threshold* definition put forth by entomologists, e.g., Stern et al. (1959, pp. 81-101), Stern, 1973 (pp. 260-261), and Flint and van den Bosch (1981, pp. 37-38). Finally, the Headley cost function (equation 2.40) is legitimate for only a unique and unspecified value of the initial pest population P_0.

The Hall and Norgaard conceptual economic threshold model has six parts:

Pest population growth function:

$$P(t) = \begin{cases} P_0e^{rt} & \text{(before spray) for } t_0 \leq t \leq t_i \\ (P_0e^{rt_i}-K)\, e^{r(t-t_i)} & \text{for } t_i < t \leq t_h \text{ (after spray)} \end{cases} \qquad (2.44)$$

Pest population kill function:

$$K = K^*[X, P(t_i)] = K^*(X, P_0e^{rt_i}) \qquad (2.45a)$$

$$K = K'(X, t_i, P_0, r) \qquad (2.45b)$$

$$K = K(X, t_i) \qquad (2.45c)$$

Pest population damage function:

$$d_t = bP(t) \qquad (2.46a)$$

$$D(t_2-t_1) = {}_{t_1}\!\int^{t_2} d(t)dt \qquad (2.46b)$$

$$D(t_h-t_0) = {}_{t_0}\!\int^{t_0} d(t)dt + {}_{t_i}\!\int^{t_i} d(t)dt \qquad (2.46c)$$

$$= \underset{\text{(before spray)}}{D_1} + \underset{\text{(after spray)}}{D_2}$$

Product Yield Function:

$$Y = N - D(t_h) \qquad (2.47)$$

Pesticide Cost Function:

$$C = \alpha X \qquad (2.48)$$

Profit Function:

$$\pi = \beta Y - C$$

$$\pi = \beta[N - D_1 - D_2] - \alpha X, \qquad (2.49)$$

where

t = time period;
r = pest population growth rate;
t_0 = planting time, it is set equal to zero;

t_i = pesticide application time;
t_h = harvest-time;
K = pests killed by pesticide application;
P_0 = initial pest population at, t_0, planting time;
X = quantity of pesticide applied;
$d(t)$ = instantaneous rate of crop damage in physical units where $d(t)$ is piecewise continuous over t_0 to t_h;
b = parameter which specifies the rate of crop damage n physical units per pest;
$D(t_2-t_1)$ = cumulative crop damage between time t_1 and t_2;
Y = physical units of yield at harvest;
β = price per unit of yield;
N = physical units of yield if no pest damage occurs;
C = total cost of pesticides;
α = cost of purchasing and applying a unit of pesticide;
X = number of units of pesticides; and
π = profit function.

Substitute the pest population growth (2.44), kill (2.47c), and rate of damage (2.45a) functions into the before and after spray damage function (2.46c), then assume $t_0=0$ and use the appropriate limits of integration to obtain

$$D(t_h-t_0) = (b/r)\{(e^{rt_h}-e^{rt_i})[P_0e^{-rt_i}K(X, t_i)] + P_0(e^{rt_i}-1)\} \tag{2.50}$$

According to Hall and Norgaard, this expression represents total pest damage at harvest-time. It has two parts consisting of damage before and after spray.

Substituting the total damage function (equation 2.50) into the profit function (equation 2.49) yields

$$\pi = \beta N-\beta(b/r)\{e^{rt_h}-e^{rt_i})[P_0-e^{-rt_i}K(X, t_i)]+P_0(e^{rt_i}-1)\}-\alpha X \tag{2.51}$$

The first order conditions with respect to timing t_i and amount X in terms of K_{ti} and K_x are:

$$K_{ti}(X, t_i) = \frac{rK(X, t_i)e^{r(t_h-t_i)}}{e^{r(t_h-t_i)} - 1} \tag{2.52}$$

$$K_X(X, t_i) = \frac{\alpha r}{\beta b[e^{r(t_h - t_i)} - 1]} \tag{2.53}$$

The explicit form of the economic threshold cannot be solved for without specific functional form for the kill function. However, equations 2.52 and 2.53 show that the economic threshold is a function of the time of harvest, pest population growth rate, the rate of crop damage per pest, pesticide effectiveness, pesticide cost, and crop price.

Talpaz and Borosh (1974, pp. 642-643; 1974, pp. 769-775) extended the Hall and Norgaard model by specifying a kill function and including a setup cost for pesticide application. That is, Talpaz and Borosh specified a cost function of the form $C+\alpha X$ where C is the setup cost and α is cost per unit of pesticide X. They used numerical integration to empirically derive an economic threshold in terms of number of treatments and dosage level for a representative cotton crop situation.

Review of Selected Pest Management Studies. There have been many extensions to and empirical applications of the basic economic threshold framework described in the previous section. Extensions of the economic threshold concept have included investigations of the influence of dynamics, uncertainty, and subjective decision maker probability assessments on the pest decision problem , e.g., Carson (1970, pp. 216-220); Hueth and Regev (1974, pp. 543-552); Talpaz and Frisbie (1975, pp. 19-25); Feder (1979, pp. 97-103); Hall and Moffitt (1982); Moffitt, Hall, and Osteen (1984, pp. 151-157); Hall and Moffitt (1985, pp. 223-229). This is only a partial list.

Several researchers have used simulation and/or stochastic dominance techniques to examine the pest management problem. Talpaz, Curry, Sharpe, DeMichele, and Frisbie (1978, pp. 469-475) used simulation and numerical nonlinear dynamic optimization techniques to model the cotton boll weevil pest decision problem. Their simulation of the cotton crop-boll weevil ecosystem includes a cotton fruiting model, a temperature dependent boll weevil population model, and a fruit drying model to determine immature weevil survival.

Musser, Tew, and Epperson (1981, pp. 119-124) examine the riskiness of alternative integrated pest management production systems using mean-variance and stochastic dominance techniques. Cochran, Lodwick, Jones, and Robison (1982) applied stochastic dominance techniques to the analysis of apple scab pest management strategies. McGuckin (1983, pp. 43-50) examining alfalfa integrated pest management strategies for alfalfa on a Wisconsin dairy farm. A simulation model of alfalfa production, weevil damage, harvesting, and feeding was used to predict farm income. Simulated distributions were evaluated using first- and -second-degree stochastic dominance techniques.

Szmedra, McClendon, and Wetzstein (1988, pp. 1,642-1,648) used a linked crop and insect population simulation model and stochastic dominance techniques to examine the soybean pest management problem. Stochastic dominance combined with mean Gini's difference criteria (Yitshaki, 1982, pp. 178-185) analysis demonstrated that a predetermined calendar date control strategy is preferred to extension economic threshold recommendations for this particular study area.

SUMMARY

This chapter develops the theoretical and methodological foundation for this study. The conceptual framework for the analysis originates from Antle (1983; 1988) and Antle and Hatchett (1986). Antle and Hatchett suggest that the sequence of decisions implemented by a farmer during uncertain production has both carryover effects and opportunity costs associated with it. Thus, the type of information about uncertain input-output relationships employed by the farmer in determining a strategy influences the outcomes of production.

Antle (1983) describes three properties of information used by farmers in formulating a strategy. This study examines how these information properties influence outcomes of some of the alternative decision strategies described by Taylor and Chavas (1980) and Antle (1983). Stochastic dominance and value of information criteria are used to evaluate the outcomes of these alternative information assumption decision rule. Concepts and techniques described by Gould (1974), Hirshleifer and Riley (1979), Hess (1982), Byerlee and Anderson (1982), and Bosch and Eidman (1987), are used to implement the economic analysis of Chapter V.

CHAPTER III

ENVIRONMENTAL INFLUENCES ON THE IRRIGATED COTTON PRODUCTION DECISION PROBLEM IN SOUTHWEST OKLAHOMA

The cotton field ecosystem is composed of a crop phenology (growth and development habit), a physical environment, and a structured pest-beneficial predator population. The purpose of this chapter is to identify the sources of environmental uncertainty in the cotton field that influence the planting, irrigation, and insect decision alternatives examined in this study.

The next three sections describe the study area, the phenology of the cotton plant and what influences its growth, and the sources of production risk and how these influence the decision problem.

Description of the Study Area

Three cotton production schemes are found in Oklahoma. Non-irrigated production accounts for about four out of five cotton acres in the state. Dryland production is found throughout the southwest and west-central crop reporting districts (Figure 1.1 in Chapter I). Average lint yields are generally low; 234 pounds per acre in the southwest district and 264 pounds in the west-central district (Oklahoma Agricultural Statistics Service data). Moisture is the primary limitation on yield potential. Input usage is low and depends on available moisture. About 63 percent of all Oklahoma cotton lint production is from non-irrigated acreage (Oklahoma Agricultural Statistics Service data). There is considerable year to year variability in both yield and production.

Tillman county has the largest dry land production with about with about one-quarter of the total acreage found in the state. Dryland lint yields between 1975 and 1988 ranged from 41 pounds [1980] to 390 pounds [1979] (Oklahoma Agricultural Statistics Service data).

The second type of cotton production in the state occurs along river-bottom land, primarily along the Washita river. This production scheme occurs on high nitrogen soils and can be characterized as semi-irrigated. A small amount of acreage is devoted to this type of production in the state (Banks, 1990).

The third type of production can be characterized as intensely managed irrigated high input cotton. There are two forms of irrigated cotton in the state; furrow irrigation primarily found in the Lugert-Altus Irrigation District, and other forms of irrigation scattered throughout the southwest and west-central districts.

The 46,600 acre Lugert-Altus Irrigation District is located in Jackson and Greer counties. The district is the study area for the analysis. Most of the land in the district is devoted to continuous, intensely managed, high-input commercial cotton production.

Land in the irrigation district that is served by the W.C. Austin project generally lies within a 15 mile radius of the city of Altus in Jackson county. The project area is in the Red River watershed and project land drains towards the Salt Fork and North Fork tributaries of that stream. The irrigation district is a political subdivision of the state of Oklahoma that was organized in 1940 (Scoville et al., 1956).

The project consists of a concrete and masonry dam on the North Fork of the Red River which forms a reservoir with a capacity of 148,000 acre feet. The project has 270 miles of water delivery canals and laterals with a capacity to irrigate 70,000 acres. The irrigation district has been limited to 46,600 acres (Scoville et al., 1956).

Jackson county has the largest irrigated cotton acreage and production in the state. About one-fifth of all the cotton grown in the state originates from Jackson County. The highest lint yields in the state are also recorded in Jackson County. The average yield for irrigated cotton between 1975 and 1988 was 555 pounds per acre. An average of 38,400 acres have been planted to irrigated cotton over that time period with a typical production of 45,086 bales per year (Oklahoma Agricultural Statistics Service data).

There are 700 farms in Jackson county. Approximately 256 of these farms raise cotton with 168 deriving more than 50 percent of their gross receipts from its production (U.S. Department of Commerce, Bureau of the Census data, 1989).

Predominant soils in the irrigation district and in Jackson county are Tillman and Hollister clay loams. These soils are intermixed and are not mapped separately. The proportion of each soil is about 60 percent Tillman and 40 percent Hollister. There are approximately 200,000 acres or about 40 percent of the total acreage in Jackson county in Tillman-Hollister soils. Tillman county has approximately 65,000 acres or about 12 percent of its total area in Tillman-Hollister soils. About 12 percent or 40,000 acres of the land area in Greer county is Tillman-Hollister (Anonymous, 1989).

Cotton Plant Phenology

The references used to develop the cotton phenology discussion are: Verhalen (1990), Banks (1990), Munro (1987, pp. 41-64), El-Zik and Frisbie

(1985), pp. 23-29), Waddle (1984, pp. 233-263), Deterling and El-Zik (1982), Mauney (1968, pp. 23-40), Tharp (1960), and Hayward (1938, pp. 411-450).

The cotton field can be divided into three zones. The first zone is the rhizoplane which is the soil medium surrounding the plant roots. This soil complex provides moisture and nutrients for uptake by the roots of the plant. Zone two is the phylloplane which includes all of the above ground parts of the plant that affect photosynthesis, transpiration, and other physiological processes. The last part of the ecosystem is the atmosphere which provides the energy and moisture to the plant and soil. The roots and the above ground parts of the plant are interdependent and respond to the atmosphere and each other (El-Zik and Frisbie, 1985, p. 39).

Cotton growth involves the orderly and predictable development of roots, stems and branches, leaves, and the fruit. Reproduction (fruit development) involves the sequential formation of floral buds (squares), flower blooms, and cotton bolls. The bolls contain cotton seed and lint, the harvested economic end products. Stages of plant development and their approximate lengths of time are in Table 3.1. A representation of the cotton fruiting cycle is in Figure 3.1.

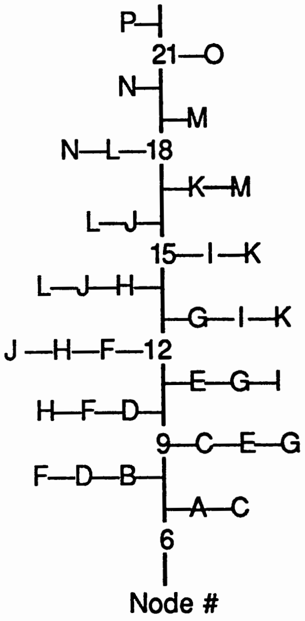
The first 30 to 40 days after planting determine the lint yield potential of the crop. After this time yield potential can only be maintained or lost. Seedling growth begins immediately after planting. Germination occurs about four to fifteen days after planting. Both the germination of the cotton seed and early seedling growth are sensitive to soil temperature and moisture conditions. Germination at or slightly below 60°F adversely affects seedling development and may cause the plant to die. Seedling growth and development is also impeded when temperatures exceed 102°F. Optimal temperature during this

TABLE 3.1

GROWTH AND DEVELOPMENT CYCLE OF THE COTTON PLANT IN SOUTHWEST OKLAHOMA

Stage of Growth	Approximate Number of Days Average	Range
Planting to seedling emergence	10	5-20
Appearance of first true leaf after emergence	8	
Appearance of second true leaf after emergence	9	
Emergence to appearance of first floral bud (Square)	35	33-38
Development of floral bud into first open flower bloom	23	20-27
First flower bloom to peak flower bloom	34	26-45
Peak flower bloom to all bolls open		
Early- and mid-season flower bloom	50	45-55
Late season flower bloom	60	55-70
Total growing time (planting to all bolls open)	140	120-160

El-Zik and Frisbie (1985, p. 27)

Cotton Plant Fruiting Diagram	Symbol	Days After First Square	Squares Per Day (Thousands)	Total Squares (Thousands)	Accumulated Fruiting Positions (Thousands)
			Per Acre		
	A	0	10	10	10
	B	3	10	40	40
	C	6	20	70	70
	D	9	20	130	130
	E	12	20	190	190
	F	15	30	280	280
	G	18	30	370	370
	H	21	30	460	460
	I	24	30	540	550
	J	27	30	600	640
	K	30	30	660	730
	L	33	30	690	820
	M	36	20	690	880
	N	39	20	660	940
	O	42	10	600	970
	P	45	10	540	1,000
		48	0	450	1,000
		51	0	360	1,000
		54	0	270	1,000
		57	0	80	1,000
		60	0	120	1,000
		63	0	60	1,000
		66	0	30	1,000
		69	0	0	1,000

Adapted from: Kerby, T.A. 1984. "Fruit Set and Retention." Summary Proceedings Western Cotton Production Conference. August 13-14, 1984, Oklahoma City, Oklahoma.

[a] Assumptions: 30,000 plants per acre, three squares per fruiting branch, three days between main stem nodes and six days between flowers on fruiting branches.

Figure 3.1. Theoretical Rate of Cotton Square Formation, Square Accumulation, and Fruiting Position Accumulation Throughout the Growing Season[a]

stage is 91°F to 93°F. Deviations from optimal temperature conditions causes slower rates of germination, primary root elongation, and shoot elongation.

The same environmental factors which delay germination and seedling growth encourage early-season seedling disease complex. The greatest lint loss attributed to disease problems is from early-season seedling disease complex (Verhalen et al., 1984). Thus, the best time for planting is influenced by expected soil temperature and moisture conditions during germination and early plant growth.

After emergence, the mainstem grows upward to produce a series of nodes (joints in the stem where leaves are attached), each with a leaf and several buds that may develop into branches, and internodes (stem tissue between two nodes). It provides support for the vegetative and reproductive framework of the plant. It also provides a conduit for the transport of moisture and nutrients from the roots.

The cotton plant starts to expand sideways by developing branches about 28 to 35 days after sowing. Development of buds into branches at each node depends on environmental conditions. Unfavorable conditions such as close spacing, drought, or low fertility can cause many of the buds to remain dormant. On the other hand, favorable conditions allow most buds to develop.

Two kinds of branches are formed by the plant: vegetative (monopodial) branches and reproductive or fruiting (sympodial) branches. Branches produced below a certain node are vegetative while those above that node are reproductive. This transition occurs between the fourth and eight node above the seedling leaves (cotyledons) depending on the variety.

Fruiting branches develop in upward succession, about one every 2 1/2- to 3 1/2-days, above this point. Vegetative branches develop in succession downward below this point. The first part of the fruiting branch to become visible is the floral bud (square). The first square normally appears 43 to 47 days after planting depending on temperature. Below normal temperature is the primary reason for a delay in the appearance of the first floral bud.

As the fruiting branch grows outward the floral bud moves away from its original position. A leaf then develops beside the floral bud that remains very small for four to seven days after the bud appears. As the leaf enlarges and unfolds, the first axillary bud at its base forms a floral bud. This floral bud then moves out from its original position to form the second internode and flower of the reproductive branch. This process of terminating a growing point with a leaf and flower and the development of the first axillary bud at the leaf base to form the next node and flower continue throughout the growing season. This sympodial type growth characteristic with a flower at each node gives these branches a zig-zag pattern.

The critical period for producing squares is from mid-June through mid-July. Floral budding increases 1 1/2- to 2 1/2-fold or more through the fourth week of squaring. Budding reaches a peak by the fifth or sixth week, then markedly decreases during the seventh to ninth week. As many as 85 percent of the bolls eventually harvested come from buds produced during the first five weeks of squaring. The plant normally sheds 40 to 50 percent of all squares under good management.

The date of the first flower bloom is conspicuous and unequivocal. It marks the start of the flowering period and is an indication of the earliness (date of maturity) of the crop. This bloom period occurs from late June or early July to mid-August. Flowers open early in the day and have a white or creamy color. Pollination occurs within a few hours with fertilization taking place 24 to 30 hours later. The fertilized ovule develop into the seed. The petals start to turn pink by evening and by the next day can be easily distinguished by their red color from newly opened flowers. These flowers shed in about a week as the fertilized ovules of the ovary grow into a seed pod or boll. Some of the fertilized ovules may fail to fully develop. If a majority of the seeds abort by not fully developing, then the boll will fall off the plant in about ten days.

The blooming of flowers on the mainstem follows a definite and constant pattern throughout the flowering period of growth of the plant and between plants in the same crop. The vertical flower blooming interval between successive fruiting branches on the mainstem is about one bloom every three days. The horizontal flowering interval between successive flowers on the same fruiting branch is about one bloom every six days (seasonal average is 5.26 to 8.85 days). This flowering pattern resembles a steadily rising cone (Figure 3.1).

The proportion of flowers which produce bolls on the fruiting branch in a normally spaced crop are about 60 percent at the first node, 30 percent at the second, and 10 percent at the third. A negligible yield is produced at the fourth and subsequent nodes. About 85 percent of the bolls are set by the third week of blooming, 10 percent during the fourth week, and less than 5 percent during the fifth through seventh weeks.

The cotton boll containing the seed and fiber rapidly develops after fertilization. A fiber reaches full length 15 to 25 days after flowering and fertilization of the ovule. Successive layers of cellulose are then deposited on the inner surface of the fiber wall in a spiral pattern. The amount and pattern of cellulose deposition determines fiber strength, fineness, and maturity--important attributes in determining the price received for the fiber.

The boll reaches full size 18 to 24 days after fertilization. An additional 24 to 40 days are needed for the boll to harden and become fully mature or ripe.

At this time the drying of the mature boll causes the boll to flare open exposing the seed and lint.

Transformation of the flower into a boll that will be retained by the plant is more effective during the early part of the season. Bolls that develop from early season flowers require about 55 days from flowers to open boll. Flowers that bloom and develop into bolls later in the season (August-September) require 60 to 80 days to mature and open. Temperature is the chief determinant of plant growth and fruiting development.

A phenomenon of cotton growth is the process of "cut-out." The plant quits producing reproductive branches and buds and uses available moisture and nutrients to develop bolls already set on the plant. Cut-out may be a temporary or permanent event. Many factors are capable of inducing the cut-out phenomena. It may be a natural or varietal response due to the plant ending its reproductive cycle. The number of bolls already set is the strongest influence on cut-out. Early maturing or determinant varieties have an accelerated cut-out process compared to full season cultivars. Short-season varieties yield about 25 percent less lint than full season cultivars when grown under a full season schedule. Environmental influences on premature cut-out include moisture stress and extreme temperatures. When environmentally induced cut-out occurs, four weeks is needed for the plant to initiate new buds. This means that seven weeks are needed between cut-out and a new bloom which will require an additional 70 days to make an open boll.

Given an economically viable plant stand at the end of the seedling stage, potential cotton lint and seed yield is determined by: 1) the number of floral buds produced per acre in a season, 2) the percentage of buds that bloom, 3) the percentage of blooms that mature, 4) and the number and weight of mature bolls produced per acre. Many factors influence fruiting, blooming, and shedding. These include variety, temperature, sunlight, soil moisture, available plant nutrients, diseases, and insect damage.

Environmental Influences on Cotton

Several environmental conditions--temperature and sunshine, moisture, and stress induced by diseases and insects--directly influence cotton plant growth and development and thus its lint yield and quality potential. This section describes the impact of these environmental influences on the planting, irrigation and insect decisions examined in this study.

Temperature and Sunshine

Cotton is a heat loving plant that requires a long growing season and at least 50 percent sunshine (Waddle, 1984, p.235). Oklahoma is on the northern edge of the U,S. cotton belt. There are many years when temperature is a limiting factor in cotton production.

Climate in southwest Oklahoma is characterized by mild winters and hot summers. The average date of the last killing frost in the spring at Altus, Oklahoma, is March 28. The average first fall killing frost is November 7. There are about 224 frost free days during the growing season; however, frost has occurred as late as April 18 and early as September 29 (Baily and Graft, 1961).

Temperature controls the plant development. It also influences the growth rate of pests that impede of cotton development. Cotton and its pests need specific quantities of radiant energy to develop from one point to another in their life-cycle (El-Zik and Frisbie, 1985, pp. 49-50).

There are lower and upper temperature bounds on the development of the organisms in the cotton ecosystem. Cotton and its pests show little or no biological growth when the air temperature is below or above these thresholds. These temperature bounds vary with the organism.

The concept of "day degrees" or "heat units" is based on these growth rate thresholds. El-Zik and Frisbie (1985, pp. 49) describe the day degrees (DD) concept as follows:

> DD are the amount of heat units within these lower and upper development thresholds, i.e., the heat units that are generating the organisms growth. Thus DD can be defined as values derived from accumulated daily minimum and maximum temperatures that are associated with various biological processes of an organism. DD are an accumulated product of temperature and time among the development thresholds for each day throughout the lifespan of the organism. The total heat units or DD necessary for an organism to complete a generation is a constant for each species. It will not change regardless of how much heat is applied to an organism or the individuals location. Accumulation of DD is initiated at a specific point in time known as a biofix. This time varies with the organism involved and is based on a specific biological date such as planting date, insect emergence or trap catch, or germination of plant pathogen propagules.

Measurement of DD is useful in decision making throughout the production cycle. Growth stage events of cotton ecosystem organisms can be determined and projected more accurately using DD rather than calendar days. Critical plant phenology and pest organism events can be predicted and used to optimize the timing of input decisions.

The general format of DD accumulation is:

Daily Day Degrees (DD)=$BT \leq AT \leq UT$

Where:

AT = Average Daily Temperature = (Temperature Maximum+Temperature Minimum)/2
BT = Base temperature below which no growth occurs
UT = Upper temperature above which no growth occurs.

According to Waddle (1984, pp. 258-61) no standard procedure has emerged for measuring heat unit accumulations for cotton. Fry (1983) presents a thorough explanation and analysis of three cotton DD accumulation methods; the mean with and without an upper threshold method, the triangulation method, and the sine-wave method.

Young, Willson and Strabala (1983) estimated growing season day degrees for cotton in southwest Oklahoma using daily temperature data (Table 3.2). They generated DD using a cosine-wave function and daily minimum and maximum temperatures. Their threshold temperatures were 12°C (53.6°F) and 33.3°C (92°F). The DD temperature thresholds and sine-wave method of accumulation used by Young et al. is the same as that used in the COTTAM (Jackson, Arkin and Hearn, 1990) and TEXCIM (Hartstack and Sterling, 1990) cotton simulation models used for the analysis in this study.

The month of May, which is planting time for cotton in southwest Oklahoma, exhibits considerable variability in heat unit accumulation. As outlined in the previous section, cotton plant seedlings are sensitive to cold. Variability in DD accumulations presents problems in obtaining a viable stand of cotton plants that will mature in a short-season environment.

The beginning of the fruiting cycle (squaring) for stripper cotton varieties occurs at approximately 850 to 900 day degrees. Picker varieties begin squaring at about 950 to 1,050 DD units. Assuming a May 15th planting date, the calendar date for square initiation occurs between June 18th to June 22nd. Stripper varieties fruit more rapidly than picker varieties with 90 percent of squares being produced by 1,400 DD units. A picker variety produced about 90 percent of its squares by 1,600 to 1,700 DD units (Young et al., 1983).

July and August are the best months for growing cotton. DD accumulations are again more variable in September, October, and November. This variability inhibits fiber maturation and quality. Seasonal accumulation of day degrees vary from 3,213 to 4,730 heat units. Under ideal growing

TABLE 3.2

RAINFALL AND DAY-DEGREE ACCUMULATIONS FOR COTTON DURING THE GROWING SEASON IN SOUTHWEST OKLAHOMA

Month/ Unit	Rainfall/Day Degrees (DD)[a] Accumulations					
	Low	Average	High	Standard Deviation	Coefficient Variation	Skewness
	Inches/DD					
May						
Rainfall	0.27	4.36	13.34	3.11	16	
DD	370	541	708	68	13	-0.13
June						
Rainfall	0.32	3.40	10.55	2.21	65	
DD	672	748	847	43	6	0.45
July						
Rainfall	0.00	1.93	8.93	1.64	85	
DD	767	851	901	28	3	-0.71
August						
Rainfall	0.07	2.14	6.49	1.72	80	
DD	731	827	898	37	4	-0.47
September						
Rainfall	0.00	2.63	7.29	2.03	77	
DD	423	649	792	71	11	-0.53
October						
Rainfall	0.00	2.46	11.76	2.73	111	
DD	250	400	584	72	18	0.12
Total Growing Season Accumulations						
Rainfall	7	19	33	7	35	
DD	3,526	4,017	4,400	178	4	-0.13

Sources: Day-degree data is from Young, J.H., L.J. Willson, and M. A. Strabala. 1983. "Temperature: Its Effect on Cotton and Cotton Insects," Research Report P-831, Agricultural Experiment Station, Division of Agriculture, Oklahoma State University. Rainfall accumulations in inches is estimated from Oklahoma State University Irrigation Research Station, Altus, data, 1948-90 (National Oceanic and Atmospheric Administration, Oklahoma Climatological Data, 1948-90).

[a] Day-degree growth thresholds are 12°C (53.6°F) and 33.3°C (92°F). Data location is Altus, Oklahoma.

conditions short season cotton varieties need 3,000 DD units and long season varieties need 4,000 DD units to mature. Any stresses to the plant increase the number of DD units needed to bring the plant to maturity (Young et al., 1983, p. 5).

Moisture

Cotton development and yield potential are also affected by the total amount and distribution of rainfall during the growing season. The cotton plant demands 562 pounds of water for each pound of total plant material produced. This is 34 percent more than the water demand for corn (Tharp, 1960, p. 11).

A minimum of about 19.68 inches of water is needed throughout the season to obtain a minimum acceptable yield. Beyond this water level, yield is a function of available water at each successive stage of growth, all other things equal (Waddle, 1984, pp. 246-247).

As the plant develops its water requirements change due to increased plant tissue and other environmental factors. In general, cotton plant water demand is low early in the season when leaf area is small, the root system is shallow, and temperature is low. Water consumption reaches a maximum during the reproductive phase in the middle of the summer. At this time leaf area is at a maximum, the root system is deep, temperature is high, and daylight is the longest. Moisture needs diminish sharply to a small amount late in the season when temperature moderates, the plant is mature, and new growth is discouraged (Longenecker and Erie, 1968, p. 324). Estimated cotton plant water demand by growth stage is presented in Table 3.3.

TABLE 3.3

ESTIMATED COTTON PLANT WATER DEMAND BY GROWTH STAGE

Stage of Plant Growth	Approximate No. Days In Stage	Yields in 480 Lb. Bales per Acre[a]		
		0.30	1.52	3.04
	Range	Inches of Water		
Seedling (planting to flower bud initiation)	40-60	3.15	3.15	3.94
Fruiting (through the 4th week of blooming)	40-50	4.72	5.51	7.87
Maturing (5th Week of blooming to first week of open boll)	15-25	7.09	9.06	12.59
Opening (1st week open to all open bolls)	35-60	4.72	10.63	14.96
Total		19.68	28.35	39.36

Adapted from: Waddle 1984, p. 246.

[a] Approximated for cotton grown in the midsouth. Lower yields were assumed to have shorter fruiting, maturation, and opening periods; higher yields, longer periods.

Southwest Oklahoma has a bimodal seasonal rainfall pattern. The heaviest rainfall amounts occur in the May through June and September through October time-periods (Table 3.2). Summer time precipitation is infrequent with four to six week periods of no precipitation being fairly common. Soils are driest in late July and August. This period is characterized by hot temperatures accompanied by strong dry winds from the south.

Farmers in the Lugert-Altus Irrigation District have an average water availability of 12-acre inches, with a median of 12-acre inches and a mode (most likely value) of 18-acre inches (estimated from data provided by Kirby, 1990). Irrigation generally occurs between July 1, and August 31 in the district. Farmers can order water at any time but because of limited availability the practice is to limit irrigation to the fruiting period. Farmers do not know their final water allocation is until early- to mid-June (Kirby, 1990).

Cotton Disease and Insect Pests

Early season pests can affect the successful establishment of a viable plant stand. Control of early season pests is important because the production of squares and bolls during the fruiting period can be adversely affected (Matthews, 1989, p. 16). Early season pests often delay plant growth. In some cases the plant can overcome early season losses if future growing conditions are favorable. However, the short growing season of Oklahoma frequently limits this possibility.

Mid- and late-season pests directly affect yield and quality through the damage or loss of fruiting structures (squares and green bolls) on the plant (Matthews, 1989, p. 16). The growing season is too short in Oklahoma for the plant to recover by producing new fruiting structures.

Cotton Disease Pests. Cotton lint yield losses from attacks by disease organisms are a significant management issue in Oklahoma. Seedling disease complex, verticillium wilt, fursarium wilt, and nematodes are among the chief disease problems (Table 3.4). Disease disrupts the function and behavior of the cotton plant which adversely affects growth and reproduction. The causes of disease include biotic and inanimate or abiotic agents. Biotic agents--viruses, bacteria, fungi, etc.--are infectious living organisms that colonize the root, stem, leaf, or fruit tissue of the host plant. Inanimate agents such as hail, wind, soil heaving and cracking, etc. that damage tissue structures expose the plant to infectious agents (El-Zik and Frisbie, 1985, pp. 31-34).

TABLE 3.4

ESTIMATED REDUCTION IN COTTON LINT YIELD FROM DISEASE AND INSECT PESTS IN OKLAHOMA

From Disease Pests:

Disease	1980 through 1988 Average	
	Percent Loss	Bales Lost
Fusarium Wilt	1.83%	6,873
Verticillium Wilt	2.15%	8,549
Bacterial Blight	0.49%	2,233
Phymatotrichum Root Rot	0.22%	645
Seedling Diseases	3.25%	12,369
Ascochyta Blight	0.37%	1,087
Boll Rot	0.48%	1,912
Nematodes	1.53%	6,996
Leaf Spot and Others	0.27%	981
Total	10.52%	41,643

From Insect Pests:

Insect	1980 through 1988 Average	
	Percent Loss	Bales Lost
Bollweevil	1.73%	2,964
Bollworm-Tobacco Budworm	6.81%	19,416
Cotton Fleahopper	0.76%	1,977
Lygus ssp.	0.00%	0.0
Cotton Leaf Perforator	0.00%	0.0
Pink Bollworm	0.00%	0.0
Spiter Mite	0.30%	489
Thrips	0.30%	957
Others	0.60%	1,386
Total	10.50%	27,189
Average Insecticide Cost Per Acre		$27.45

Source: <u>Proceedings Beltwide Cotton Production Research Conferences</u>, 1980 through 1988 Issues, National Cotton Council of America, Memphis, Tennessee.

Four variables affect the rate at which a disease epidemic progresses: the initial inoculum, the infection rate, time, and stage of development of the host cotton plant. Methods to control disease outbreaks should focus on reducing the initial inoculum density, survival and dispersal of the inoculum, the rate of infection, and the time exposure of cotton to disease organisms (El-Zik and Frisbie, 1985, p. 33).

Seedling disease complex composed of several seedborne and soil-inhabiting fungi and bacteria has direct and indirect effects on early cotton plant growth. Pathogens that attack seedlings may cause seed rot and seedling death. This reduces the plant population and may cause root damage to remaining plants, thus adversely affecting future fruit production. Control measures include: 1) using resistant varieties; 2) seed treatments; 3) preparation of a firm, moist, and warm seed bed to promote fast emergence and growth. The last item involves delaying planting until soil temperatures are above 65°F for several days in a row.

Verticillium wilt is a potential problem in irrigated cotton. Cool air and soil conditions can trigger a disease outbreak. Temperatures between 71.7°F and 77°F (22°C to 25°C) are favorable for disease development. Low temperatures at night can trigger early season disease development if maximum day temperatures do not exceed 86°F (30°C) [El-Zik and Frisbie, 1985, p. 98]. Verticillium wilt is most effectively controlled by planting resistant varieties and cultural practices that raise soil temperatures, specifically cutting off irrigation in late August (Verhalen, 1990). The crop should be managed to promote rapid fruit set and maturity to minimize vegetative growth (Verhalen et al., 1984; El-Zik and Frisbie, 1985, p. 99).

Cotton Insect Pests. Cotton insects that feed on plant structures interfere with growth and reproduction by causing leaf malformation or abscision and/or elevated square and boll shedding. This shedding may be directly caused by feeding on squares and bolls or indirectly through the withdrawal of nutrients from other plant structures or the loss of leaves (El-Zik and Frisbie, 1985, p. 30).

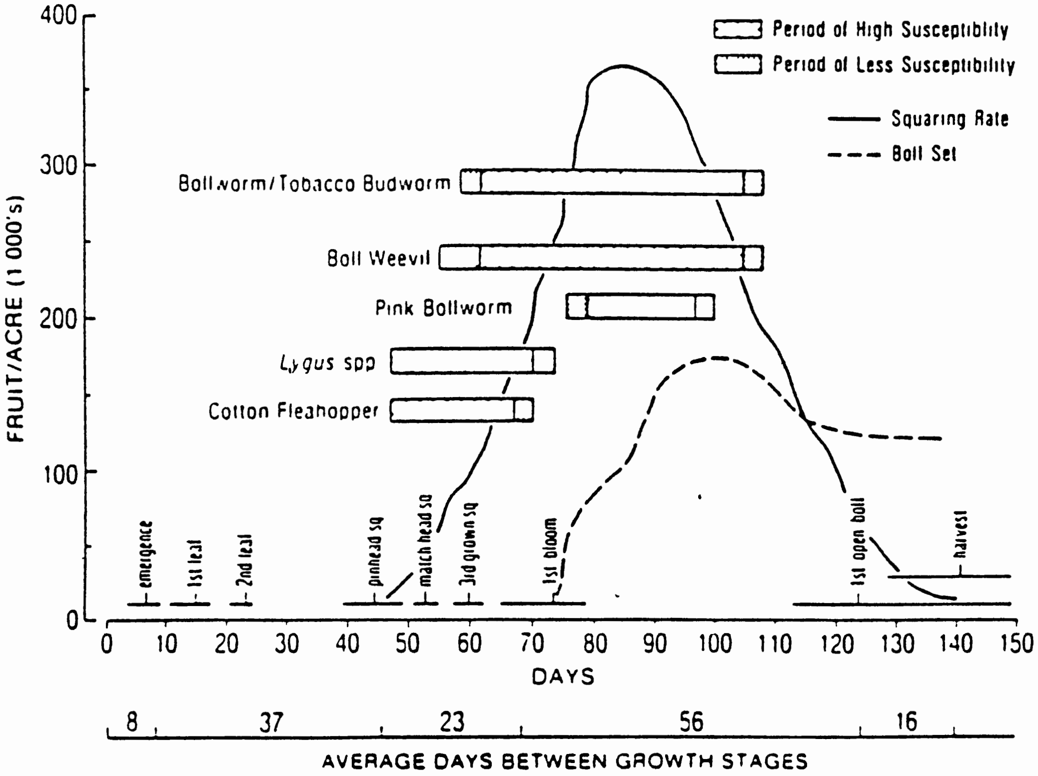
The three primary insect pests in Oklahoma are: fleahoppers, boll weevils, and the bollworm-tobacco budworm complex (Table 3.4). They are primarily mid-season pests that attack the fruiting structures of the plant, and thus have the greatest economic consequence. Spider mites and thrips are secondary insect problems in Oklahoma (Table 3.4).

El-Zik and Frisbie (1985, p. 31) state the following regarding insect management strategies:

> It is important to understand the synchrony of the time of pest attack relative to a susceptible cotton plant stage. This is critical in knowing the amount of damage inflicted and the potential management areas for the reduction of this damage. This is to say that the mere occurrence of insects or insect populations in space and time may or may not result in economic damage. This largely depends on the age and susceptibility of the specific plant part under attack.

Figure 3.2. illustrates the seasonal occurrence of the three primary insect pests in relation to the growth of the cotton plant.

The cotton fleahopper prefers to feed on growing terminals and squares. Damage is caused by sucking juices from the tiny squares causing them to turn brown and fall from the plant. Injury generally is of a local nature and is caused by salivary juices injected into the plant. However, a mass attack can disrupt the development of the whole plant. In a short-season environment, where growers rely on an early fruit set, a heavy infestation can cause a complete loss of the crop (Pfadt, 1985, pp. 229-370).



Adapted from: El-Zik and Frisbie 1985, p. 31.

Figure 3.2. Development of the Cotton Plant in Relation to the Development of Fleahopper, Boll Weevil, and Bollworm-Tobacco Budworm Complex Populations.

There are three stage in the life of a fleahopper: the egg , nympth, and adult stages (Young, 1969, pp. 10-11).[1] Fleahoppers overwinter in the egg stage mainly inside the stems of wild plants such as goatweed. Eggs hatch early in the spring. Population numbers depend on a favorable sequence of host plants as well as favorable temperature and moisture conditions. The insect feeds on weeds during the spring. When weeds mature in early summer, adult fleahoppers migrate to squaring cotton. In late summer and early fall, adults of the last generation return to the wild host, primarily goatweed (Pfadt, 1985, pp. 229-370).

Egg development depends on temperature and available moisture. Eggs on average hatch in seven to eight days. Nympths develop rapidly, passing through five instars in as few as 10 days, to reach adult stage. Adult females feed for three to four days before they begin to insert eggs into the stems and other host plant parts. They lay eggs singly using an ovipositor. Females live 14 to 29 days and produce about 21 eggs. Males have a somewhat shorter life span (Pfadt, 1985, pp. 229-370).

The boll weevil has historically been the most destructive cotton insect in Oklahoma. It moved into Oklahoma from Mexico and Texas at the turn of the century. Control efforts succeeded in eliminating the boll weevil as a problem during the 1970's and early 1980's (Verhalen et al., 1984, p. 9). However, the boll weevil has again become a significant insect management problem during

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[1] Insects develop from eggs. Once the egg hatches, the insect grows through a series of molts, i.e., shedding its cuticle and expanding into a larger one. The larva (plural form is larvae) is the immature, wingless feeding form that hatches from the egg of many insects. Metamorphosis, involving a change in external form of the larva, occurs at each molt. The stadium is the time interval between molts. The instar is the form assumed by the insect during a particular stadium. A pupa (plural form is pupae) is an intermediate usually quiescent (inactive) stage of a metamorphic insect that occurs between the larva and imago. The imago (final instar) is the sexually mature, typically winged adult state of the insect. A stage is a distinct, sharply different period in the lifecycle of the insect (Harwood, 1985, pp. 68-83).

the 1980's. Price and Karner (1989, p. 195) estimated that 270,000 acres of cotton were infested with weevil populations above the recommended treatment threshold with a 3.75 percent reduction in yield.

The boll weevil over-winters as an adult in brush, grass, crop debris, cotton stalks, fence rows, etc. Emergence from over-wintering generally occurs from April to early June. The total number of weevils that appear in the spring varies considerably by location and year. Emergence is a function of numbers entering hibernation the previous fall and the rate of survival over the winter (Cross, 1983, pp. 53-70).

Approximately five to 10 percent of the weevils weather the winter. Survival is lowest during winters with sharp freezes and no insulating snow cover. This is especially true during winters when both freezes and intermittent warm periods. Mortality is lowest during mild winters (Cross, 1983, pp. 53-70).

The adult boll weevils first start to feed on the tender terminals of young cotton seedlings. The weevils start to feed on young squares, their preferred food choice, once the fruiting cycle begins (Figure 3.2). They will also attack young bolls. Weevils puncture squares both for feeding and for egg laying. The average first occurrence of punctured squares is in mid-June (Coppock).

The long snout (rostrum) of the female is used to drill a hole into the square. Eggs are deposited individually at the bottom of the punctures. After laying the egg, the puncture is sealed with a sticky substance secreted by the female. A wart like appearance at the site of the puncture distinguishes an egg puncture from feeding damage. A female lays from 100 to 300 eggs during her approximately 30 day life span.

The young weevil larva feeds for seven to 14 days inside the square or boll. The young larva passes through three instars as it transforms into a pupa within its feeding place. The square that is being fed on generally abscises and falls to the ground in three to five days after egg hatching. Three to five days after pupation the adult emerges through a hole cut to the outside. The weevil life-cycle is completed in about 30 days. Variations in the cycle are a function of average temperature. Females of the new generation begin laying eggs after three to four days. As many as five generations of weevils develop each season (Cross, 1983, pp. 53-70).

A portion of the boll weevil population begins to go into a physiological dormancy (diapause) in late August. The percentage of the population that goes into diapause increases in September. This percentage decreases in October as a larger proportion of the weevils have moved from the cotton field into other litter. Weevils do have the capability to migrate, especially in late season, when they are looking for food sources (Cross, 1983, pp. 53-70). Cross (1983, p. 61) states that weevils in west Texas have migrated up to 50 miles, especially when isolated fields do not have adequate moisture and cover for over-wintering.

Bollworms (Heliothis zea) and tobacco budworms (Heliothis virescens) have caused the most cotton crop damage from insects in Oklahoma. These two insects are so similar in both their biology and damage to cotton that they can be discussed together (Anonymous, 1984, pp.40-44).

The estimated average crop loss from the Heliothis spp. complex from 1979 through 1988 was about seven percent (Table 3.4). Individual field losses can be much higher. Price and Karner (1989, p.195) estimated that 150,000 acres in 1988 were infested with Heliothis spp. populations above the recommended treatment threshold.

Heliothis spp. can cause significant damage by feeding on the young floral buds, flowers, and green bolls (Figure 3.2). Damaged structures are either partially or totally loss. Feeding may also expose bolls to infection by pathogenic organisms causing boll rot or stained lint problems. Older larvae do the most damage (Anonymous, 1984, pp. 40-44). Both species have shown considerable resistance to many common insecticides such as synthetic pyrethroids (Menn et al., 1989, pp. 101-121). Typically, the damage from Heliothis spp. is the greatest when natural enemies have been destroyed by insecticides applied to control other insects such as fleahoppers and boll weevils (Anonymous, 1984, pp. 40-44).

Heliothis spp. spend the winter as pupae in the soil. Most pupae do not over-winter in cultivated field. Typical over-wintering sites include alfalfa fields, pastures, road sides, and other non-tilled areas (Young et al., 1983, p. 6). Tillage operations destroy most pupae in cultivated fields. They emerge as adults moths from March through May in Oklahoma. The period of emergence lasts from three to six weeks (Young et al., 1983, p. 6). Their over wintering survival rate is very low at less than 0.1 percent (Young and Price, 1977, pp. 627-628).

Cotton is not the strongly preferred host for Heliothis spp., thus the timing of infestations depends on the availability of other crops such as corn, sorghum, alfalfa, etc. Corn is the preferred host for the bollworm. When corn is available bollworms attack it first, then a later generation will move into cotton after the corn matures (Anonymous, 1984, pp. 40-44).

Heliothis spp. usually do not lay eggs on cotton for the first 900 day degrees of cotton plant growth. This period generally covers the month of May through the first half of June regardless of planting date (Young et al., 1983, p.8). The most important period of potential damage from Heliothis spp. is during peak squaring, or from 1,200 to 1,800 day degrees in the growth cycle. This period is from mid-July through late August (Young et al., 1983, p. 7). Cotton plants are most attractive to egg-laying females during this time when flowering is occurring and when vegetation is lush, especially after an irrigation (Anonymous, 1984, pp. 40-44).

Heliothis spp. eggs are laid individually near the top of the plant on young leaves or on the bracts of small squares. A female is capable of laying more than a 1,000 eggs. After the eggs hatch, the larvae often eat their egg shells, then move to young leaves for a few hours before starting on small squares. The first and second instars primarily feed on small squares but also feed on vegetative buds as they grow. As the instars grow they feed more on larger fruiting structures. The fourth and fifth instars feed on large squares, flowers, and green bolls. The instar chews a hole at the base of the boll and begins to hollow it out through its feeding. The larvae often move about the plant feeding on a large number of bolls without finishing any one of them. This pattern causes more damage since the boll will be loss by shedding or attacked by disease organisms through the hole (Munro, 1987, pp. 154-157).

The economic consequences of a Heliothis spp. infestation in cotton are a function of: 1) larvae numbers, 2) the age of the larvae, and 3) the time at which damage occurs during the fruiting cycle (Anonymous, 1984, pp. 40-44). The fifth instar larvae are the most destructive. They damage more fruit than younger larvae and attack older fruit which are harder to replace. The older, larger larvae (beyond third instar) are difficult to kill with chemicals. Consequently, monitoring and control strategies must be aimed at eggs and small larvae (Anonymous, 1984, pp. 40-44). Heliothis spp. infestations are generally spotty, usually starting in a so called "hot spot" in the field that increases in size with each generation. Fields that are located next to each other often have very different levels of infestation (Anonymous, 1984, pp. 40-44).

Larval development takes about two weeks in warmer weather and up to a month in cool weather. Mature larvae burrow into the soil to pupate. The adult moths emerge from the pupae at night and climb to the top of the cotton plant where they dry their wings off. Mating generally occurs within 48 hours of emergence and egg laying begins within about 72 hours. All adult activity, including flight, mating, egg laying, and feeding happen at night. Adults live for 10 to 14 days in the summer and up to a month in cool weather (Anonymous, 1984, pp. 40-44).

The emergence of adults from the pupae during spring and early summer is about 12 days. During late summer an increasing number of pupae from each generation enter a state of physiological dormancy called diapause. These pupae over-winter until the spring when the adults emerge. The life cycle of Heliothis zea. in terms of day degrees is presented in Table 3.5.

The cotton field contains many life forms that interact with pests populations throughout the growing season. These parasites, predators, and pathogens are important in determining both whether economically significant pest damage occurs and the timing of damage in the cotton field. The value of preserving these beneficial life forms in the cotton field as a natural insect regulatory has only recently been understood (El-Zik, 1985, pp. 82-83).

Most of the entomology research in this area has centered on the impact of predators on Heliothis zea. populations in cotton. Researchers have recorded that predators destroy from 15 to 41 percent of bollworm eggs laid in the field. Further, 60 percent or more of first instar larvae can be destroyed by predators (El-Zik, 1985, pp. 82-83).

TABLE 3.5

GENERALIZED *HELIOTHIS ZEA*. DAY DEGREES GROWTH MODEL

Growth Stage	Day Degrees (DD)[a] Minimum	Average	Maximum	Range	Cumulative Average
Egg	50	65	70	20	
Larvae	345	350	380	55	65
Pupae	365	370	390	25	415
Adult Prelaying	55	60	70	15	785
Total	815	845	910	95	845

Source: Young, J.H., L.J. Willson, and M. A. Strabala. 1983. "Temperature: Its Effect on Cotton and Cotton Insects," Research Report P-831, Agricultural Experiment Station, Division of Agriculture, Oklahoma State University, Stillwater.

[a] Grow model by Young et al. based on field grown insects at Tipton and Altus, Oklahoma, and laboratory grown larvae.

The common insect predators found in Southwest Oklahoma cotton fields are (Young et al., 1980):

Lady Beetle (Various spp.)
Collops beetle (*Collops* spp.)
Lacewing bugs (*Chrysopa* spp.)
Minute pirate bugs (*Orius* spp.)
Damsel bug/Nabids (*Nabis* spp.)
Bigeyed bug (*Geogous* spp.)
Insidious flower bug (*Orius insidious*)
Spiders (Various spp.)

Spider play an important role in the cotton ecosystem. They are considered to be general predators that lower the density of pest populations during the growing seasons. The other predators can act to suppress pest population outbreaks (El-Zik, 1985, pp. 82-83).

Researchers have found that any combination of the primary *Heliothis* spp. predators equal to or greater than the number of bollworm-budworm eggs keeps the population from causing economic damage (El-Zik, 1985, pp. 82-83). Young and Willson (1984, pp. 33-38) reported that if one or more predators such as collops spp. are present per 0.8 meter of row, then damage to cotton is unlikely to occur. Thus control strategies should consider the impact of beneficial predators on pest populations.

Summary

This chapter identified the principal sources of environmental uncertainty that influence the planting, irrigation, and insect decision alternatives examined in this study. Soil temperature and soil moisture are the two sources of uncertainty for the planting decision problem. The primary influences on the irrigation decision problem are stage of plant growth, temperature, rainfall and soil moisture. Finally, the primary factors that affect the insect decision problem are stage of plant growth, insect population dynamics and numbers, and beneficial predator numbers.

CHAPTER IV

EMPIRICAL FRAMEWORK

The cotton production decision problem involves the management of a biologically complex field ecosystem. The crop responds to both its uncertain growing environment and to the succession of inputs applied by the producer over the growing season. The dynamic and stochastic character of this process is inherently risky to the producer because of uncertain knowledge about the outcomes of management choices.

The objective of this chapter is to construct an empirical framework that considers the impact of uncertain climate and pest events on cotton crop development, yield potential, and its resulting influence on the decision making process. This framework is used to generate distributions of cotton seed and lint yields and net enterprise income for the decision alternatives at each stage. These outcome distributions and their probabilities form the basis for the economic analysis performed in Chapter V.

First is a description of the two simulation models and the data used for this study. Next is a brief explanation of the representative southwest Oklahoma farm situation. The last three sections describe the methodology to generate outcome distributions for the planting, irrigation, and pest decision problem analysis.

Description of the Simulation Models and Data Used for the Analysis

Complete field experimentation data collected over a period of years to represent all the decision alternatives and environmental conditions for the economic analysis are not available. Biophysical simulation has been used by a number of economists to overcome data problems in order to conduct production economic analysis (e.g., Musser and Tew, 1984; McGuckin et al., 1987; and Mjelde et al., 1988). Trapp (1989) argues for the use of dynamic, process based simulation models in production economic analyses.

Two daily time-step computer simulation models are used to represent the cotton field ecosystem. The first is "COTTAM," a cotton plant growth and development model from the Blackland Research Center, Texas A&M University System, Temple, Texas. The second cotton model used in this study is "TEXCIM40" (**TEX**as **C**otton **I**nsect **M**odel version 4.0), a cotton pest-predator simulator and decision aid from Texas A&M University, College Station, Texas.

The structure of the COTTAM model and its assumptions are thoroughly described in Jackson and Arkin (1982, pp. 61-64); Jackson, Arkin, and Hearn (1988, pp. 846-854); and Jackson, Arkin, and Hearn (1990, pp. 52-159). Thus, only a brief description of the model is presented here.

COTTAM is a daily time-step, process based, computer model that simulates the morphological and physiological growth characteristics of a cotton plant stand on a per hectare (acre) basis. Plant growth and development is driven by day degree unit (heat unit) accumulation that is conditioned by moisture and carbohydrate stress. It consists of a main program with yearly, seasonal, and daily loops that calls a series of subroutines and functions. These algorithms mimic the soil water profile and growth and development of the stand in response to management inputs and changing climate conditions. The complete Fortran computer program has over 6,000 lines of code including comments and 36 subroutines within its structure.

There are several reasons for using the COTTAM model in this study. Jackson and Arkin (1982, pp. 61-64) state that the COTTAM model belongs to a class of what can be called "simple process" models. It is an applications oriented model with suitable, but not burdensome, detail to reasonably simulate cotton plant responses to management and environmental inputs. Thus, the model is flexible enough to be adapted to an economic analysis of cotton production under Oklahoma growing conditions.

Second, the data needed to operate the model are, for the most part, derived from readily available sources. Complex process models such as GOSSYM (Baker et al., 1983) require substantial financial and data resources to setup, calibrate, and implement. On the other hand, limited scope process models such as MINICOT (Fry et al., 1981) are useful for simulating a limited phase of the production cycle and/or a limited number of decisions.[1]

Third, the Fortran computer code for the COTTAM model has been made available for use by researchers. The code is well documented and the

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[1] According to Jackson and Arkin (1982, p 62), computerized cotton models can be divided into three categories· 1) limited scope models, 2) simple process models, and 3) complex process models The following is an expanded version of an incomplete list of cotton models by category presented by Jackson and Arkin.

Limited Scope Models.
SIMPLECOT (Wilson et al., 1972)
BOLL PERIOD (Wanjura, 1981)
FRUITING FORMS (Wallach, 1980)
SIRATAC (Hearn, 1980)
MINICOT (Fry et al , 1981)

Simple Process Models:
IPM-COTTON (Wang et al., 1977)
COTTAM (Jackson et al., 1990)

Complex Process Models
COTTON (Stapleton et al , 1973)
COTCROP (Jones et al., 1978, 1983)
SIMCOT (McKinion et al , 1974, 1975)
GOSSYM (Baker et al , 1981)
TEXCIM40 (Sterling et al., 1988, 1989, 1990)

program structure is relatively easy to understand. Thus, the code can be modified to accommodate the specific objectives and needs of the economic analysis.

Further, the model contains methods to account for moisture stress conditions that influence growing cotton in southwest Oklahoma. Finally, the model has been validated under Rolling Plains growing conditions. The model was run against field plot data from the Texas A&M University Vegetable Research Station at Munday, Texas, about 70 miles southwest of Altus, Oklahoma. Jackson et al. (1990, p. 105) state that the model simulated square and boll numbers along with lint yields that were somewhat higher than those measured. They believe that there are several reasons that account for the differences. First, specific soil profile information was not available so it was approximated. Second, square and boll losses due to insects in the COTTAM model are assumed to remain constant throughout the growing season. However, insect damage during the growing season varies with the fluctuating pest population. Finally, there may be errors in the measurement of square and boll numbers from the field plot.

Table 4.1 summarizes the soil profile and 43-years of daily weather data (1948-1990) used to operate the COTTAM model. Daily solar radiation flux values were generated using the "WGEN" daily weather variable simulation model (Richardson and Wright, 1984). Values were generated using actual daily rainfall data.

The TEXCIM40 model is used to simulate fleahopper, boll weevil, and tobacco-budworm/bollworm population numbers and dynamics in response to

TABLE 4.1

DATA USED IN THE COTTAM COTTON PLANT SIMULATION MODEL

Tillman-Hollister Soil Water Profile (Inches)[a]

Soil Profile	Field Capacity[b]	Permanent Wilting Point[b]	Plant Available Water(PAW)	PAW/ Inch	Bulk Density (gm/cm)[d]	Soil Clay[d]
0-9	4.0	1.9	2.1	0.24	1.37	36%
9-15	2.8	1.4	1.4	0.23	1.55	36%
15-27	6.1	3.1	3.0	0.25	1.55	36%
27-39	6.9	3.5	3.4	0.28	1.55	36%
39-51	7.3	3.8	3.5	0.29	1.57	36%

Physical Properties of the Tillman-Hollister Soil Profile

Item	Value
Average Field Soil Surface Slope (Percent)[a]	0.50
Average USDA/SCS Runoff Curve Number[c]	79.00
Hydraulic Conductivity K (centimeters/day)[d]	0.023
Stage 1 Evaporation Soil Coefficient (centimeters)[e]	0.40
Stage 2 Evaporation Soil Coefficient (centimeters/day$^{1/2}$)[e]	0.28
Dry Soil Albedo (Percent/100)[f]	0.15
Assumed Planting Depth Soil-Air Temperature Ratio	1.00

Daily Weather Data	Unit	Period
Daily Solar Radiation Flux[a]	Langleys/Day	1948-1990
Wet-Day Mean[h]	470 Langleys/Day	
Dry-Day Mean[h]	290 Langleys/Day	
Wet- and Dry-day Amplitude[h]	198 Langleys/Day	
Latitude[a]	34°35"	
Daily Maximum Air Temperature[a]	Centigrade	1948-1990
Daily Minimum Air Temperature[a]	Centigrade	1948-1990
Daily Precipitation[a]	Millimeters	1948-1990
Potential Evapotranspiration Correction Factor[c]	1.50	

[a] SOURCE: U.S. Dept. Comm., NOAA. Okla. Climate. Data, OSU Irrig. Res Stat., Altus, Index No. 0179, Division No. 07.

[b] Field capacity defined as 1/3 and permanent wilting point defined as 15 atmosphere percentage, respectively.

[c] SOURCE: Jackson et al., 1990.

[d] SOURCE: U.S. Dept. Agri., SCS Soils-5 Data Base. Ames, Ia

[e] Stage 1=0.26+6 29•K; Stage 2=0.24+1.72*K (Jackson et al., 1990).

[f] SOURCE: Dugas and Ainsworth, 1983.

[g] Generated using "WGEN" (Richardson and Wright, 1984).

[h] SOURCE: Richardson and Wright, 1984.

environment and management inputs (Hartstack, Sterling and Dean, 1990). The model also simulates the influence of predator populations and chemical control measures on insect mortality. It also uses cotton field fruit count data to estimate lint yield loss from insects.

TEXCIM, as far as this author knows, is the only model available that simulates the three major insect pests found in southwest Oklahoma. However, a severe impediment to implementing TEXCIM is a paucity of appropriate pest population data for input into the model. Only six years of data are available for the analysis. Weekly pheromone trap data moth count are used as input in the model to simulate general population numbers and dynamics for the period 1985-1990 (Karner, 1991). A summary of the data used to operate the TEXCIM40 model is presented in Table 4.2. The average wind run and relative humidity values for 1956-1970 are used to represent wind and humidity conditions in each weather year (1985-1990).

TEXCIM has three insect submodels within its structure. The next few paragraphs briefly describe each submodel.

The fleahopper component of the model is based primarily on work by Sterling and Hartstack (1979, pp. 649-654). Previous fall temperatures are used to forecast the spring emergence of overwintering fleahoppers. Spring-time temperature and rainfall are then used to estimate the timing of spring diapause emergence from wild host plants. The model projects forward from diapause emergence to simulate populations colonizing cotton. The model consists of a series of stochastic emergence cohorts using a 50 percent emergence threshold temperature of 14.65° C (58° F). These cohorts represent successive generations of insects emerging and colonizing the field.

TABLE 4.2

DATA USED IN THE TEXCIM40 COTTON-PEST-PREDITOR SIMULATION MODEL

Daily Weather Data	Unit	Period
Solar Radiation Flux[a]	Langleys/day	1985-1990
Wet-Day Mean[b]	470 Langleys/Day	
Dry-Day Mean[b]	290 Langleys/Day	
Wet- and Dry-day Amplitude[b]	198 Langleys/Day	
Latitude[c]	34°35"	
Maximum Air Temperature[c]	Fahrenheit	1985-1990
Minimum Air Temperature[c]	Fahrenheit	1985-1990
Precipitation[c]	Inches	1985-1990
Minimum Daily Relative Humidity[d]	Percent	1956-1970
Daily Wind Run[d]	Miles/Hour/Day	1956-1970

Insect Pheromone Trap Data[e]	Unit	Period
Boll Weevil (<u>Anthonomus grandis</u>)	Count/Week	1985-1990
Boll Worm (<u>Heliothis zea</u>)	Count/Week	1985-1990
Tobacco Budworm (<u>Heliothis virscerns</u>)	Count/Week	1985-1990

[a] Daily solar radiation generated using "WGEN" daily weather variable simulation model (Richardson And Wright, 1984). Values generated using actual daily rainfall data.

[b] SOURCE: Richardson and Wright. 1984. ARS-8, Washington D.C.: U.S. Dept. Ag., ARS.

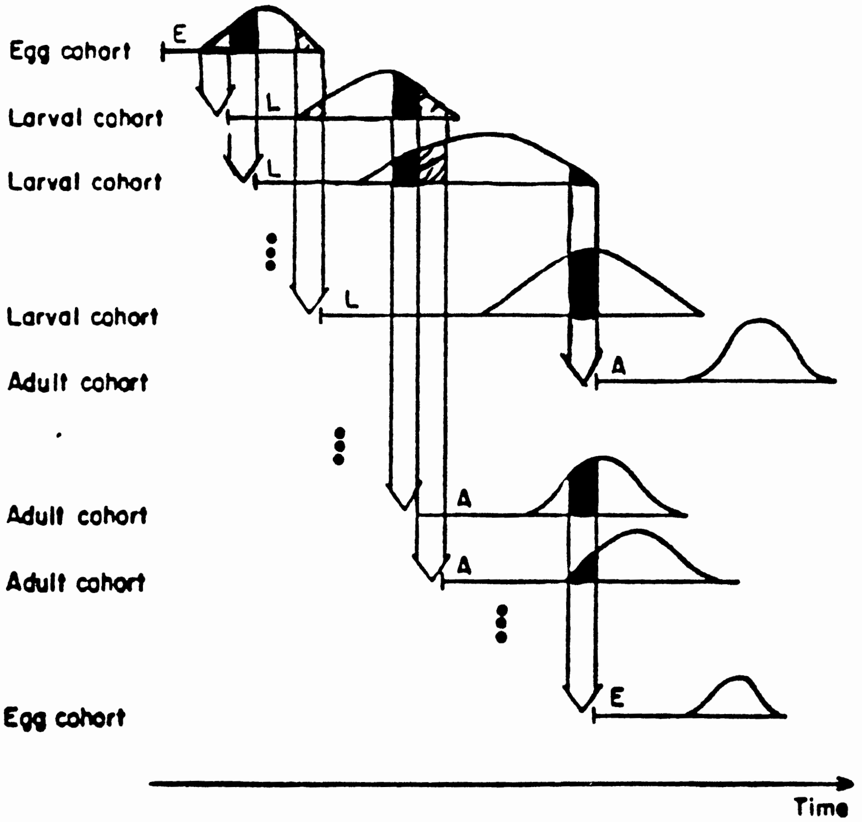
[c] SOURCE: U.S. Dept. Comm., NOAA. Okla. Climate. Data, OSU Irrig. Res. Stat., Altus, Index No. 0179, Division No. 07.

[d] SOURCE: U.S. Dept. Comm., NOAA. Okla. Climate. Data, Airport, Stat., Altus.

[e] SOURCE: Myles Karner, Extension Cotton Entomologist, Oklahoma State University, Cotton Research and Extension Center, Altus, Oklahoma.

The second submodel is called MOTHZV which simulates Heliothis spp. population dynamics. It is the most detailed component of the TEXCIM model. The structure of MOTHZV model is thoroughly described in Hartstack and Hollingsworth (1974, pp. 112-115) and Hartstack et al. (1976). A daily day-degree time-step and pheromone trap counts (1985-1990) are used by the model to simulate the timing and per acre numbers of Heliothis spp. for three age classes: eggs, small larvae, and large larvae (Table 4.2). Population dynamics and numbers are influenced in the model by mortality caused by predators and insecticides. The model also has a cotton fruit injury function which simulates the influence of larval age structure on damage to cotton fruit.

The final insect submodel simulates boll weevil population numbers and dynamics. Model development is extensively described in Feldman and Curry (1983, pp. 392-402), Schoolfield (1983), and Curry, Sharpe, DeMichele, and Cate (1980, pp. 1897-223). Boll weevil population growth consists of a series of stochastic cohorts representing all insects starting a specific stadium during the same time interval. The pattern of cohort development is illustrated in Figure 4.1. Insect development, reproduction, and survival are a function of a daily temperature time-step. Pheromone trap moth count data (1985-1990) are used to estimate population numbers and dynamics (Table 4.2). The cotton crop-insect interaction component simulates insect behavior and preference for egg laying sites, the shedding of insect infested squares and young fruit, the influence of fruit drying on boll weevil mortality, and mortality caused by predators and insecticides.



Adapted from: Curry, Guy L., Peter J. H. Sharpe, Done W. DeMichele. 1980. "Towards a Management Model of the Cotton-Boll Weevil Ecosystem." *Journal of Environmental Management*, Vol. 11, p. 208.

Figure 4.1. Schematic of Boll Weevil Population Development Dynamics and Stochastics

Representative Farm Situation Assumptions

A wheat/stocker and cotton enterprise representative southwest Oklahoma farming situation developed by Walker (1990) is used as the basis for net enterprise return estimation. The farmer is assumed to have 288 acres of irrigated cotton with the other 872 acres devoted to wheat, dryland cotton, pasture, and set aside. The irrigated cotton acreage is located within the Lugert-Altus Irrigation District described in Chapter III. Financial data from a picker irrigated cotton budget developed by Walker and Banks (1990) are used to allocate revenue and costs for the economic analysis.

Many factors influence the cotton lint price received by a farmer. The primary determinants of price are government programs and global market demand and supply conditions. Quality characteristics of the fiber, and thus the premium or discount paid depending on market conditions, are influenced primarily by varietal type and environmental conditions within the field. This study does not examine price and quality variability caused by market and field environmental conditions. Instead, a single expected price for cotton lint and seed is used for the economic analysis.

Net income over variable costs to the 288 acre irrigated cotton enterprise is the financial criterion for the economic analysis. The net enterprise income criterion is used for the stochastic dominance analysis to avoid the problems described by Raskin and Cochran (1986, pp. 204-210). Specific revenue and cost allocations at each decision stage are described with the results and analysis in Chapter V.

Planting Decision Problem Analysis Simulation Framework

Three decisions are considered for the planting economic analysis: when to plant? what to plant? and how much to plant? Farmers contemplate planting any time between mid-April and mid-June. Their decision of when to plant considers the tradeoff between a higher potential yield from planting early and the number of planting operations incurred due to unfavorable weather and pest conditions. Planting early results in increased potential for a higher but much more variable yield. However, unfavorable soil temperature conditions in the early portion of the planting season can result in replantings which significantly impact planting variable costs. This contrasts with planting later when yields are less variable and the chances of replanting and its resulting cost are diminished.

Five calendar planting dates running in two-week intervals that span the planting period are specified for the simulation analysis: April 19, May 3, May 17, May 31, and June 14. These two-week intervals to represent the time period after which the farmer must decide whether to replant the stand due to adverse environmental conditions (Banks, 1990; Verhalen, 1990).

Three soil temperature derived planting date strategies are also specified for the planting analysis. These timed strategies are based on a 10-day moving average of minimum soil temperature at the four inch depth. Sowing occurs when one of three temperature threshold levels--60°F, 65°F, or 70°F--are reached. The temperature rule is a proxy or forecast of when satisfactory soil conditions occur for germination and early seedling growth. It is an imperfect predictor since temperature can decline below the threshold level, and less favorable conditions for emergence and growth can occur. These timed strategies are contrasted with the imperfect calendar date predictor strategies in the economic analysis.

The four inch 10-day minimum soil temperature average is used for several reasons. Soil temperature at the four inch depth is measured at a weather station in the study area, thus it is a predictor that is available to farmers (Oklahoma State University Irrigation Research Station, Altus). Further, the 10-day four inch measurement is more stable (reliable) than temperatures using a shorter time-period or a shallower depth. The basis for this is from a study by Holekamp et al. (1960) examining the influence of soil temperature on time of planting in the Texas High Plains. Conditions in the high plains are comparable to the Rolling Plains. They conclude that farmers should use a 10-day average of minimum soil temperature at the four- to eight-inch depth to determine time of planting.

Minimum daily soil temperature data for 1978 through 1990 from the Oklahoma State University Irrigation Research Station, Altus, are used to estimate the timed planting dates. Actual weather station temperature measurements are used for the 1978 through 1990 simulation years. The following is used to estimate minimum daily soil temperatures for the 1948 through 1977 simulation years,

$$\mathrm{DMST}_t = \mathrm{PROP} \bullet ((\mathrm{DAIRT}_t + \mathrm{DAIRT}_{t-1} + \mathrm{DAIRT}_{t-2})/3) \tag{4.1}$$

where DMST_t is daily minimum soil temperature, PROP is a proportionality coefficient estimated using OLS, and DAIR_t is daily average air temperature. The three day moving average of daily air temperature is regressed on thirteen years of daily soil temperature data (1978-1990) to estimate the proportionality coefficient (Table 4.3).

TABLE 4.3

PLANTING TIME SOIL TEMPERATURE STATISTICS

Minimum Daily Soil Temperature Estimation Equation Statistics:[a]

Item	Value
Equation: $DMST_t = 0.909 \cdot ((DAIRT_t + DAIRT_{t-1} + DAIRT_{t-2})/3)$	
Root Mean Square Error	6.32
Theil's Proportions of Inequality	
Bias Proportion U^M	0.002929
Variance Proportion U^S	0.000031
Covariance Proportion U^C	0.997040
Average Soil Temperature	
Actual	56.96
Predicted	56.61
Standard Deviation Soil Temperature	
Actual	15.99
Predicted	15.95
Coefficient of Variation Soil Temperature	
Actual	28.07
Predicted	28.17

Soil Temperature Summary for Five Calendar Planting Dates:[b]

Planting Date	Minimum	Maximum	Average
Plant April 19th			
Average	57	70	63
Standard Deviation	6	7	5
Maximum	67	77	72
Minimum	47	60	57
Plant May 3rd			
Average	60	73	66
Standard Deviation	6	7	5
Maximum	69	86	76
Minimum	51	59	59
Plant May 17th			
Average	65	80	73
Standard Deviation	8	7	7
Maximum	76	92	84
Minimum	52	67	61
Plant May 31st			
Average	69	81	75
Standard Deviation	5	5	5
Maximum	77	88	82
Minimum	62	71	67
Plant June 14th			
Average	72	88	80
Standard Deviation	6	7	5
Maximum	99	82	87
Minimum	61	78	73

---

[a] $DMST_t$ is daily minimum soil temperature and $DAIRT_t$ is daily average air temperature.

[b] Estimated from daily soil temperature data measured at the Oklahoma State University Irrigation Research Station, Altus 1978-1990

Thiel's *proportions of inequality* are used to evaluate the *expost* simulation of daily soil temperatures (Pindyck and Rubinfeld, 1981, pp. 360-367) (Table 4.3). The bias proportion, a measure of systematic error in the simulated series, is very low. This indicates that the average value of the simulated series is very close to the average of the actual series. The variance proportion measure indicates that the equation is capable of replicating the variability found in the actual series. Finally, the covariance proportion, a measure of systematic error, is high; thus most error in the model is random and not systematic.

The estimated planting times for the three soil temperature rules are presented in Table 4.4. These planting dates are used in the flexible strategy portion of the planting time economic analysis conducted in Chapter V.

Producers have three variety choices: long season (Acala) varieties, medium season (Delta) varieties, or short season (Plains) varieties. Acala varieties have the greatest yield potential when day-degrees are not a limiting factor of production. However, shorter and medium season varieties can outperform longer season varieties when day-degrees are limiting.

The final part of the decision problem is the seed planting rate. A harvest-time plant population of 50 to 60 thousand plants per acre on irrigated production is considered optimal with satisfactory yield response occurring between 30 to 60 thousand plants per acre (Banks, 1990; Verhalen, 1990). Populations exceeding this level can have a significant negative impact on yields. Five seeding rates ranging from a potential under planting to a possible over planting are specified for the calendar date analysis: 60,000, 80,000, 100,000, 120,000, and 140,000 seeds per acre.

Five target plant population levels are specified for the soil temperature rule planting analysis. Seeding rate to achieve the target plant population is

TABLE 4.4

SOIL TEMPERATURE DETERMINED PLANTING DATES FOR THREE 10-DAY MOVING AVERAGE THRESHOLD LEVELS

	10-Moving Average Soil Temperature Threshold		
Simulation Year	60° F Rule Month/Day	65° F Rule Month/Day	70° F Rule Month/Day
1948	4 / 21	5 / 22	6 / 10
1949	5 / 02	5 / 24	6 / 05
1950	4 / 29	5 / 23	6 / 15
1951	4 / 27	5 / 05	6 / 19
1952	5 / 05	5 / 08	6 / 09
1953	4 / 30	5 / 24	5 / 26
1954	4 / 11	4 / 27	6 / 12
1955	4 / 19	4 / 22	5 / 08
1956	4 / 29	5 / 06	5 / 14
1957	4 / 24	5 / 22	6 / 13
1958	4 / 28	5 / 21	5 / 28
1959	4 / 08	5 / 02	5 / 04
1960	4 / 16	5 / 19	6 / 05
1961	4 / 23	4 / 27	6 / 06
1962	4 / 22	5 / 09	5 / 13
1963	4 / 02	4 / 18	5 / 13
1964	4 / 20	4 / 23	5 / 26
1965	4 / 10	5 / 09	6 / 09
1966	5 / 13	5 / 18	5 / 23
1967	4 / 01	4 / 07	6 / 08
1968	4 / 22	5 / 31	6 / 09
1969	5 / 08	5 / 25	6 / 01
1970	4 / 26	5 / 13	6 / 14
1971	4 / 02	4 / 18	5 / 13
1972	4 / 20	4 / 23	5 / 26
1973	4 / 10	5 / 09	6 / 09
1974	5 / 13	5 / 18	5 / 23
1975	4 / 01	4 / 07	6 / 08
1976	4 / 22	5 / 31	6 / 09
1977	5 / 08	5 / 25	6 / 01
1978	4 / 09	5 / 16	5 / 24
1979	4 / 21	5 / 15	6 / 30
1980	5 / 31	6 / 06	6 / 19
1981	5 / 31	6 / 10	6 / 27
1982	5 / 25	6 / 14	6 / 30
1983	5 / 26	5 / 29	6 / 18
1984	5 / 03	5 / 12	5 / 18
1985	4 / 22	5 / 13	6 / 03
1986	4 / 26	5 / 06	6 / 06
1987	4 / 27	5 / 04	5 / 15
1988	4 / 30	5 / 14	6 / 01
1989	4 / 06	4 / 25	4 / 29
1990	4 / 24	5 / 16	5 / 21

determined by expected seedling survival as a function of planting time soil temperature. The equation developed by Holecamp et al. (1960) is used to estimate seeding rate in year t:

$$\text{Seeding Rate}_t = TP/((1.63 \cdot ST_t - 59.8)/100), \tag{4.2}$$

where TP is the target plant population and ST_t is the 10-day moving average of minimum daily soil temperature in year t.

Two cotton field environmental relationships are incorporated into the existing structure of the COTTAM model to directly account for the uncertainty of obtaining a plant stand under Rolling Plains growing conditions.

The first field relationship is seedling survival and emergence. Unfavorable soil temperature at planting is the fundamental climatic factor that influences the decision problem. Its consequences are witnessed through reduced or wiped out plant stands from the direct affect of cold temperatures and the indirect influence of temperature on increased susceptibility to seedling disease problems and herbicide injury. These factors influence yield potential and replanting expenses.

The minimum soil temperature for germination is approximately 60°F with the most favorable germination and seedling growth occurring at about 93°F (Tharp, 1960). Average soil temperature in the study area for the early (April 19th) planting data is 63°F with a range of 57°F to 72°F (Table 4.3). This contrasts with an average soil temperature of 80°F with a range of 73°F to 87°F for the late (June 14th) planting date (Table 4.3).

A linear relationship from a seven year field trial study of the soil temperature-stand survival is used to determine plant population for each planting date (Holekamp et al., 1960),

$$\text{stand survival}_i = (1.63 \cdot ST_i - 59.8)/100, \tag{4.3}$$

where ST_i is a 10-day moving average of minimum daily soil temperature at plant $date_i$. Equation (4.3) is used to estimate mean and variance of seedling survival for each planting date strategy by employing 13-years of soil temperature data from the weather station in the study area (Oklahoma State University Irrigation Research Station, Altus). A truncated lognormal is used to generate random plant stand survival values for each planting date X_{it} over the 43-year period using these means and variances,

$$x_{it} = m_{it} + s_{it} \bullet z_{it} \quad 0 \leq x_{it} \leq 0.60, \tag{4.4}$$

where m_{it} is the average survival proportion for plant date i in year t, s_{it} is the standard deviation of survival proportion for plant date i in year t, and z_{it} is a lognormally distributed random variate generated for plant date i in year t. Survival proportion is multiplied by seeding rate to determine per acre plant population for plant date i in year t which is then incorporated into COTTAM.

The truncated lognormal is specified since it generates positive survival values between zero and 60 percent. The 60 percent maximum value accounts for the concept that about 80 percent of the seeds germinate. Of those that germinate, a maximum of 80 percent survive the seedling stage. Of those that survive the seedling stage, a maximum of 95 percent survive to harvest. This procedure accounts for the direct and indirect consequences of soil temperature on plant population as a function of planting time. A summary of simulated percent seedling survival for each planting strategy is in Table 4.5.

Ideally, the emergence relationship in the cotton field should also be treated as a random variable that is correlated with soil temperature conditions. One possible candidate for the emergence relationship is the binomial probability distribution. The binomial would generate success or failure of stand emergence. Unfortunately, a search of the literature did not provide any data to specify the parameters of the binomial. The only guidance on emergence is an expert opinion that farmers have an average of 1.3 to 1.6 plantings and can plant as many as four to five times (Banks, 1990).

Thus, an algorithm in the COTTAM model is used to determine time to emergence for plant date i in year t. The first phase of emergence is assumed to occur in one day for an average daily soil temperature at the planting depth of 25.5°C (78°F). This phase one development rate declines linearly to three days at 15.5°C (60°F). The model assumes soil moisture does not influence stage one. The second phase of emergence is the function

$$ENC = 0.0853 - 0.0057/(41.9 - ST) \cdot (ST - 34.44)^2 \cdot WATCO, \tag{4.5}$$

where ENC is the hypocotyl elongation rate (centimeters/hour), ST is soil temperature, and WATCO is a water stress function.

Emergence for plant date i in year t occurs when the accumulated hypocotyl length is equal to seed planting depth. Elongation rate is delayed or declines when temperature is above 34.44°C (94°F) or below 14.4°C (58°F). It is assumed that the stand will be replanted when time of emergence is greater than 14 days (Banks, 1990; Verhalen, 1990). The number of simulated planting operations for each initial planting date is presented in Table 4.6. Using the emergence algorithm in COTTAM to mimic the number of planting operations appears to underestimate the number of plantings witnessed by farmers (Banks, 1990). This procedure accounts for the adverse influence of soil temperature on the cotton plant stand for the early planting dates; however, it does not account for plant stand washouts caused by heavy rainfall events. This could explain the difference between the expert opinion number of 1.3 to

TABLE 4.5

SIMULATED STAND SURVIVAL FOR EACH PLANTING DATE STRATEGY

	Calendar Date Planting Strategy					Soil Temp Rule		
Year	April 19	May 3	May 17	May 31	June 14	60°F	65°F	70°F
	Percent							
1948	29	39	40	41	60	56	38	57
1949	31	40	60	53	54	42	50	51
1950	32	37	39	60	60	39	44	60
1951	33	51	41	52	52	45	44	60
1952	31	40	49	46	41	27	58	57
1953	31	54	42	51	60	43	53	53
1954	38	55	45	48	60	37	52	50
1955	39	39	39	60	58	39	40	54
1956	40	35	60	54	48	45	38	55
1957	26	32	38	58	54	35	47	54
1958	35	32	41	39	60	45	40	55
1959	25	31	47	46	57	46	45	53
1960	34	35	51	60	52	30	47	56
1961	32	48	52	60	55	35	41	60
1962	27	31	53	45	48	34	45	57
1963	20	55	52	53	47	35	38	56
1964	31	39	45	48	54	39	47	56
1965	24	34	36	52	57	46	47	59
1966	39	44	33	57	58	30	46	50
1967	33	37	47	47	58	49	44	55
1968	25	56	48	52	60	40	52	52
1969	30	39	34	48	55	35	60	52
1970	35	45	44	48	55	39	56	55
1971	22	38	60	49	60	49	38	56
1972	30	54	57	60	59	46	42	52
1973	31	60	44	55	60	39	54	52
1974	40	34	58	51	60	41	46	59
1975	43	31	45	41	51	33	39	52
1976	27	42	41	54	47	40	45	54
1977	28	50	47	55	44	33	44	54
1978	26	39	38	50	60	36	44	60
1979	34	48	39	43	60	38	49	59
1980	39	48	42	48	58	48	47	59
1981	25	34	33	47	55	47	50	57
1982	30	37	46	57	47	29	41	58
1983	40	53	39	45	56	31	45	56
1984	45	39	47	60	56	43	52	44
1985	24	48	60	60	46	33	53	60
1986	26	37	43	47	53	34	50	53
1987	46	39	55	50	53	47	48	58
1988	33	40	37	49	60	33	41	60
1989	39	51	41	57	47	27	48	54
1990	35	46	51	56	58	40	42	56
Max.	46	60	60	60	60	56	60	60
Min.	20	31	33	39	41	27	38	44
Ave.	32	42	46	51	55	39	46	55
Std.	6	8	8	6	5	7	5	4

TABLE 4.6

THE NUMBER OF SIMULATED PLANTING OPERATIONS AS OF EACH INITIAL PLANTING DATE FOR THE 43-YEAR SIMULATION CYCLE

	Calendar Date Planting Strategy					Soil Temp Rule		
Year	April 19	May 3	May 17	May 31	June 14	60°F	65°F	70°F
1948	1	1	1	1	1	1	1	1
1949	1	1	1	1	1	1	1	1
1950	1	1	1	1	1	1	1	1
1951	3	2	1	1	1	1	1	1
1952	1	1	1	1	1	1	1	1
1953	1	1	1	1	1	1	1	1
1954	1	1	1	1	1	1	1	1
1955	1	1	1	1	1	1	1	1
1956	3	2	1	1	1	1	1	1
1957	1	1	1	1	1	1	1	1
1958	1	1	1	1	1	1	1	1
1959	2	1	1	1	1	1	1	1
1960	1	1	1	1	1	1	1	1
1961	1	1	1	1	1	1	1	1
1962	1	1	1	1	1	2	1	1
1963	4	3	2	1	1	1	2	1
1964	1	1	1	1	1	1	1	1
1965	1	1	1	1	1	1	1	1
1966	2	1	1	1	1	1	1	1
1967	1	1	1	1	1	1	1	1
1968	1	1	1	1	1	1	1	1
1969	1	1	1	1	1	1	1	1
1970	1	1	1	1	1	1	1	1
1971	4	3	2	1	1	2	2	2
1972	1	1	1	1	1	1	1	1
1973	1	1	1	1	1	1	1	1
1974	2	1	1	1	1	1	1	1
1975	1	1	1	1	1	1	1	1
1976	1	1	1	1	1	1	1	1
1977	1	1	1	1	1	1	1	1
1978	3	2	1	1	1	1	1	1
1979	1	1	1	1	1	2	1	1
1980	1	1	1	1	1	1	1	1
1981	1	1	1	1	1	1	1	1
1982	1	1	1	1	1	1	1	1
1983	1	1	1	1	1	2	1	1
1984	1	1	1	1	1	1	1	1
1985	1	1	1	1	1	1	1	1
1986	1	1	1	1	1	1	1	1
1987	1	1	1	1	1	1	1	1
1988	1	1	1	1	1	1	1	1
1989	1	1	1	1	1	1	1	1
1990	1	1	1	1	1	1	1	1
Ave	1.35	1.16	1.05	1.00	1.00	1.09	1.05	1.02
Std	0.81	0.48	0.21	0.00	0.00	0.29	0.21	0.15
Max	4.00	3.00	2.00	1.00	1.00	2.00	2.00	2.00

This could explain the difference between the expert opinion number of 1.3 to 1.6 plantings (Banks, 1990) and the number of simulated replanting operations.

The second field relationship is plant characteristics as a function of plant population. Two cotton plant traits are significantly influenced by field population. Expected boll weight and first main stem node fruiting branch help determine the carrying capacity of the plant and the timing of fruiting initiation. Both are model inputs and both significantly influence the final seed cotton yield outcome. Boll weight data from a field trial study by Ray et al. (1959) is used to develop the linear equation,

$$BSIZE_{it} = 6.39 - 0.00001412 \cdot CRPOP_{it}, \tag{4.6}$$

where $BSIZE_{it}$ is expected boll size for plant date i in year t and $CRPOP_{it}$ is plant population for plant date i in year t (Table 4.7).

Expected first main stem node fruiting branch number determines initiation of fruit production. It is a function of variety and of plant population. In general, short-season varieties start fruiting site development on a lower main stem branch number than do later maturing varieties (Jackson et al., 1990). Two assumptions are utilized to determine first fruit branch number as a function of varietal type and plant population. First, the average first fruit branch for each variety is assumed to be: short=5, medium=6, and long=7. These three average values are assumed to correspond to a plant population of 40,469 per acre (11 plants per meter^2). Second, the mainstem node with a fruit branch is changed by one node for each 11 plant per meter^2 increase in plant population (Buxton et al., 1977). These two assumptions are used to define,

$$EMSN_{it}^{short} = 4.64 + 0.000008517 \cdot CRPOP_{it}, \tag{4.7}$$

$$EMSN_{it}^{medium} = 5.64 + 0.000008517 \cdot CRPOP_{it}, \text{ and} \tag{4.8}$$

$$EMSN_{it}^{long} = 6.64 + 0.000008517 \cdot CRPOP_{it}, \tag{4.9}$$

where $EMSN_{it}$ is expected first main stem node fruit branch number and $CRPOP_{it}$ is plant population for plant date i in year t (Table 4.7).

The COTTAM model, 1948-1990 daily weather data (Oklahoma State University Irrigation Research Station, Altus), and representative study area soil profile data are (Oklahoma State University Irrigation Research Station, Altus) used to generate yield outcomes for the alternative planting strategies. Initial soil moisture at the beginning of the 43-year run is assumed to be 0.18 inches. This is the average of soil moisture on January 1 for a 6-year period (1964 - 1969) at the Oklahoma State University Irrigation Research Station, Altus. The model simulates a continuous soil moisture balance for the 43-year cycle from this initial level. This assumption allows the model to track scarce overwinter soil moisture which has an important impact on time of planting.

Several assumptions regarding subsequent irrigation and pest management decisions are specified in order to obtain yield outcomes. Irrigation is restricted to the fruiting period of the plant because scarce water is not used in the early growing season (Kirby, 1990). Sixteen total acre inches of water are applied in four four-inch applications on a two-week schedule starting June 28 and ending August 9. Irrigation efficiency is assumed to be 60 percent. These assumptions are consistent with observed practices in the irrigation district used for this study. Additionally, it is assumed that the rate of fruit shedding caused by insects is 15 percent implying a "good" level of insect management (Jackson et al., 1990).

TABLE 4.7

EXPECTED SEED COTTON BOLL WEIGHT AND FIRST MAIN STEM BRANCH NODE NUMBER ON WHICH A FRUITING BRANCH APPEARS AS A FUNCTION OF PLANT POPULATION

Expected Boll Weight as a Function of Plant Population:[a]

Plant Population Per Acre	Bolls to Make a Pound of Seed Cotton	Weight of One Cotton Boll in Grams
18,100	73	6.2
33,500	78	5.8
50,000	80	5.7
64,600	83	5.5
77,400	85	5.3

Boll Weight = 6.39 - 0.00001412 • Plant Population[b]
(0.09) (0.00000166)

Standard Error of the Estimate = 0.08

Coefficient of Determination (R^2) = 0.96

Expected First Main Stem Node Branch Number ($EMSN_o$) on which a Fruiting Branch Appears as a Function of Plant Population:[c]

<u>Short-Season Variety</u>: $EMSN_o$ = 4.64 + 0.000008517 • Plant Population

<u>Medium-Season Variety</u>: $EMSN_o$ = 5.64 + 0.000008517 • Plant Population

<u>Long-Season Variety</u>: $EMSN_o$ = 6.64 + 0.000008517 • Plant Population

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[a] SOURCE: Ray, L. L., E. B. Hudspeth, And E. R. Holekamp. 1959. "Cotton Planting Rate Studies on the High Plains," MP-358, p. 16, College, Station, Texas: Texas Agricultural Experiment Station.

[b] This linear regression relationship was estimated using the data of Ray et al. (1959, p. 16).

[c] These three linear main stem node relationships are based on two assumptions: 1. Short-season varieties start fruiting site development on a lower main stem branch number than do later maturing varieties [Jackson et al., 1990, p.53]. 2. The lowest mainstem node with a fruiting branch is raised about one node for each 11 plants/meter^2 increase in plant population [Buxton et al., 1977, p. 932].

Irrigation Decision Problem Analysis Simulation Framework

Numerous approaches to the irrigation decision problem are found in the agricultural economics literature. Researchers such as Harris and Mapp (1986, pp. 298-305), McGuckin et al. (1987, pp. 123-133), Bosch and Eidman (1987. pp. 658-668), and Talpaz and Mjelde (1988, pp. 184-192) have used daily time-step simulation experimentation to generate outcomes for their economic analysis. However, their methods for analyzing these outcomes are quite different.

Harris and Mapp and Bosch and Eidman used an expected utility maximizing approach to analyzing simulation outcomes. Harris and Mapp used stochastic dominance criteria to rank water conserving and intensive irrigation decision alternatives for agents with non-neutral risk preferences. By comparison, Bosch and Eidman used Generalized Stochastic Dominance (GSD) to value alternative information assumption irrigation rules for agents with non-neutral risk preferences.

This contrasts with the simulation and numerical optimization approaches of McGuckin et al. and Talpaz and Mjelde. McGuckin et al. used a random time frame dynamic programming approach to compare revenue maximizing stress and non-stress irrigation strategies. Talpaz and Mjelde used quadratic programming techniques to determine a net income maximizing variable soil moisture trigger irrigation decision rule.

This analysis examines the value of alternative calendar date and timed irrigation strategies given uncertain water availability and non-neutral risk preferences. The COTTAM simulation model, 1948-1990 daily wether data, and representative Tillman-Hollister study area soil profile data are used to generate lint yield outcomes for the irrigation decision problem analysis (Table

4.1). Generalized stochastic dominance criteria are used to identify the risk efficient irrigation strategies. GSD is also used to value information about timing and water availability in formulating an irrigation decision rule. Preferred strategies identified from the planting decision analysis are used to determine time of planting, variety maturity-length choice, and seeding rate.

There are several attributes of the study area cotton field growing environment that influence the decision problem. Both rainfall and irrigation water availability are limited within the Lugert-Altus Irrigation District (L-AID). Average water allocation in the district is about 12 acre inches and varies from less than six inches to as much as 24 inches (Kirby, 1990). With a 25 percent cotton set aside this increases average water available to 16 acre inches. Farmers do not know what their final water allocation is until after planting. This generally occurs in mid-June (Kirby, 1990). Farmers to a certain extent can adjust acreage or purchase additional water from other land owners in the district. An examination of irrigation allocation records for the 43-year period (1948-1990) found that farmers had 16 acre inches or less in 23 years (53 percent), between 16 and 20 acre inches in five years (12 percent), between 20 and 24 inches in eight years (19 percent), and greater than 24 inches in seven years (16 percent) [data from Kirby, 1990].

The common practice is to limit irrigation to the fruiting period of the plant because water is limited (Kirby, 1990). The April-May-early June period is a time of above average rainfall so there is generally enough for early plant growth. Thus, the typical irrigation period is from mid- to late-June through late-August or mid-September.

Another important attribute of the decision problem is overwinter precipitation. Initial soil moisture at the beginning of the 43-year simulation cycle is assumed to be 0.18 inches. This is the average soil moisture on

January 1 for a 6-year period (1964-1969) at the Oklahoma State University Irrigation Research Station, Altus. The model simulates a continuous moisture balance for the soil profile over the 43-year cycle from this initial level. This assumption allows the model to track scarce overwinter moisture which is an important influence on the irrigation decision problem in some years.

Both calendar and timed irrigation decision criterion are examined in the irrigation analysis. The calendar strategy involves following a set calendar date schedule of 12- to 14-day interval irrigations. This is a common practice in the irrigation district and assumes no information about the current state of the crop (Banks, 1990).

The decision criterion for the timed strategies is to schedule irrigations using information about available moisture in the root extraction zone of the soil profile. The problem is to determine the soil moisture threshold x_i as a fraction of total plant available water (PAW) [field capacity minus permanent wilting point in each soil layer] in the root zone at which to trigger an irrigation (Table 4.1). That is, irrigate when soil moisture is $\leq x_i$ where $0.0 \leq x_i \leq 1.0$. This strategy uses current state information about the soil profile and stage of plant growth.

The general pattern of cotton plant water use under irrigation as a function of plant growth stage is: less than 0.10 inches per day from emergence to first square; 0.10 to 0.25 inches per day from first square to first bloom; 0.25 to 0.40 inches per day from first bloom through peak bloom to first open boll; and gradually decreasing to 0.15 inches per day at harvest (Tharp, 1960, p.11).

Soil water use and cotton plant water stress in the COTTAM model (Jackson et al., 1990) are based on the algorithms of Ritchie (1972, pp. 1,204-1,213). The total amount of water lost (demand) from the field by both soil evaporation (Es) and plant transpiration [evaporation from plant surfaces] (Ep) is calculated from potential evapotranspiration (ETp). Potential evapotranspiration is primarily a function of solar radiation, temperature, relative humidity, and wind speed and turbulence. ETp is estimated using the Priestly and Taylor equation (P-T) subroutine in the COTTAM model. This subroutine is used due to insufficient relative humidity and wind run data (available 1954-1970) to implement the modified Penman ETp equation (PEN) subroutine in the model. Dugas and Ainsworth (1983) in a comparison of the P-T and PEN equations found that the P-T equation underestimated ETp when compared to PEN and pan evaporation values in a subhumid climate (Western Texas).

A P-T ETp location correction factor is used to calibrate the model to account for wind and relative humidity conditions in the study area (Table 4.1). Simulated July P-T and PEN ETp values over the 1954-1970 period were compared in an attempt to see how well the model estimated ETp. July is the period of greatest evaporative demand in Oklahoma. Cumulative July PEN and P-T ETp values are generally very close to each other for the 1954-70 period. However, there is more variation in daily P-T ETp values than in daily PEN ETp values. It appears that the model does a reasonable job of simulating evaporative demand under Oklahoma growing conditions using the calibrated P-T equation.

Plant transpiration (Ep) is calculated using

$$\mathrm{Ep}=\mathrm{ETp} \cdot 0.53 \cdot \mathrm{LAI}^{0.5} \cdot \mathrm{WATCO}, \tag{4.10}$$

where ETp is potential evapotranspiration, LAI is the ratio of the surface area of the vegetation to that of the ground underneath (leaf area index), and WATCO ($0.0<\mathrm{WATCO}<1.0$) is a multiplicative plant process based stress factor. WATCO equals one until soil moisture declines below specified plant process thresholds, and declines to zero when soil moisture is zero. The soil moisture fraction plant process stress thresholds are 0.50 for leaf growth, 0.40 for vegetative growth, and 0.30 for transpiration and net photosynthesis.

Soil evaporation is calculated using a two-stage model by Ritchie (1972, pp. 1,204-1,213). During stage 1, soil evaporation is limited only by energy availability until a soil dependent quantity of water is removed (the Stage 1 soil evaporation coefficient in Table 4.1). That is, soil evaporation is a function of energy that penetrates the plant canopy

$$Es = ETp \bullet e^{(-0.39\ LAI)} \tag{4.11}$$

where ETp is potential evapotranspiration and LAI is the leaf area index. After the stage 1 quantity is removed, further evaporation is restricted by conductivity of the soil and is proportional to the square root of time

$$Es = STG2 \bullet T^{0.5}, \tag{4.12}$$

where STG2 is the stage 2 proportionality constant (Table 4.1) and T is time in days.

Thus, the soil moisture budget at time t, SM_t in the COTTAM model, is expressed as

$$SM_t = SM_{t-1} + RAIN_t - RUNOFF_t + RRIG_t - Ep_t - Es_t, \tag{4.13}$$

where SM_{t-1} is the previous day soil water balance, $RAIN_t$ is daily precipitation, $RUNOFF_t$ is daily rainfall runoff, $RRIG_t$ is net irrigation water applied on day t, Ep_t is daily plant transpiration, and Es_t is daily soil evaporation.

Water withdrawal from the soil profile occurs within the effective root extraction zone (REZ). The REZ is assumed to penetrate the soil profile at a rate that parallels accumulated day degrees. The root penetration rate is described by

$$\text{RTGROW} = -3.20\ [\text{BULKD}_i - (1.52 - 0.00646\ \text{CLAY}_i)] + 2.0 \quad \text{and} \tag{4.14}$$

$$\text{RTDEP} = \text{RTDEP} + \text{RTGROW} \bullet 0.25, \tag{4.15}$$

where RTGROW is the relative REZ growth rate, RTDEP is the depth of the root zone, BULKD_i is the soil layer wet bulk density and, CLAY_i soil layer clay fraction (Table 4.1). Root zone growth is assumed to have a maximum penetration rate of 0.25 centimeters per day degree.

The following simulation protocol is used to develop seed cotton distributions for the irrigation decision problem analysis. The irrigation trigger criteria soil moisture is assumed to be the weighted average fraction of plant available water PAW in the root zone of the soil profile specified in Table 4.1. Irrigation can occur any time between June 28th and August 31st. This time period is consistent with practices in the district, i.e., irrigate during the fruiting period and cease irrigation at the beginning of September to avoid verticillium wilt problems (Verhalen, 1990).

Seven soil moisture fraction irrigation trigger levels are simulated over the 43-year cycle: 0.20, 0.25, 0.30, 0.35, 0.40, 0.45, and 0.50. Four total seasonal irrigation water levels are assumed for the analysis: 1) unlimited irrigation water, 2) 16 acre inches, 3) 20 acre inches, and 4) 24 acre inches. Irrigation efficiency is assumed to be 60 percent under the furrow irrigation conditions of the L-AID. Thus net water availabilities to the plant are 9.6, 12, and 14.4 acre inches, respectively. The four total seasonal water availability outcomes are replicated using 43-years of daily weather data.

The unlimited water availability assumption represents the perfect soil water information solution, i.e., perfect knowledge of water demand by the plant over the irrigation season. The other water levels represent three possible quantities of water that the farmer might have available going into the irrigation season, either through actual allocation or purchase of allocation. In reality, farmers are faced with a wide variety of possible water allocations going into the irrigation season. However, three water levels are assumed to simplified the analysis. The 16 acre inch allocation is assumed to be the most likely value and occurs in 23 years, the 20 acre inch value occurs in 13 years, and the 24 acre inch allocation occurs in eight years. The water application rate is assumed to be four acre inches per irrigation. This implies four, five, and six irrigations in the 16, 20, and 24 acre inch available years, respectively.

The objective is to find the intraseasonal soil moisture trigger threshold rule for a given water availability that allocates water over the fruiting period to maximize expected utility for agents with non-neutral risk preferences. The water allocation dependent trigger rule is compared with calendar date irrigation strategy. The calendar date water allocations are: 1) irrigate on June 28th, July 12th, July 26th, and August 9th when 16 acre inches in available; 2) irrigate on June 28th, July 12th, July 26th, August 9th, and August 23rd when 20 acre inches are available; and irrigate on June 28th, July 10th, July 22th, August 3rd, August 15th, and August 27th when 24 acre inches are available. The final assumption for the irrigation analysis is that the rate of fruit shedding caused by insects is the same as in the planting analysis (15 percent).

Pest Decision Problem Analysis Simulation Framework

The insect decision problem analysis is limited to six years of available insect population numbers and dynamics data (Table 4.2). The preferred planting and irrigation decision strategy decision sets are the basis for the analysis, i.e., variety, time of planting, seeding rate and irrigation information. Simulated fruit count data from the preferred decision set are input into the

TEXCIM model, i.e., simulated per acre square (bud), flower, and boll counts. The initial plant mapping (fruit count) set assumes no insect damage. This set is updated with new information about insect damage at each decision point.

Weekly pheromone trap moth count data (1985-1990) are used to specify Heliothis spp.and boll weevil population numbers and dynamics for a representative cotton field in the Lugert-Altus Irrigation district (Table 4.2). Daily temperature and moisture data are used to simulate fleahopper numbers and dynamics. Moth count and weather data are used as input in the TEXCIM model to simulate insect numbers and yield loss until the first spray decision. The TEXCIM model is then used to simulate the no spray and after spray insect numbers and yield outcome until the next spray decision. The insect population and lint yield damage outcome data set for each simulation year is updated using this procedure until harvest. Harvest is assumed to occur when the field is 100 percent open boll. A light level of beneficial predators is assumed for the analysis, i.e., one or less predators per four plants (A default level specified in the TEXCIM model).

Oklahoma State University recommendations for insecticide chemical use are followed for the four spray strategies simulated (Anonymous, 1990). The insecticides used for cotton fleahopper, Heliothis spp., and boll weevil control in the simulation analysis are presented in Table 4.8. The assumed effectiveness of these insecticides against insects and predators is also presented in Table 4.8 (Harstack, Sterling and Dean, 1990). Total mortality represents the total percentage of insects in each growth stage killed by the insecticide. Time to mortality is the total time in days until total mortality is achieved.

Four pest control strategies are simulated for the 1985 through 1990 weather years: 1) the no action strategy, 2) a typical calendar date spray

TABLE 4.8

INSECTICIDES USED FOR THE SIMULATION OF THE FOUR SPRAY STRATEGIES AND THEIR ASSUMED EFFECTIVENESS AGAINST COTTON FLEAHOPPERS, HELIOTHIS SPP., AND BOLL WEEVILS

Cotton Insect	Stage	Mortality Total (%)/ Time to Total (Days)	Insecticide				
			Dicrotophos	Oxamyl	Methomyl	Cypermethrin	Parathion
			Percent/Days				
Fleahopper	Eggs	Total Mortality	5	5	5	5	5
		Time of Mortality	1.5	1.5	1.5	1.5	1.5
	Nymphs	Total Mortality	99	99	99	99	99
		Time of Mortality	4.3	4.3	4.3	4.3	4.3
	Adults	Total Mortality	98	98	98	98	98
		Time of Mortality	4.3	4.3	4.3	4.3	4.3
Heliothis spp.	Eggs	Total Mortality	86	78	86	84	78
		Time of Mortality	1.5	1.5	1.5	1.5	1.5
	Small Larvae	Total Mortality	80	72	80	89	72
		Time of Mortality	2.5	2.5	2.5	4.3	2.5
	Large Larvae	Total Mortality	58	36	58	65	36
		Time of Mortality	2.5	2.5	2.5	4.3	2.5
	Adults	Total Mortality	70	78	70	72	78
		Time of Mortality	2.5	2.5	2.5	4.3	2.5
Boll Weevil	Adults	Total Mortality	70	78	70	72	78
		Time of Mortality	2.5	2.5	2.5	4.3	2.5
Natural Enemies		Total Mortality	90	90	90	95	95
		Time of Mortality	15	15	15	15	15

SOURCE: Harstack, Albert W., Winfield L. Sterling and Allen Dean. 1990. "TEXCIM40: The Texas Cotton-Insect Model." MP-1646, p. 94. College Station Texas: Texas Agricultural Experiment Station.

strategy followed by some producers in the L-AID (Karner, 1991), 3) the Oklahoma Cooperative Extension Service insect control strategy guidelines (Karner, 1989; Anonymous, 1990), and 4) a dynamic spray threshold strategy (Hartstack and Sterling, 1988, pp. 370-374). Each strategy represents an assumption about information used to determine insect control measures. Generalized stochastic dominance criteria are used to identify the risk efficient strategies and to estimate agent willingness to pay for each information level strategy over the no information strategy.

The no spray strategy represents the cumulative insect damage that would be witnessed if no action is taken for control. In some years this strategy would result in considerable yield and revenue loss while in others it might be the most cost effective.

The second strategy simulated is a calendar date spray schedule that might be followed by some producers in the Lugert-Altus Irrigation district (Karner, 1991):

1. **7th to 9th true leaf (about June 25)**: Spray for fleahoppers and boll weevils.

2. **Prebloom: (about July 10)**: Spray again for fleahoppers and boll weevils.

3. **July 10 through September 15**: Farmer attempts to identify hatching Heliothis spp. eggs in the field and spray with that event. Eggs are easier to find than larvae. They end up spraying five times or about every 10 days, i.e, on about July 20th, July 30th, August 9th, August 19th, and August 29th.

4. **Heavy boll weevil year**. If it is a heavy boll weevil infestation year, then the producer will go on a five day spray schedule beginning in mid-August and through mid-September. Every other application includes a spray for Heliothis spp.

This strategy ignores information about the impact that insect numbers, beneficial predator numbers, stage of plant growth, and the current value of the crop have on the economics of the pest control decision.

The next strategy simulated over the six year period is the Oklahoma Cooperative Extension Service recommended insect control strategy for an irrigated cotton producer (Karner, 1989, pp. 81-82; Anonymous, 1990):

1. **4th to 6th true leaf**: Avoid spraying insecticide if possible to let beneficial predator populations build up. Apply insecticide only if extreme fleahopper and boll weevil infestations are encountered.

2. **Pinhead to 1/3 grown square**: Apply an insecticide for boll weevil and cotton fleahoppers (40 fleahoppers per 100 plants). Apply an ovicide if Heliothis spp. eggs are detected.

3. **Squaring to 1st week of Bloom (June 25 to July 10)**: Apply an insecticide (Carbamate or Organophosphate) to control Heliothis spp. if 10 eggs and small larvae are found per 100 plants. Include an insecticide for boll weevils if detected. Boll weevil control should begin when 15 to 25 percent infested squares are detected. Applications should be made on a four to five day schedule until infested squares drop below 15 percent. Pyrethoid insecticides should be used only when both Heliothis spp. and boll weevils are above recommended treatment thresholds

4. **July 10 to September 15**: Treat for Heliothis spp. when 5 small larvae are found per 100 plants. Synthetic pyrethoids can be used.

5. **After September 15**: Include an insecticide for boll weevil control in the harvest aid program. Conduct a quick harvest and destroy and incorporate stalks as soon as possible after harvest. Control Heliothis spp. if population exceeds 10 small larvae per 100 terminals.

This strategy uses information about insect numbers in the field and rule of thumb damage thresholds in formulating a spray decision rule.

The final strategy simulated using the 1985 through 1990 environmental data set is the dynamic spray threshold strategy (Harstack and Sterling, 1988, pp. 370-374). The dynamic threshold considers information about the forecasted value of harvestable fruit on the plant before and after insect damage at time t.

Many of the early set insect damaged fruit can be replaced by either increased boll production or retention. However, if the new fruit does not have time to mature, then the potential damage to fruit has greater value. This is the basis for the fruit age value component in the TEXCIM model.

At each decision point, the expected day degrees to harvest and boll age class information are used to determine if the fruit can mature by the predicted harvest date. If the fruit cohort cannot mature, then its value is zero.
If the fruit has some probability of survival, then the quantity of harvestable fruit in each age class is determined using:

$$\text{FRTFAC} = (e^{(-.5\ (\text{AGE}-1050))}/(2000\ e^{(-0.25\ \text{COHORT})})^{2}) \qquad (4.16)$$

where FRTFAC = probability of fruit cohort survival to harvest ($0.0 \leq \text{FRTFAC} \leq 1.0$);
AGE = FRTAGE • DDSOB;
COHORT = ((DD1SQ - FRTAGE) DDSOB)/100);
FRTAGE = fruit age in physiological time (1.0 = mature boll);
DD1SQ = day degrees since first fruit, and
DDSOB = day degrees required from square to open boll.

Equation (4.16) considers only natural stress and does not consider replacement of fruit by increased production.

To consider the influence of compensation by the plant, it is assumed that an increase in the number of bolls (boll load) on the plant reduces the compensation effect by the plant. The probability of compensation by the crop (PRBCOMP) is assumed to be a decreasing linear function of boll load (BLOAD)

$$\text{PRBCOMP} = 1.0 - \text{BLOAD} \quad (0.0 \leq \text{PRBCOMP} \leq 1.0), \qquad (4.17)$$

where boll load is the estimated number of bolls per acre at a decision point divided by the expected yield in number of bolls per acre at harvest. The plant can replace any fruit lost if the season is long enough. However, the older the age of the fruit the higher the probability of a delay in crop maturity. Thus, the equation for the ability of the plant to compensate (COMPAGE) is

$$\text{COMPAGE} = 1.0 - \text{FRTAGE} \bullet 1.66 \quad (0.0 \leq \text{COMPAGE} \leq 1.0), \tag{4.18}$$

and the combined influence of boll load and fruit age on probability to compensate is

$$\text{PRBCOMPT} = \text{PRBCOMP} \bullet \text{COMPAGE}. \tag{4.19}$$

Thus the lower the probability of compensation, the higher the probability of a delay in maturity (CMPDELAY):

$$\text{CMPDELAY} = \text{FRTAGE} \bullet (1.0 - \text{PRBCOMP}). \tag{4.20}$$

Let CDAM represent the estimated cumulative percent pest damage that has already occurred in the field. Insect damage that has already occurred reduces the ability of the plant to compensate for damage (i.e., less surplus fruit available). Thus, the total probability of compensation TPC is

$$\text{TPC} = 1.0 - \text{PRBCOMPT} \bullet (1.0\text{-CDAM}) \tag{4.21}$$

and the adjusted probability of fruit cohort survival (FRTACT) for each age class of fruit is

$$\text{FRTFACT} = \text{FRTFAC}/(1.0 - \text{PRBCOMPT} \bullet (1.0 - \text{CDAM})). \tag{4.22}$$

Summing the probabilities times the estimated current quantity of fruit in each age class yields the expected quantity of harvestable fruit, i.e.,

$$\sum_{i} \mathrm{FRTACT}_i \cdot \mathrm{QF}_i, \tag{4.23}$$

where QF_i is the estimated quantity of fruit in age class i. The relationship developed by Harstack and Sterling (1988) to describe the compensation by the plant for insect damage is used to estimate fruit quantity loss by insects at time t.

The decision of when to spray is described by

$$\mathrm{NI}_t = \mathrm{P} \cdot (\mathrm{HFQ}_t^{\mathrm{Before}} - \mathrm{HFQ}_t^{\mathrm{After}}) - \mathrm{CONTROL}_t, \tag{4.24}$$

where NI_t is the expected net income per acre gain or loss for a spray application at time t, P is expected cotton lint price per pound, $\mathrm{HFQ}_t^{\mathrm{Before}}$ is the expected harvestable lint yield per acre at time t before the forecasted insect damage, $\mathrm{HFQ}_t^{\mathrm{After}}$ is the expected harvestable lint yield per acre at time t after the forecasted insect damage, and $\mathrm{CONTROL}_t$ is the cost of insect control. The cost of insect control includes the cost of the insecticide and the cost of application. An insect spray application is assumed to occur when the dollar value of the five day forecast of cumulative lint yield damage exceeds the cost of control. The TEXCIM model estimate of insect damage at time t using projected pest population numbers and current harvestable fruit quantity is the forecast mechanism.

This dynamic spray threshold strategy uses forecast information about the current value of the crop, damage by insects, and the ability of the crop to compensate for insect damage given the current stage of fruit production. Thus, it incorporates the Integrated Pest Management and Economic Threshold concepts described in The Review of Pest Management Concepts section of

Chapter II (Stern et al., 1959; Headley, 1972; Hall and Norgaard, 1973; Stern, 1973; Flint and van den Bosch, 1981).

CHAPTER V

RESULTS AND ANALYSES

This chapter presents: 1) the simulated lint yield results from the empirical framework developed in Chapter IV and 2) an economic analysis of net enterprise income results at each decision stage. An analysis of the planting decision problem is presented in the first section. Results from the irrigation strategy analysis come next. The final part of this chapter examines the pest decision problem.

Planting Decision Problem Economic Analysis

There are four steps to implementing the planting decision economic analysis. First, yield distributions for the alternative calendar date and soil temperature planting decision rules are generated using the COTTAM daily time-step cotton plant growth and development simulation model (Jackson et al., 1990). Next, costs and returns are allocated to each decision alternative to construct distributions of net enterprise income for the base economic analysis. Stochastic dominance criteria are then used to identify risk efficient planting strategies. Finally, the value of further information about more flexible planting strategies is evaluated using generalized stochastic dominance criteria.

Simulated Lint Yield Results and Analyses

Cotton lint yield outcomes for every combination of five planting dates, three variety maturity-length choices, and five seeding rates were simulated using the methods, assumptions, and data described in Chapter IV. Daily weather data from 1948 through 1990 were used to generate a 43-year seed-cotton yield distribution for each decision alternative.

This portion of the analysis examines several facets of the simulated lint yield outcomes: 1) average yield levels and variability, 2) the effect of variety type as measured by earliness (how rapidly the variety matures) on yield response under Rolling Plains growing conditions, 3) the influence of stochastic plant population on yield response, and 4) the effect of time of planting on yield response. Where possible, simulated yield outcomes are compared with actual field experimental plot data from the Oklahoma State University Irrigation Research Station, Altus to validate the results.

Summaries of simulated lint yields for short-, medium-, and long-season varieties are presented in Tables 5.1, 5.2, and 5.3, respectively. Average lint yield among the 25 short-season strategies is 856 pounds per acre (Table 5.1). This contrasts with a 779 pound average for the medium-season strategies (Table 5.2) and 695 pounds among the 25 long-season tactics (Table 5.3).

The highest expected yield alternative is the short-season variety planted on May 31 using a 100,000 seeding rate (975 pounds per acre). By comparison, the highest producing medium-season strategy generates nine percent less lint yield on the average (May 17 planting date and a 120,000 seeding rate averaging 891 pounds per acre). Ten of the 25 short-season strategies produce more lint than the best medium-season alternative. Furthermore, fourteen of the short-season strategies out produced the highest expected yield for the long-season alternative (May 17 planting date and a 120,000 seeding rate averaging 841 pounds per acre).

TABLE 5.1

ALTERNATIVE STRATEGIES FOR SHORT-SEASON VARIETIES USING A 43-YEAR SIMULATION SEQUENCE TO DERIVE COTTON LINT YIELD RESULTS

Strategy		Lint Yield[a]				
Planting Date	Seed Acre	Average	Standard Deviation	Maximum Value	Minimum Value	Skewness
Mo./Day	Thousands	Pounds/Acre				
4/19	60	696	172	1,024	335	-0.26
5/03	60	725	156	1,057	380	-0.21
5/17	60	778	147	1,238	524	0.83
5/31	60	869	116	1,284	648	1.07
6/14	60	739	122	1,126	506	0.91
4/19	80	775	198	1,169	294	-0.47
5/03	80	831	183	1,257	431	-0.34
5/17	80	883	157	1,381	572	0.72
5/31	80	944	116	1,312	632	0.55
6/14	80	803	129	1,142	512	0.23
4/19	100	841	214	1,247	409	-0.46
5/03	100	880	200	1,370	427	-0.31
5/17	100	941	156	1,461	540	0.62
5/31	100	975	126	1,305	604	-0.10
6/14	100	808	141	1,149	485	0.02
4/19	120	881	208	1,278	448	-0.34
5/03	120	902	206	1,453	424	-0.14
5/17	120	959	163	1,508	496	0.47
5/31	120	968	132	1,264	569	-0.37
6/14	120	784	147	1,136	452	0.05
4/19	140	909	206	1,274	456	-0.48
5/03	140	901	209	1,465	422	-0.05
5/17	140	947	169	1,521	456	0.35
5/31	140	922	140	1,214	518	-0.30
6/14	140	734	155	1,122	406	0.20

[a] Simulations conducted using 1948 through 1990 daily weather data from a weather station at the Oklahoma State University Irrigation Research Station, Altus.

TABLE 5.2

ALTERNATIVE STRATEGIES FOR MEDIUM-SEASON VARIETIES USING A 43-YEAR SIMULATION SEQUENCE TO DERIVE COTTON LINT YIELD RESULTS

Strategy		Lint Yield[a]				
Planting Date	Seed Acre	Average	Standard Deviation	Maximum Value	Minimum Value	Skewness
Mo./Day	Thousands	Pounds/Acre				
4/19	60	596	120	795	360	-0.30
5/03	60	644	136	1,034	333	0.39
5/17	60	705	128	1,115	503	0.60
5/31	60	753	126	1,112	522	0.62
6/14	60	622	122	988	383	0.61
4/19	80	692	152	979	371	-0.11
5/03	80	747	171	1,178	348	-0.02
5/17	80	817	150	1,261	561	0.38
5/31	80	846	130	1,156	511	-0.04
6/14	80	651	138	1,045	386	0.58
4/19	100	761	189	1,142	360	-0.18
5/03	100	816	188	1,288	385	-0.15
5/17	100	871	156	1,343	460	0.01
5/31	100	870	135	1,135	483	-0.36
6/14	100	648	145	1,035	366	0.43
4/19	120	808	206	1,203	355	-0.38
5/03	120	848	192	1,352	386	-0.06
5/17	120	891	161	1,362	407	-0.26
5/31	120	859	134	1,102	451	-0.54
6/14	120	625	147	1,008	353	0.36
4/19	140	824	217	1,260	356	-0.41
5/03	140	853	196	1,379	372	-0.00
5/17	140	880	169	1,369	386	0.26
5/31	140	813	131	1,087	412	-0.44
6/14	140	590	137	921	325	0.28

[a] Simulations conducted using 1948 through 1990 daily weather data from a weather station at the Oklahoma State University Irrigation Research Station, Altus.

TABLE 5.3

ALTERNATIVE STRATEGIES FOR LONG-SEASON VARIETIES USING A 43-YEAR SIMULATION SEQUENCE TO DERIVE COTTON LINT YIELD RESULTS

Strategy		Lint Yield[a]				
Planting Date	Seed Acre	Average	Standard Deviation	Maximum Value	Minimum Value	Skewness
Mo./Day	Thousands	Pounds/Acre				
4/19	60	552	108	786	261	-0.04
5/03	60	610	117	958	386	0.72
5/17	60	667	131	1,001	468	0.56
5/31	60	660	112	1,006	445	0.98
6/14	60	532	128	854	271	0.01
4/19	80	632	151	979	291	0.29
5/03	80	714	156	1,138	393	0.35
5/17	80	762	160	1,132	471	0.21
5/31	80	746	135	1,064	463	0.32
6/14	80	555	139	891	265	-0.06
4/19	100	695	191	1,122	298	0.21
5/03	100	782	178	1,249	386	-0.04
5/17	100	826	172	1,222	413	-0.25
5/31	100	776	148	1,145	443	0.06
6/14	100	551	142	893	244	-0.14
4/19	120	737	206	1,216	351	0.25
5/03	120	818	185	1,299	367	-0.32
5/17	120	841	175	1,239	389	-0.47
5/31	120	764	152	1,151	423	-0.02
6/14	120	528	154	853	120	-0.58
4/19	140	766	207	1,271	363	0.17
5/03	140	825	186	1,311	348	-0.49
5/17	140	825	180	1,230	359	-0.56
5/31	140	721	158	1,127	396	0.00
6/14	140	494	160	772	21	-1.10

[a] Simulations conducted using 1948 through 1990 daily weather data from a weather station at the Oklahoma State University Irrigation Research Station, Altus.

Selected cotton variety irrigated test results for 1980-1988 at Altus, Oklahoma, are presented in Table 5.4 (Oklahoma Cotton Variety Tests, 1980-1988 issues). Lint yields for that period varied from 160 to 1,239 pounds per acre. This compares to a range of 21 to 1,508 pounds per acre across the 75 simulated strategies over the 43-year period. The highest yielding variety classified as short in maturity averaged 917 pounds per acre in the test plots ('Paymaster 145'). This compares with a 904-pound average for the highest yielding variety classified as medium in maturity ('Stoneville 506'). The lowest average yielding variety in the test plot were the 'Acala' varieties classified as full-season or late in maturity (at 672 pounds per acre).

The COTTAM model appears to emulate general lint yield levels and variability as found in actual test plot data. However, one of the problems with examining specific variety maturity-yield response from test plot data is that some cultivars are classified as early to medium maturity or medium to late in maturity and so on, depending on who is subjectively doing the classifying. Varieties are also classified by "determinacy," which is closely related to earliness. Determinant varieties set fruit early and then "cut out" while indeterminant varieties set fruit for a longer (more-or-less indefinite) period of time. Thus, a variety could have a complex qualitative classification. For example, the variety Stoneville 506 is classified as early-to-medium in maturity with a moderately indeterminate growth habit (Thomas et al., p. 21). Further, there are many other characteristics that may influence yield response for a specific variety, e.g., pest resistance, drought resistance, etc. Thus, it is difficult to measure variety maturity-lint yield response using qualitative criteria.

TABLE 5.4

LINT YIELD AND PERCENT FIRST HARVEST FOR SELECTED COTTON VARIETIES IN IRRIGATED VARIETY TRIALS AT ALTUS, 1980 THROUGH 1988

Variety	Average	Standard Deviation	Maximum Value	Minimum Value	Coefficient of Variation
Tamcot CAMD-E					
Lint Yield	822	243	1,077	299	30
% 1st Harvest	78	18	98	44	23
Paymaster 145					
Lint Yield	917	273	1,234	273	30
% 1st Harvest	77	19	94	40	25
Pioneer/Lankart PR-75					
Lint Yield	843	203	1,084	392	24
% 1st Harvest	77	16	93	52	20
Tamcot SP21/SP21S					
Lint Yield	816	214	1,124	340	26
% 1st Harvest	76	12	91	59	15
Westburn M					
Lint Yield	816	235	1,075	283	29
% 1st Harvest	75	16	94	50	21
Lankart LX571					
Lint Yield	711	202	918	339	28
% 1st Harvest	74	94	46	23	17
Stoneville 825					
Lint Yield	840	230	1,067	280	27
% 1st Harvest	73	15	95	60	20
Stoneville 506					
Lint Yield	904	238	1,239	368	26
% 1st Harvest	72	13	93	54	18
Stoneville 213[b]					
Lint Yield	781	244	931	290	31
% 1st Harvest	71	14	93	51	20
Deltapine 55/50					
Lint Yield	885	252	1,070	239	28
% 1st Harvest	69	18	94	50	25
Deltapine 41					
Lint Yield	832	231	989	249	28
% 1st Harvest	68	13	84	48	20
Acala SJ-5/SJC-1					
Lint Yield	672	261	957	160	39
% 1st Harvest	62	12	84	52	19

SOURCE: Verhalen, L.M. and numerous others. "Cotton Variety Tests, Oklahoma." Okla, State Univ. CR-2094, 1981-1989 issues.

[a] Yield statistics reflect 1980-1988 data and percent first harvest statistics reflect 1980-85 data.

[b] Yield statistics reflect 1980-1986 data.

The COTTAM model emulates only one characteristic of cotton varieties, i.e., the maturity-lint yield response in the form of an index. Jackson et al. (1990) state that the COTTAM model variety index "is relative to cotton maturity type. The smaller the index the earlier the maturity and more determinant the variety (p. 33)." An index value of one is for a short-season type and results in a shorter plant reproductive period and a faster fruit production rate. This contrasts with an index value of three for a long-season type which produces a longer plant reproductive period with a slower fruit production rate.

A quantitatively determined proxy for variety maturity earliness (how fast the variety matures) is the percentage of total yield derived from the first harvest (Verhalen, 1990). Examination of the percent first harvest-lint yield data in Table 5.4 and the simulated yield results suggests an inverse relationship between variety maturity length and lint yield, i.e., earlier-maturing varieties produce more on average than later maturing varieties under Oklahoma growing conditions. Variety field trial data are used to test this hypothesis and to validate the variety maturity index in the COTTAM simulation model under Oklahoma growing conditions.

Thus, the variety-yield response relationship to be tested can be stated as: a variety with an average higher first harvest quantity should on average yield higher than a variety with a lower average first harvest quantity ceteris paribus. Such statistics were taken for 15 years at the Irrigation Research Station at Altus (Oklahoma Cotton Variety Tests, 1960-61, 1963-1966, 1969, 1973-74, and 1980-85 issues). Varieties grown for only one year were excluded from the data set. The 165 observations across the 15 years of data represent three of the major varietal types: Plains (short-season), Delta (medium-season), and Acala (long-season) varieties.

A pooled cross-sectional time series model was specified to test the earliness-yield response hypothesis. First harvest yield quantity was regressed on total yield. Binary variables were specified for each data year to account for varying planting and harvesting dates, management practices, environmental conditions, and other unknown factors. Because the disturbance term is correlated with both the independent and dependent variables, the instrumental variable technique was used to estimate the model. The instruments are the binary variables and final yield. Results of the model are presented in Table 5.5. The first harvest quantity coefficient is tested using the following hypothesis:

Null Hypothesis: Quantity 1st Harvest Coefficient ≤ 0

Alternative Hypothesis: Quantity 1st Harvest Coefficient > 0

The t-statistic on the first harvest quantity coefficient (26.49) is greater that the t-table value (1.96). Furthermore, the sign on the coefficient is positive. Thus, the null hypothesis is rejected; and the results demonstrate that a significant positive relationship exists between first harvest quantity (variety earliness) and lint yield under Oklahoma growing conditions.

Two conclusions can be drawn from this analysis of the test plot data. First, the variety index component of the COTTAM model accurately portrays variety maturity-lint yield response under Oklahoma growing conditions. Second, results suggest that a producer should choose a variety with a high first harvest quantity (short-season variety) all other characteristics being equal, e.g., pest resistance, drought resistance, quality characteristics, etc. The relationship between variety earliness (and determinacy) and lint yield is an important factor in the planting decision economic analysis.

TABLE 5.5

RESULTS FROM A MODEL TO TEST THE HYPOTHESIS OF A POSITIVE RELATIONSHIP BETWEEN COTTON VARIETY EARLINESS AND LINT YIELD UNDER OKLAHOMA IRRIGATED GROWING CONDITIONS[a]

Model Statistics	Value
Observations	165.
R-squared	0.9587
Adjusted R-squared	0.9546
Standard Error of Regression	53.9839
Log Likelihood	-883.8430
Dependent Variable	
Mean	718.6788
Standard Deviation	253.2930
Sum of Squared Residuals	434224.4000
F-statistic	230.7639

Model Coefficient Results

Variable	Coefficient	Standard Error	t-statistic	2-tail Significance
Intercept				
(Binary 1985)	126.5668	27.0215	4.6839*	0.000
1st Harvest Quantity	1.0957	0.0414	26.4910*	0.000
Binary 1960	91.8951	24.5691	3.7403*	0.000
Binary 1961	37.4263	23.4444	1.5964	0.110
Binary 1963	172.0589	23.1652	7.4275*	0.000
Binary 1964	131.2365	24.4822	5.3605*	0.000
Binary 1965	-87.9374	26.8683	-3.2729*	0.001
Binary 1966	10.5600	24.1000	0.4382	0.661
Binary 1969	-2.0701	22.8091	-0.0908	0.928
Binary 1973	107.7746	23.4326	4.5993*	0.000
Binary 1974	-74.6909	25.1742	-2.9670*	0.003
Binary 1980	-128.8968	22.0233	-5.8528*	0.000
Binary 1981	-72.2566	25.0115	-2.8889*	0.004
Binary 1982	297.2015	21.3027	13.9513*	0.000
Binary 1983	- 4.3623	21.3742	-0.2041	0.838
Binary 1984	144.2569	20.8574	6.9163*	0.000

[a] Fifteen years of variety test data from the Irrigation Research Station at Altus were used to estimate the model. Percent first harvest quantity is the proxy for variety earliness.

* Statistically significant: t-table (= 0.025, d.f. = 149) = 1.960

Another important element of the planting decision problem is the influence of time of planting on lint yield. Simulated lint yields by varietal type as a function of planting time and seeding rate are illustrated in Figures 5.1, 5.2, and 5.3, respectively. The three figures show the expected concave relationship between time of planting and lint yield. The highest average short-season yield occurs on the May 31 planting date (Figure 5.1; 100,000 seeding rate). This contrasts with the highest average medium and long season yields at the May 17 planting date (Figures 5.2 and 5.3, respectively; 120,000 and 120,000 seeding rates, respectively).

Verhalen (1989) conducted a five-year (1984-1988) field trial study of the influence of time of planting on lint yield at Altus, Oklahoma. Cotton was planted on seven different dates beginning on the first Friday in May of each year. The approximate time between plantings was one week. A spit plot experimental design was followed using two varieties, 'Westburn M' and Stoneville 506 (varieties in main plot and planting dates in subplots). Average lint yields for each planting date were:

Number 1 (about May 3): 645 pounds per acre
Number 2 (about May 11): 638 pounds per acre
Number 3 (about May 17): 656 pounds per acre
Number 4 (about May 24): 707 pounds per acre
Number 5 (about May 31): 694 pounds per acre
Number 6 (about June 7): 544 pounds per acre
Number 7 (about June 14): 462 pounds per acre

These average yields as a function of planting time are plotted along with the simulated yields in Figures, 5.1, 5.2, and 5.3. The highest average yield in the planting time field trial occurs around May 24. Thus it appears that the simulation model approximates the lint yield as a function of the planting time relationship found in the test plot data.

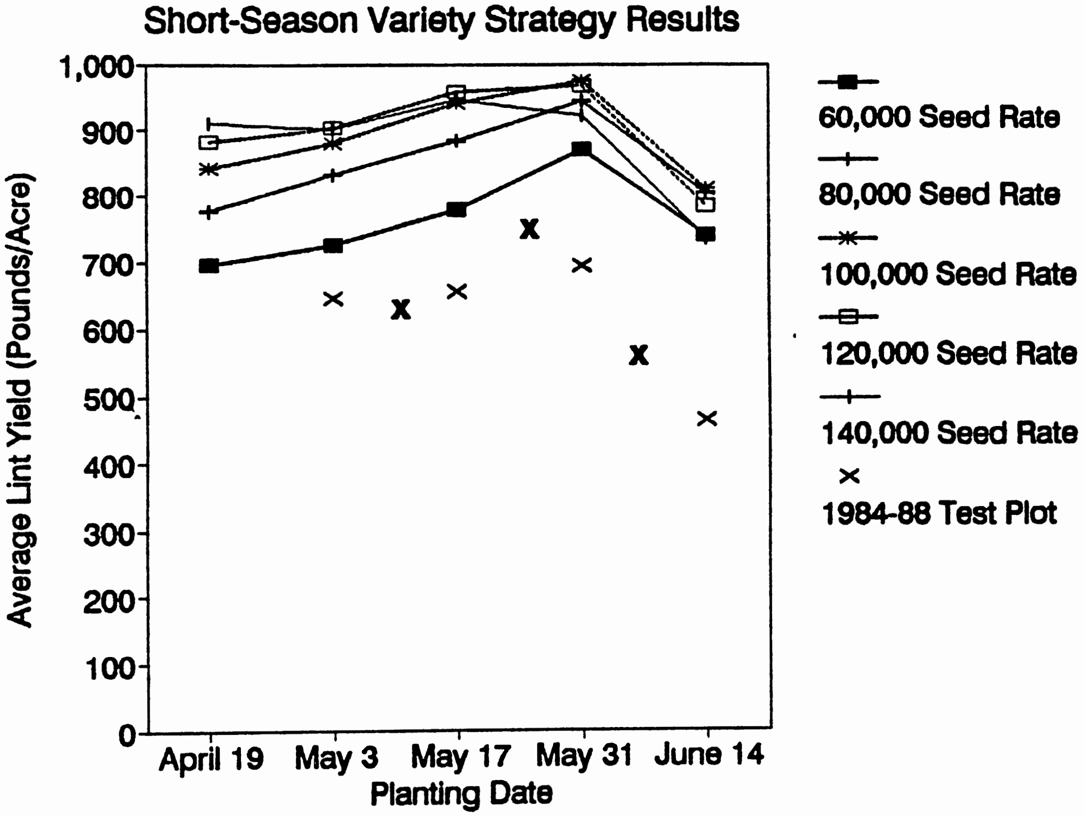


Figure 5.1. Simulated Short-Season Variety Cotton Lint Yield as a Function of Planting Time, Seeding Rate and Stochastic Plant Population

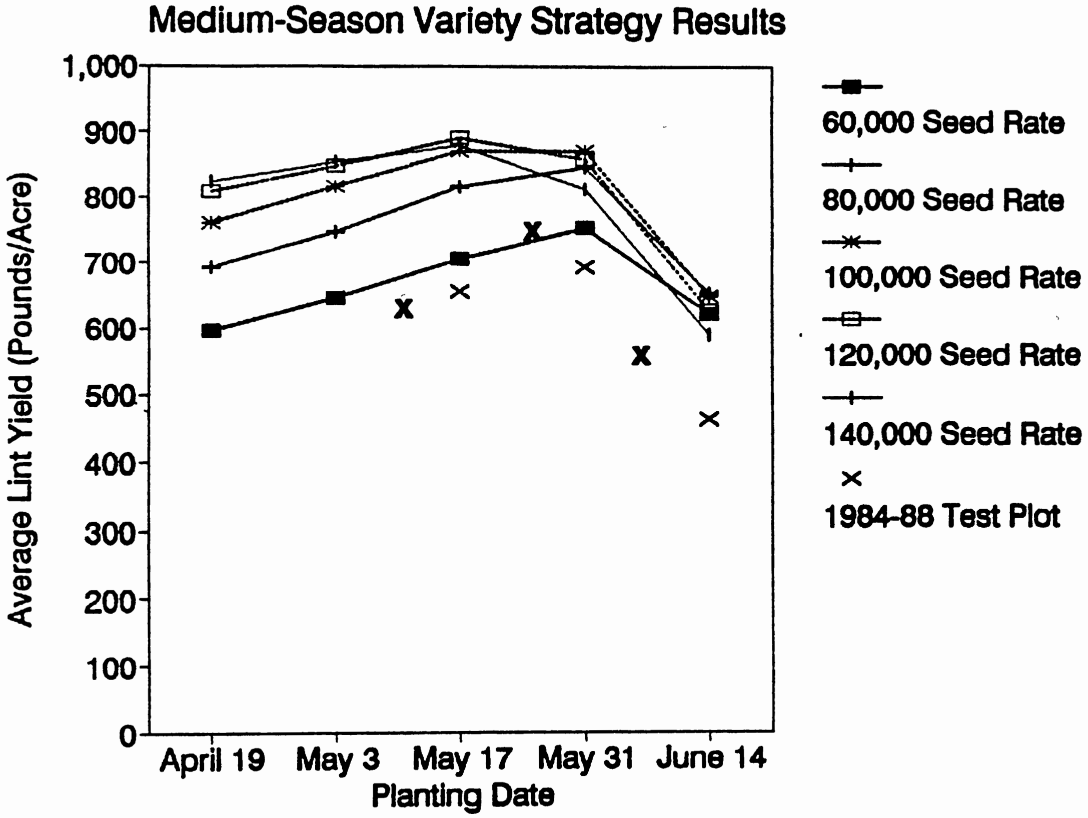


Figure 5.2. Simulated Medium-Season Variety Cotton Lint Yield as a Function of Planting Time, Seeding Rate and Stochastic Plant Population

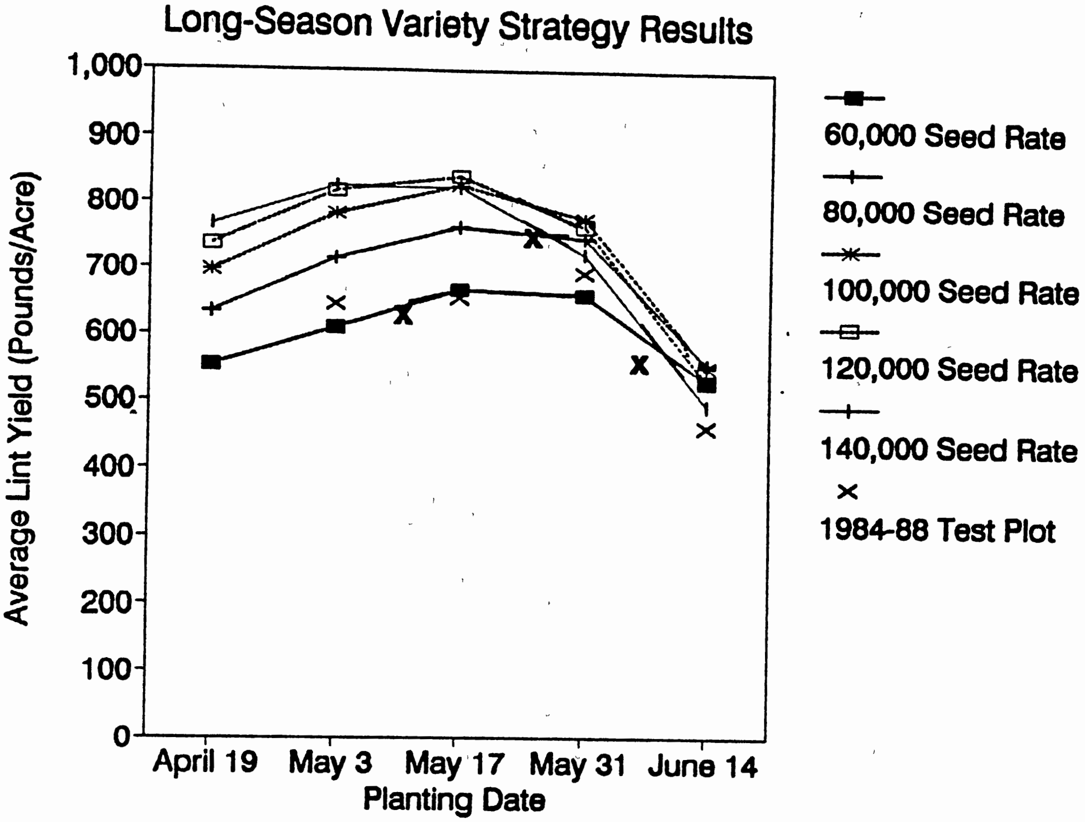


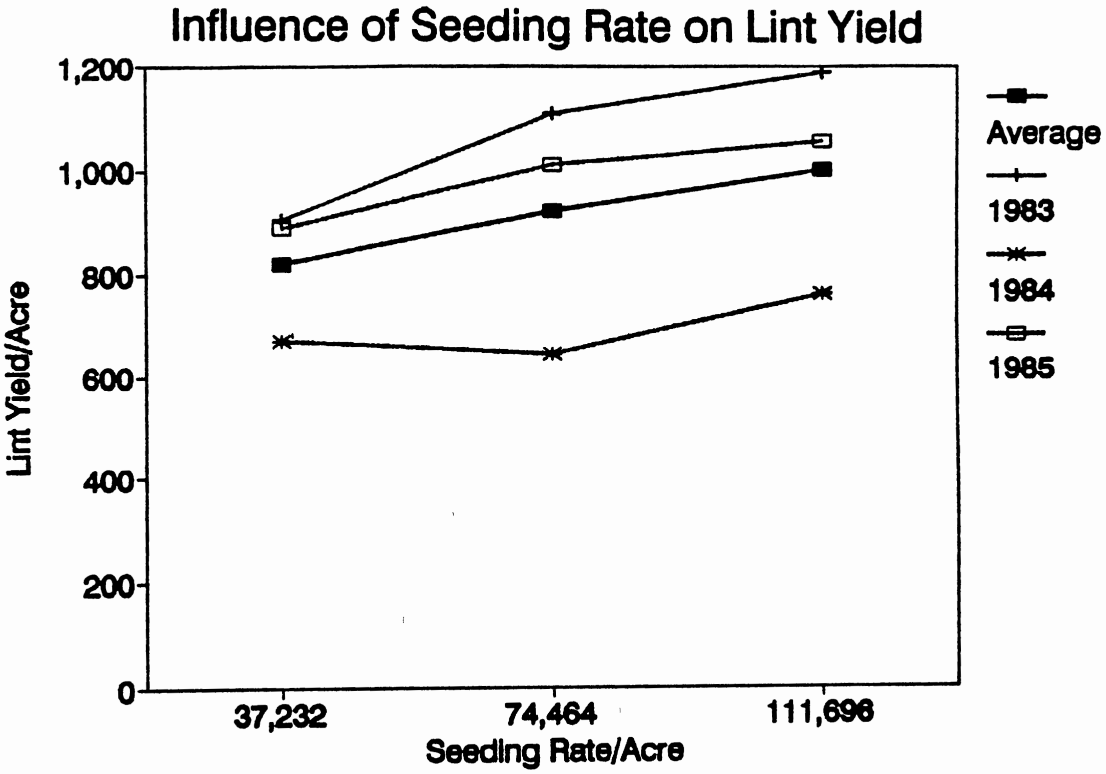
Figure 5.3. Simulated Long-Season Variety Cotton Lint Yield as a Function of Planting Time, Seeding Rate and Stochastic Plant Population

The final ingredient of the planting decision problem is the influence of seeding rate and stochastic plant population on lint yields. Cotton has the ability to do well under a fairly wide range of plant populations, i.e, between 30,000 to 60,000 plants per acre under irrigation. It is thought that an optimal population is somewhere between 50,000 to 60,000 plants per acre (Banks, 1990; Verhalen, 1990).

Hofmann et al. (1988, pp. 834-836) found a positive influence between seeding rate (and thus plant population) and lint yield in a three year field trial study under irrigation. Figure 5.4 illustrates the seeding rate-lint yield response for one of the three locations in the study. Cotton was planted on the same date using three seeding rates. Seven out of the nine replications showed a significant positive seeding rate-lint yield response.

As described in Chapter IV, surviving plant population is primarily a function of soil temperature. As temperature rises, expected survival increases. In turn plant population influences the height of the first mainstem fruiting branch and boll size. Excessive plant populations cause later initiation of fruiting and fewer and smaller bolls on each plant. Thus inadequate or excessive plant populations can adversely influence yield.

The three lint yield summary figures (5.1, 5.2, 5.3) illustrate the influence of seeding rate and stochastic plant population on yields. At the early planting date higher seeding rates result in higher yields. However as survival increases the higher seeding rates result in an excess plant population causing a drop in yield. The highest average yielding short-season strategy has an average plant population of 51,442 per acre (Plant on May 31 using a 100,000 seeding rate). However, the higher seeding rate of 140,000 on May 31 increases average plant population to 72,019 and decreases the average yield to 947. The modified simulation model accurately portrays the positive



Hofmann, W.C., D. L. Kittock, and M. Alemayehu. 1988. "Planting Seed Density in Relation to Cotton Emergence and Yield." Agronomy Journal, Vol 80, September-October, p. 835.

Figure 5.4. The influence of Seeding Rate on Lint Yield Response in a Three Field Trial Study

response of yield to plant population up to a point with a subsequent decline there-after.

The interaction between planting time, seeding rate, and plant population has important consequences on the economics of the planting decision problem.

Base Economic Analysis

Net enterprise income distributions that are the basis for the planting decision economic analysis were constructed using: 1) the simulated cotton lint and seed yield distributions described in the previous section, 2) the number of planting operation incurred for each initial planting date (Table 4.3 in Chapter IV), and 3) the revenue and cost allocation assumptions presented in Table 5.6 for the representative farm situation described in Chapter IV. Summaries of the 75 net enterprise revenue distributions by variety maturity length are presented in Tables 5.7, 5.8, and 5.9, respectively.

Generalized stochastic dominance (GSD) criteria are used to identify the utility maximizing planting strategies. Five frequently cited GSD criteria are assumed for the economic analysis:

1. First-degree stochastic dominance (r_1=-∞, r_2=+∞) [Quirk and Saposnik, 1962];
2. Risk preference (r_1=-0.0008, r_2=-0.0001) [from Raskin and Cochran, 1986b];
3. Approximately risk neutral (r_1=-0.000001, r_2=0.000001) [from Raskin and Cochran, 1986b];
4. Broadly risk averse [second-degree stochastic dominance] (r_1=0.00, r_2=+∞) [Fishburn (1964); Hanoch and Levey (1969); Hadar and Russell (1969); and Hammond (1969)];

TABLE 5.6

PLANTING ECONOMIC ANALYSIS REVENUE AND COST ALLOCATIONS[a]

Item	Dollars
Cotton Prices	
Expected Seed Price/Pound	0.04
Expected Lint Price/Pound (Grade 41, Staple 35)	0.60
Planting Input Variable Costs/Acre/Planting	
Pesticide/Acre/Planting	8.00
Rotary Hoe Variable Cost/Acre/Planting (Labor, Fuel, Lube, & Repair)	2.32
Planting Variable Cost/Acre/Planting (Labor, Fuel, Lube, & Repair)	3.70
Variety Seed Cost/Acre/Planting	
60,000/Acre Seeding Rate	8.00
80,000/Acre Seeding Rate	10.67
100,000/Acre Seeding Rate	13.33
120,000/Acre Seeding Rate	16.00
140,000/Acre Seeding Rate	18.67
Total Planting Variable Costs/Acre/Planting	
60,000/Acre Seeding Rate	22.02
80,000/Acre Seeding Rate	24.69
100,000/Acre Seeding Rate	27.36
120,000/Acre Seeding Rate	30.03
140,000/Acre Seeding Rate	32.69
Other Variable Costs Kept Constant	
Total Preplanting Variable Cost/Acre	58.14
Total Irrigation Variable Cost/Acre	52.97
Total Pesticide & Harvest-Aid Chemical Variable Cost/Acre	74.10
Mid-Season Tillage	16.83
Harvest Variable Costs	
Custom & Picking & Hauling/Pound Lint Harvested	0.12
Ginning Processing/Pound Lint Harvested	0.10

[a] Revenue and cost allocations estimated using budget data developed by Walker and Banks (1990) for irrigated picker cotton in the Lugert-Altus Irrigation District.

TABLE 5.7

ALTERNATIVE SHORT-SEASON VARIETY STRATEGY COTTON NET ENTERPRISE INCOME RESULTS, 1948 THROUGH 1990 WEATHER YEARS

Strategy		Net Enterprise Income[a]				
Planting Date	Seed/ Acre	Average	Standard Deviation	Maximum Value	Minimum Value	Skewness
Mo./Day	Thousands	Dollars				
4/19	60	25,369	22,351	69,301	(20,114)	-0.21
5/03	60	30,429	20,033	72,823	(14,039)	-0.19
5/17	60	37,702	18,926	95,860	4,676	0.82
5/31	60	49,575	14,828	101,563	20,882	0.98
6/14	60	32,317	15,604	81,563	1,875	0.87
4/19	80	34,991	25,649	87,456	(26,206)	-0.42
5/03	80	43,353	23,502	97,722	(8,332)	-0.32
5/17	80	50,684	20,209	113,574	10,202	0.71
5/31	80	58,509	14,854	104,432	18,002	0.45
6/14	80	39,811	16,571	82,795	1,876	0.18
4/19	100	42,420	27,811	96,806	(11,778)	-0.39
5/03	100	48,920	25,606	111,544	(9,562)	-0.28
5/17	100	57,417	20,069	123,007	5,123	0.56
5/31	100	61,818	16,217	102,716	13,511	-0.20
6/14	100	39,655	18,148	82,870	(2,420)	-0.02
4/19	120	46,866	27,411	100,136	(8,302)	-0.25
5/03	120	51,174	26,618	121,320	(10,656)	-0.13
5/17	120	58,954	21,072	128,259	(1,344)	0.40
5/31	120	60,079	17,031	96,692	8,205	-0.45
6/14	120	35,743	19,039	80,463	(7,556)	0.02
4/19	140	49,336	27,454	99,702	(7,456)	-0.33
5/03	140	49,971	27,090	122,209	(11,596)	0.00
5/17	140	56,623	21,962	129,248	(7,403)	0.27
5/31	140	53,241	18,103	89,491	730	-0.37
6/14	140	28,446	20,005	77,846	(14,318)	0.17

[a] Net enterprise income distributions estimated using 1948 through 1990 simulated cotton lint and seed yields and budget data for irrigated picker cotton in the Lugert-Altus Irrigation District (Walker and Banks, 1990).

TABLE 5.8

ALTERNATIVE MEDIUM-SEASON VARIETY STRATEGY COTTON NET ENTERPRISE INCOME RESULTS, 1948 THROUGH 1990 WEATHER YEARS

Strategy		Net Enterprise Income[a]				
Planting Date	Seed/ Acre	Average	Standard Deviation	Maximum Value	Minimum Value	Skewness
Mo./Day	Thousands	Dollars				
4/19	60	13,004	16,335	40,128	(21,375)	-0.30
5/03	60	19,740	17,466	69,588	(20,020)	0.39
5/17	60	27,753	16,837	79,953	2,174	0.60
5/31	60	34,283	16,157	79,367	4,331	0.62
6/14	60	16,978	15,733	63,590	(14,136)	0.61
4/19	80	23,929	19,249	61,800	(16,274)	-0.12
5/03	80	32,362	21,742	87,347	(18,807)	-0.01
5/17	80	41,471	19,383	97,993	8,741	0.41
5/31	80	45,678	16,757	84,253	2,025	-0.11
6/14	80	20,029	17,741	70,119	(14,627)	0.53
4/19	100	32,009	24,026	83,979	(18,395)	-0.09
5/03	100	40,580	24,042	100,825	(14,692)	-0.13
5/17	100	47,661	20,303	107,738	(5,259)	0.01
5/31	100	47,991	17,444	80,693	(2,392)	-0.42
6/14	100	18,743	18,622	68,063	(17,916)	0.39
4/19	120	37,065	26,348	91,160	(19,826)	-0.24
5/03	120	43,844	24,668	108,291	(15,793)	-0.02
5/17	120	49,471	21,099	109,324	(13,043)	-0.27
5/31	120	45,816	17,299	76,343	(7,222)	-0.59
5/14	120	14,980	18,899	63,827	(20,381)	0.32
4/19	140	38,251	28,061	97,844	(20,397)	-0.23
5/03	140	43,599	25,366	110,926	(18,422)	0.04
5/17	140	47,314	22,201	109,483	(16,477)	-0.27
5/31	140	38,942	17,010	73,541	(13,183)	-0.49
6/14	140	9,730	17,640	51,350	(24,290)	0.24

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[a] Net enterprise income distributions estimated using 1948 through 1990 simulated cotton lint and seed yields and budget data for irrigated picker cotton in the Lugert-Altus Irrigation District (Walker and Banks, 1990).

TABLE 5.9

ALTERNATIVE LONG-SEASON VARIETY STRATEGY COTTON NET ENTERPRISE INCOME RESULTS, 1948 THROUGH 1990 WEATHER YEARS

Strategy		Net Enterprise Income[a]				
Planting Date	Seed/ Acre	Average	Standard Deviation	Maximum Value	Minimum Value	Skewness
Mo./Day	Thousands	Dollars				
4/19	60	6,779	13,773	37,679	(29,581)	0.13
5/03	60	15,289	15,106	59,752	(12,892)	0.77
5/17	60	23,133	16,971	65,174	(2,452)	0.54
5/31	60	22,187	14,353	65,592	(5,828)	0.92
6/14	60	5,167	16,479	46,259	(28,766)	-0.02
4/19	80	16,123	18,780	61,682	(26,482)	0.37
5/03	80	28,034	20,014	82,221	(13,410)	0.37
5/17	80	34,626	20,816	81,293	(3,166)	0.18
5/31	80	32,586	17,302	72,261	(4,301)	0.26
6/14	80	7,368	17,892	50,208	(30,386)	-0.08
4/19	100	23,379	23,853	79,315	(26,184)	0.32
5/03	100	36,104	22,851	95,600	(15,076)	-0.03
5/17	100	42,274	22,224	92,088	(11,427)	-0.28
5/31	100	35,613	19,054	82,425	(7,711)	0.00
6/14	100	6,139	18,352	49,717	(33,816)	-0.16
4/19	120	27,868	25,931	91,394	(19,945)	0.39
5/03	120	39,819	23,821	101,273	(18,356)	-0.31
5/17	120	43,369	22,713	93,401	(15,421)	-0.51
5/31	120	33,318	19,652	82,323	(10,969)	-0.07
6/14	120	2,375	19,853	43,796	(50,465)	-0.60
4/19	140	30,699	26,421	96,927	(19,578)	0.34
5/03	140	39,944	24,106	102,041	(21,733)	-0.46
5/17	140	40,395	23,324	91,492	(20,169)	-0.60
5/31	140	26,947	20,452	78,454	(15,302)	-0.04
6/14	140	(2,821)	20,689	32,623	(63,894)	-1.10

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[a] Net enterprise income distributions estimated using 1948 through 1990 simulated cotton lint and seed yields and budget data for irrigated picker cotton in the Lugert-Altus Irrigation District (Walker and Banks, 1990).

5. Slightly risk averse (r_1=0.0001, r_2=0.0004) [from Raskin and Cochran, 1986b];
6. Strongly risk averse (r_1=0.0004, r_2=0.001) [from Raskin and Cochran, 1986b]; and

Risk efficient set results from the stochastic dominance analysis of the 75 alternatives are presented in Table 5.10.

Thirteen of the simulated strategies are in the first-degree stochastic dominance (FSD) efficient set. All FSD strategies utilize the short-season (plains) variety. None of the medium- or long-season maturity choices are in the FSD set. The exclusion of medium- and long-season strategies from the FSD set appears to reflect the variety maturity-lint yield relationship described in the previous section. None of the medium and long maturity strategies exhibited positive marginal utility in terms of net enterprise revenue.

The FSD set also clearly shows the influence of planting time, seeding rate, and stochastic plant population on the decision problem. None of the late (June 14th) planting strategies are in the FSD set. Planting in mid-June does not allow enough growing season to take advantage of the yield potential of even a short maturity variety. Exclusion of the 140,000 seeding rate for the last two planting dates reflects the negative influence of excess population on yield. Further, the exclusion of lower seeding rates at the first three planting dates indicates the impact of inadequate plant populations on yield.

Restricting the absolute risk aversion lower and upper bounds to include only risk neutral agents reduced the efficient set to one strategy. This is the May 31 planting date using the 100,000 seeding (Table 5.7). It is the highest expected net enterprise income return among the 75 alternatives ($61,818). It is also the highest average yield strategy among the alternatives (975 pounds per acre).

TABLE 5.10

BASE ECONOMIC ANALYSIS RISK EFFICIENT PLANTING STRATEGY SETS

Planting Date	Planting Rate Per Acre				
	60,000	80,000	100,000	120,000	140,000
	(First-Degree Stochastic Dominant Set)				
April 19				Short	Short
May 3			Short	Short	Short
May 17		Short	Short	Short	Short
May 31	Short	Short	Short	Short	
June 14					
	(Risk Preference Efficient Set)				
April 19					
May 3					
May 17					Short
May 31					
June 14					
	(Risk Neutral Efficient Set)				
April 19					
May 3					
May 17					
May 31			Short		
June 14					
	(Second-Degree Stochastic Dominance Set)				
April 19					
May 3					
May 17					
May 31	Short	Short	Short		
June 14					
	(Slight Risk Aversion Efficient Set)				
April 19					
May 3					
May 17					
May 31	Short	Short			
June 14					
	(Strong Risk Aversion Set)				
April 19					
May 3					
May 17					
May 31	Short				
June 14					

[a] Short, medium, and long refer to variety maturity length.

Limiting preferences to include only risk averse agents (SSD) produces an efficient set of three May 31 planting date strategies. The SSD set includes the risk neutral and the two lowest seeding rate strategies (80,000 and 60,000).

The May 31 planting date using the 80,000 seeding rate has an average net return of $58,509 which is $3,309 value than for the risk neutral strategy. However, this strategy has a $4,491 higher minimum value than the 100,000 seeding rate strategy ($18,002 compared to $13,511).

The final member of the SSD set, which uses the 60,000 seeding rate, has an expected value of $49,575. Ten short-season strategies have a higher average net enterprise return (Table 5.7). This strategy has the highest minimum value among the 75 alternatives ($20,882).

Further narrowing preferences to include just slightly risk averse agents (r_1=0.0001, r_2=0.0004) eliminates the 100,000 seeding rate from the risk averse efficient set. The two remaining distributions are positively skewed and have the highest minimum values. A positively skewed distribution is characterized as having a lower limit but no theoretical upper bound. By contrast, the highest average net return distribution is negatively skewed. Negative skewness results when the observed values have an upper limit and no significant lower bound.

Stochastic Dominance was used to estimate the premium need to adopt one planting strategy over another (Raskin and Cochran, 1986a). Using this technique, the least that an agent in this class would need to be compensated to adopt the highest average net return over the dominant 80,000 seeding rate strategy is $1,707. The most that one agent would require to adopt the dominant 80,000 seeding rate strategy is $4,497. This compares with $0.00 and $7,006, respectively, for the 60,000 seeding rate strategy.

Strongly risk averse agents (r_1=0.0004, r_2=0.001) prefer the 60,000 planting rate strategy from the SSD set. This strategy is the most positively skewed among the 75 alternatives and has the highest minimum value. The smallest premium needed for one agent in this class to adopt the highest average net return strategy over the dominant strategy is $7,006. Conversely, the largest premium required for one agent to adopt the highest average net return strategy over the dominant strategy is $7,370.

Planting on May 17th using a 140,000 seeding rate is the strategy identified for agents classified as risk preferring. These agents appear to prefer the tradeoff of some expected return in exchange for the highest maximum net enterprise return among the 75 alternatives ($129,248). Agents in this class would need a premium of between $1,825 and $26,532 to adopt the highest average return over the dominant strategy.

Stochastic dominance analysis identifies four dominant base planting tactics for agents identified as either risk neutral, risk averse, or risk seeking. Using a short- season variety strategy is preferred by all agents. The May 31 planting time is preferred by both risk neutral and averse agents. Seeding rate and its influence on plant population and the distribution of lint yield appears to be the critical factor in determining which strategy is preferred.

The analysis to this point has examined inflexible planting strategies, i.e, follow the same strategy year after year. It is analogous to the open loop decision rule discussed in Chapter II. That is, the inflexible decision rule is based on all a priori knowledge of system behavior and is not influenced by the current state of the field ecosystem. The next section explores the potential value of more information about a flexible planting strategy for different classes of agents. That is, the value of using current field environment state conditions in formulating a planting decision rule.

Flexible Strategy Economic Analysis

This section assesses the value of alternative information in formulating a planting decision rule. The first part examines the potential value of additional variety choice, seeding rate, and time of planting information over the preferred base planting strategies. Then the use of an alternative predictor that is subject to error in formulating a flexible planting decision strategy is evaluated in the second part of this section. This flexible strategy predictor considers the current system state plus a priori knowledge of the system in formulating the decision rule.

The value of additional planting decision information is examined using a modified version of the Gould and Hess definition (Chapter II) and Generalized Stochastic Dominance (GSD). Gould (1974, pp. 64-84) and Hess (1982, pp. 231-238) define information value as the difference in expected utility between an optimal act chosen under certainty and an optimal act chosen under uncertainty. Unfortunately, this definition does not allow interpersonal comparisons since utility is only unique up to some positive linear transformation. A procedure using GSD criteria, as first suggested by Bosch and Eidman (1987, pp. 658-668), is used to overcome this problem.

An option in the GSD program developed by Raskin and Cochran (1986) is employed for the valuation analysis. This option calculates the premium needed to shift the dominant net income distribution so that both the dominant and comparison distributions lie in the same risk efficient set. The lower (upper) bound value as defined by absolute risk aversion represents the least (most) that someone within the specified class of agents would pay for the dominant strategy. Stated differently, the lower bound is the minimum value all individuals within the absolute risk aversion interval would be willing to pay for the dominant strategy.

Thus, the value of information definition for the flexible planting strategy analysis is stated as:

> the minimum (maximum) amount an individual within the specified class of agents would pay (in each and every state of nature) for the use of the dominant (perfect information) net enterprise income distribution compared to the uncertain (base planting strategy) net enterprise income distribution.

The three decision components of the planting problem - - variety choice, seeding rate, and time of planting - - are valued using this definition and GSD.

Decision maker willingness to pay for perfect planting strategy information over the four dominant base planting tactics is presented in Table 5.11. There is little or no willingness to pay for variety choice, seeding rate, and time of planting information for agents classified as risk preferring. Perfect information about the decision problem does not result in a more desirable distribution of net income for this class of agents in the form of a higher maximum value. A similar conclusion holds for the strong risk aversion decision maker case. Additional information does not yield a more desirable income distribution in the form of a higher minimum value for agents in this class.

The valuation results are more mixed for the slight risk aversion and risk neutral cases. There is no additional value for variety choice information for both classes of decision makers. However, there is some value for perfect information about seeding rate: ranging from \$1.25 per acre to \$7.64 per acre on the lower bound. The only class of agents where there is value on additional time of planting information is for the risk neutral case (\$23.31 per acre on the lower bound).

TABLE 5.11

DECISION MAKER WILLINGNESS TO PAY (WTP) FOR PERFECT VARIETY CHOICE, SEEDING RATE AND TIME OF PLANTING INFORMATION

	Base Strategy			WTP for additional information on:		
Efficiency Criteria	Variety	Plant Date	Seed Rate/ Acre	Variety Choice	Seed Rate	Time of Planting
		Mo./Day	Thousands	——Per Acre Dollar Values——		
Risk Preference	Short	5/17	140			
Lower Bound				0.00	0.00	0.00
Upper Bound				0.42	1.63	4.19
Risk Neutral	Short	5/31	100			
Lower Bound				0.00	5.17	23.31
Upper Bound				0.00	6.00	29.69
Risk Aversion						
Slight	Short	5/31	80			
Lower Bound				0.00	7.64	0.00
Upper Bound				0.00	10.58	8.80
Slight	Short	5/31	60			
Lower Bound				0.00	1.25	0.00
Upper Bound				0.00	31.42	8.80
Strong	Short	5/31	60			
Lower Bound				0.00	0.01	0.00
Upper Bound				0.00	1.25	0.00
Broad (SSD)	Short	5/31	100			
Lower Bound				0.00	5.42	0.00
Upper Bound				0.00	25.59	27.90
Broad	Short	5/31	80			
Lower Bound				0.00	3.50	0.00
Upper Bound				0.00	17.90	27.90
Broad (SSD)	Short	5/31	60			
Lower Bound				0.00	0.01	0.00
Upper Bound				0.00	4.95	27.90

Table 5.12 displays the net enterprise revenue maximizing perfect information set for 43-year simulation cycle. Fourteen of the 75 base planting strategies are in the perfect information set. The short maturity variety strategy dominates the perfect information set in 42 out of the 43 years. The perfect certainty solution results in a 75 pound increase in average lint yield over the highest average calendar strategy (plant a short-season variety on May 31 using a 100,000 seeding rate). Net enterprise income is increased by $9,655 over the highest average base strategy.

The most frequent planting time in the perfect certainty set is the May 31st date (20 out of the 43 years). The 100,000 and 120,000 seeding rates occur most frequently on the May 31st planting date (eight and seven times, respectively). The second most numerous planting time in the perfect information set is the May 17th time (eleven times). The April 19th date occurs nine times and the May 3rd date three times. None of the June 14th strategies are in the perfect information set.

The perfect information sets for each planting date are presented in Tables 5.13 through 5.17. Average net income and lint yield reach a peak on the May 17th planting date. However, average net returns are only $642 higher than for the May 31 planting date. The highest maximum yield occurs on the May 17th planting date while the highest minimum yield occurs on the May 31st date. Perfect information about seeding rate on the May 31 planting date increases average net income over highest average return strategy by $1,609.

The short maturity strategy dominates the May 31st and June 14th planting date perfect information sets. Medium and long maturity strategies come into play for the April 19th, May 3rd, and May 17th planting dates. However, expected returns are higher at the May 17th and 31st dates than at the earlier planting dates.

TABLE 5.12

NET ENTERPRISE INCOME MAXIMIZING PERFECT INFORMATION SET

Year	Sow Date	Variety	Seeding Rate	Lint Yield	Net Enterprise Income	Day Degrees[a]	Planting Soil Temp.	Plant Population
	Mo./Day		Thousands	Pounds/Acre	Dollars		°F	Per Acre
1948	5/03	SHORT	120	1,047	69,793	2,054	63	46,800
1949	5/31	SHORT	100	1,000	64,295	1,857	66	53,000
1950	5/17	SHORT	140	1,521	129,248	1,990	62	54,600
1951	5/31	SHORT	100	1,054	72,718	1,924	67	52,000
1952	5/31	SHORT	100	1,001	66,189	1,978	64	46,000
1953	5/31	SHORT	60	908	54,228	1,979	78	30,600
1954	4/19	SHORT	100	980	63,391	2,405	59	38,000
1955	4/19	SHORT	100	1,009	65,809	2,409	62	39,000
1956	5/17	MEDIUM	80	1,003	66,916	2,203	71	48,000
1957	5/17	SHORT	140	972	60,393	1,970	62	53,200
1958	5/17	SHORT	120	1,321	106,710	2,227	64	49,200
1959	5/17	SHORT	120	1,224	93,586	2,048	62	56,400
1960	5/31	SHORT	100	1,088	76,297	1,960	68	60,000
1961	4/19	SHORT	140	1,073	72,612	2,256	52	44,800
1962	4/19	SHORT	120	1,278	100,136	2,431	56	32,400
1963	5/31	SHORT	100	1,029	69,353	2,167	67	53,000
1964	5/17	SHORT	100	944	58,573	2,124	65	45,000
1965	5/31	SHORT	120	1,042	69,763	1,990	66	62,400
1966	5/31	SHORT	100	939	56,051	1,846	69	57,000
1967	5/31	SHORT	80	815	40,865	1,892	66	37,600
1968	5/31	SHORT	120	1,121	79,622	1,914	65	62,400
1969	5/31	SHORT	120	1,032	68,590	1,830	69	57,600
1970	5/31	SHORT	60	648	20,882	1,815	67	28,800
1971	5/31	SHORT	100	1,023	68,569	2,167	67	49,000
1972	5/17	SHORT	80	917	55,721	2,124	65	45,600
1973	5/31	SHORT	120	1,072	73,684	1,990	66	66,000
1974	5/17	SHORT	100	941	56,829	2,010	63	58,000
1975	5/31	SHORT	80	783	36,668	1,892	66	32,800
1976	5/31	SHORT	100	1,120	80,136	1,914	65	54,000
1977	5/31	SHORT	120	1,032	68,532	1,830	69	66,000
1978	4/19	SHORT	140	1,115	78,953	2,380	59	36,400
1979	5/31	SHORT	120	1,182	86,939	1,913	65	51,600
1980	4/19	SHORT	100	954	59,679	2,339	52	39,000
1981	4/19	SHORT	140	1,035	68,842	2,282	62	35,000
1982	4/19	SHORT	140	1,153	83,716	2,191	59	42,000
1983	5/17	SHORT	120	976	62,170	2,096	62	46,800
1984	5/03	SHORT	120	1,054	71,710	2,029	59	46,800
1985	5/17	SHORT	100	1,061	73,669	2,108	66	60,000
1986	5/03	SHORT	140	1,173	86,655	2,161	64	51,800
1987	5/31	SHORT	120	1,204	90,244	1,918	65	60,000
1988	5/17	SHORT	120	996	64,199	2,099	66	44,400
1989	4/19	SHORT	140	1,194	88,150	2,140	53	54,600
1990	5/31	SHORT	80	1,207	92,234	1,872	73	44,800
Average				1,052	71,473	2,063	64	48,660
Standard Deviation				147	18,464	173	5	9,732
Maximum				1,521	129,248	2,431	78	66,000
Minimum				648	20,882	1,815	52	28,800

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[a] Day-degrees estimated using a 12 °C lower threshold and 33.3° C upper threshold.

TABLE 5.13

APRIL 19 PLANT DATE NET INCOME PERFECT INFORMATION SET

Year	Variety	Seeding Rate	Lint Yield	Net Enterprise Revenue	Day Degrees[a]	Planting Soil Temp.	Plant Population
		Thousands	Pounds/Acre	Dollars		°F	Per Acre
1948	SHORT	140	891	48,937	2,194	58	40,600
1949	MEDIUM	140	976	60,376	2,214	53	43,400
1950	LONG	140	1,271	96,927	2,217	53	44,800
1951	SHORT	120	992	48,718	2,332	51	49,200
1952	SHORT	80	454	(5,394)	2,351	51	24,800
1953	SHORT	140	867	46,034	2,365	52	43,400
1954	SHORT	100	980	63,391	2,405	59	38,000
1955	SHORT	100	1,009	65,809	2,409	62	39,000
1956	SHORT	100	824	34,220	2,497	55	35,000
1957	SHORT	140	903	51,299	2,173	51	36,400
1958	SHORT	140	1,274	99,702	2,442	50	49,000
1959	SHORT	140	1,078	64,223	2,328	50	43,400
1960	SHORT	140	1,010	64,843	2,352	60	47,600
1961	SHORT	140	1,073	72,612	2,256	52	44,800
1962	SHORT	120	1,278	100,136	2,431	56	32,400
1963	SHORT	100	1,011	51,426	2,624	65	52,000
1964	SHORT	100	795	37,910	2,425	59	31,000
1965	SHORT	140	1,045	69,012	2,397	60	33,600
1966	MEDIUM	120	872	38,249	2,197	58	52,800
1967	SHORT	80	743	31,827	2,275	61	26,400
1968	MEDIUM	140	831	41,639	2,239	58	35,000
1969	SHORT	140	603	12,089	2,205	57	42,000
1970	SHORT	80	565	9,346	2,238	58	28,000
1971	SHORT	100	1,023	44,931	2,624	65	49,000
1972	SHORT	100	790	37,171	2,425	59	30,000
1973	SHORT	140	1,026	66,481	2,397	60	43,400
1974	MEDIUM	140	794	26,911	2,197	58	47,600
1975	SHORT	80	641	18,322	2,275	61	34,400
1976	SHORT	140	866	46,201	2,239	58	37,800
1977	SHORT	140	576	8,624	2,205	57	39,200
1978	SHORT	140	1,115	78,953	2,380	59	36,400
1979	LONG	140	1,032	67,377	2,264	56	47,600
1980	SHORT	100	954	59,679	2,339	52	39,000
1981	SHORT	140	1,035	68,842	2,282	62	35,000
1982	SHORT	140	1,153	83,716	2,191	59	42,000
1983	SHORT	100	790	37,915	2,317	51	40,000
1984	MEDIUM	120	1,017	66,846	2,129	54	54,000
1985	SHORT	140	1,017	65,940	2,368	59	33,600
1986	SHORT	140	1,041	69,461	2,287	57	36,400
1987	SHORT	120	1,118	79,735	2,363	58	55,200
1988	SHORT	140	968	59,698	2,330	52	46,200
1989	SHORT	140	1,194	88,150	2,140	53	54,600
1990	LONG	140	719	26,677	2,249	59	49,000
Average			935	53,604	2,316	57	41,000
Standard Deviation			193	24,912	114	4	7,841
Maximum			1,278	100,136	2,624	65	55,200
Minimum			454	(5,394)	2,129	50	24,800

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[a] Day-degrees estimated using a 12° C lower threshold and 33.3° C upper threshold.

TABLE 5.14

MAY 3 PLANT DATE NET INCOME PERFECT INFORMATION SET

Year	Variety	Seeding Rate	Lint Yield	Net Enterprise Revenue	Day Degrees[a]	Planting Soil Temp.	Plant Population
		Thousands	Pounds/Acre	Dollars		℉	Per Acre
1948	SHORT	120	1,047	69,793	2,054	63	46,800
1949	SHORT	140	1,004	63,957	2,119	60	56,000
1950	SHORT	140	1,465	122,209	2,113	59	51,800
1951	SHORT	120	992	57,365	2,204	64	49,200
1952	LONG	140	704	25,744	2,257	58	56,000
1953	SHORT	80	889	51,210	2,257	61	43,200
1954	MEDIUM	120	901	52,564	2,277	62	66,000
1955	LONG	140	834	42,265	2,292	68	54,600
1956	SHORT	100	824	42,099	2,377	63	35,000
1957	SHORT	140	909	52,201	2,072	59	44,800
1958	MEDIUM	140	1,291	101,932	2,351	57	44,800
1959	SHORT	140	1,078	73,638	2,175	69	43,400
1960	SHORT	140	994	62,746	2,239	59	49,000
1961	SHORT	120	1,008	64,988	2,115	62	57,600
1962	SHORT	140	1,089	75,342	2,314	60	43,400
1963	SHORT	100	1,011	59,305	2,496	61	52,000
1964	MEDIUM	140	795	37,457	2,274	63	54,600
1965	SHORT	120	923	54,447	2,283	58	40,800
1966	MEDIUM	120	872	46,897	2,134	54	52,800
1967	SHORT	80	790	37,780	2,160	59	29,600
1968	MEDIUM	120	997	63,962	2,144	57	67,200
1969	LONG	140	904	51,385	2,105	59	54,600
1970	SHORT	60	559	9,251	2,123	61	27,000
1971	SHORT	100	1,023	52,811	2,496	61	49,000
1972	MEDIUM	100	799	39,526	2,274	63	54,000
1973	SHORT	60	968	62,451	2,283	58	36,000
1974	MEDIUM	140	794	36,326	2,134	54	47,600
1975	SHORT	80	677	23,123	2,160	59	24,800
1976	SHORT	140	1,009	64,770	2,144	57	58,800
1977	LONG	120	917	53,834	2,105	59	60,000
1978	SHORT	140	1,103	77,633	2,290	59	54,600
1979	MEDIUM	120	1,078	73,979	2,165	58	57,600
1980	SHORT	120	764	34,320	2,239	58	57,600
1981	SHORT	120	902	52,313	2,150	64	40,800
1982	SHORT	140	1,107	77,851	2,121	56	51,800
1983	SHORT	120	901	52,277	2,211	62	63,600
1984	SHORT	120	1,054	71,710	2,029	59	46,800
1985	SHORT	100	1,040	70,790	2,254	59	48,000
1986	SHORT	140	1,173	86,655	2,161	64	51,800
1987	SHORT	140	1,034	67,994	2,220	63	54,600
1988	SHORT	100	986	63,589	2,241	56	40,000
1989	SHORT	100	1,109	78,904	1,997	65	51,000
1990	LONG	140	978	60,199	2,168	64	64,400
Average			960	58,595	2,204	60	49,605
Standard Deviation			161	20,382	108	3	9,753
Maximum			1,465	122,209	2,496	69	67,200
Minimum			559	9,251	1,997	54	24,800

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[a] Day-degrees estimated using a 12° C lower threshold and 33.3° C upper threshold.

TABLE 5.15

MAY 17 PLANT DATE NET INCOME PERFECT INFORMATION SET

Year	Variety	Seeding Rate	Lint Yield	Net Enterprise Revenue	Day Degrees[a]	Planting Soil Temp.	Plant Population
		Thousands	Pounds/Acre	Dollars		°F	Per Acre
1948	SHORT	100	1,002	64,841	1,940	62	40,000
1949	SHORT	100	964	60,211	2,009	60	60,000
1950	SHORT	140	1,521	129,248	1,990	62	54,600
1951	SHORT	120	1,007	66,012	2,079	63	49,200
1952	SHORT	100	869	48,953	2,100	68	49,000
1953	SHORT	100	909	52,893	2,177	58	42,000
1954	SHORT	120	953	59,350	2,195	57	54,000
1955	SHORT	140	995	63,349	2,081	66	54,600
1956	MEDIUM	80	1,003	66,916	2,203	71	48,000
1957	SHORT	140	972	60,393	1,970	62	53,200
1958	SHORT	120	1,321	106,710	2,227	64	49,200
1959	SHORT	120	1,224	93,586	2,048	62	56,400
1960	SHORT	100	1,010	66,429	2,118	62	51,000
1961	SHORT	120	954	57,856	1,965	65	62,400
1962	SHORT	140	997	63,828	2,131	71	74,200
1963	SHORT	100	1,011	67,184	2,316	73	52,000
1964	SHORT	100	944	58,573	2,124	65	45,000
1965	LONG	140	914	52,345	2,145	64	50,400
1966	SHORT	140	915	52,256	2,010	63	46,200
1967	SHORT	60	800	39,834	2,042	63	28,200
1968	LONG	120	1,048	70,045	2,045	60	57,600
1969	LONG	140	926	54,036	1,999	61	47,600
1970	SHORT	60	641	20,057	1,971	69	26,400
1971	SHORT	100	1,023	60,690	2,316	73	49,000
1972	SHORT	80	917	55,721	2,124	65	45,600
1973	MEDIUM	140	992	62,505	2,145	64	61,600
1974	SHORT	100	941	56,829	2,010	63	58,000
1975	SHORT	80	735	30,571	2,042	63	36,000
1976	SHORT	140	1,042	69,023	2,045	60	57,400
1977	SHORT	120	998	64,523	1,999	61	56,400
1978	SHORT	140	839	43,149	2,169	65	53,200
1979	MEDIUM	140	1,127	79,402	2,056	62	54,600
1980	SHORT	120	922	54,955	2,121	63	50,400
1981	SHORT	140	900	51,222	2,061	57	46,200
1982	SHORT	120	1,140	83,187	2,013	61	55,200
1983	SHORT	120	976	62,170	2,096	62	46,800
1984	SHORT	80	979	63,436	1,884	67	37,600
1985	SHORT	100	1,061	73,669	2,108	66	60,000
1986	SHORT	120	1,062	72,888	2,010	66	51,600
1987	LONG	100	1,044	70,500	2,070	67	55,000
1988	SHORT	120	996	64,199	2,099	66	44,400
1989	SHORT	140	1,132	80,388	1,884	62	57,400
1990	LONG	100	1,127	81,031	2,048	67	51,000
Average			997	64,069	2,074	64	50,665
Standard Deviation			143	18,071	96	4	8,733
Maximum			1,521	129,248	2,316	73	74,200
Minimum			641	20,057	1,884	57	26,400

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[a] Day-degrees estimated using a 12° C lower threshold and 33.3° C upper threshold.

TABLE 5.16

MAY 31 PLANT DATE NET INCOME PERFECT INFORMATION SET

Year	Variety	Seeding Rate	Lint Yield	Net Enterprise Revenue	Day Degrees[a]	Planting Soil Temp.	Plant Population
		Thousands	Pounds/Acre	Dollars		°F	Per Acre
1948	SHORT	100	842	44,039	1,804	64	41,000
1949	SHORT	100	1,000	64,295	1,857	66	53,000
1950	SHORT	80	1,312	104,432	1,840	66	48,000
1951	SHORT	100	1,054	72,718	4,924	67	52,000
1952	SHORT	100	1,001	66,189	1,978	64	46,000
1953	SHORT	60	908	54,228	1,979	78	30,600
1954	SHORT	140	989	63,305	2,055	65	67,200
1955	SHORT	100	924	55,394	1,936	67	60,000
1956	SHORT	100	1,007	66,514	2,025	70	54,000
1957	SHORT	100	861	47,201	1,827	66	58,000
1958	SHORT	140	1,062	72,017	2,042	73	54,600
1959	SHORT	100	1,066	73,673	1,868	68	46,000
1960	SHORT	100	1,088	76,297	1,960	68	60,000
1961	SHORT	80	953	58,889	1,808	67	48,000
1962	SHORT	100	890	51,150	1,942	71	45,000
1963	SHORT	100	1,029	69,353	2,167	67	53,000
1964	SHORT	100	895	51,897	1,970	68	48,000
1965	SHORT	120	1,042	69,763	1,990	66	62,400
1966	SHORT	100	939	56,051	1,846	69	57,000
1967	SHORT	80	815	40,865	1,892	66	37,600
1968	SHORT	120	1,121	79,622	1,914	65	62,400
1969	SHORT	120	1,032	68,590	1,830	69	57,600
1970	SHORT	60	648	20,882	1,815	67	28,800
1971	SHORT	100	1,023	68,569	2,167	67	49,000
1972	SHORT	80	867	49,013	1,970	68	48,000
1973	SHORT	120	1,072	73,684	1,990	66	66,000
1974	SHORT	100	914	52,900	1,846	69	51,000
1975	SHORT	80	783	36,668	1,892	66	32,800
1976	SHORT	100	1,120	80,136	1,914	65	54,000
1977	SHORT	120	1,032	68,532	1,830	69	66,000
1978	SHORT	120	961	59,173	1,985	69	60,000
1979	SHORT	120	1,182	86,939	1,913	65	51,600
1980	SHORT	100	833	44,101	1,974	68	48,000
1981	SHORT	120	1,031	68,314	1,909	69	56,400
1982	SHORT	100	1,013	67,370	1,862	66	57,000
1983	SHORT	120	957	59,738	1,970	65	54,000
1984	SHORT	60	901	53,967	1,718	69	36,000
1985	SHORT	100	969	61,680	1,953	70	60,000
1986	SHORT	140	1,056	70,464	1,883	65	65,800
1987	SHORT	120	1,204	90,244	1,918	65	60,000
1988	SHORT	120	929	55,184	1,958	64	58,800
1989	SHORT	100	973	61,097	1,692	74	57,000
1990	SHORT	80	1,207	92,234	1,872	73	44,800
Average			989	63,427	1,918	68	52,242
Standard Deviation			123	15,579	96	3	9,497
Maximum			1,312	104,432	2,167	78	67,200
Minimum			648	20,882	1,692	64	28,800

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[a] Day-degrees estimated using a 12° C lower threshold and 33.3° C upper threshold.

TABLE 5.17

JUNE 14 PLANT DATE NET INCOME PERFECT INFORMATION SET

Year	Variety	Seeding Rate	Lint Yield	Net Enterprise Revenue	Day Degrees[a]	Planting Soil Temp.	Plant Population
		Thousands	Pounds/Acre	Dollars		°F	Per Acre
1948	SHORT	80	512	1,876	1,629	73	48,000
1949	SHORT	100	777	34,952	1,691	67	54,000
1950	SHORT	100	1,068	71,970	1,675	69	60,000
1951	SHORT	120	932	55,794	1,770	67	62,400
1952	SHORT	120	832	43,014	1,772	75	49,200
1953	SHORT	80	817	41,511	1,771	79	48,000
1954	SHORT	80	780	37,988	1,872	72	48,000
1955	SHORT	100	897	51,560	1,785	65	58,000
1956	SHORT	80	739	31,859	1,825	75	38,400
1957	SHORT	80	735	31,242	1,657	72	43,200
1958	SHORT	80	922	55,565	1,826	79	48,000
1959	SHORT	100	938	56,587	1,692	71	57,000
1960	SHORT	80	1,000	65,304	1,778	70	41,600
1961	SHORT	100	888	49,094	1,622	70	55,000
1962	SHORT	100	765	34,250	1,784	68	48,000
1963	SHORT	120	990	63,134	1,972	73	56,400
1964	SHORT	80	809	40,974	1,799	73	43,200
1965	SHORT	80	878	49,795	1,806	70	45,600
1966	SHORT	80	725	28,901	1,645	74	46,400
1967	SHORT	80	717	28,064	1,696	75	46,400
1968	SHORT	80	983	62,696	1,727	73	48,000
1969	SHORT	80	849	45,656	1,671	69	44,000
1970	SHORT	60	537	6,173	1,658	70	33,000
1971	SHORT	100	985	63,157	1,972	73	60,000
1972	SHORT	80	778	37,032	1,799	73	47,200
1973	SHORT	100	883	49,771	1,806	70	60,000
1974	SHORT	60	715	28,338	1,645	74	36,000
1975	SHORT	80	718	28,209	1,696	75	40,800
1976	SHORT	100	945	57,054	1,727	73	47,000
1977	SHORT	100	849	44,888	1,671	69	44,000
1978	SHORT	80	706	27,475	1,820	68	48,000
1979	SHORT	100	1,149	82,870	1,761	67	60,000
1980	SHORT	80	759	34,857	1,778	73	46,400
1981	SHORT	100	779	35,939	1,719	74	55,000
1982	SHORT	100	722	29,105	1,701	70	47,000
1983	SHORT	80	645	20,140	1,824	66	44,800
1984	SHORT	80	685	24,936	1,523	75	44,800
1985	SHORT	120	837	43,547	1,766	71	55,200
1986	SHORT	120	923	53,498	1,707	71	63,600
1987	SHORT	100	941	56,671	1,744	69	53,000
1988	SHORT	80	708	27,705	1,787	71	48,000
1989	SHORT	120	640	16,759	1,544	66	56,400
1990	SHORT	80	953	59,085	1,670	73	46,400
Average			824	42,070	1,739	71	49,428
Standard Deviation			135	17,083	92	3	7,146
Maximum			1,149	82,870	1,972	79	63,600
Minimum			512	1,876	1,523	65	33,000

[a] Day-degrees estimated using a 12° C lower threshold and 33.3° C upper threshold.

The perfect information set results suggest that a predictor of which variety to plant is of little value. An example of such a rule is an expected day-degree criterion to determine which variety maturity length to use at a particular planting date. On the other hand, data in the perfect information sets suggest that additional knowledge about seeding rate and time of planting may be of value in decision making. This was shown in the results of the valuation analysis in Table 5.11.

The final part of the flexible planting economic analysis examines the use of a soil temperature predictor to determine time of planting and seeding rate. Soil temperature is the fundamental influence on yield potential going out of the seedling germination, emergence and growth stage. Thus the soil temperature is a proxy for, or a predictor of environmental conditions for early plant growth in the field. However, as with the calendar date strategy, it is an imperfect predictor of field conditions for early plant growth and its influence on yield potential. This flexible rule approach attempts to incorporate information about the current ecosystem state in determining time of planting and seeding rate.

Three soil temperature rules were simulated using the methods, assumptions, and data described in Chapter IV. The crop is assumed to be planted when the minimum daily soil temperature at the four inch depth achieves a specified threshold for ten consecutive days. The three temperature thresholds are 60° F, 65° F, and 70° F. Five target plant populations are used for the analysis: 40,000, 45,000, 50,000, 55,000, and 60,000 plants per acre. The seedling rates and seed costs for the soil temperature rule analysis are presented in Table 5.18. The other variable costs for the analysis are the same as those presented in Table 5.6.

Simulated soil temperature rule lint yield and net enterprise income results are presented in Table 5.19. Average lint yields varied from 875 to 936

TABLE 5.18

SOIL TEMPERATURE PLANTING RULE ANALYSIS SEEDING RATES AND SEED COSTS

Target Plant Population	Seeding	Soil Temperature Threshold 60°F	65°F	70°F
40,000/Acre	Rate/Acre	105,263	86,674	73,665
	Cost/Acre	$14.04	$11.56	$9.82
45,000/Acre	Rate/Acre	118,421	97,508	82,873
	Cost/Acre	$15.79	$13.00	$11.05
50,000/Acre	Rate/Acre	131,579	108,342	92,081
	Cost/Acre	$17.54	$14.45	$12.28
55,000/Acre	Rate/Acre	144,737	119,177	101,289
	Cost/Acre	$19.30	$15.89	$13.51
60,000/Acre	Rate/Acre	157,895	130,011	110,497
	Cost/Acre	$21.05	$17.33	$14.73

TABLE 5.19

ALTERNATIVE SHORT-SEASON VARIETY 10-DAY SOIL TEMPERATURE RULE STRATEGY 43-YEAR SIMULATION SEQUENCE COTTON LINT YIELD/NET ENTERPRISE INCOME RESULTS

10-Day Soil Temperature/Target Population Rule	Lint Yield Per Acre/Net Enterprise Income				
	Average	Standard Deviation	Maximum Value	Minimum Value	Skewness
	Pounds/Dollars				
60°F/40,000	901	169	1,419	547	0.32
	52,191	22,244	118,070	7,132	0.29
65°F/40,000	924	173	1,459	579	0.27
	54,762	22,606	122,735	10,932	0.26
70°F/40,000	859	170	1,071	413	-0.98
	47,239	21,913	75,263	(10,541)	-1.01
60°F/45,000	929	203	1,493	439	-0.03
	53,358	27,128	126,580	(8,265)	-0.04
65°F/45,000	924	174	1,434	591	0.13
	54,739	22,702	119,558	12,489	0.13
70°F/45,000	875	178	1,120	409	-0.97
	49,003	22,864	81,782	(11,400)	-1.00
60°F/50,000	934	209	1,493	445	-0.18
	53,369	28,094	125,999	(7,999)	-0.19
65°F/50,000	934	182	1,459	584	0.05
	55,678	23,562	122,314	10,295	0.06
70°F/50,000	882	183	1,131	394	-0.99
	49,505	23,629	82,867	(13,799)	-1.01
60°F/55,000	934	209	1,476	462	-0.28
	53,411	28,014	123,356	(6,370)	-0.32
65°F/55,000	936	189	1,460	566	-0.05
	55,495	24,434	122,059	7,158	-0.03
70°F/55,000	882	185	1,139	384	-0.98
	49,362	24,006	83,138	(15,341)	-0.99
60°F/60,000	915	216	1,434	429	-0.35
	49,739	29,709	117,509	(11,245)	-0.36
65°F/60,000	927	193	1,478	545	-0.04
	53,862	25,166	123,930	4,011	-0.03
70°F/60,000	875	178	1,136	429	-0.84
	47,812	22,944	82,854	(9,885)	-0.84

pounds per acre. The highest average lint yield strategy is the 65° F - 55,000 target population rule (936 pounds per acre). However, two other strategies have virtually the same yield average: the 60° F - 50,000 target population (934 pounds per acre) and 65° F - 50,000 target population strategies (934 pounds per acre).

The highest expected net income strategy is the 65° F - 50,000 target population rule ($55,678). However, several other strategies have average net enterprise returns that are virtually the same. The highest minimum income strategy is the 65° F - 45,000 target population rule ($12,489). On the other hand, the highest maximum return soil temperature rule is the 60° F - 50,000 target population strategy. In general, the 65° F rule resulted in the highest average and minimum net enterprise income. This outcome is consistent with the perfect information set analysis results. The average soil temperature at planting time in the perfect information set is 64° F (Table 5.12).

However, none of the soil temperature rules dominated the four preferred calendar planting date strategies. The use of a soil temperature planting rule over a calendar date rule does not result in a more desirable outcome distribution. The minimum premiums needed to adopt the highest expected net income soil temperature rule over the preferred calendar date rule are presented in Table 5.20. This premium represents the amount needed to make a class of agents indifferent between the two rules. It also represents the minimum improvement in income from the timed decision rule before it would be preferred.

The final part of the planting decision analysis compares a soil temperature planting rule with the preferred calendar date strategies. The soil temperature strategy uses current stage environmental information as a predictor of when to plant and what seeding rate to use. This strategy is

TABLE 5.20

MINIMUM PREMIUM NEEDED TO ADOPT THE 10-DAY 65°F SOIL TEMPERATURE THRESHOLD/50,000 TARGET PLANT POPULATION DECISION RULE OVER THE PREFERRED BASE PLANTING STRATEGIES

	------Base Strategy------				
Efficiency Criteria	Variety	Planting Date	Seeding Rate/ Acre	Upper Bound	Lower Bound
		Mo./Day	Thousands	$/Ac.	$/Ac.
Risk Preference	Short	5/17	140	21.26	24.08
Risk Neutral	Short	5/31	100	16.26	26.23
Risk Aversion					
Slight	Short	5/31	80	28.92	43.80
Slight	Short	5/31	60	32.05	57.59
Strong	Short	5/31	60	38.01	40.89

comparable to the open loop with feedback solution described in Chapter II (Antle, 1983). That is, the decision rule is developed with 1) a priori information about behavior of the system and 2) current stage information about environmental influences on the system. This contrasts with the calendar date planting strategy which is analogous to the open loop strategy (Antle, 1983). The open loop solution only uses a priori information in formulating a decision rule. The open loop rule is superior to the open loop with feedback rule for formulating a planting strategy under Oklahoma growing conditions.

Irrigation Decision Problem Economic Analysis

The objective of this analysis is to examine the influence of available irrigation water on sequential decision strategy rules. The four preferred calendar date planting strategies identified in the previous section are the basis for this analysis. These preferred planting strategies were developed using an expected water allocation of 16-acre inches. Water was applied using a four inch per application 14-day schedule beginning on June 28th of each simulation year.

The first part of this analysis examines decision maker willingness to pay for perfect crop soil water demand information over the base calendar date irrigation schedule. Next is an investigation of the soil moisture trigger threshold rule that distributes water over the fruiting period such that it maximizes expected utility for a given irrigation allocation. These water allocation dependent soil moisture trigger rules are then compared with a 12- to 14-day calendar irrigation schedule. The analysis also examines the value of revising the preferred planting strategy given information about water allocation and soil moisture.

Cotton lint outcomes were simulated using the methods, assumptions, and data described in Chapter IV. Net enterprise income distributions for the irrigation economic analysis were constructed using: 1) cotton seed and lint outcomes for each decision alternative simulated using 43-years of daily weather data (1948-1990), and 2) the revenue and cost allocation assumptions presented in Table 5.21 for the representative farm situation described in Chapter IV.

Perfect Irrigation Water Availability Results and Analyses

The first component of the irrigation decision problem examined is decision maker willingness to pay for perfect information about crop soil water demand. The July-August irrigation period is a time of low rainfall and high evaporative demand from plant and soil surfaces. Average rainfall during July is 1.93 inches and has ranged from 0.00 to 8.93 inches. During August average rainfall is 2.14 inches and has varied from 0.07 to 6.49 inches (Table 2.2 in Chapter II). Potential evapotranspiration during the flowering period in cotton (July-August) is estimated to be one centimeter per day (Jackson et al. 1990, p. 97). Thus information about crop water demand could have considerable value for decision makers in the irrigation district.

Seed cotton outcomes were simulated using the 43-year weather data set and the four preferred planting strategies as a basis for the irrigation analysis. The four preferred base calendar planting strategies are:

1. Short-season variety planted on May 31 using a 100,000 seeding rate. This is the preferred strategy for the risk neutral agent (r_1=-0.000001, r_2=0.000001);

2. Short-season variety planted on May 31st using an 80,000 seeding rate. This is a preferred strategy for the slightly risk averse agent (r_1= -0.0001, r_2=0.0004);

TABLE 5.21

IRRIGATION ECONOMIC ANALYSIS REVENUE AND COST ALLOCATIONS[a]

Item	Dollars
Cotton Prices	
Expected Seed Price/Pound	0.04
Expected Lint Price/Pound (Grade 41, Staple 35)	0.60
Irrigation Variable Costs	
L-AID Water District/Acre Charge	4.50
Expendable Tools & Siphons/Acre	2.00
Labor Hours/Irrigation/Acre	0.73
Labor/Irrigation/Acre	3.29
Water Cost/Acre Inch	
16-Acre Inch Water Allocation	2.71
20-Acre Inch Water Allocation	2.40
24-Acre Inch Water Allocation	2.08
Other Variable Cost/Acre Kept Constant	
Preplanting	58.14
Planting	
Plant on May 31 at 100,000 Rate	27.36
Plant on May 31 at 80,000 Rate	24.69
Plant on May 31 at 60,000 Rate	22.02
Plant on May 17 at 140,000 Rate	32.69
Mid-Season Tillage	16.83
Pesticides & Chemicals	74.10
Harvest Variable Costs	
Custom Picking & Hauling/Pound Lint Harvested	0.12
Ginning & Processing/Pound Lint Harvested	0.10

[a] Revenue and cost allocations estimated using budget data developed by Walker and Banks (1990) for irrigated picker cotton in the Lugert-Altus Irrigation District.

3. Short-season variety planted on May 31st using a 60,000 seeding rate. This is a preferred strategy for the slightly risk averse agent (r_1=0.0001, r_2=0.0004) and the strongly risk averse agent (r_1=0.0004, r_2=0.001); and

4. Short-season variety planted on May 17th using a 140,000 seeding rate. This is the preferred strategy for the risk seeking agent (r_1=-0.0008, r_2=0.0001).

The seven soil moisture fraction trigger threshold decision alternatives simulated are 0.20, 0.25, 0.30, 0.35, 0.40, 0.45, and 0.50. An unlimited amount of water is assumed to be available for irrigation. Irrigation occurs anytime between June 28th and August 31st in each simulation year.

The model fills the root extraction zone of the soil profile each time the soil moisture threshold is reached. That is, the model fills the root zone profile when 50 to 80 percent of available moisture has been depleted at time t. Lower (higher) threshold levels (e.g., 80 percent depletion) result in larger (smaller) irrigation amounts and less (more) frequent irrigations.

Results for the preferred soil moisture threshold triggers for each base planting strategy are presented in Table 5.22. Water use ranged from 19 to 40 acre inches per year across the 43-year simulation cycle. The highest average irrigation water use occurred for the May 17th 140,000 seeding rate strategy (31 acre inches). The risk efficient soil moisture threshold for all four classes of decision makers is 0.40 inch per inch. This assumes unlimited water availability and the base preferred planting strategy for each class of decision makers in identifying the efficient soil moisture threshold.

Perfect crop water availability increases lint yield by 354 pound per acre over the base calendar irrigation rule for the May 31st 100,000 seeding rate strategy (Table 5.1). This strategy is still the highest expected return strategy in the efficient set. However, the minimum lint yield value for the 43-year period

TABLE 5.22

PERFECT IRRIGATION WATER DEMAND INFORMATION SET FOR THE FOUR PREFERRED BASE PLANTING STRATEGIES SIMULATED OVER THE 43-YEAR WEATHER PERIOD

Base Short-Season Strategy Plant Date	Base Short-Season Strategy Seeds/Acre	Item	Preferred Soil Moisture Trigger	Average	Standard Deviation	Maximum Value	Minimum Value	Skewness
Mo./Day	Thousands		in./in.	Dollars/Pounds/Inches				
5/31	100	Net Income	0.40	$91,149	$9,905	$109,527	$75,085	0.12
		Lint Yield		1,329	79	1,495	1,175	0.19
		Water Amount		28	4.17	38	19	0.52
5/31	80	Net Income	0.40	$89,481	$10,418	$111,041	$71,126	0.17
		Lint Yield		1,306	82	1,464	1,145	-0.03
		Water Amount		27	4	38	19	0.45
5/31	60	Net Income	0.40	$80,273	$11,025	$102,211	$58,063	0.05
		Lint Yield		1,220	85	1,373	1,035	-0.23
		Water Amount		26	4	36	18	0.48
5/17	140	Net Income	0.40	$86,019	$15,277	$124,432	$54,265	0.49
		Lint Yield		1,310	120	1,559	1,016	0.04
		Water Amount		31	5	40	20	-0.16

increased from 604 to 1,175 pounds per acre for the 100,000 seeding rate strategy. The 100,000 seeding rate strategy has the highest minimum lint yield and net income value in the updated efficient set. This compares to the highest minimum lint and net revenue values for the 60,000 and 80,000 seeding rate strategies under the base calendar date irrigation rule 16 acre inch allocation assumption. The risk preference strategy, plant on May 17th using a 140,000 seeding rate, still has the highest maximum lint yield and net income value in the perfect information preference set. The perfect water availability results suggest that risk averse agents could possibly revise their planting strategy given better information about irrigation over the base calendar date strategy.

Decision maker willingness to pay for perfect water demand information is presented in Table 5.23. Per acre willingness to pay values are estimated using the following value of information definition and Generalized Stochastic Dominance:

> the minimum (maximum) amount an individual within the specified class of agents would pay for the use of the dominant perfect water availability information net enterprise income distribution compared to base calendar date 16 acre inch irrigation strategy.

The willingness to pay analysis indicates that risk seeking agents place little or no value on additional information on crop water demand. This information does not result in a higher maximum net enterprise income value when compared to the calendar date strategy. This compares with agents classified as risk neutral who have a per acre willingness to pay for crop soil water information of $102.

Willingness to pay for perfect crop soil water information is highest among agents classified as risk averse. The value of perfect information ranges from $116 per acre for the slight risk aversion case to $125 per acre for the

TABLE 5.23

DECISION MAKER WILLINGNESS TO PAY (WTP) FOR PERFECT IRRIGATION WATER DEMAND INFORMATION OVER THE BASE CALENDAR DATE IRRIGATION STRATEGY

	Preferred Short-Season Planting Strategy			WTP over the Base Strategy:	
Efficiency Criteria	Original/ Revised	Plant Date	Seeds/ Acre	Lower Bound	Upper Bound
		Mo./Day	Thousands	---Per Acre Dollar Value---	
Risk Preference	Original	5/17	140	0.00	22.30
Risk Neutral	Original	5/31	100	101.56	102.13
Risk Aversion					
Slight	Original	5/31	80	129.43	174.80
	Revised	5/31	100	136.84	186.68
Slight	Original	5/31	60	115.51	124.89
	Revised	5/31	100	157.68	177.97
Strong	Original	5/31	60	124.89	128.29
	Revised	5/31	100	177.97	185.92

strong risk aversion case on the lower bound (plant on May 31st using 60,000 seeding rate).

Table 5.23 also presents the willingness to pay for a revised planting strategy given perfect crop water information. This is determined by comparing all updated preferred strategies. The updated May 31 100,000 seeding rate strategy dominated the updated 60,000 and 80,000 seeding rate strategies for the slight and strong risk aversion categories. The value of a revised planting strategy given perfect crop water information is $177.97 per acre on the lower bound in the strong risk aversion class. Willingness to pay for a revised strategy in the slight risk aversion category is $136.84 per acre for the 80,000 seeding rate and $157.68 per acre for the 60,000 seeding rate on the lower bound.

Variable Irrigation Water Allocation Results and Analyses

This portion of the irrigation decision analysis examines the value of soil water information under different water allocation levels. Three seasonal irrigation allocations are assumed for the analysis: 16, 20, and 24 acre inches. The farm decision maker is assumed to maintain a minimum of 16 acre inches. As described in Chapter IV, this can be done either through adjusting acreage or buying allocation. It is assumed that the decision maker purchases allocation.

However, there is little or no information on the cost of purchasing additional irrigation resources in a water short year. In 1990 the cost of water was $2.08 per acre inch for a 24 inch allocation to producers in Lugert-Altus Irrigation District (Kirby, 1990). For the purpose of this analysis, it is assumed that water cost increases by 15 percent in a 20 acre inch year and 30 percent in a 16 acre inch year. Thus the cost of maintaining a 16-acre inch level is assumed to be $2.71 per acre inch (130 percent of $2.08). The cost of maintaining a 20-acre inch level is assumed to be $2.41 per acre inch (115 percent of $2.08). An allocation of 24 acre inches is assumed to cost $2.08 per acre inch (Table 5.21). As described in Chapter IV, the 16 acre inch allocation occurs in 23-years (≤16), the 20 acre inch allocation occurs in 13-years (<16 and <24), and the 24 acre inch allocation occurs in seven years (≤24) over the 43-year weather period. Irrigation water allocation is assumed to be independent of local rainfall.

The seven soil moisture fraction trigger threshold decision alternatives simulated are 0.20, 0.25, 0.30, 0.35, 0.40, 0.45 and 0.50 inch per inch of plant available water. Irrigations can occur anytime between June 28th and August 31st in each simulation year. The calendar date irrigation schedule rules are: 1) four irrigations on a 14-day schedule beginning on June 28th in a 16 acre inch year, 2) five irrigations on a 14-day schedule beginning on June 28th in a 20 acre inch year, and 3) six irrigations on a 12-day schedule beginning on June 28th in a 24 acre inch year. Four inch applications are assumed for both the soil moisture trigger threshold and the calendar date rules. The objective is to find the irrigation rule that distributes irrigation water for a given allocation such that it maximizes expected utility.

Simulated lint yields for the 16, 20, and 24 acre inch water allocation levels are presented in Tables 5.24, 5.25, and 5.26. Each water allocation level was replicated 43 times using the 1948-1990 daily weather data set. Results are presented as a function of the base preferred planting strategy and soil moisture threshold or calendar date irrigation rule.

The simulated soil moisture trigger yield results show that the higher trigger levels (e.g., 0.40 to 0.50 in./in.) do not allocate water in an optimal manner. Most of the available water allocation under these higher trigger levels

TABLE 5.24

ALTERNATIVE CALENDAR DATE AND SOIL MOISTURE TRIGGER IRRIGATION STRATEGY 43-YEAR SIMULATION SEQUENCE COTTON LINT YIELD RESULTS FOR A 16 ACRE INCH WATER ALLOCATION

Base Short-Season Strategy		Calendar/ Soil	Lint Yield per Acre				
Planting Date	Seed/ Acre	Moisture Trigger	Average	Standard Deviation	Maximum Value	Minimum Value	Skewness
Mo./Day	Thousands	in./in.	Pounds/Acre				
5/31	100	14-Day	975	126	1,305	604	-0.1
		0.20	871	94	1,178	666	0.7
		0.25	994	133	1,230	584	-0.81
		0.30	886	172	1,325	524	0.2
		0.35	756	182	1,280	497	1.01
		0.40	658	169	1,197	404	0.98
		0.45	575	157	1,053	323	0.86
		0.50	537	146	1,010	311	1.06
5/31	80	14-Day	944	116	1,312	632	0.55
		0.20	797	130	1,153	538	0.18
		0.25	984	125	1,233	617	-0.56
		0.30	888	150	1,318	608	0.45
		0.35	764	173	1,288	521	1.21
		0.40	665	161	1,224	434	1.17
		0.45	580	147	1,068	372	1.09
		0.50	534	141	1,013	331	1.25
5/31	60	14-Day	869	116	1,284	648	1.07
		0.20	637	156	1,130	370	0.8
		0.25	879	135	1,170	605	-0.04
		0.30	853	132	1,262	628	0.68
		0.35	747	145	1,243	495	1.47
		0.40	651	149	1,170	417	1.16
		0.45	562	138	1,032	361	1.21
		0.50	505	136	977	301	1.45
5/17	140	14-Day	947	169	1,521	456	0.35
		0.20	857	116	1,117	538	-0.17
		0.25	982	181	1,350	438	-0.87
		0.30	923	203	1,511	455	0.28
		0.35	786	194	1,525	437	1.29
		0.40	679	169	1,256	308	0.59
		0.45	615	154	1,155	311	0.74
		0.50	582	143	1,057	312	0.7

TABLE 5.25

ALTERNATIVE CALENDAR DATE AND SOIL MOISTURE TRIGGER IRRIGATION STRATEGY 43-YEAR SIMULATION SEQUENCE COTTON LINT YIELD RESULTS FOR A 20 ACRE INCH WATER ALLOCATION

Base Short-Season Strategy			Lint Yield per Acre				
Plant Date	Seeds/ Acre	Calendar/ Soil Moisture Trigger	Average	Standard Deviation	Maximum Value	Minimum Value	Skewness
Mo./Day	Thousands	in./in.	Pounds/Acre				
5/31	100	14-Day	1,039	94	1,332	890	0.88
		0.20	873	92	1,178	734	0.94
		0.25	1,085	78	1,230	872	-0.38
		0.30	1,077	129	1,325	690	-0.64
		0.35	791	152	1,207	532	0.65
		0.40	654	151	1,068	419	0.81
		0.45	622	166	1,179	363	0.91
		0.50	561	149	1,045	323	0.95
5/31	80	14-Day	996	100	1,337	841	1.19
		0.20	797	130	1,153	537	0.18
		0.25	1,032	96	1,232	832	0.01
		0.30	1,067	110	1,318	859	-0.06
		0.35	901	158	1,362	608	0.76
		0.40	741	161	1,224	505	0.93
		0.45	630	156	1,205	373	1.16
		0.50	559	145	1,067	353	1.21
5/31	60	14-Day	907	116	1,310	701	1.10
		0.20	637	156	1,130	370	0.80
		0.25	893	137	1,170	640	-0.09
		0.30	999	107	1,262	833	0.20
		0.35	883	131	1,321	646	1.04
		0.40	729	145	1,170	505	0.95
		0.45	613	145	1,166	361	1.28
		0.50	532	139	1,029	330	1.37
5/17	140	14-Day	987	135	1,524	760	1.65
		0.20	879	102	1,117	682	0.08
		0.25	1,051	119	1,350	741	-0.31
		0.30	1,099	164	1,511	627	-0.29
		0.35	943	187	1,527	588	0.87
		0.40	783	180	1,483	381	0.85
		0.45	672	159	1,158	353	0.38
		0.50	613	146	1,071	313	0.46

TABLE 5.26

ALTERNATIVE CALENDAR DATE AND SOIL MOISTURE TRIGGER IRRIGATION STRATEGY 43-YEAR SIMULATION SEQUENCE COTTON LINT YIELD RESULTS FOR A 24 ACRE INCH WATER ALLOCATION

Base Short-Season Strategy		Calendar/ Soil	Lint Yield per Acre				
Plant Date	Seeds/ Acre	Moisture Trigger	Average	Standard Deviation	Maximum Value	Minimum Value	Skewness
Mo./Day	Thousands	in./in.	Pounds/Acre				
5/31	100	12-Day	1,094	78	1,271	966	0.40
		0.20	873	92	1,178	734	0.94
		0.25	1,090	75	1,254	925	0.06
		0.30	1,182	79	1,325	1,003	-0.51
		0.35	977	151	1,359	674	0.31
		0.40	824	169	1,284	551	0.80
		0.45	672	159	1,213	425	0.92
		0.50	586	151	1,060	353	0.85
5/31	80	12-Day	1,066	87	1,274	908	0.40
		0.20	797	130	1,153	537	0.18
		0.25	1,033	97	1,232	832	0.02
		0.30	1,153	80	1,318	950	-0.24
		0.35	1,061	128	1,362	739	0.00
		0.40	830	163	1,296	580	0.89
		0.45	680	152	1,235	421	1.09
		0.50	584	145	1,077	373	1.06
5/31	60	12-Day	982	106	1,231	770	0.08
		0.20	637	156	1,130	370	0.80
		0.25	893	137	1,170	640	-0.09
		0.30	1,042	97	1,260	837	-0.05
		0.35	1,024	107	1,321	823	0.31
		0.40	820	144	1,263	586	1.03
		0.45	666	143	1,194	415	1.10
		0.50	560	137	1,040	362	1.25
5/17	140	12-Day	1,061	139	1,445	758	0.47
		0.20	879	102	1,117	682	0.08
		0.25	1,066	100	1,350	785	0.07
		0.30	1,183	117	1,511	908	0.39
		0.35	1,107	156	1,527	765	0.45
		0.40	896	179	1,533	517	0.54
		0.45	749	159	1,190	424	0.02
		0.50	647	155	1,121	313	0.35

is used up early in the irrigation season causing a reduced yield response. Thus there is not enough water available towards the end of the period to meet crop water needs.

The highest average lint yields for any of the 12 combinations of preferred planting strategies and water allocations occurs under one of the soil moisture threshold rule alternatives. The calendar date rule does not produce the highest expected lint yield for any of the four planting strategies. The highest average yielding soil moisture trigger occurs under the May 31st 100,000 seeding rate strategy, i.e., 994 pounds per acre under a 16 acre inch allocation (0.25 in./in), 1,085 pounds per acre under a 20 acre inch allocation (0.25 in./in.), and 1,182 pounds per acre under a 24 inch allocation (0.30 in./in.).

The highest maximum lint yields still occur under the May 17th 140,000 seeding rate strategy (risk preference strategy). However, additional water resources and soil moisture information do not produce a higher maximum yield over the base calendar date irrigation schedule using 16 acre inches of water.

Simulated lint yield outcomes are more mixed for two risk averse agent preferred strategies (May 31st planting date using the 60,000 and 80,000 seeding rates). The highest minimum yields occur for the calendar date irrigation rule under a 16 acre inch allocation for the 60,000 and 80,000 seeding rate strategies (648 and 632 pounds per acre, respectively). However, the highest minimum yield among the 32 sixteen acre inch allocation strategies simulated is for the 0.20 in./in. trigger rule for the 100,000 seeding rate strategy (666 pounds per acre).

Simulated minimum lint yield level results are different for both the 20 and 24 acre inch allocation assumptions (Table 5.25 and 5.26, respectively). The highest minimum yield among the 32 twenty acre inch allocation strategies simulated is for the 100,000 seeding rate calendar date irrigation rule (890 pounds per acre). By contrast, the highest minimum yielding 24 acre inch allocation strategy is the 0.30 trigger rule for the 100,000 seeding rate strategy (1,003 pounds per acre).

Risk efficient soil moisture threshold strategy summaries for the 16, 20, and 24 acre inch allocation levels are presented in Table 5.27. There are two parts to the stochastic dominance results. The column in Table 5.27 labeled original is the soil moisture threshold efficient set as a function of water allocation given the original preferred base planting strategy. The column labeled revised comprises the soil moisture threshold efficient set given the ability to revise the original planting strategy using soil moisture and water allocation information.

The preferred risk neutral strategy for a 16 acre inch allocation is the May 31st planting date using a 100,000 seeding rate and 0.25 in./in. soil moisture threshold. None of the other updated soil moisture information planting strategies dominated this choice for risk neutral agents.

Three soil moisture trigger thresholds are in the slight risk aversion set for the 16 inch allocation using the original preferred planting strategy (0.25 in./in. for the 80,000 seeding rate; 0.25 and 0.30 in./in. for the 60,000 seeding rate). Updating the information set to include knowledge about soil moisture generates the potential for a revised planting decision for risk averse agents. The May 31st planting date using a 100,000 seeding rate and 0.20 in./in. soil moisture threshold dominates the original slight and strong risk aversion planting strategies. This strategy has the highest minimum net income value among the updated 16 acre inch decision sets.

TABLE 5.27

SOIL MOISTURE IRRIGATION TRIGGER STRATEGY RISK EFFICIENT SET RESULTS FOR THE 16, 20, AND 24 ACRE INCH WATER ALLOCATION LEVELS SIMULATED OVER THE 1948-1990 DAILY WEATHER SET

Base Short-Season Strategy		Soil Moisture Trigger	Net Enterprise Income Dollars					Soil Moisture Trigger Efficient Set for a given Planting Strategy:[a]	
Plant Date	Seeding Rate		Average	Standard Deviation	Maximum Value	Minimum Value	Skewness	Original	Revised
Mo./Day	Thousands	in./in.							
			(16 Acre Inch Water Allocation Assumption 1948-1990 Simulation Sequence)						
5/31	100	0.20	47,895	13,316	95,578	18,641	1.05		Slight, Strong
		0.25	61,504	17,467	94,229	8,123	-0.75	Neutral	Neutral
5/31	80	0.25	61,038	16,622	96,030	13,134	-0.48	Slight	
5/31	60	0.25	48,590	17,954	92,104	12,367	0.07	Slight	
		0.30	44,628	17,273	99,806	15,404	0.74	Slight, Strong	
5/17	140	0.30	50,823	26,378	125,025	(10,340)	0.22	Prefer	Prefer
		0.35	32,963	25,136	126,852	(13,132)	1.22	Prefer	Prefer
			(20 Acre Inch Water Allocation Assumption 1948-1990 Simulation Sequence)						
5/31	100	0.25	71,854	10,664	95,309	43,241	-0.03	Neutral	Neutral, Slight, Strong
5/31	80	0.30	69,475	14,280	103,649	42,364	-0.03	Slight	
5/31	60	0.30	61,565	14,276	100,887	39,565	0.33	Slight,	Strong
5/17	140	0.30	71,562	21,580	126,432	9,772	-0.30	Prefer	Prefer
		0.35	51,108	24,236	124,781	4,861	0.82	Prefer	Prefer
			(24 Acre Inch Water Allocation Assumption 1948-1990 Simulation Sequence)						
5/31	100	0.30	82,475	10,410	105,301	58,555	-0.28	Neutral	Neutral, Slight, Strong
5/31	80	0.30	79,539	10,545	105,090	54,878	0.01	Slight	
5/31	60	0.30	66,242	12,893	101,791	41,196	0.20	Slight,	Strong
5/17	140	0.30	81,103	15,593	127,872	43,905	0.49	Prefer	Prefer
		0.35	70,986	20,460	126,569	26,331	0.46	Prefer	Prefer

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[a] Neutral=risk neutral; prefer=risk preference; slight=slight risk aversion; and strong=strong risk aversion.

Two soil moisture trigger thresholds strategies are in the risk preference set (0.30 and 0.35 in./in.). None of the other updated soil moisture information planting strategies dominated this choice for risk preferring agents.

The preferred risk neutral strategy for a 20 acre inch allocation is the May 31st planting date using a 100,000 seeding rate and 0.25 in./in. soil moisture threshold. None of the other updated soil moisture information planting strategies dominated this choice for risk neutral agents.

One soil moisture trigger threshold is in the slight risk aversion set for the 20 inch allocation using the original preferred planting strategy (0.30 in./in. for the 60,000 and 80,000 seeding rates). Updating the information set to include knowledge about soil moisture again yields the potential for a revised planting decision for risk averse agents. The risk neutral strategy, planting on May 31st planting date using a 100,000 seeding rate and 0.25 in./in. soil moisture threshold, dominates the original slight and strong risk aversion planting strategies. This strategy has the highest minimum net income value among the updated 20 acre inch decision sets.

The same two dominant soil moisture trigger thresholds found for the 16 inch allocation hold for the 20 inch allocation for risk preferring agents (0.30 and 0.35 in./in.). None of the other 20 inch allocation updated soil moisture information planting strategies dominated this choice for risk preferring agents.

The preferred risk neutral strategy for a 24 acre inch allocation is the May 31st planting date using a 100,000 seeding rate and 0.30 in./in. soil moisture threshold. None of the other updated soil moisture information planting strategies dominated this choice for risk neutral agents.

One soil moisture trigger threshold is in the slight risk aversion set for the 24 inch allocation using the original preferred planting strategy (0.30 in./in. for the 60,000 and 80,000 seeding rates). Updating the information set to include knowledge about soil moisture gives rise to a possible revision of the planting decision for risk averse agents. The risk neutral strategy, planting on May 31st planting date using a 100,000 seeding rate and 0.30 in./in. soil moisture threshold, dominates the original slight and strong risk aversion planting strategies. This strategy has the highest minimum net income value among the updated 24 acre inch decision sets.

The same two dominant soil moisture trigger thresholds found for the 16 and 20 inch allocations hold for the 24 inch allocation for risk preferring agents (0.30 and 0.35 in./in.). None of the other 20 inch allocation updated soil moisture information planting strategies dominated this choice for risk preferring agents.

Updated risk efficient set calendar date irrigation rule strategy summaries for the 16, 20, and 24 acre inch allocation levels are presented in Table 5.28. The preferred planting strategy for risk averse agents given a 20 or 24 inch allocation is the May 31st 100,000 seeding rate strategy using 0.25 and 0.30 in/in. threshold irrigation rules, respectively.

The last portion of the irrigation analysis examines the value of a flexible decision rule using soil moisture and water allocation information compared to a calendar date irrigation rule. The 1948-1990 daily weather set and the water allocation distribution scenario described in the first part of this section are used to conduct the analysis (i.e, 16 acre inch allocation in 23-years, 20 acre inch allocation in 13-years, and 24 acre inch allocation in seven years over the 43-year weather period).

The alternative decision rules examined are:

1. Calendar date irrigation schedule using the original preferred planting strategy.

TABLE 5.28

CALENDAR DATE IRRIGATION STRATEGY RISK EFFICIENT SET RESULTS FOR THE 16, 20, AND 24 ACRE INCH WATER ALLOCATION LEVELS SIMULATED OVER THE 1948-1990 DAILY WEATHER SET

Base Short-Season Strategy		Calendar Date Schedule	Net Enterprise Income					Set for a given Planting Strategy:[a]	
Plant Date	Seeding Rate		Average	Standard Deviation	Maximum Value	Minimum Value	Skewness	Original	Revised
Mo./Day	Thousands								
			(16 Acre Inch Water Allocation Assumption 1948-1990 Simulation Sequence)						
5/31	100	14-Day	58,929	16,217	99,827	10,622	-0.20	Neutral	Neutral
5/31	80	14-Day	55,622	14,854	101,544	15,121	0.45	Slight	Slight
5/31	60	14-Day	46,688	14,828	98,676	17,995	0.98	Slight, Strong	Slight,Strong
5/17	140	14-Day	53,602	22,015	126,360	(10,280)	0.29	Prefer	Prefer
			(20 Acre Inch Water Allocation Assumption 1948-1990 Simulation Sequence)						
5/31	100	14-Day	64,844	11,892	101,021	46,266	0.81	Neutral	Neutral, Slight, Strong
5/31	80	14-Day	60,036	12,598	102,454	40,721	1.15	Slight	
5/31	60	14-Day	49,301	14,688	99,733	23,134	1.06	Slight,	Strong
5/17	140	14-Day	56,796	17,220	124,368	26,361	1.59	Prefer	Prefer
			(24 Acre Inch Water Allocation Assumption 1948-1990 Simulation Sequence)						
5/31	100	12-Day	70,430	9,841	93,060	52,775	0.33	Neutral	Neutral, Slight, Strong
5/31	80	12-Day	67,573	11,035	94,240	46,975	0.34	Slight	
5/31	60	12-Day	57,480	13,592	88,057	30,599	0.05	Slight,	Strong
5/17	140	12-Day	64,879	17,876	112,726	24,534	0.43	Prefer	Prefer

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[a] Neutral=risk neutral; prefer=risk preference; slight=slight risk aversion; and strong=strong risk aversion.

2. Updated preferred planting strategy calendar date irrigation schedule identified in Table 5.28.

3. Preferred single soil moisture threshold trigger rule using the original preferred planting strategy.

4. Variable soil moisture threshold trigger rule identified in Table 5.27 using the original preferred planting strategy.

5. Variable soil moisture threshold trigger rule using the preferred revised planting strategy identified in Table 5.27.

A summary of the net income outcomes for the alternative planting-irrigation strategies considered under this variable irrigation water allocation distribution is presented in Table 5.29.

Both the single and variable soil moisture threshold irrigation rules dominate the calendar date rule for decision makers classified as risk neutral. Average net income is increased by $3,266 and $4,740, respectively, over the calendar date strategy. Decision maker willingness to pay for irrigation strategy information is presented in Tables 5.30 and 5.31.

The variable soil moisture rule dominates the single trigger rule. Willingness to pay for information on the influence of available irrigation allocation on the preferred soil moisture threshold rule is $5.05 per acre on the lower bound (Table 5.30). The value of a variable soil moisture rule over the calendar irrigation rule is $16.34 on the lower bound for risk neutral agents (Table 5.31).

By contrast, the calendar date irrigation strategy dominates for slight risk aversion planting strategy (planting on May 31st using an 80,000 seeding rate). A calendar irrigation schedule using a planting strategy based on water allocation yields a premium of between $6.93 and $11.90 per acre over the flexible planting-soil moisture threshold strategy (Table 5.31). The calendar schedule net income distribution has the highest minimum value among the 80,000 seeding rate comparisons: $33, 781 (Table 5.29).

TABLE 5.29

SIMULATED NET ENTERPRISE INCOME SUMMARIES FOR THE ALTERNATIVE PLANTING-IRRIGATION STRATEGIES CONSIDERED UNDER A VARIABLE IRRIGATION WATER ALLOCATION SCENARIO OVER THE 1948-1990 WEATHER DATA SET

Efficiency Criteria	Short-Season Strategy			Net Enterprise Income				
Planting Soil Moisture Strategy Comparisons	Planting Date	Seeding Rate	Irrigation Allocaitons Rule	Average	Standard Deviation	Maximum Value	Minimum Value	Skewness
	Mo./Day	Thousands	16, 20 & 24 in.	Dollars				
RISK NEUTRAL								
Calendar Strategy	5/31	100	14, 14, & 12 Day	62,613	14,955	99,827	31,076	0.15
Soil Moisture Strategy								
Single Soil Moisture	5/31	100	0.25, 0.25, 0.25	65,879	15,663	94,229	24,447	-0.54
Variable Soil Moisture	5/31	100	0.25, 0.25, 0.30	67,353	16,961	99,492	24,447	-0.40
SLIGHT RISK AVERSION								
Calendar Strategy								
Original Planting	5/31	80	14, 14, & 12 Day	59,015	14,424	101,544	33,781	0.78
Revised Planting	5/31	80						
		& 100	14, 14, & 12 Day	61,014	15,012	101,544	33,781	0.55
Soil Moisture Strategy								
Single Soil Moisture	5/31	80	0.25, 0.25, 0.25	63,336	15,281	98,192	22,737	-0.10
Variable Soil Moisture	5/31	80	0.25, 0.30, 0.30	66,116	16,475	97,026	22,737	-0.18
Revised Planting	5/31	100	0.25, 0.25, 0.30	60,157	19,807	99,492	29,620	0.34
SLIGHT & STRONG RISK AVERSION								
Calendar Strategy								
Original Planting	5/31	60	14, 14, & 12 Day	49,450	15,298	98,676	26,278	0.91
Revised Planting	5/31	60						
		& 100	14, 14, & 12 Day	58,506	17,842	98,676	26,278	0.40
Soil Moisture Strategy								
Single Soil Moisture	5/31	60	0.30, 0.30, 0.30	54,283	18,479	99,806	18,365	-0.21
Variable Soil Moisture	5/31	60	0.25, 0.30, 0.30	55,267	17,659	92,104	18,564	0.04
Revised Planting	5/31	100	0.25, 0.25, 0.30	60,157	19,807	99,492	29,620	0.34
RISK PREFERENCE								
Calendar Strategy	5/17	140	14, 14, & 12 Day	55,695	20,456	126,360	10,074	0.87
Soil Moisture Strategy								
Single Soil Moisture	5/17	140	0.30, 0.30, 0.30	60,780	28,833	125,025	(2,295)	-0.18
Single Soil Moisture	5/17	140	0.35, 0.35, 0.35	50,757	33,128	126,852	(13,132)	0.05

TABLE 5.30

DECISION MAKER WILLINGNESS TO PAY (WTP) FOR SOIL MOISTURE AND WATER ALLOCATION INFORMATION

Efficiency Criteria\Planting-Soil Moisture Strategy Comparison	Original Short-Season Strategy Planting Date	Original Short-Season Strategy Planting Rate	WTP for: Lower Bound	WTP for: Upper Bound
Dominant vs. Comparison	Mo./Day	Thousands	Per Acre Dollar Value	
Risk Neutral Planting Strategy	5/31	100		
Variable over Single Trigger			5.05	5.19
Slight Risk Aversion Planting Strategy	5/31	80		
Variable over Single Trigger			0.00	3.18
Revised over Single Trigger			0.00	0.00
Slight Risk Aversion Planting Strategy	5/31	60		
Variable over Single Trigger			0.73	3.19
Revised over Single Trigger			24.85	36.84
Strong Risk Aversion Planting Strategy	5/31	60		
Variable over Single Trigger			35.98	37.96
Revised over Single Trigger			36.84	38.76

TABLE 5.31

DECISION MAKER WILLINGNESS TO PAY FOR A SOIL MOISTURE THRESHOLD VERSUS A CALENDAR DATE IRRIGATION RULE

	Original Short-Season Strategy		WTP for:	
Efficiency Criteria\Planting-Soil Moisture Strategy Comparison	Planting Date	Planting Rate	Lower Bound	Upper Bound
Dominant vs. Comparison	Mo./Day	Thousands	Per Acre Dollar Value	
Risk Neutral Planting Strategy	5/31	100		
Single Trigger over Calendar			11.25	11.43
Variable Trigger over Calendar			16.34	16.58
Slight Risk Aversion Planting Strategy	5/31	80		
Revised Calendar over Calendar			0.07	0.34
Revised Calendar over Single Trigger			4.65	35.54
Revised Calendar over Variable Trigger			1.46	35.54
Revised Calendar over Revised Trigger			18.13	21.18
Slight Risk Aversion Planting Strategy	5/31	60		
Revised Trigger over Revised Calendar			6.93	11.90
Revised Trigger over Calendar			13.93	19.51
Revised Trigger over Single Trigger			24.84	36.84
Revised Trigger over Variable Trigger			21.67	35.98
Strong Risk Aversion Planting Strategy	5/31	60		
Revised Trigger over Revised Calendar			11.84	12.70
Revised Trigger over Calendar			12.29	13.37
Revised Trigger over Single Trigger			36.83	38.96
Revised Trigger over Variable Trigger			35.98	37.96

On the other hand, the flexible planting-soil moisture strategy dominates for the May 31st planting date-60,000 seeding rate comparisons. Willingness to pay for slightly risk averse agents to use a planting-soil moisture threshold over a calendar rule using water allocation information is $6.93 per acre on the lower bound. The value of soil moisture over the calendar rule for strongly risk averse agents is $11.84 per acre on the lower bound.

A risk seeking agent is indifferent between the two preferred soil moisture rules (0.30 and 0.35 in./in.) and the calendar strategy (Table 5.26).

This portion of the economic analysis examined the value of soil moisture and available irrigation water information in the sequential decision problem. The four preferred planting strategies identified in the planting decision results are the basis for the analysis. Two components of this decision problem were examined: 1) the influence of irrigation water availability on the preferred soil moisture trigger threshold, and 2) the value of a revised planting decision given water allocation and soil water information. The soil moisture threshold rules were compared with a calendar date irrigation strategy.

Soil moisture and irrigation water allocation information is of value to agents classified as risk neutral. It is not of value to decision makers identified as risk preferring. Results are mixed for agents identified as risk averse. Analysis of the irrigation alternatives under three water allocation assumptions using 43-years of weather data found that a soil moisture rule dominates the calendar rule for risk averse agents. However, an evaluation using a 43-year variable water allocation scenario had varied outcomes. One planting strategy preferred by slightly risk averse agents is dominated by the calendar irrigation rule. Another planting strategy preferred by both slightly and strongly risk averse agents is dominated by a soil moisture rule.

This analysis suggests that the different information properties described in Chapter II influence the preferred decision rule (Antle, 1983). The planting and irrigation strategy preferred by agents defined as risk preferring does not incorporate information about water allocation and soil moisture. Thus, an open loop or certainty equivalence approach is preferred by risk preferring agents.

This contrasts with the use of additional irrigation information by risk neutral agents in formulating a planting and irrigation decision rule. Thus, the risk neutral agent prefers the open loop with feedback approach i.e., information received after production begins is used along with a priori knowledge in formulating a sequential decision rule.

Finally, the analysis suggests that decision makers classified as risk averse may prefer a more "wide sense" approach decision rule, i.e., an actively adaptive or closed loop strategy. Irrigation information may result in a revised planting decision and an updated irrigation strategy.

Pest Decision Problem Economic Analysis

The final portion of the economic analysis examines the insect management decision problem. Four alternative information level spray strategies are analyzed using lint yield outcomes generated with six years of weather and insect count data (1985-1990). Cotton lint outcomes were simulated using the methods, assumptions, and data described in Chapter IV.

The planting strategy for the analysis was the short-season variety planted on May 31st using a 100,000 seeds per acre rate. The irrigation strategy is 16 acre inches applied in four equal applications on a two-week schedule starting June 28th. The COTTAM cotton plant simulation model was used to simulate cotton lint yield outcomes under the assumption of zero insect damage for the 1985 through 1990 weather period (Jackson et al., 1990). Lint yield outcomes under the no insect damage assumption represents moisture and carbohydrate stress conditions. Simulated plant fruit count data (i.e., per acre square and boll numbers) and plant population data from the no insect damage outcomes were used for estimating cumulative insect damage loss for the four spray strategies.

The TEXCIM cotton-pest-predator simulation model was then used to simulate fleahopper, Heliothis spp., and boll weevil damage before and after an insecticide application to the cotton crop (Hartstack et al., 1990). Daily weather and weekly pheromone moth count data were used to specify insect population numbers and dynamics for a representative cotton field in the Lugert-Altus Irrigation District (Karner, 1991).

The moth count, weather, and fruit count data were used as input in the TEXCIM model to simulate insect numbers and yield loss until the first spray decision for each strategy. The TEXCIM model was then used to simulate no spray and after spray insect numbers and yield outcomes until the next spray decision. The insect population and lint yield loss outcome data set for each simulation year was updated for each subsequent spray operation until harvest. Harvest was assumed to occur when the field is 100 percent open boll.

The four insect spray strategies examined in this analysis are: 1) do not spray (No Action), 2) a calendar date schedule (Calendar Date), 3) the Oklahoma Cooperative Extension Service cotton insect spray guidelines (Field Count), and 4) a dynamic spray threshold strategy (Field Count + Fruit Value). Each strategy represents a different level of information used for deciding when to spray.

The no action strategy assumes that insect damage is not important. By contrast, the calendar date spray strategy assumes insect damage is occurring but does not consider the impact of pest numbers, predator numbers, stage of plant growth, and expected value of the crop on the economics of the spray choice. Cooperative Extension Service spray strategy guidelines consider the impact of pest numbers, predator numbers, and stage of plant growth in determining when to spray (Karner, 1989; Anonymous, 1990). The guidelines do not directly consider the expected value of the crop in formulating a spray rule. An insect spray operation was assumed to occur when a certain number of insects per 100 plants was counted in the field or a specified damage threshold was reached. The dynamic spray strategy considers additional information about expected crop value in relation to growth stage and the ability of the cotton plant to compensate for insect damage (Hartstack and Sterling, 1988, pp. 370-374). An insect spray application for the dynamic threshold was assumed to occur when the dollar value of the five day forecast of cumulative lint yield damage due to insects was greater than the cost of control. Revenue and cost allocations for analyzing the net enterprise income outcomes for each strategy are presented in Table 5.32.

Simulated cotton lint yield loss outcomes from fleahoppers, Heliothis spp., and boll weevils, 1985 through 1990, for each spray strategy are presented in Table 5.33. Lint yields for each insecticide spray rule are presented in Tables 5.34.

Simulated lint yield loss by insect varied considerably across simulation years. The largest source of yield loss from insects was from Heliothis spp. followed by boll weevils and fleahoppers. This ranking is consistent with the estimated Oklahoma lint yield loss ordering for Heliothis spp., boll weevils, and fleahoppers presented in Table 3.4 in Chapter III. The timing of simulated insect

TABLE 5.32

COTTON INSECT PEST ECONOMIC ANALYSIS REVENUE AND COST ALLOCATIONS[a]

Item	Dollars
Cotton Prices	
Expected Seed Price/Pound	0.04
Expected Lint Price/Pound (Grade 41, Staple 35)	0.60
Insecticide Variable Costs/Acre	
Chemical Cost/Application/Acre[b]	9.07
Application Cost/Acre	2.75
Other Variable Costs/Acre Kept Constant	
Preplanting	58.14
Plant on May 31 at 100,000 Rate	27.36
Irrigation	52.97
Mid-Season Tillage	16.83
Harvest-Aid	15.00
Harvest Variable Costs	
Custom Picking & Hauling/Pound Lint Harvested	0.12
Ginning & Processing/Pound Lint Harvested	0.10

[a] Revenue and cost allocations estimated using budget data developed by Walker and Banks (1990) for irrigated picker cotton in the Lugert-Altus irrigation district.

[b] This cost represents the average per application cost of cotton insecticide chemicals as specified in the budget by Walker and Banks (1990).

TABLE 5.33

SIMULATED COTTON LINT YIELD LOSS OUTCOMES FOR FOUR INSECTICIDE SPRAY DECISION RULES

Year	Insect Spray Decision Rule	Simulated Lint Yield Loss from:				
		Fleahoppers	*Heliothis* spp.	Boll Weevils	Total	Perc. Loss
		Pounds Per Acre				
1985	No Action	112	206	0	318	29
	Calendar Date	56	116	0	172	16
	Field Count	86	71	0	157	14
	Field Count + Fruit Value	46	83	0	129	12
1986	No Action	74	766	36	876	79
	Calendar Date	31	236	7	274	25
	Field Count	49	145	15	209	19
	Field Count + Fruit Value	47	162	12	221	20
1987	No Action	124	313	268	705	53
	Calendar Date	50	103	8	161	12
	Field Count	77	145	61	283	21
	Field Count + Fruit Value	81	63	43	187	14
1988	No Action	141	314	178	633	60
	Calendar Date	45	78	5	128	12
	Field Count	82	74	16	172	16
	Field Count + Fruit Value	65	110	17	192	18
1989	No Action	176	48	478	702	64
	Calendar Date	64	17	7	88	8
	Field Count	176	34	52	262	24
	Field Count + Fruit Value	41	47	10	98	9
1990	No Action	48	88	65	201	15
	Calendar Date	19	57	2	78	6
	Field Count	48	105	43	196	14
	Field Count + Fruit Value	48	88	65	201	15

TABLE 5.34

SIMULATED COTTON LINT YIELD OUTCOMES FOR FOUR INSECTICIDE SPRAY DECISION RULES

Year	Insecticide Spray Decision Rule:			
	No Action	Calendar Date	Field Count	Field Count + Fruit Value
	Pounds of Lint Per Acre			
1985	779	925	940	968
1986	234	836	901	889
1987	613	1,157	1,035	1,131
1988	427	932	888	868
1989	407	1,021	847	1,011
1990	1,177	1,300	1,182	1,177
Ave.	606	1,029	966	1,007
Std.	336	172	124	126
Max.	1,177	1,300	1,182	1,177
Min.	234	836	847	868
Skewness	0.72	0.56	0.93	0.26

infestations in the field was consistent with the observed occurrence of insect problems in the study area as described by Karner (1989) and Young et al. (1983). Simulated fleahopper infestations occurred from late June to mid-July. Simulated Heliothis spp. and boll weevil infestations occurred during July and August. Thus, the model using weather and pheromone trap moth count data from the study area appears to accurately portray the general seasonal dynamics of insect occurrence and damage.

The TEXCIM model simulated heavy Heliothis spp. lint yield losses in four out of the six weather years (1985, 1986, 1987, and 1988). Simulated lint yield losses ranged from 48 pounds per acre in 1989 to 766 pounds per acre in 1986 (Table 5.33). Heavy boll weevil infestations were observed in three out of the six weather years (1987, 1988, and 1989). Lint yield reductions due to boll weevils varied from zero pounds per acre in 1985 to 478 pounds per acre in 1989 (Table 5.33). Simulated lint loss from fleahoppers ranged from 48 pounds per acre in 1990 to 176 pounds per acre in 1989 (Table 5.33).

The number of spray applications and the type of insect control used varied by strategy. The average number of spray applications per year for the calendar date strategy (Calendar Date) was eight; seven in the light boll weevil infestation years (1985, 1986, and 1990) and nine in the heavy boll weevil years (1987, 1988, and 1989).

The percentage gain in lint yield over the no action strategy varied from nine percent in 1990 to 56 percent in 1989 (Table 5.33). The calendar date strategy improved average lint yield by 423 pounds per acre over the no action spray strategy (Table 5.34). Average net enterprise income using the calendar date strategy increased by $26,643 over the no action spray strategy (Table 5.35).

TABLE 5.35

SIMULATED NET ENTERPRISE INCOME OUTCOMES FOR FOUR INSECTICIDE SPRAY DECISION RULES

Year	Insecticide Spray Decision Rule: No Action	Calendar Date	Field Count	Field Count + Fruit Value
	Net Enterprise Income Dollars			
1985	53,840	49,105	57,875	71,749
1986	(17,620)	36,808	48,662	50,506
1987	31,442	71,338	72,541	84,988
1988	7,613	42,793	50,675	54,877
1989	4,762	53,705	54,569	69,429
1990	104,569	96,687	101,813	104,569
Ave.	30,763	57,406	63,856	72,686
Std.	43,668	22,143	20,530	19,523
Max.	104,569	96,687	101,813	104,569
Min.	(17,620)	36,808	48,662	50,506
Skewness	0.71	0.88	1.20	0.49

An average of four spray applications per year was conducted under the Cooperative Extension Service spray guidelines strategy (Field Count). This was one-half the number of spray operations implemented for the calendar date strategy. Fleahopper infestations above the treatment threshold of 40 insects per 100 plants were not reached during any of the six weather years. Consequently, no spray operations for fleahopper control were conducted under the field count strategy. Boll weevil damage rose above the recommended treatment threshold in two years. One spray operation was conducted for boll weevils in 1987 and two were conducted in 1989. The number of spray operations conducted for Heliothis spp. control in each simulation year was: five in 1985, six in 1986, three in 1986, five in 1988, one in 1989, and one in 1990.

The percentage gain in lint yield over the no action strategy varied from one percent in 1990 to 60 percent in 1989 (Table 5.33). Average lint yield per acre (1985-1990) for the field count strategy was not as high as the calendar date strategy; 966 pounds per acre compared to 1,029 pounds per acre (Table 5.34). However, average net enterprise income for the field count spray strategy increased by $6,450 over the calendar date strategy (Table 5.35).

The average number of spray operations conducted for the dynamic spray threshold strategy (Field Count + Fruit Value) was three per year. Spray applications for fleahopper control were conducted in four out of the six simulation years (1985, 1987, 1988, and 1989). One spray operation was conducted for boll weevils in 1987 and two were conducted in 1989. The number of spray operations conducted for Heliothis spp. control were: one in 1985, five in 1986, two in 1987, and two in 1988. No measures for insect control were implemented for the 1990 simulation year. The five day forecast of the value of insect damage did not exceed the cost of control for each insect during 1990.

The percentage gain in lint yield over the no action strategy ranged from zero percent in 1990 to 59 percent in 1986 (Table 5.33). The dynamic spray strategy yielded the highest average net enterprise income among the four spray strategies simulated ($72,686). This strategy placed more value on the control of fleahoppers than the field count strategy. One possible reason for this difference is the short season for growing cotton in Oklahoma. The fruit value as a function of growth stage component of the dynamic threshold places a larger value on early set fruit because of the short season. Hence, the higher value of fleahopper control under the dynamic spray strategy as compared to the field count strategy.

The dynamic spray strategy is analogous to the actively adaptive and closed loop solution strategies described in Chapter II (Taylor and Chavas, 1980; Antle, 1983). It uses past and current knowledge along with a forecast of how the current decision influences future outcomes. Simulation analysis results suggest that there is considerable value for this "wide sense approach," i.e., using information about the current value of the crop, damage by insects, and the ability of the crop to compensate for insect damage give the current stage of fruit production in formulating a spray strategy.

Decision maker willingness to pay (WTP) for the dynamic spray strategy over the other three spray strategies is presented in Table 5.36. Results are reported for risk neutral and broadly risk averse (second-degree stochastic dominance) agents.

Willingness to pay for the dynamic (Field Count + Fruit Value) over the field count spray strategy is $30 per acre for agents defined as risk neutral (lower absolute risk aversion interval bound value). This compares to $6.96 per

TABLE 5.36

DECISION MAKER WILLINGNESS TO PAY (WTP) FOR PEST MANAGEMENT INFORMATION

WTP For Field Count Plus Fruit Value Strategy:

Efficiency Criteria/Decision Rule	Lower Bound	Upper Bound
	Per Acre Dollar Value	
Risk Neutral		
Field Count	30.00	30.86
Calendar Date	49.39	49.77
No Action	143.33	147.75
Broad Risk Aversion (SSD)		
Field Count	6.96	35.75
Calendar Date	44.76	58.64
No Action	145.57	236.50

acre for agents defined as broadly risk averse. Thus, information about current crop worth and the ability of the plant stand to compensate for pest damage is of value in pest management.

By comparison, the calendar date spray strategy assumes that insect damage is occurring but does not consider other information in formulating a spray strategy. Decision maker willingness to pay for the dynamic over the calendar date spray strategy is $49.39 per acre for agents defined as risk neutral (lower absolute risk aversion interval bound value). The value of a dynamic over a calendar date spray strategy for agents defined as broadly risk averse is $44.76 per acre.

The final portion of this economic analysis examined the pest decision problem. The dynamic spray strategy dominates the Cooperative Extension Service, calendar date, and no action strategies. A "wide sense approach" using information about current crop value, damage by insects, and ability of the crop to compensate for insect damage is of value to risk neutral and risk averse agents.

CHAPTER VI

SUMMARY AND CONCLUSIONS

This chapter is a summary of the research conducted in this dissertation. The first three sections restate the rationale, objectives, and methods used to implement the analysis. The next three sections summarize the results and conclusions for the planting, irrigation, and pest economic analysis. The final section presents some concluding comments.

Review of the Rationale for the Study

Cotton is an important crop and source of income for many farmers in southwest Oklahoma. However, average Oklahoma lint yields for both dryland and irrigated production have lagged behind the rest of the U.S. Additional information about the complex interactions that influence the economics of input choices could enhance producer welfare by improving efficiency and profitability. The study also provided basic knowledge of how management choices interact with uncertain environmental conditions in the cotton field.

Review of the Study Objectives

The specific objectives of the study were:

1. To identify and synthesize into a coherent sequential decision framework the salient features and relationships of the cotton production problem in southwest Oklahoma.

2. To generate yield and net enterprise incomes that reflect the growth habit of the cotton plant, uncertain environmental conditions, and the management choices actually witnessed in southwest Oklahoma.

3. To analyze the economic consequences of alternative information level assumptions on optimal decision strategies.

4. To assess the influence of uncertain information in developing decision rules on farmer profit and risk.

5. To develop management decision information and risk reduction strategies useful to southwest Oklahoma cotton farmers.

Review of Methods used in the Study

The conceptual framework for this analysis drew from sequential decision making theory and concepts (Antle, 1983, 1988; Antle and Hatchett, 1986) and value of information theory and concepts (Gould 1974; Hirschleifer and Riley 1979; Hess 1982; Byerlee and Anderson 1982; Bosch and Eidman 1987).

Two daily time-step simulation models were used to generate lint yield outcomes for a representative irrigated cotton field in southwest Oklahoma. COTTAM simulates the growth and development of the cotton plant in response to management and environmental inputs (Jackson et al., 1990). TEXCIM simulates the principal cotton plant-pest-beneficial predator relationships in response to management and environmental inputs (Hartstack et al. 1990). The study used 43-years of daily weather data (1948-1990), representative soil profile data, and six years of cotton insect pheromone trap data (1985-1990) to represent environmental conditions in the field ecosystem (Oklahoma State University Irrigation Research Station, Altus).

Three parts of the sequential decision problem were examined in the economic analysis: planting, irrigation, and pest management. Alternative calendar date and timed strategies under different information assumptions were simulated for each portion of the decision problem. These decision alternative were evaluated using stochastic dominance and value of information criteria.

Planting Decision Economic Analysis

The first portion of the planting decision analysis was a validation of the planting decision lint yield response relationships specified in the COTTAM model. The next part was an evaluation of the calendar date planting strategies using stochastic dominance criteria. Then the value of variety maturity-length, seeding rate, and time of planting information was examined using stochastic dominance criteria. The final portion of the planting decision analysis compares the preferred calendar date strategies with a soil temperature decision rule using stochastic dominance criteria.

The average simulated lint yield for the 25 short-season variety calendar date strategies is 856 pounds per acre. This contrasts with a 779 pound average for the 25 medium-season strategies and 695 pounds for the 25 long-season tactics.

The highest yielding alternative is the short-season variety planted on May 31 using a 100,000 seeding rate (975 pounds per acre). By comparison, the highest producing medium maturity-length variety strategy generates nine percent less lint yield on average (May 17 planting date and a 120,000 seeding rate averaging 891 pounds per acre). The highest yielding long season maturity-length variety averaged 841 pounds per acre (Planting on May 17 using a 120,000 seeding rate).

Irrigated variety field plot test data and a field plot study of the influence of planting time on yields were used to validate the simulated calendar date planting strategy lint yield results (Oklahoma State University Irrigation

Research Station, Altus). The COTTAM model was found to emulate the general lint yield levels and variability found in the field plot. Further, the variety index component of the COTTAM model accurately portrayed the variety maturity-lint yield response relationship under field plot growing conditions. The results suggest that a producer should choose a short maturity-length variety with a high first harvest quantity when all other characteristics are held constant, e.g., pest resistance, drought resistance, quality characteristics, etc.

The simulation model was also found to approximate the concave lint yield as a function of planting time relationship found in the field trial data. The model was also found to satisfactorily simulate lint yields as a function of stochastic plant population. At the early planting date higher seeding rates result in higher yields. However as survival increases the higher seeding rates result in an excess plant population causing a drop in lint yield per acre.

Stochastic dominance analysis identified four dominant planting decision strategies for agents identified as either risk neutral, risk averse, or risk seeking. Using a short maturity-length variety strategy is preferred by all agents. The May 31 planting time is preferred by both risk neutral and risk averse agents. This contrasts with the May 17 planting date being preferred by risk seeking agents. Seeding rate and its influence on plant population and the distribution of lint yields appears to be the critical factor in determining which strategy is preferred.

The next part of the planting analysis examined the potential value of information about a more flexible strategy. Results suggest that more information about variety maturity-length is of little value to the four classes of decision makers. However, the valuation analysis showed varying willingness to pay for additional seeding rate and time of planting information.

The final part of the planting decision analysis compares a soil temperature planting rule with the preferred calendar date strategies. The soil temperature strategy uses current stage environmental information as a predictor of when to plant and what seeding rate to use. This strategy is comparable to the open loop with feedback solution (Antle, 1983). That is, the decision rule is developed with 1) a priori information about behavior of the system and 2) current stage information about environmental influences on the system. This contrasts with the calendar date planting strategy which is analogous to the open loop strategy (Antle, 1983). The open loop solution only uses a priori information in formulating a decision rule.

Stochastic dominance analysis indicates that none of the soil temperature planting rules dominant the preferred calendar strategies. Current stage information in the form of an imperfect predictor (soil temperature) does not result in a more desirable net enterprise income distribution. This result holds for the risk neutral, risk averse and risk preferring classes of decision makers examined in this study. Thus, under Oklahoma growing conditions the calendar date (open loop) planting rule dominates the soil temperature (open loop with feed back) planting strategy.

Irrigation Decision Economic Analysis

This portion of the analysis examined the influence of available irrigation water on the sequential decision problem. The decision set for the four preferred calendar date planting strategies identified in the planting decision analysis was the basis for the irrigation analysis, i.e., time of planting, variety choice, and seeding rate information. Two components of this decision problem were examined: 1) the influence of irrigation water availability on the preferred soil moisture trigger threshold, and 2) the value of a revised planting decision given water allocation and soil water information. Soil moisture threshold irrigation rules were compared with a calendar date irrigation strategy.

The first part of this analysis examines decision maker willingness to pay for perfect crop soil water demand information over the base calendar date irrigation schedule. The risk efficient soil moisture threshold for the risk neutral, risk seeking, and risk preferring classes of agents is 0.40 inch per inch. This assumes unlimited water availability and the preferred calendar date planting strategy for each class of agents in identifying the efficient soil moisture threshold.

The willingness to pay analysis indicates that risk preferring agents do not value additional information about crop water demand. This information does not result in a higher maximum net enterprise income value in the distribution of outcomes when compared to the calendar date irrigation strategy. On the other hand, agents classified as risk neutral or risk averse exhibit a willingness to pay for perfect crop soil water demand information. The perfect water availability results suggest that risk averse agents may revise their planting strategy given better information about irrigation over the base calendar date strategy.

The next part of the irrigation analysis investigates the soil moisture trigger threshold rule for a given irrigation allocation that distributes water over the fruiting period such that it maximizes expected utility. Three irrigation water allocations were assumed for the analysis: 16, 20, and 24 acre inches. Two soil moisture trigger rules were examined in this portion of the analysis. The first strategy examined is a soil moisture trigger rule that is dependent on the available irrigation water allocation (variable trigger rule). The second is a single soil moisture trigger that is not dependent on available irrigation allocation (single trigger rule). These soil moisture trigger rules were then compared with a 12- to 14-day calendar irrigation schedule. The analysis also examined the value of revising the preferred planting strategy given information about water allocation and soil moisture.

Soil moisture and irrigation water allocation information was of value to agents classified as risk neutral. The irrigation allocation dependent variable soil moisture trigger rule dominates the single soil moisture trigger and calendar date irrigation strategies. However, this additional information did not result in a revised planting strategy for agents in this class.

Information about irrigation water allocation and soil moisture is not of value to agents identified as risk preferring. Soil moisture and irrigation water allocation information value results were mixed for agents defined as risk averse. The first part of the analysis examined the 43-year (1948-1990) outcome distributions generated for each water allocation assumption (16, 20, 24 acre inches). The analysis found that the variable soil moisture trigger rule dominates the single soil moisture trigger rule for risk averse agents. Results also indicate a revision of the planting strategy given water allocation and soil moisture information for agents defined as risk averse.

However, an *ex ante* evaluation using a 43-year variable water allocation scenario yielded more mixed results. The assumed 43-year variable water allocation scenario was: 16 acre inches in 23-years, 20 acre inches in 13-years, and 24 acre inches in seven years. Results show that one planting strategy was preferred by slightly risk averse agents is dominated by the calendar irrigation rule. Another planting strategy preferred by both slightly and strongly risk averse agents was dominated by the variable trigger soil moisture rule. In both cases there was a willingness to pay for a revised planting strategy given water allocation information.

This analysis suggests that the different information properties described by Antle (1983) influence the preferred decision rule. The planting and irrigation strategy preferred by agents defined as risk preferring does not incorporate information about water allocation and soil moisture. Thus, the open loop or certainty equivalence approach (Taylor and Chavas, 1980; Antle, 1983) was preferred by risk preferring agents.

This contrast with the use of additional irrigation information by risk neutral agents in formulating a planting and irrigation decision rule. Thus, the risk neutral agent prefers the open loop with feedback approach (Antle, 1983), i.e., information received after production begins is used along with a priori knowledge in formulating a sequential decision rule.

Finally, the analysis suggests that decision makers classified as risk averse may prefer a more "wide sense" approach decision rule, i.e., an actively adaptive or closed loop strategy (Taylor and Chavas, 1980; Antle, 1983). Additional irrigation information may result in a revised planting decision and an updated irrigation strategy.

Pest Decision Problem Economic Analysis

The final portion of the economic analysis examined the insect management decision problem. Four alternative information level spray strategies were analyzed using six years of weather and insect count data (1985-1990): 1) do not spray (No Action), 2) a calendar date schedule (Calendar Date), 3) the Oklahoma Cooperative Extension Service cotton insect spray guidelines (Field Count), and 4) a dynamic spray threshold strategy (Field Count + Fruit Value). Each strategy represents a different level of information used for deciding when to spray.

Simulated lint yield loss by insect varied considerably from year to year. The largest source of yield loss from insects was from Heliothis spp. followed by boll weevils and fleahoppers. This ranking is consistent with estimates of cotton lint yield loss from insects in Oklahoma. The timing of simulated insect infestations in the field were consistent with the observed occurrence of insect problems in the study area.

The average number of spray applications and the type of insect control used varied by strategy: eight for the calendar date strategy, four for the Cooperative Extension Service strategy, and three for the dynamic spray threshold strategy.

Average net enterprise income using the calendar date strategy increased by $26,643 over the no action spray strategy. Using the Cooperative Extension Service strategy increased average net enterprise income by $6,450 over the calendar date strategy. The dynamic spray threshold strategy yielded the highest average net enterprise income among the four spray strategies simulated--$8,830 more than for the field count strategy. This strategy is preferred by agents classified as risk neutral and risk averse.

The dynamic spray strategy is analogous to the actively adaptive and closed loop solution strategies (Taylor and Chavas, 1980; Antle, 1983). It uses past and current knowledge along with a forecast of how the current decision influences future outcomes. Simulation analysis results suggest that there is considerable value for this "wide sense approach," i.e., using information about the current value of the crop, damage by insects, and the ability of the crop to compensate for insect damage give the current stage of fruit production in formulating a spray strategy.

Concluding Comments

This study examined the economic consequences associated with a sequence of decisions in a complex agricultural production problem. The results suggest that the simulation, stochastic dominance, and information valuation approach used in this study is an effective way of examining such a problem. The analysis also empirically demonstrated the interaction between the properties of information and the risk preferences of agents in formulating a sequential decision rule. Thus, further empirical research about these interactions could provide a better understanding of how information influences the farm decision making process.

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VITA 2

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