40th Annual Conference of the Australian Agricultural and Resource Economics Society,
University of Melbourne, 13-15 February 1996.

RISK ATTITUDE, PLANTING CONDITIONS AND THE VALUE OF CLIMATE FORECASTS TO A DRYLAND WHEAT GROWER

G.R. MARSHALL AND K.A. PARTON
Departments of Agricultural and Resource Economics, and Health Studies,
respectively, University of New England, Armidale, N.S.W.

RISK ATTITUDE, PLANTING CONDITIONS AND THE VALUE OF CLIMATE FORECASTS TO A DRYLAND WHEAT GROWER

G.R. MARSHALL AND K.A. PARTON

Departments of Agricultural and Resource Economics, and Health Studies,
respectively, University of New England.

The value of a climate forecasting system based on phases of the Southern Oscillation was estimated for a representative dryland wheat grower in the vicinity of Goondiwindi. In particular the effects on this estimate of risk attitude and planting conditions were examined. A recursive stochastic programming approach was used to identify the grower's utility-maximising action set in the event of each of the climate patterns over the period 1894-1991 recurring in the imminent season. The approach was repeated with and without use of the forecasts. The choices examined were, at planting, nitrogen application rate and cultivar and, later in the season, choices of proceeding with or abandoning each wheat activity. The value of the forecasting system was estimated as the maximum amount the grower could afford to pay for its use without expected utility being lowered relative to its non-use.

Keywords: Climate forecasting; information value; expected utility theory.

1. INTRODUCTION

1.1 Background

The Drought Policy Review Task Force (1990) proposed that the responsibility for managing climate be shifted away from government and onto growers and that drought be accepted as a normal feature of the commercial environment of agriculture. The National Drought Policy (NDP) announced in 1992 aimed to facilitate the shift to farmer self-preparedness by measures including government funding of drought-related research and additional education programs. Climate forecasting was identified in particular as a way of enabling farmers to mitigate the adverse financial consequences of drought (White 1994).

Climate forecasting aims to move farmers as far as possible to a situation of certainty regarding future seasonal conditions and to thereby increase the likelihood that good decisions will lead to successful outcomes. As noted by Anderson (1991), however, research into climate forecasting is not the only form of research with the potential to reduce climate-related production risk. Plant breeding, for instance, can also reduce production risk by improving crop or pasture performance under climatically-stressed conditions. Indeed, "a first objective of wheat improvement in Australia was to produce varieties sufficiently drought-resistant to cope with the short seasons and hard finishing conditions" (Callaghan 1973).

Expenditure under the NDP was projected to be $15.1 million over a four year period, including $2.1 million for research into opportunities such as climate forecasting (Department of Primary Industry and Energy 1992). This funding is of sufficient magnitude to warrant economic analyses designed to compare returns from climate forecasting research with returns from other types of research, such as plant breeding, aiming to increase farmers' self-preparedness in managing climatic variability.

Economic analysis also has a role in identifying where the greatest returns in climate forecasting research are likely to lie. Mjelde, Sonka, Dixon and Lamb (1988), for instance, compared the benefits to maize producers of making less accurate climate forecasts available earlier with those available from making more accurate forecasts available later.

1.2 The Climate Forecasting System

A recent development in climate forecasting has been identification of 'phases' of the Southern Oscillation (SO) by Stone and Aulicems (1992). The phases relate to trends in the Southern Oscillation Index (SOI) over two consecutive months. The SOI measures atmospheric pressure differences bewteen Tahiti and Darwin. Phase 1 (Phase 2) corresponds with a consistently negative (positive) SOI over that period. Phase 3 (Phase 4) corresponds with a rapidly falling (rising) SOI over that period and Phase 5 corresponds with the SOI being consistently near zero. When past records of rainfall, or temperature, are partitioned into those corresponding to the SOI phases, then frequency distributions for each SOI phase relating to rainfall or temperature in subsequent months can be produced. These frequency distributions can be used as probability distributions in climate forecasting (Stone 1994).

Phase 1 or Phase 3 identified in late autumn is associated with a high probability of below average rainfall during the following winter and spring at many locations in eastern Australia, whereas Phase 2 or Phase 4 identified at this time is associated with a high probability of above average rainfall (Stone *et al.* undated). For Goondiwindi in the north-eastern grain belt, the rainfall probability distribution associated with Phase 5 was found to be similar to that derived using all years in the historical record (Stone and Hammer 1992).

1.3 Study Objectives

The primary objective in this study was to contribute information for decision-making with respect to allocation of resources to, and within, climate forecasting research by estimating the value to farmers of the climate forecasting system base on SO phases. Subsidiary objectives were to examine how the value of the forecasting system is affected by (i) a farmer's attitude to risk; and (ii) planting conditions.

2. THEORY AND PREVIOUS STUDIES

2.1 Theory

Bacquet *et al.* (1976) estimated the value to pear orchardists from forecasts issued daily regarding the likelihood of a frost occurring overnight. Byerlee and Anderson (1982) valued the benefits of rainfall forecast information for fodder conservation. Mjelde *et al.* (1988), Mjelde and Cochran (1988), Mazzocco *et al.* (1992) and Mjelde and Dixon (1993) addressed various issues in valuing the benefits of climate forecasts for maize producers.

Each of these studies, apart from Mjelde and Cochran (1988), valued climate forecasting using expected utility (EU) theory. Application of EU theory requires that both the prior probability distribution (PrPD) of outcomes and the risk attitude of the decision-maker, encapsulated in a von Neumann-Morgenstern utility function *U*(.), be precisely specified (Anderson *et al.* 1977). Mjelde and Cochran (1988) used stochastic efficiency criteria which satisfy the axioms of EU theory but do not require precise specification of risk attitude. The optimal action according to EU theory is that which maximises expected utility, where the expected utility of an action is given by weighting the utility associated with each outcome by the probability of the outcome occurring

The action satisfying this criterion *without* access to a climate forecast is the prior optimal action. A climate forecast allows a decision-maker's prior probability distribution for outcomes to be revised using Bayes' formula to obtain a posterior probability distribution (PoPD). The action satisfying the EU criterion *with* access to a particular forecast is the Bayes' action. The set of actions satisfying this criterion for each possible forecast is the Bayes' strategy. The expected utility of the Bayes' strategy is given by the weighted average of the utilities of the Bayes' actions, where the weighting given to the utility of a particular Bayes' action is the probability that its associated forecast will be issued (Anderson *et al.* 1977).

The monetary value of a forecasting system is given by the maximum amount the decision-maker could afford to pay for its use without expected utility of the resulting Bayes' strategy falling below expected utility of the prior optimal action.

Hilton (1981) found that only characteristics of the system itself (eg. accuracy and timeliness of forecasts) have a consistent directional effect on the value of information. Changes in factors that are external to the system (eg. risk attitude and degree of prior uncertainty) will not necessarily exhibit such a consistent effect. Byerlee and Anderson (1982) and Mjelde and Cochran (1988), for instance, each found that the value of climate forecasts did not monotonically increase with the level of risk aversion of the decision-maker.

The axioms underlying expected utility (EU) theory have come under challenge (Schoemaker 1982). Notwithstanding these challenges, this decision theory has remained the one predominantly used in economic analysis (Machina 1989). Hardaker *et al.* (1991, p. 9) justified continued application of EU theory on the basis that "it seems that no better operational framework has yet found wide acceptance".

2.2 Methods Used in Previous Studies

In all of the studies identified above, the value of climate forecasting was estimated for a small set (sometimes of one) of case study farmers. The parameters required to apply EU theory were specified and the values of the various information systems deduced accordingly.

This approach can be used to explore the impact on the value of climate forecasting of hypothetical variation in the decision environment. Byerlee and Anderson (1982) and Mjelde and Cochran (1988), for example, used the case study approach to analyse the impact of variation in risk attitudes on the value of climate forecasting, while Bacquet *et al.* (1976), Mjelde *et al* (1988), Mjelde and Cochran (1988) and Mazzocco *et al.* (1992) used this approach to explore the effect on value of forecasts of varying assumptions regarding the prior probability distributions held by decision-makers.

A problem of valuing climate forecasts using case study farms is that of extrapolating results obtained from a non-statistically chosen sample to obtain a value for all farmers in a district and/or industry (Bacquet *et al.* 1976). This problem, however, is common to all technology evaluations relying on analyses of case study farms. Dillon and Hardaker (1980, p. 31) concluded that this "is a process requiring judgement and experience. Obviously, a good knowledge of the relevant features of the farms in the population of concern helps in drawing inferences".

2.3 Accounting for Risk Attitude

There are four major approaches for dealing with risk attitude: (1) assume risk-indifference and therefore a goal of maximising (minimising) of expected monetary gains (losses) (eg. ; Mjelde *et al.* 1988, Mazzocco *et al.* 1992; Mjelde and Dixon 1993); (2) specify a utility function based on previous research (eg. Byerlee and Anderson 1982); (3) use stochastic efficiency criteria to avoid the need to specify a particular utility function (eg. Mjelde and Cochran 1988); and (4) directly elicit farmers' risk attitudes (eg. Bacquet *et al.* 1976).

Of the above approaches, the second appears to remain the most popular among decision analysts seeking to account for risk preference in their models. It avoids the costs of direct elicitation and can, with judicious variation of the risk preference parameter, emulate the third approach in identifying upper and lower bounds on the value of a technology.

Approach (2) requires that the functional form of $U(.)$ be chosen. Forms invoking decreases in risk aversion with increasing wealth appeal to the intuition of economists (Anderson *et al.* 1977). The quadratic form used by Byerlee and Anderson (1982) counter-intuitively assumes that absolute risk aversion increases with increasing wealth. The negative exponential form which has been popular among agricultural economists in recent years (eg. Easter and Paris 1983; Kingwell *et al.* 1992; Kingwell and Schilizzi 1994; and Ogisi *et al.* 1994) assumes that absolute risk aversion is unaffected by wealth. The constant relative risk aversion (CRRA) functional form does accord with intuition and, furthermore, recent empirical testing by Pope and Just (1991) found that farmer behaviour could be better explained by a CRRA functional form than by the negative exponential form. The CRRA functional form is given in equation 2.1:

$$U = \pi^{1-R_r}/(1 - R_r) \qquad R_r > 0, R_r \neq 1 \tag{2.1}$$

where π is some measure of financial performance and $R_r = RW$ is the coefficient of relative risk aversion with R being the coefficient of absolute risk aversion and W being initial wealth (Hey 1979).

2.4 Prior Probability

In valuing forecasts, the process is to assess the marginal benefits that accrue from introducing additional information to a situation characterised by some prior knowledge level. In all of the studies surveyed the PrPDs of decision-makers were assumed rather than directly elicited. In the studies by Byerlee and Anderson (1982) and Mjelde and Dixon (1993) the PrPD was assumed equivalent to a historical climatic frequency distribution. Bacquet *et al.* (1976) also used this assumption as well as an assumption that the decision-maker has no prior information. Mjelde *et al.* (1988), Mjelde and Cochran (1988) and Mazzocco *et al.* (1992) used a historical frequency distribution as well as alternative assumptions that climatic conditions in the imminent season will be (1) identical to those in the previous one;
(2) identical to those in the worst of the years in the data set; and (3) identical to those in the best of the years in the data set.

Use of historical frequencies in decision analysis "involves a strong subjective presumption that the historical structure is unchanged and is relevant to the specific planning period under review" (Anderson *et al.* 1977). Use of historical frequencies also implicitly assumes that a decision-maker is fully cognisant of, and chooses to use only, this information in framing a probability distribution (Norris and Kramer 1990).

2.5 Embedded Risk

In Bacquet *et al.* (1976) and Byerlee and Anderson (1982) it was implicitly assumed that outcomes of climatic risk arise after all decisions have been made. In such a situation identification of the prior optimal action and the Bayes' strategy involves only arithmetical calculation.

However, most decisions about farming systems are subject to risks which are embedded within the decision process rather than appearing only after all decisions have been made (Hardaker *et al.* 1991). Trebeck and Hardaker (1972), Hardaker *et al.* (1991) and Dorward

(1994) concluded that models of farmer behaviour need to explicitly account for the tactical choices that arise during a season as the outcomes of embedded risk unfold.

The decision problems addressed by Mjelde *et al.* (1988), Mjelde and Cochran (1988), Mazzocco *et al.* (1992) and Mjelde and Dixon (1993) involved embedded risk and sequential decision models were accordingly developed to account for tactical choices arising at successive stages distinguished by increasing climate information. The models utilised a stochastic dynamic programming (SDP) framework under which backward recursion endogenously accounted for opportunity costs of decisions at each stage in terms of options precluded in subsequent stages. The approach used by Mjelde and Cochran (1988) was internally inconsistent, however, since risk aversion was assumed when valuing forecasts while, as noted in Section 2.3, risk indifference was assumed when specifying the objective function of the model used to identify the optimal action for a given decision environment.

3. METHOD AND DATA

3.1 The Case Study Enterprise

Research developing the climate forecasting system based on SO phases has largely focussed on its use by farmers in the northern grain belt of eastern Australia. This area extends from Dubbo in northern New South Wales to Emerald in southern Queensland. Stone *et al.* (undated, p. 4) characterises wheat growing in this area as follows: "Rainfall is variable, summer dominant, and limiting, rarely exceeding evaporative demand in any month. Successful wheat cropping has developed by utilising soil water stored during the summer fallow prior to the wheat crop". Scoccimarro *et al.* (1994, map 2b) found the coefficient of variation of wheat yield over the period 1978-79 to 1992-93 for most of this region (at greater than 0.53) generally exceeded that for other grain growing regions in Australia.

The native fertility of soils in this region made it suitable for producing wheat of Prime Hard quality which attracts a significant price premium. However, continuous cropping in the area has depleted this fertility (Dalal and Mayer 1987). Decisions made at planting time regarding application of nitrogen fertiliser have become increasingly important as a result. The optimal planting window for wheat is short due to the desirability of capitalising on a very short optimal window for flowering, which is limited by low radiation receipt and frosting on one side and rapidly rising temperatures and evaporative demand on the other (Woodruff 1992). Choice among cultivars according to their varietal development pattern provides farmers with some control over flowering date despite the stochastic nature of planting opportunities. Choices of planting time, varietal development pattern and fertiliser strategy within this environment thus involve complex decisions (Woodruff 1992).

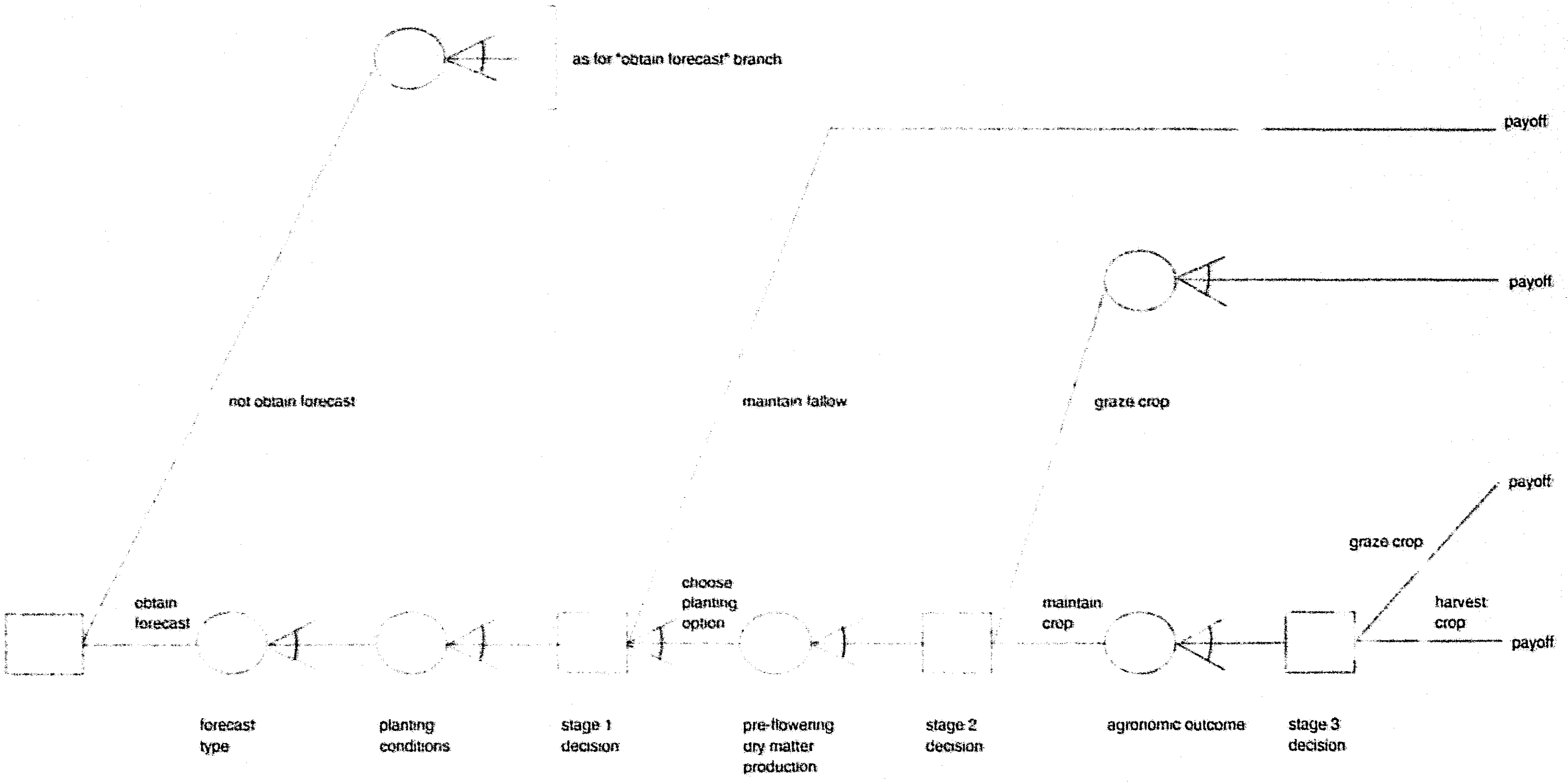
Accounting for this complexity requires in-depth analysis of the situation of individual decision-makers. This study was limited to analysis of one such situation. The case study related to a representative wheat grower in the vicinity of Goondiwindi in the Western Downs/Maranoa district of southern Queensland. The case study focussed on a farm representative of the 'small wheat area' stratum of wheat growers in this district defined by Smith (1995a,b). Average property size for this group was estimated to be 2,083 hectares (ha). The average area cropped per year over 1990-91 to 1992-93 was 338 ha, of which wheat accounted for 217 ha and other winter crops accounted for 113 ha. Average area of summer crops was only 8 ha (Smith 1995a,b).

The case study focussed on the wheat enterprise of the representative farm. However, the whole farm consequences of decisions and outcomes within the wheat enterprise were also accounted for as discussed in the following section.

3.3 The Grower's Sequential Decision Problem

In this study the value of the climate forecasting system was assessed in terms of the benefits it provides for choosing nitrogen application rates and wheat varieties at the time of planting opportunity. A descriptive model of the sequence of decisions relevant to this focus is represented as an outline decision tree in Figure 1. Options branch from decision nodes which are denoted by squares, and states branch from event nodes which are denoted by circles. The decision tree is in outline form insofar as the forks at some of the decision and

Figure 1: Outline decision tree for the wheat enterprise



event nodes (ie., those with three prongs joined by an arc) symbolically represent a larger number of discrete options or states.

The figure deals with the decision problem for a single paddock and a particular set of planting conditions. The planting conditions modelled were date of planting opportunity (five variants) and soil moisture (percentage of field capacity) (two variants) and soil nitrogen (two variants) as at that date. Twenty sets of planting conditions were considered, composed of all possible combinations of these variants. The planting dates chosen represented the 10, 30, 50, 70 and 90 percentile values of the historical frequency distribution, while the levels for soil moisture and soil nitrogen were estimated to represent the 10 and 90 percentile values of their respective distributions. Since climatic conditions during a wheat growing season in this region are independent of these types of planting conditions (pers. comm., R. Stone, QDPI/CSIRO Agricultural Production Systems Research Unit, Toowoomba, July 1995), the PrPD of wheat season climatic events was assumed equivalent to the historical frequency distribution (derived from the 98-year period 1894 to 1991) regardless of the set of planting conditions being analysed.
If the grower decides to obtain the forecast, one of five forecasts (ie., SO phases) will be issued at the subsequent event node. Another event node follows relating to the conditions experienced at planting. If the grower does not obtain the forecast the event node relating to planting conditions immediately follows the first decision node.

Next along each branch is the decision node relating to stage 1 (ie., planting opportunity) of the wheat growing season. The decision model allowed for choice at this stage among eleven nitrogen application rates and three varieties differing in development pattern. The option of continuing the fallow commenced in summer was also accounted for.

The event node situated to the right of the stage 1 decision node relates to the level of dry matter production prior to flowering. Four classes of pre-flowering dry matter production were distinguished. Next to the right is a decision node relating to options available at flowering (stage 2). The choice at flowering was that of whether a crop planted at stage 1 should be maintained or grazed. A decision to graze avoids the cost of harvesting and provides added feed at a time when fodder reserves such as hay would most likely be distributed to livestock, thus reducing the cost of subsequently replenishing fodder reserves.

Next to the right is an event node relating to the agronomic outcomes at stage 3 (ie., which depend on the type of season experienced between flowering and grain maturity). This is followed to the right by a decision node relating to options available at the time of grain maturity in mid to late spring (stage 3). The choice here was whether a crop should be harvested or grazed. The benefits of grazing at stage 3 were of the same type as described above for grazing at stage 2.

Note that the 'terminal' options from which payoffs arise are 'maintain fallow' (at stage 1), 'graze crop' (at stage 2), 'graze crop' (at stage 3) and 'harvest crop' (at stage 3).

3.4 Probability Distributions

Derivation of probabilities for the event nodes shown in Figure 3.1 following the stage 1 and stage 2 decision nodes assumed that the representative grower is aware of historical climate data as a result of *information* technology such as the computerised RAINMAN decision support system (Murphy 1993). Thus the value of the climate forecasting system arises only from adding information to that already available from a thorough historical knowledge.

The PrPD for pre-flowering dry matter production event node was accordingly derived by assuming that the grower judges that each of the relevant events recorded from 1894 to 1991 is equally likely to recur. Thus the prior probability of the event in a particular past year recurring was assumed to be 1/98

The PoPD regarding this event was derived by (a) obtaining 'hindcasts' of which of the five possible forecast types would have been issued in each of the 98 past years (pers. comm., R. Stone, July 1995); (b) partitioning the series of past years according to forecast type; and (c) setting the probability that the pre-flowering event in a particular past year will recur in the imminent season, if that particular SO phase is the one currently identified, equal to the reciprocal of the number of past years associated with that class. For instance, there were 14 past years associated with end-April SO phase 1. The probability that each of the pre-flowering events in these years would recur in the imminent season if this forecast type were issued was thereby calculated to be 1/14.

Regardless of access to a climate forecast, information regarding pre-flowering dry matter production becomes available by the time a stage 2 decision is required. The grower's PrPD for stage 3 agronomic outcomes was deduced by simulating the way the grower would utilise this information in order to predict agronomic outcomes at stage 3. The method involved calculating, for each of the 98 years, the average of pre-flowering dry matter production over the three varietal types. A cumulative probability distribution was constructed from these data and quartile values were determined. Each of the 98 years was then partitioned into one of four classes bounded by the quartile values. The prior probability that the stage 3 agronomic outcome in a particular past year will recur in the imminent season, if the outcome at flowering falls within the same dry matter class as was the case in that past year, was set equal to the reciprocal of the number of past years associated with that class.

The climate forecasting system may also have value for decisions made at stage 2. However, the PoPDs for stage 3 agronomic outcomes were assumed equivalent to the PrPD since re-partitioning the years allocated to each dry-matter class according to its associated SO phase would have left too few years per partition to allow adequate representation of these posterior distributions.

It was assumed that outcomes of stage 3 decisions (ie., whether to harvest or graze) are known by the grower with certainty.

3.5 Net Payoffs

The next step in applying the case study approach was to identify, for every combination of event outcomes, the monetary consequence (or net payoff) of each option available at the decision nodes for stages 1 to 3. Where an option was a terminal option this required only straightforward budgeting. However, for precursor options this also involved identifying the 'follow-on' options that would be chosen in the subsequent stage/s.

Identifying the follow-on options that would subsequently be chosen if a particular option were chosen at a given stage involved applying backward induction or "averaging out and folding back" (Anderson *et al.* 1977, p. 125) to the decision tree represented in Figure 1. A detailed description of how this was performed is provided in Marshall (1996).

The benchmark farm-gate return for ASW quality wheat (minimum of 10 per cent protein) was assumed to be $125/t. Benchmark farm-gate returns for the Prime Hard (min. 13 per cent protein), Australian Hard (min. 11.5 per cent protein) and Feed grades of $175/t, $140/t and $80/t respectively were chosen as representative of the returns that might be expected on average in the foreseeable future. For each grade other than Feed grade, an adjustment of $5 per one percentage point deviation in protein above the grade benchmark and, in the case only of ASW wheat, below the benchmark, also applied.

Calculation of the net payoff from an option in the event of a previous year's climatic conditions recurring in the imminent season required simulation of the agronomic consequences of those conditions. This was performed by staff of the Agricultural Production Systems Research Unit (APSRU) at Toowoomba using the wheat module of the Agricultural Production Simulation Model (McCown *et al.*, in press). Simulations were performed for each of the 20 different combinations of planting conditions. The simulation data did not account for effects of frosts on grain yield and quality. The method by which these effects were handled is detailed in Marshall (1996). The effect on grain protein of grain yield losses due to frost damage was assumed on the advice of G. Hammer (pers. comm., QDPI/CSIRO APSRU, Toowoomba, September 1995) to be governed by a relationship as reported in Woodruff (1992). This meant that the financial impact of a loss of grain yield due to frost damage could be offset to some extent by a corresponding increase in grain protein.

3.6 Risk Attitude

The grower's risk attitude was represented using a constant relative risk aversion (CRRA) functional form. To test the effect of increasing risk aversion on the value of the forecasting system, sensitivity testing was performed using two alternative 'risk-averse' settings for R_r. Anderson and Dillon (1992, p. 55) noted that "speculations as to likely values of (R_r) have ranged from about unity to two" but that "values as small as 0.5 might be presumed if an individual were regarded as hardly concerned at all with risk". Accordingly a value for R_r of 1.5 was chosen in this study to represent the attitude of a typically risk-averse grower and a value of 0.75 to represent a grower who is less risk-averse than typical. In order to value the forecasting system for a risk-indifferent grower, the forecasting system was also valued with R_r set equal to zero.

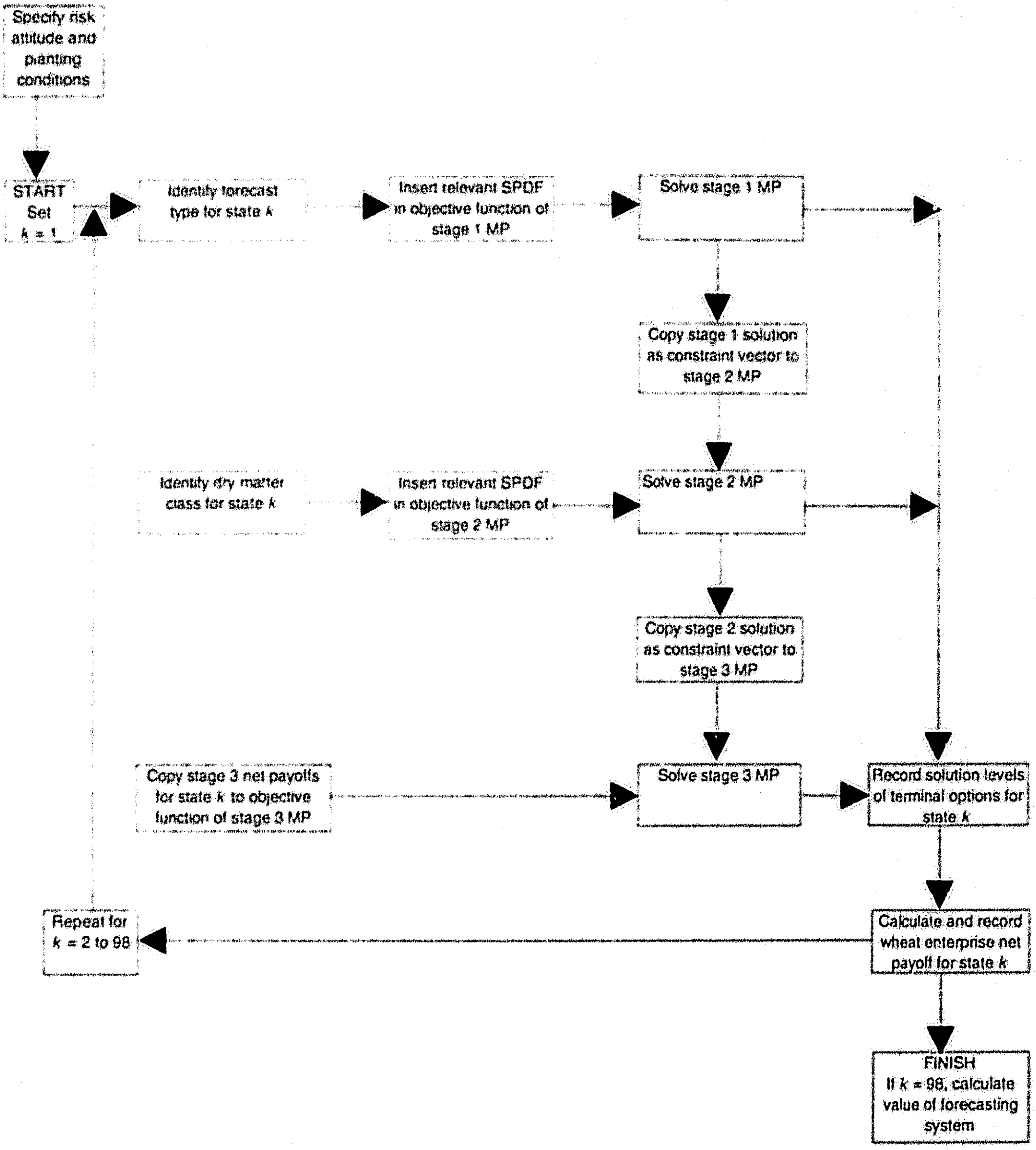
The argument of the utility function was terminal wealth, W, where $W = W_0 + P$, W_0 is initial wealth apportioned to the wheat enterprise and P is annual profit from the wheat enterprise. W_0 was estimated as described in Marshall (1996) to be $225,073. The coefficient of absolute risk aversion, R, corresponding with this level of W_o when $R_r = 0.75$ is 3.3×10^{-6}. For $R_r = 1.5$ the corresponding value of R is 6.7×10^{-6}. This range compares favourably with the range of 2×10^{-6} to 6×10^{-6} used in Patten *et al.* (1988), with the range of 3×10^{-6} to 5×10^{-6} used in Kingwell (1994b) and with the point value of 3×10^{-6} used in Kingwell and Schilizzi (1994).

3.7 Identifying the Prior Optimal Action and Bayes' Strategy

Identification of the prior optimal action and the Bayes' strategy given a particular set of planting conditions and a particular risk attitude was achieved by means of a sequential decision model illustrated in Figure 2. The model was composed of three mathematical programs (MPs), each representing one of the three stages of the decision process illustrated in Figure 1. Each MP was designed to identify, for the relevant decision stage, the options that would maximise expected utility in the imminent season.

The DEMP mathematical programming framework proposed by Lambert and McCarl (1985) was chosen since (a) it is consistent with expected utility theory; (b) the only restriction on the form of the utility function is that it be concave or quasi-concave; and (c) probability distributions for option net payoffs can be directly represented using data sampled from the

Figure 2: A general description of the process of modelling sequential decisions and valuing the forecasting system



historical record, thereby (i) avoiding the need to assume a distributional form; and (ii) implicitly capturing correlations among net payoffs of the various options.

The DEMP framework applied in this study was:

$$\underset{\underline{\Delta}_b}{\text{Max}} \sum_{k=1}^{n} P(\theta_{kb})\, U(W_0 + \underline{a}_{kb}\, \underline{\Delta}_b)$$

Subject to:

$$\underline{T}_b\, \underline{\Delta}_b \leq \underline{l}_{kb}$$
$$\underline{\Delta}_b \geq 0$$

where there are n states of nature (ie., climatic conditions associated with previous years) that may recur in the imminent season, $P(\theta_k)$ is the probability of the climatic conditions associated with the kth previous year recurring in the imminent season, W_0 is initial wealth, $\underline{\Delta}_b$ is a vector of the options available at stage b, $\underline{a}_{kb}$ is the vector of net payoffs per unit of $\underline{\Delta}_b$ under the kth state of nature, $\underline{T}_b$ is the matrix of technical coefficients and $\underline{l}_{kb}$ is the vector of constraint limits applying at stage b under the kth state of nature.

As noted in Section 3.6, $U(.)$ was specified using a CRRA functional form. This form is concave and is therefore consistent with the DEMP framework. Its use necessitates solution by a non-linear programming algorithm. What's*Best!*™ software was used for this purpose.

The EU criterion may lead to diversification among options if the grower is risk-averse and the consequences of alternative options are not perfectly correlated (Anderson *et al.* 1977). It is therefore necessary to distinguish an action, which involves choosing one or more options at each stage, and an option. A grower's flexibility to diversify among available options is characteristically limited, however, by paddock sizes and by the demands on management of running multiple crops with differing requirements. The area of 210 ha assumed to be available for wheat cropping was accordingly assumed to be comprised of three 70 ha paddocks. The grower was thus limited to choosing a maximum of three options at any particular stage. This was enforced in the MPs by restricting option levels to integer values relating to 70 ha paddocks.

The level of the land use constraint in the stage 1 MP was accordingly set at three paddocks. The constraint sets of the three MPs related only to land use.

As shown in Figure 2, stage 2 land use constraint limits were recursively determined by optimal stage 1 option levels. Similarly, stage 3 land use constraint limits were recursively determined by optimal stage 2 option levels. The modelling approach may thus be called recursive stochastic programming (RSP). A macro written in Visual Basic™ code was used to automate application of the approach.

3.9 Net Payoff from the Wheat Enterprise

In order to calculate the net payoff outcome of a prior optimal action it was necessary to (a) identify the net payoffs for the associated terminal prior optimal options as calculated at the decision stage at which termination occurs; (b) deduct from these net payoffs those costs which are sunk costs from the standpoint of the termination stage but are nevertheless costs that need to be considered in determining the effect on the gross margin of the wheat growing enterprise; (c) sum the adjusted net payoff values relating to each of the terminal options in order to determine the gross margin obtained from the wheat enterprise; and (d) deduct the fixed cost of the wheat enterprise from its gross margin. This fixed cost was estimated as described in Marshall (1996) to be $33,395 per year. The corresponding wealth outcome was calculated by adding the profit outcome to initial wealth.

An analogous process was required to determine the outcome of a particular Bayes' strategy.

3.10 Valuing the Climate Forecasting System for the Wheat Enterprise

The data derived and parameters assumed as detailed in earlier sections were used to find the value of the climate forecasting system for each combination of planting conditions and risk attitude. As noted in Section 2.1, this value is given by the maximum amount the grower could afford to pay to use the system without the expected utility of the Bayes' strategy falling below expected utility of the prior optimal action.

4. RESULTS

4.1 Value of the Climate Forecasting System

Estimates of the value of the forecasting system under various sets of planting conditions are presented in Tables 1, 2 and 3 for the cases where the representative grower was assumed to be risk-indifferent (ie., $R_r = 0$), to demonstrate a 'lower than typical' level of risk aversion (ie., $R_r = 0.75$) and to demonstrate a 'typical' level of risk aversion (ie., $R_r = 1.5$) respectively.

Since the probability of each of the (a) five dates of planting opportunity occurring is approximately the same; (b) two levels of initial soil nitrogen occurring is approximately the same; and (c) two levels of initial soil moisture occurring is approximately the same; it is therefore valid to use the sample of 20 combinations of planting conditions to estimate the mean value of the forecasting system given a particular risk attitude. The mean values for the alternative risk attitudes are shown in Table 4. It is evident that the relationship

Table 1: Value of climate forecasting under various planting conditions when R_r equals 0

Initial soil nitrogen	Initial soil moisture	Date of planting opportunity				
		15th May	26th May	3rd June	15th June	28th June
		$/ha	$/ha	$/ha	$/ha	$/ha
40 kg/ha	50%	6.30	4.75	2.51	1.04	0.00
	80%	11.27	5.75	3.39	2.80	1.84
70 kg/ha	50%	7.42	4.74	3.21	1.28	0.28
	80%	2.53	6.01	4.20	2.88	1.87

Table 2: **Value of climate forecasting under various planting conditions when R_r equals 0.75**

Initial soil nitrogen	Initial soil moisture	Date of planting opportunity				
		15th May	26th May	3rd June	15th June	28th June
		$/ha	$/ha	$/ha	$/ha	$/ha
40 kg/ha	50%	6.97	4.66	2.16	0.97	0.00
	80%	4.34	6.14	3.22	2.94	1.64
70 kg/ha	50%	7.83	4.90	2.84	1.16	0.12
	80%	5.14	6.26	4.23	2.86	1.94

Table 3: **Value of climate forecasting under various planting conditions when R_r equals 1.5**

Initial soil nitrogen	Initial soil moisture	Date of planting opportunity				
		15th May	26th May	3rd June	15th June	28th June
		$/ha	$/ha	$/ha	$/ha	$/ha
40 kg/ha	50%	7.30	4.58	1.88	0.90	0.00
	80%	7.36	6.24	3.62	3.10	1.47
70 kg/ha	50%	8.21	4.81	2.49	1.05	0.03
	80%	7.79	6.29	4.55	2.92	2.02

Table 4: Effect of risk attitude on the mean value of the climate forecasting system

Class of risk attitude	R_r	Mean value of forecasting system ($ per ha available for wheat growing)
Risk-indifferent	0.00	3.70
Less risk-averse than typical	0.75	3.52
Typically risk-averse	1.50	3.83

between degree of risk aversion and mean value of the forecasting system is not consistent in direction.

With 20 possible combinations of planting and three alternative grower risk attitudes, the climate forecasting system was evaluated under 60 distinct scenarios. The value of the forecasting system was estimated to be positive in all but three of these scenarios. Under these conditions the value of forecasting was zero. The estimated value of climate forecasting varied considerably according to grower risk attitude and planting conditions. The highest estimated value was $11.27/ha/yr (ie., $2,367/yr for the 210 ha wheat growing area of the representative farm).

The results demonstrate the following predominant tendencies: (1) the value of forecasting tends to increase as planting opportunity becomes earlier (three exceptions out of the 60 scenarios); (2) the value of forecasting tends to be greater when soil moisture at planting is at the higher level (four exceptions); and (3) the value of forecasting tends to be higher when mineralised soil nitrogen at planting is at the higher level (four exceptions). These tendencies indicate that climate forecasts will usually benefit the wheat grower more when planting conditions are relatively good than when they are relatively poor.

The data included in Tables 1 to 3 were reconfigured in Tables A1.1 to A1.4 (Appendix 1) to be in a form more suitable for exploring the effect on the value of forecasting of increasing aversion to risk. It is apparent from these tables that there is no general relationship to the effect that the value of the climate forecasting system to the representative grower consistently increases (or decreases) as s/he becomes more risk-averse. Byerlee and Anderson (1982) and Mjelde and Cochran (1988) made similar findings. However, a few tendencies can be noted. Namely, the relationship between system value and risk aversion is more likely to be positive (a) the earlier a planting opportunity occurs; (b) the higher the level of soil nitrogen at planting; and (c) the higher the level of soil moisture at planting. In short, the relationship between the value of climate forecasting and the representative grower's degree of risk aversion will more certainly be positive the more optimal are planting conditions.

The analysis thus confirms Hilton's (1981) conclusion that variation in factors external to an information system (instanced in this study by risk attitude and planting conditions) will not necessarily have a consistent directional effect on its value.

4.2 Characteristics of the Prior and Posterior Probability Distributions for Monetary Outcomes

Insight into the patterns of climate forecasting system value discussed above can be obtained by comparing the prior and posterior probability distribution functions (PDFs) for monetary outcomes. Such a comparison was performed by referring to descriptive statistics for the prior and posterior PDFs for profit under various planting conditions and degrees of risk aversion as presented in Tables A2.1 to A2.12 (Appendix 2).

A number of generalisations can be made regarding the mean of the prior PDF for profit: (1) mean profit increases as planting opportunity becomes earlier; (2) mean profit is greater when initial soil moisture is at the higher level; (3) mean profit is greater when initial soil nitrogen is at the higher level; and (4) mean profit mainly remains constant, or occasionally declines (ie., if the change in risk attitude is sufficient to obtain a change in the prior optimal action), as degree of risk aversion increases. In the occasional scenarios referred to under

(4), the declines in mean profit are associated with reductions in standard deviation. The prior PDFs are in general negatively skewed (as evidenced by the measure of relative skewness being negative for all combinations of risk attitude and planting conditions).

Use of forecasting increased mean profit in all of the 60 situations analysed except for three in which mean profit was unchanged. These situations, corresponding with the least agronomically favourable of the combinations of planting conditions analysed, were those associated with the forecasting system having zero value.

The directional effect of use of climate forecasting on the standard deviation of profit is inconsistent, nor are strong tendencies evident. The effect of use of climate forecasting on the skewness of the profit distribution is also not consistent in direction. When soil moisture is at the lower of the two levels, use of forecasting does consistently reduce the negative skewness of the distribution. When soil moisture is at the higher of the two levels, however, the effect is not consistent in direction.

5. SUMMARY AND CONCLUSIONS

In this study the value of a particular climate forecasting system for wheat growing by a representative grower in the vicinity of Goondiwindi was estimated across a range of decision environments. The decision environments differed both in terms of the grower's risk attitude and in terms of planting conditions.

The system was found to have value in all but three of the 60 decision environments analysed. The mean value of the forecasting system across the various sets of planting conditions analysed was estimated to lie within the range of $3.52 to $3.83 per hectare available for wheat growing (the range due to the range of risk attitudes assumed).

One possible benchmark for assessing the relative significance of the above values is the estimate by Brennan (1989) that on average the release of a new wheat variety provides yield and quality benefits to growers of $3.38/t. For an average Goondiwindi wheat yield of 1.4 t/ha (Lawrence 1993), this is equivalent to a farm-level benefit of $4.73/ha/yr. Hence the mean annual benefit to the representative grower from the development of the forecasting system is lower than that from the development of an average new wheat variety. Assessment of the relative economic merits of the two types of research project, however, would require that the costs of each also be accounted for.

The estimated value of the forecasting system varied considerably according to grower risk attitude and planting conditions. It is not possible to conclude that the value of the forecasting system will invariably be higher (a) the earlier a planting opportunity occurs; (b) the higher the level of initial soil nitrogen; (c) the higher the level of initial soil moisture; or (d) the more risk-averse the grower; nor that it will be invariably lower. However, the results indicate that as planting conditions become more optimal the value of the forecasting system to the representative grower (a) will *usually* increase; and (b) is *more likely* to increase with increasing risk-aversion.

The approach used in this study could usefully be adapted to value the benefits of the climate forecasting system in a range of other decision environments, thereby gaining sufficient observations to be able to estimate more confidently the aggregate benefits of use of the system for wheat growing in the north-eastern grain belt.

This approach could also be adapted to value climate forecasting systems other than the one addressed in this study. Prospects for progress in climatological research of relevance to seasonal forecasting (Nicholls 1994; Hunt 1994) suggests climate forecasting systems, like other agricultural inputs, will be subject to innovation in coming years.

REFERENCES

Anderson, J.R. (1991), 'A framework for examining the impacts of climate variability', in Muchow, R.C. and Bellamy, J.A. (eds), *Climatic Risk in Crop Production: Models and Management for the Semiarid Tropics and Subtropics*, C.A.B. International, Wallinford, U.K., 1-18.

Anderson, J.R. and Dillon, J.L. (1992), *Risk Analysis in Dryland Farming Systems*, Farm Systems Management Series, FAO, Rome.

Anderson, J.R., Dillon, J.L. and Hardaker, B. (1977), *Agricultural Decision Analysis*, Iowa State University Press, Ames, Iowa.

Bacquet, A.E., Halter, A.N. and Conklin, F.S. (1976), 'The value of frost forecasting: a Bayesian appraisal', *American Journal of Agricultural Economics* 58, 511-520.

Brennan, J.P. (1989), 'An analytical model of a wheat breeding program', *Agricultural Systems* 31(4), 349-66.

Byerlee, D. and Anderson, J.R. (1982), 'Risk, utility and the value of information in farmer decision making', *Review of Marketing and Agricultural Economics* 50 (3), 231-246.

Callaghan, A.R. (1973), 'The impact of drought on Australian wheat production and marketing', in Lovett, J.V. (ed.), *The Environmental, Economic and Social Significance of Drought*, Angus and Robertson, Sydney, 99-120.

Dalal, R.C. and Mayer, R.J. (1987), 'Long-term trends in soils under continuous cultivation and cereal cropping in southern Queensland. VII. Dynamics of nitrogen mineralisation potential and microbial biomass', *Australian Journal of Soil Research* 25, 461-472.

Department of Primary Industries and Energy (1992), *New National Drought Policy*, Press release DPIE92/67C, Department of Primary Industry and Energy, Canberra.

Dillon, J.L. and Hardaker, J.B. (1980), *Farm Management Research for Small Farmer Development*, FAO Agricultural Services Bulletin No. 41, FAO, Rome.

Dorward, A. (1994), 'Farm planning with resource uncertainty: a semi-sequential approach', *European Review of Agricultural Economics* 21, 309-324.

Drought Policy Review Task Force (1990), *National Drought Policy*, Volume 1, Report of the Drought Policy Review Task Force, Australian Government Publishing Service, Canberra.

Easter, C.D. and Paris, Q. (1983), 'Supply response with stochastic technology and prices in Australia's rural export industries', *Australian Journal of Agricultural Economics* 27, 12-30.

Hardaker, J.B., Pandey, S. and Patten, L.H. (1991), 'Farm planning under uncertainty', *Review of Marketing and Agricultural Economics* 59, 9-22.

Hey, J.D. (1979), *Uncertainty in Microeconomics*, Martin Robertson, Oxford.

Hilton, R.W. (1981), 'The determinants of information value: synthesizing some general results', *Management Science* 27(1), 57-64.

Hunt, B.G. (1994), 'The use of global climatic models in deriving seasonal outlooks', *Agricultural Systems and Information Technology* 6 (2),11-15.

Kingwell, R.S., Morrison, D.A. and Bathgate, A.D. (1992), 'The effect of climatic risk on dryland farm management', *Agricultural Systems* 39, 153-175.

Kingwell, R.S. and Schilizzi, S.G.M. (1994), 'Dryland pasture improvement given climatic risk', *Agricultural Systems* 45, 175-91.

Kingwell, R. (1994a), 'Effects of tactical responses and risk aversion on farm wheat supply', *Review of Marketing and Agricultural Economics* 62(1), 29-42.

Kingwell, R.S. (1994b), 'Risk attitude and dryland farm management', *Agricultural Systems* 45, 191-202.

Lambert, D.K. and McCarl, B.A. (1985), 'Risk modeling using direct solution of nonlinear approximations of the utility function', *American Journal of Agricultural Economics* 67(4), 846-52.

Lawrence, D. (1992), 'Crop choice', in French, V. (ed.), *Western Downs and Maranoa Crop Management Notes*, Department of Primary Industries, Queensland, Brisbane, 1-4.

Ogisi, M.E., Hardaker, J.B. and Torkamani, J. (1994), 'Utility efficient programming: an valuation', Paper presented at the 38th Annual Conference of the Australian Agricultural Economics Society, Victoria University, Wellington, New Zealand, 7-11 February.

Machina, M.J. (1989), 'Choice under uncertainty: problems solved and unsolved', in Hey, J.D. (ed.), *Current Issues in Microeconomics*, MacMillan, Houndmills, UK, 12-46.

Marshall, G.R. (1996), Risk attitude, planting conditions and the value of climate forecasts to a dryland wheat grower, Unpublished M.Ec. dissertation, Faculty of Economics, Business and Law, University of New England, Armidale.

Mazzocco, M.A., Mjelde, J.W., Sonka, S.T., Lamb, P.J. and Hollinger, S.E. (1992), 'Using hierarchical systems aggregation to model the value of information in agricultural systems; an application for climate forecast information', *Agricultural Systems* 40, 393-412.

McCown, R.L. (in press), 'APSIM: an agricultural production system simulation model for operational research', *Mathematics and Computers in Simulation.*

Mjelde, J.W. and Cochran, M.J. (1988), 'Obtaining lower and upper bounds on the value of seasonal climate forecasts as a function of risk preferences', *Western Journal of Agricultural Economics* 13(2), 285-293.

Mjelde, J.W. and Dixon, B.L. (1993), 'Valuing the lead time of periodic forecasts in dynamic production systems', *Agricultural Systems* 42, 41-55.

Mjelde, J.W., Sonka, S.T., Dixon, B.L. and Lamb, P.J. (1988), 'Valuing forecast characteristics in a dynamic agricultural production system', *American Journal of Agricultural Economics* 70, 674-684.

Murphy, R. (1993), 'Computerised decision support packages for farming', in French, V. (ed.), *Western Downs and Maranoa Crop Management Notes*, Department of Primary Industries, Queensland, Brisbane, 217-218.

Nicholls, N. (1994), 'The use of statistical models in deriving seasonal climate outlooks', *Agricultural Systems and Information Technology* 6 (2), 10-11.

Norris, P.E. and Kramer, R.A. (1990), 'The elicitation of subjective probabilities with applications to agricultural economics', *Review of Marketing and Agricultural Economics* 58(2&3), 127-147.

Patten, L.H., Hardaker, J.B. and Pannell, D.J. (1988), 'Utility-efficient programming for whole-farm planning', *Australian Journal of Agricultural Economics* 32(2&3), 88-97.

Pope, R.D. and Just, R.E. (1991), 'On testing the structure of risk preferences in agricultural supply analysis', *American Journal of Agricultural Economics* 73(3), 743-748.

Scoccimarro, M., Mues, C. and Topp, V. (1994), *Climatic Variability and Farm Risk*, ABARE, Canberra.

Schoemaker, P.J.H. (1982), 'The expected utility model: its variants, purposes, evidence and limitations', *Journal of Economic Literature* 20, 529-563.

Smith, K. (1995a), *An Economic Study of the Queensland Grain Industry 1987-88 to 1989-90*, Queensland Department of Primary Industries, Brisbane.

Smith, K. (1995b), *An Economic Study of the Queensland Grain Industry 1990-91 to 1992-93*, Queensland Department of Primary Industries, Brisbane.

Stone, R. (1994), 'Adapting climate information for the benefit of agriculture in Australia', *Agricultural Systems and Information Technology* 6 (2), 34-41.

Stone, R. and Auliciems, A. (1992), 'SOI phase relationships with rainfall in eastern Australia', *International Journal of Climatology* 12, 625-636.

Stone, R.C. and Hammer, G.L. (1992), 'Seasonal climate forecasting in crop management', *Proceedings of the 6th Australian Society of Agronomy Conference, Armidale, February 1992*, Australian Society of Agronomy, Parkville, Victoria, 218-221.

Stone, R., Hammer, G. and Abawi, Y. (undated), Usefulness of Rainfall and Frost Prediction in Management of Wheat in North-Eastern Australia, Final report on GRDC Project DAQ119, Queensland Department of Primary Industries, Toowoomba.

Trebeck, D.B. and Hardaker, J.B. (1972), 'The integrated use of simulation and stochastic programming for whole farm planning under risk', *Australian Journal of Agricultural Economics* 16 (2), 115-126.

White, D.H. (1994), 'Editorial', *Agricultural Systems and Information Technology* 6 (4), 5.

Woodruff, D.R. (1992), ''WHEATMAN' a decision support system for wheat management in subtropical Australia', *Australian Journal of Agricultural Research* 43, 1483-99.

APPENDIX 1: EFFECT OF RISK ATTITUDE ON VALUE OF CLIMATE FORECASTING

Table A1.1: Effect of risk attitude on value of climate forecasting when soil nitrogen = 40 kg/ha and soil moisture = 50%

R_r	Date of planting opportunity				
	15th May	26th May	3rd June	15th June	28th June
	$/ha	$/ha	$/ha	$/ha	$/ha
0	6.30	4.75	2.51	1.04	0.00
0.75	6.97	4.66	2.16	0.97	0.00
1.5	7.30	4.58	1.88	0.90	0.00

Table A1.2: Effect of risk attitude on value of climate forecasting when soil nitrogen = 40 kg/ha and soil moisture = 80%

R_r	Date of planting opportunity				
	15th May	26th May	3rd June	15th June	28th June
	$/ha	$/ha	$/ha	$/ha	$/ha
0	11.27	5.75	3.39	2.80	1.84
0.75	4.34	6.14	3.22	2.94	1.64
1.5	7.36	6.24	3.62	3.10	1.47

Table A1.3: Effect of risk attitude on value of climate forecasting when soil nitrogen = 70 kg/ha and soil moisture = 50%

R_r	Date of planting opportunity				
	15th May	26th May	3rd June	15th June	28th June
	$/ha	$/ha	$/ha	$/ha	$/ha
0	7.42	4.74	3.21	1.28	0.28
0.75	7.83	4.90	2.84	1.16	0.12
1.5	8.21	4.81	2.49	1.05	0.03

Table A1.4: Effect of risk attitude on value of climate forecasting when soil nitrogen = 70 kg/ha and soil moisture = 80%

R_r	Date of planting opportunity				
	15th May	26th May	3rd June	15th June	28th June
	$/ha	$/ha	$/ha	$/ha	$/ha
0	2.53	6.01	4.20	2.88	1.87
0.75	5.14	6.26	4.23	2.86	1.94
1.5	7.79	6.29	4.55	2.92	2.02

APPENDIX 2: MEASURES OF THE PRIOR AND POSTERIOR PDFS FOR PROFIT

Table A2.1: Measures of the prior and posterior PDFs for profit. Assumptions: soil nitrogen = 40 kg/ha; soil moisture = 50%; $R_r = 0$

Date of planting opportunity	Distribution	Measures of PDF for profit		
		Mean ($)	Standard deviation	Relative skewness
15th May	Prior	(13 006)	19 189	(0.91)
	Posterior	(11 682)	18 160	(0.51)
26th May	Prior	(13 283)	14 480	(1.47)
	Posterior	(12 285)	14 882	(1.19)
3rd June	Prior	(15 392)	12 777	(1.24)
	Posterior	(14 866)	14 287	(0.95)
15th June	Prior	(19 150)	9 481	(0.64)
	Posterior	(18 932)	9 927	(0.39)
28th June	Prior	(22 213)	7 330	(0.28)
	Posterior	(22 213)	7 330	(0.28)

Table A2.2: Measures of the prior and posterior PDFs for profit. Assumptions: soil nitrogen = 40 kg/ha; soil moisture = 80%; $R_r = 0$

Date of planting opportunity	Distribution	Measures of PDF for profit		
		Mean ($)	Standard deviation	Relative skewness
15th May	Prior	7 378	34 889	(1.49)
	Posterior	9 746	33 386	(1.32)
26th May	Prior	4 491	22 276	(2.12)
	Posterior	5 698	21 573	(2.38)
3rd June	Prior	2 704	18 630	(2.22)
	Posterior	3 415	19 568	(2.38)
15th June	Prior	373	14 079	(2.11)
	Posterior	961	13 497	(2.13)
28th June	Prior	(6 156)	11 631	(1.54)
	Posterior	(5 770)	12 693	(1.27)

**Table A2.3: Measures of the prior and posterior PDFs for profit.
Assumptions: soil nitrogen = 70 kg/ha; soil moisture = 50%; $R_r = 0$**

Date of planting opportunity	Distribution	Measures of PDF for profit		
		Mean ($)	Standard deviation	Relative skewness
15th May	Prior	(5 092)	18 889	(0.92)
	Posterior	(3 533)	18 272	(0.39)
26th May	Prior	(5 212)	16 398	(1.25)
	Posterior	(4 216)	15 283	(1.23)
3rd June	Prior	(7 579)	12 481	(1.25)
	Posterior	(6 905)	14 763	(0.96)
15th June	Prior	(11 199)	9 155	(0.68)
	Posterior	(10 932)	9 899	(0.43)
28th June	Prior	(14 386)	7 029	(0.27)
	Posterior	(14 327)	8 377	(0.06)

**Table A2.4: Measures of the prior and posterior PDFs for profit.
Assumptions: soil nitrogen = 70 kg/ha; soil moisture = 80%; $R_r = 0$**

Date of planting opportunity	Distribution	Measures of PDF for profit		
		Mean ($)	Standard deviation	Relative skewness
15th May	Prior	13 321	26 585	(1.89)
	Posterior	13 851	28 052	(1.61)
26th May	Prior	12 657	22 095	(2.16)
	Posterior	13 919	21 484	(2.39)
3rd June	Prior	10 446	18 431	(2.22)
	Posterior	11 329	18 289	(2.35)
15th June	Prior	8 176	13 901	(2.11)
	Posterior	8 780	13 945	(2.22)
28th June	Prior	1 814	13 270	(1.29)
	Posterior	2 206	12 971	(1.16)

Table A2.5: Measures of the prior and posterior PDFs for profit. Assumptions: soil nitrogen = 40 kg/ha; soil moisture = 50%; R_r = 0.75

Date of planting opportunity	Distribution	Measures of PDF for profit		
		Mean ($)	Standard deviation	Relative skewness
15th May	Prior	(13 006)	19 189	(0.91)
	Posterior	(11 273)	16 602	(0.56)
26th May	Prior	(13 283)	14 480	(1.47)
	Posterior	(12 285)	14 882	(1.19)
3rd June	Prior	(15 392)	12 777	(1.24)
	Posterior	(14 866)	14 287	(0.95)
15th June	Prior	(19 150)	9 481	(0.64)
	Posterior	(18 932)	9 927	(0.39)
28th June	Prior	(22 213)	7 330	(0.28)
	Posterior	(22 213)	7 330	(0.28)

Table A2.6: Measures of the prior and posterior PDFs for profit. Assumptions: soil nitrogen = 40 kg/ha; soil moisture = 80%; R_r = 0.75

Date of planting opportunity	Distribution	Measures of PDF for profit		
		Mean ($)	Standard deviation	Relative skewness
15th May	Prior	5 469	26 951	(1.85)
	Posterior	6 028	23 631	(1.56)
26th May	Prior	4 491	22 276	(2.12)
	Posterior	5 670	20 767	(2.47)
3rd June	Prior	2 704	18 630	(2.22)
	Posterior	3 329	17 782	(2.47)
15th June	Prior	373	14 079	(2.11)
	Posterior	961	13 497	(2.13)
28th June	Prior	(6 156)	11 631	(1.54)
	Posterior	(5 776)	12 494	(1.30)

Table A2.7: Measures of the prior and posterior PDFs for profit. Assumptions: soil nitrogen = 70 kg/ha; soil moisture = 50%; $R_r = 0.75$

Date of planting opportunity	Distribution	Measures of PDF for profit		
		Mean ($)	Standard deviation	Relative skewness
15th May	Prior	(5 092)	18 889	(0.92)
	Posterior	(3 583)	16 905	(0.53)
26th May	Prior	(5 274)	14 225	(1.51)
	Posterior	(4 226)	14 672	(1.22)
3rd June	Prior	(7 579)	12 481	(1.25)
	Posterior	(6 910)	14 055	(0.95)
15th June	Prior	(11 199)	9 155	(0.68)
	Posterior	(10 932)	9 899	(0.43)
28th June	Prior	(14 386)	7 029	(0.27)
	Posterior	(14 339)	7 889	(0.09)

Table A2.8: Measures of the prior and posterior PDFs for profit. Assumptions: soil nitrogen = 70 kg/ha; soil moisture = 80%; $R_r = 0.75$

Date of planting opportunity	Distribution	Measures of PDF for profit		
		Mean ($)	Standard deviation	Relative skewness
15th May	Prior	13 321	26 585	(1.89)
	Posterior	14 098	23 618	(1.59)
26th May	Prior	12 657	22 095	(2.16)
	Posterior	13 892	20 957	(2.42)
3rd June	Prior	10 446	18 431	(2.22)
	Posterior	11 281	17 504	(2.49)
15th June	Prior	8 176	13 901	(2.11)
	Posterior	8 770	13 730	(2.19)
28th June	Prior	1 814	13 270	(1.29)
	Posterior	2 206	12 971	(1.16)

Table A2.9: Measures of the prior and posterior PDFs for profit.
Assumptions: soil nitrogen = 40 kg/ha; soil moisture = 50%; R_r = 1.5

Date of planting opportunity	Distribution	Measures of PDF for profit		
		Mean ($)	Standard deviation	Relative skewness
15th May	Prior	(13 207)	16 747	(1.07)
	Posterior	(11 273)	16 602	(0.56)
26th May	Prior	(13 283)	14 480	(1.47)
	Posterior	(12 285)	14 882	(1.19)
3rd June	Prior	(15 392)	12 777	(1.24)
	Posterior	(14 940)	13 395	(1.09)
15th June	Prior	(19 150)	9 481	(0.64)
	Posterior	(18 932)	9 927	(0.39)
28th June	Prior	(22 213)	7 330	(0.28)
	Posterior	(22 213)	7 330	(0.28)

Table A2.10: Measures of the prior and posterior PDFs for profit.
Assumptions: soil nitrogen = 40 kg/ha; soil moisture = 80%; R_r = 1.5

Date of planting opportunity	Distribution	Measures of PDF for profit		
		Mean ($)	Standard deviation	Relative skewness
15th May	Prior	5 469	26 951	(1.85)
	Posterior	5 918	22 035	(1.43)
26th May	Prior	4 244	19 980	(2.41)
	Posterior	5 467	19 411	(2.45)
3rd June	Prior	2 704	18 630	(2.22)
	Posterior	3 302	17 367	(2.52)
15th June	Prior	373	14 079	(2.11)
	Posterior	961	13 497	(2.13)
28th June	Prior	(6 156)	11 631	(1.54)
	Posterior	(5 779)	12 443	(1.30)

Table A2.11: Measures of the prior and posterior PDFs for profit. Assumptions: soil nitrogen = 70 kg/ha; soil moisture = 50%; $R_r = 1.5$

Date of planting opportunity	Distribution	Measures of PDF for profit		
		Mean ($)	Standard deviation	Relative skewness
15th May	Prior	(5 335)	16 449	(1.08)
	Posterior	(3 583)	16 905	(0.53)
26th May	Prior	(5 274)	14 225	(1.51)
	Posterior	(4 226)	14 672	(1.22)
3rd June	Prior	(7 579)	12 481	(1.25)
	Posterior	(6 910)	14 055	(0.95)
15th June	Prior	(11 199)	9 155	(0.68)
	Posterior	(10 932)	9 899	(0.43)
28th June	Prior	(14 386)	7 029	(0.27)
	Posterior	(14 346)	7 695	(0.10)

Table A2.12: Measures of the prior and posterior PDFs for profit. Assumptions: soil nitrogen = 70 kg/ha; soil moisture = 80%; $R_r = 1.5$

Date of planting opportunity	Distribution	Measures of PDF for profit		
		Mean ($)	Standard deviation	Relative skewness
15th May	Prior	13 321	26 585	(1.89)
	Posterior	13 984	22 031	(1.46)
26th May	Prior	12 339	19 590	(2.55)
	Posterior	13 892	20 957	(2.42)
3rd June	Prior	10 446	18 431	(2.22)
	Posterior	11 257	17 231	(2.52)
15th June	Prior	8 176	13 901	(2.11)
	Posterior	8 765	13 653	(2.16)
28th June	Prior	1 814	13 270	(1.29)
	Posterior	2 206	12 971	(1.16)