The Australian Journal of Agricultural and Resource Economics, 44:2, pp. 269–287

Assisting decision-making in Queensland barley production through chance constrained programming†

V. Jyothi Gali and Colin G. Brown*

A chance constrained programming model is developed to assist Queensland barley growers make varietal and agronomic decisions in the face of changing product demands and volatile production conditions. Unsuitable or overlooked in many risk programming applications, the chance constrained programming approach nonetheless aptly captures the single-stage decision problem faced by barley growers of whether to plant lower-yielding but potentially higher-priced malting varieties, given a particular expectation of meeting malting grade standards. Different expectations greatly affect the optimal mix of malting and feed barley activities. The analysis highlights the suitability of chance constrained programming to this specific class of farm decision problem.

1. Introduction

The Queensland barley industry encapsulates much of what Australia's agricultural industries currently experience. New demand patterns, volatile production conditions and changing institutional arrangements pose major challenges for barley growers and other industry participants. Meeting these challenges and adapting to the changing conditions requires a range of sophisticated information and new insights. This study seeks to provide some of this information.

Barley can be grown for malting or feed grain. The higher-priced malting barley can only be grown from malting varieties that yield less than feed varieties. In the past, Queensland growers primarily have planted malting varieties. However, barley grown from malting varieties often does not meet protein and grain size standards, and is sold on the lower-priced, feed barley

† The authors gratefully acknowledge the comments of two anonymous referees in the preparation of this article.

* V. Jyothi Gali is Senior Research Officer, Business Strategy Unit, Queensland Department of Primary Industries, Queensland and Colin G Brown is Senior Lecturer, School of Natural and Rural Systems Management, the University of Queensland, Hartley Teakle Building, Brisbane.

market. The dilemma for growers is whether to plant lower-yielding malting varieties that realise higher prices if the malting grade standards are met, or to plant higher-yielding but lower-priced feed varieties. Apart from varietal choice, growers must also select agronomic practices that determine barley yields and protein levels. Highly variable production conditions in Queensland in the 1990s, that have influenced barley yields, protein levels, and thus the ability to meet malting grade standards, complicate the varietal and agronomic choices. Growth in the intensively fed livestock industry, now the main customer of Queensland-grown barley,[1] adds to the list of factors growers need to consider.

Requirements of the two main end-use markets, along with issues involved for growers in meeting these specifications, follow. The decision problem faced by growers is argued to be closely modelled by chance constrained programming. The results and approach then reported reveal the insights chance constrained programming sheds on the choices faced by barley growers.

2. Background

Barley can be used for malting or as livestock feed. The protein content of malting barley determines the suitability of the grain for malting and performance of the malt for brewing.[2] To achieve a uniform rate of modification from barley to malt, maltsters and brewers desire a narrow band of around 10 per cent protein. Uneven protein distributions within batches of grain result in different rates of grain modification and inconsistencies in brewery performance. Purchasing grain with high protein increases costs to the brewer through the loss of extract and beer filtration inefficiencies. Small differences in protein level, consistency, and germination rate significantly affect the value of malt to the brewer. Thus maltsters have specific requirements, offering premiums in the market for a consistent protein range between 8.5 to 12.5 per cent.

Conversely, protein variability in feed barley is less important. Gali, Brown and Wegener (1998) demonstrated that the implicit marginal value of protein in feed barley is not large, although it does depend on the livestock

[1] The proportion of Queensland grown barley used for feed grain rose from 40 per cent in 1984 to 80 per cent in 1994 (Gali 1998).

[2] For the brewer, protein is good and bad. Too much protein induces haze formation in beer, which can be a problem in the filtration process in the brewery, and in the market as the beer ages. Conversely, too little protein reduces foam and increases the risk of undernourishing the yeast. In the malthouses, lower protein barley malts more rapidly.

type and protein range.[3] In practice, livestock feeders in Queensland pay no premium for protein in feed barley, preferring to source other feed inputs for their protein requirements, and to use feed barley for energy.

Chirchir (1994) found the relationship between nitrogen application, grain yield and grain protein in barley complex and, at times, seemingly contradictory. The amount of nitrogen applied to cereals usually determines grain yield and protein content due to its high mobility in the soil and ease of absorption by the roots. Malting barley varieties, unlike feed varieties and wheat, are selected for low grain nitrogen content. Farmers growing malting barley are concerned that protein content may be unacceptably high with nitrogen application, and thus lead to the loss of premiums. Growers of feed barley are concerned that the use of high rates of nitrogen may be uneconomical (Birch and Long 1990).

Abnormal production conditions in the period since detailed records were kept preclude a full understanding of the distribution of protein levels in malting and feed barley receivals. The box plots in figure 1 indicate the variability in protein levels in 1992–93, a particularly dry season, and in 1995–96, a more normal season. Not only was the median protein level for malting barley lower in the dry season (10.6 per cent) than in the normal season (11.8 per cent), but the distribution was also greater. For feed barley, the variability in protein level in the dry season exceeded that in the normal season, although the median protein level was higher in the dry season. In dry seasons, the rainfall is lower, temperatures higher, and fertilisers are not applied, resulting in greater variation in protein levels.

Another relationship exists between protein content and grain size, the other important attribute in malting grade standards. Large grain is associated with low protein content and low percentage screenings (Goyne 1995).[4] High temperatures during grain filling result in small grain and more screenings. The median protein value for feed barley in 1992–93 exceeded that in 1995–96 when, because of the dry season, grain size was small leading to high protein levels.

[3] Raising protein level in feed barley from 8 per cent to 14 per cent increased the implicit price of feed barley fed to beef cattle by $A8 to $A12 per tonne, by $A6.20 to $A7.60 per tonne for pigs depending on liveweight, and had no impact on the implicit price of feed barley fed to dairy cattle (Gali *et al.* 1998).

[4] Grain size is defined according to barley grain retained above a 2.5 mm screen, whereas screenings are defined as all matter passing through a 2.2 mm screen, whether barley grain, barley chaff, other grains, weed seeds, etc. For malting grade barley, GRAINCO, the major marketer of barley in Queensland, specifies that 75 to 85 per cent by weight meets this minimum size, and that screenings represent a maximum of 3 to 5 per cent by weight.

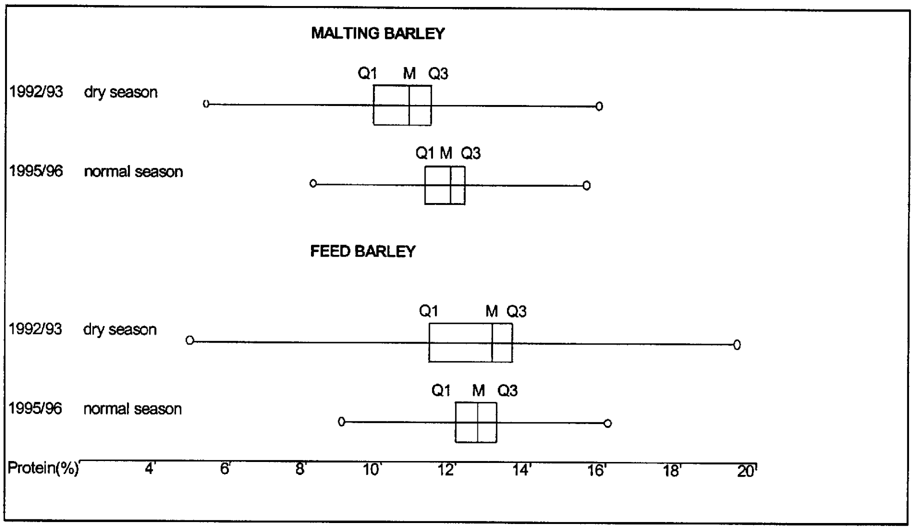

Figure 1 Protein variability in Queensland barley receivals for selected years

Note: The horizontal axis represents protein level in percentages. M represents the median protein level, Q1 represents the first quartile (25 per cent of grain receivals are below this protein level), and Q3 is the third quartile (25 per cent of receivals are above this protein level). The box represents the Inter-quartile Range, and the circles at the end of each whisker represent 2 standard deviations from the mean protein levels. The wider the box and the longer the whisker, the greater is the variance of protein, and the higher is the risk for maltsters in their malting processing.
Source: GRAINCO receival dockets

The major marketer of barley in Queensland, GRAINCO estimates that malting varieties account for 60 to 90 per cent of barley sown, despite only 20 to 50 per cent of all barley receivals meeting the malting grade standards. The seemingly irrational predominance of malting varieties is partly historical, partly behavioural as some growers enjoy the status of producing the higher quality malting barley, partly institutional with the overwhelming focus of the breeding system on malting varieties, and partly a lack of information on the effect of varietal choice and agronomic practices given the complexity of the decision problem. This article focuses on the latter factor.

A survey of barley growers by Gali (1998) revealed widespread concern over meeting malting grade standards, but also highlighted great differences in attitudes to the risk in meeting these standards across individual growers. The survey and subsequent interviews with agricultural scientists revealed that growers make choices about variety and certain agronomic practices, such as fertiliser at sowing, but then have few tactical options open to them to meet the malting grade standards. Thus from a grower's perspective, once having made a varietal choice, they then face a fixed probability of meeting the standards. As discussed below, this decision problem lends itself closely to chance constrained programming.

3. Analytical approach

3.1 General approach

A plethora of literature exists on handling variability in farm planning. Risk programming approaches have appeared since the 1950s to account for variability in the farm objective function. Some of the key developments include Freund (1956) for quadratic risk programming, Hazell (1971) for mean of total absolute deviations (MOTAD), Chen and Baker (1974) for marginal risk constrained linear programming, Tauer (1983) for target MOTAD, Okunev and Dillon (1988) for mean Gini analysis, Patten *et al.* (1988) for utility efficient programming, and Berbel (1993) for mean partial absolute deviations.[5]

Variability in the constraint set has been accommodated by various stochastic programming approaches. Among the more popular of these approaches has been discrete stochastic programming as reported in Cocks (1968) and Rae (1971a, 1971b). Discrete stochastic programming has enjoyed widespread use in farm planning and other studies because of its allowance for risks in constraint coefficients, resources, and the objective function.[6] It is particularly suited to two-stage decision problems where strategic decisions are made in a first stage, and tactical adjustments follow in response to particular states of nature. The discrete stochastic programming approach allows for the incorporation of detailed adjustment activities.

Chance constrained programming (CCP), first reported in Charnes and Cooper (1959), has been another stochastic programming approach used in farm planning. Since Charnes and Cooper's seminal work, methodological advances in CCP have occurred to accommodate variability in resource supplies and technical coefficients. Application of the CCP approach to agricultural problems include optimal feedmixes (Chen 1973), feed supply

[5] For an outline and critique of these approaches, see Hardaker *et al.* (1991) and Gali (1998).

[6] Kingwell (1994) used discrete stochastic programming to model a grain farming system in Western Australia, while Brown and Drynan (1986) showed its application to abattoir location, size and commodity flows in Queensland.

(Wicks and Guise 1978), yield variability (Easter and Paris 1983; Paris and Easter 1985; Paris 1989), and soil conservation (Zhu *et al.* 1994; Johnson and Segarra 1995). Where discrete stochastic programming has absolute constraints that are met in the stochastic case by the choice of tactical decisions in each state of nature, CCP allows constraints to be met with a particular level of probability. In some CCP applications, penalty costs can be associated with the probabilities of not meeting particular constraints.

CCP formulation has enabled smaller, more tractable models than discrete stochastic programming by replacing the adjustment activities needed for each state of nature by a set of probabilistic constraints. Nowadays, the need for smaller, more tractable models has decreased, and the rich specification of adjustment activities in each state of nature has made discrete stochastic programming a more rigorous planning tool in many applications, especially where sequential decisions are involved.

Unfortunately, the case modelled here of the sowing and agronomic decisions of barley growers does not fit the two-stage decision problem. As Gali (1998) reported, barley growers make choices about varieties and agronomic practices at sowing based on their expectation of seasonal conditions. They then have few management options open to them once seasonal conditions become known. Conversely, the chance constraints in the CCP formulation closely mimic this decision-making environment and behaviour of barley growers.

The CCP formulation based on these probabilistic (protein) chance constraints indicates optimal crop activities, agronomic practices, and other farm activities that should be pursued, given an expectation or acceptance that the malting grade standards will be met a certain proportion of the time. The solution does not reveal the consequences of what happens when the malting grade standards are not met. Although the general CCP formulation allows for incorporation of penalty costs associated with violation of chance constraints, determination of penalty costs in this case is not trivial. Penalty costs are not merely the premium of malting barley over feed barley as the optimal solution contains a mix of malting barley, feed barley and other crop and farm activities. Instead, the penalty costs depend on a complex set of relationships between yield levels, applied nitrogen, soil type and weather conditions.

Thus the CCP formulation and information contained in this article reveal only selected insights for the barley grower.[7] To be fully informed, growers also need information on costs associated with not meeting the malting grade standards when various risks are taken. Nevertheless, because the chance

[7] Gali (1998), for instance, also used passive, single-stage discrete stochastic programming to examine other dimensions of the risky decisions faced by barley growers.

constraint formulation so closely captures the decision problem perceived by barley growers, it provides information of direct relevance to them. Hence the advice contained in the optimal farm plans that appear in the columns of table 1 and that are discussed in the fourth section can be tailored to the specific beliefs or attitudes that individual barley growers have in meeting the malting grade standards. Growers in the survey of Gali (1998) reported that it was precisely this information that they lacked and were most interested in.

3.2 The model

A grain farming systems programming model for the Darling Downs region of Queensland was developed based on data from an extensive survey of grain farms in this region by Smith (1995a, 1995b).[8] Arable land was divided into dryland and irrigated land. Dryland and irrigated land were further divided into three soil classes (low-fertility, medium-fertility and high-fertility) based on years of cultivation and soil nitrogen status, with each soil class characterised by different input–output relationships.

Crop activities were defined for each soil type and for other characteristics (such as separate feed and malting barley varieties). The other main crop enterprises in the model were wheat and sorghum. Wheat is an important competitive, intra-season crop with barley, and protein variability in wheat is also important. Unlike barley, wheat is not bound within prescribed limits, with higher protein wheat normally receiving a premium price. Inclusion of sorghum was essential because it is an inter-season competitive crop with barley on the production side, and the main competitive feed crop on the demand side. Agronomic response data for sorghum in the model drew on the study by Dowling and Vaschina (1996).

Crop rotation requirements were incorporated in a manner similar to the method outlined in Hazell and Norton (1986). Winter crops such as wheat and barley rotate with summer crops like sorghum. An inequality constraint prevents the winter crop area from exceeding the summer crop area. That is, sorghum can alternate with barley and wheat, but not all barley and wheat can be alternated with sorghum.

Altogether the model had 172 activities and 54 constraints and was solved with the GAMS/MINOS non-linear programming solver. Full details of the model are reported in Gali (1998, Chapter 8 and Appendix V).

The core of the model and the results reported in the fourth section, however, lie in the chance constrained part of the formulation, and the following description focuses on this part of the model.

[8] Some 80 to 90 per cent of barley in Queensland is grown on the Darling Downs.

The general model specification was:

$$\text{Maximize } Z = \sum_{j=1}^{n} C_j X_j \tag{1}$$

Subject to

$$\sum_{i=1}^{m} \sum_{j=1}^{n} a_{ij} X_j \leq b_i \tag{2}$$

$$P\left\{ \sum_{j=1}^{n} a_{ij} X_j \leq b_i \right\} \geq \alpha_i \tag{3}$$

where:

- Z is the objective function with the largest possible total farm gross margin;
- C_j is the gross margin of a unit of the jth activity;
- X_j is the level of the jth farm activity;
- a_{ij} is the quantity of ith resource required to produce one unit of the jth activity;
- b_i is the level of the ith resource or constraint;
- P is the probability that the ith constraint will be met;
- α_i is the minimum probability of meeting the ith constraint.

By assuming normality and knowledge of the mean and variance of the distribution, equation 3 can be transformed into non-linear deterministic equivalents according to Taha (1992).[9] In this case, a_{ij} is normally distributed with mean, $E(a_{ij})$, and variance, $\text{var}(a_{ij})$. The covariance of a_{ij} and a'_{ij} is given by Cov a_{ij}, a'_{ij}.

Consider the ith constraint:

$$P\left\{ \sum_{j=1}^{n} a_{ij} X_j \leq b_i \right\} \geq \alpha_i \tag{4}$$

[9] A normal distribution was used to approximate the actual distribution of protein levels given the absence of sufficient data to define the true distribution as discussed in the second section. On computational grounds, assuming normality facilitates derivation of the deterministic equivalents of the chance constraints (equations 11 and 12). Paris and Easter (1985) claimed that any suitable density functions with finite moments could be used to derive the deterministic equivalents, although there has been no application of alternative distributions in applied studies. A logical extension of this study, therefore, is to specify the true distribution of protein levels as data become available and, if protein levels prove to be distributed non-normally, the re-derivation of the deterministic equivalents of the chance constraints.

and define:

$$h_i = \sum_{j=1}^{n} a_{ij} X_j \tag{5}$$

Then h_i is normally distributed with

$$E(h_i) = \sum_{j=1}^{n} E(a_{ij}) X_j \tag{6}$$

and

$$\mathrm{var}\{h_i\} = X^T D_i X \tag{7}$$

where T is the transposed matrix, $X = (x_1, \ldots, x_n)^T$, and

$$D_i = i\text{th covariance matrix} = \begin{pmatrix} \mathrm{var}(a_{i1}) \ldots \mathrm{cov}(a_{i1}, a_{in}) \\ . \\ . \\ . \\ \mathrm{cov}(a_{in}, a_{i1}) \ldots \mathrm{var}(a_{in}) \end{pmatrix}$$

Now:

$$P\{h_i \leq b_i\} = P\left\{ \frac{h_i - E(h_i)}{\sqrt{\mathrm{var}(h_i)}} \leq \frac{b_i - E(h_i)}{\sqrt{\mathrm{var}(h_i)}} \right\} \geq \alpha_i \tag{8}$$

where $\dfrac{h_i - E(h_i)}{\sqrt{\mathrm{var}(h_i)}}$ is standard normal with a mean of zero and a variance of one.

Thus:

$$P(h_i \leq b_i) = \Phi\left(\frac{b_i - E(h_i)}{\sqrt{\mathrm{var}(h_i)}} \right) \tag{9}$$

where Φ represents the cumulative distribution function of the standard normal distribution. Let $K_{\alpha i}$ be the standard normal value such that $\Phi(K_{\alpha i}) = 1 - \alpha_i$. The condition $P(h_i \leq b_i) \geq \alpha_i$ is realised if and only if

$$\frac{b_i - E(h_i)}{\sqrt{\mathrm{var}(h_i)}} \geq K_{\alpha i}$$

This yields the following non-linear constraint:

$$\sum_{j=1}^{n} E(a_{ij}) X_j + K_{\alpha i} \sqrt{X^T D_i X} \leq b_i \tag{10}$$

which is equivalent to the original chance constraint reported in equation 3. For special cases where the normal distributions are independent as in the present study,[10] namely, Cov $(a_{ij}, a'_{ij}) = 0$, then the constraint reduces to:

$$\sum_{j=1}^{n} E(a_{ij})X_j + K_{ai}\sqrt{\sum_{j=1}^{n} \mathrm{var}(a_{ij})X_j^2} \leq b_{iU} \tag{11}$$

$$\sum_{j=1}^{n} E(a_{ij})X_j - K_{ai}\sqrt{\sum_{j=1}^{n} \mathrm{var}(a_{ij})X_j^2} \geq b_{iL} \tag{12}$$

where b_{iU} is the upper limit for protein percentage in malting grade barley, and b_{iL} is the lower limit. Thus the mean protein level is adjusted by its probabilistic variance to meet the malting grade standards. The term $K_{ai}\sqrt{\sum_{j=1}^{n} \mathrm{var}(a_{ij})X_j^2}$ reflects the variability above or below mean protein levels.

These relationships mean that the malting grade standards fall within the upper and lower limits specified in equations 11 and 12 for at least α_i per cent of the time. The α parameter reflects the risk each grower is prepared to accept to meet the malting grade standards based on their experience in growing barley, knowledge of soil properties, agronomic management practices, weather forecasts, and attitudes to risks.

Equation 3 specifies the stochastic chance constraints, while equations 11 and 12 are the deterministic equivalents of the chance constraints. The values of the technical coefficients in the chance constraints are stochastic, and have probability density functions associated with them that can be summarised as $a_{ij} \sim N(\mu, \sigma^2)$.

The CCP formulation assumes that barley growers are prepared to violate the malting grade standards at least some of the time, because they are unable to meet the standards all of the time. Thus both the average protein of barley and its variance are important in developing a model to incorporate barley grower intentions.

A simple numerical example serves to illustrate the operation of the chance constraints (equations 11 and 12), as well as the impact of protein variance and the probability of meeting the malting grade standards. Consider the case of malting barley grown on dryland medium-fertility soils with 80 kg per hectare of nitrogen that yields an average of 10.8 per cent protein. With

[10] Although, for the reasons outlined in the second section, the exact protein distribution has not been identified, the limited data available reveal that each malting barley activity appears to have its own distribution of protein levels for a given nitrogen level and soil type reflecting the importance of these two factors. Thus the a_{ij}'s are assumed to be independently distributed.

a protein variance of 0.9 per cent, then from equations 11 and 12, protein levels for this activity fall within the range 8.6 per cent to 13 per cent in 99 per cent of cases (α_I equal to 0.99).[11] In this case, the activity only just meets the lower protein level bound implied in the malting grade standards of 8.5 per cent protein and would not meet the upper bound of 12.5 per cent. For the case where the malting grade standards had to be met only 90 per cent of the time (α_I equal to 0.9), the protein range for this activity would narrow to 9.6 per cent to 12 per cent protein, and so would become feasible. However, if protein variance was 3 per cent protein rather than 0.9 per cent, protein content for this activity would vary from 8.6 per cent protein to 13 per cent protein in 90 per cent of cases. The fourth section reports some of the impacts of changing protein variance and the probability of meeting the malting grade standards on the optimal plan and expected profits.

The protein chance constraints link to the full suite of malting barley and feed barley activities. For any particular level of α, the model solution adjusts optimally to meet the new deterministic equivalents of the chance constraints based on the full set of relationships between the crop and other farm activities and resource constraints contained in the grain farming systems model. The matrix formulation of the chance constraint rows are described in detail in Gali (1998, section 8.3.2, figure 8.1, figure 8.2, and Appendix VI).

3.3 Data

To capture the realism and breadth of information required, this study drew upon a variety of secondary sources, especially as the severe drought in the region from 1991 to 1995 that prevented the growing of many grain crops made it difficult to obtain reliable agronomic response data from farmers.

Physical data for a typical grain farm were taken from the reports of Smith (1995a, 1995b) who surveyed grain properties in the Darling Downs region in 1987–88 and 1989–90. Most of the barley grown in Queensland comes from the Central Downs. The average size of 448 hectares for a typical grain property on the Central Downs was taken from this study of Smith along with the labour requirements. Soil types in the survey of Smith and in the model presented here were divided into three broad groups based on years of cultivation. Low-fertility soils have been subjected to more than 60 years of cultivation and require high rates of nitrogen fertiliser to improve yield and protein levels. Medium-fertility soils have been cultivated for 20 to 60 years, while high-fertility soils have been brought into cultivation more recently.

[11] From equation 11: $10.8 + 1.65^{*}0.9^{0.5} = 13$, and from equation 12: $10.8 - 1.65^{*}0.9^{0.5} = 8.6$.

Agronomic response data for barley came from a barley growth model developed as part of a Grains Research and Development Corporation project.[12] Specifically, a series of barley experiments on irrigated and dryland soils carried out in the Darling Downs region of Queensland reported the response to applied nitrogen in terms of yield and protein for different soils under irrigated and dryland conditions. With respect to wheat, a long-term trial has been in progress on the Darling Downs for the past 20 years to study the effects of fertilisers on grain yield and protein levels, and wheat yield response to nitrogen was taken from Strong (1981, 1989).

Unit costs and returns and some per hectare input requirements for activities in the model came from Queensland Department of Primary Industries publications for winter and summer crop management notes for the Darling Downs region (QDPI 1995, 1996). The gross margins estimated for each activity also drew upon variable costs calculated according to the nitrogen applied, yield responses, and 1995–96 GRAINCO grain prices.

4. Results

Table 1 outlines the optimal activities and their levels for different probabilities of meeting the protein constraint embodied in the malting grade standards. In general, malting barley is not an optimal choice for irrigated soils. Without the application of nitrogen under assured soil moisture content, it is difficult to achieve malting grade standards. On the other hand, nitrogen application may improve yield, which in turn can cause 'dilution' of the protein. With moderate yield, a higher protein level could be obtained, but again it may not meet the malting grade standards. However, on low-fertility soils with high amounts of nitrogen under irrigated conditions, malting barley yields more grain with consistent protein levels and low variability that can meet the standards. Thus malting barley entered the optimal plan on these irrigated low-fertility soils. On the irrigated medium-fertility soils, feed barley at low nitrogen levels came into the optimal plan. Wheat was the preferred option for irrigated high-fertility soils with high rates of nitrogen that can produce high yield and protein levels and so generate a large gross margin. Wheat was also the preferred choice for the high-fertility dryland soils, while sorghum at high rates of nitrogen entered the optimal plan for the dryland medium-fertility soils.

The activities mentioned above remained at the same level irrespective of the probability of meeting the malting grade standards, indicating their

[12] Results relevant to this study arising out of the GRDC Project, UQ17, appear in Birch *et al.* (1993), Chirchir (1994), and Goyne (1995).

Table 1 Optimal crop activities (hectares) and relative profits ($A) for various probabilistic chance constraints

Irrigation status	Soil fertility	Crop	Nitrogen fertiliser (kg/ha)	Probability of meeting the malting barley protein constraint (α): Deterministic base model	0.99	0.95	0.90	0.85	0.80	0.75	0.70	0.65	0.60	0.55	0.50
				(hectares)											
Irrigated	High	Wheat	160	36.0	36.0	36.0	36.0	36.0	36.0	36.0	36.0	36.0	36.0	36.0	36.0
	Medium	Feed barley	40	36.0	36.0	36.0	36.0	36.0	36.0	36.0	36.0	36.0	36.0	36.0	36.0
	Low	Malting barley	40	24.0	24.0	24.0	24.0	24.0	24.0	24.0	24.0	24.0	24.0	24.0	24.0
Dryland	High	Wheat	120	86.4	86.4	86.4	86.4	86.4	86.4	86.4	86.4	86.4	86.4	86.4	86.4
	Medium	Sorghum	120	82.0	82.0	82.0	82.0	82.0	82.0	82.0	82.0	82.0	82.0	82.0	82.0
		Feed barley	120	82.0	78.6	77.3	76.1	74.8	73.3	71.3	68.4	63.7	53.9	22.7	–
		Malting barley	40	–	1.5	2.1	2.7	3.3	4.0	5.0	6.3	8.5	12.8	26.4	–
			120	–	1.9	2.6	3.2	3.9	4.7	5.8	7.3	9.8	14.6	29.4	82.0
			160	–	–	–	–	–	–	–	–	–	0.8	3.2	–
	Low	Feed barley	160	96.0	88.2	85.7	83.4	81.1	78.4	74.9	70.1	62.2	46.2	–	–
		Malting barley	80	–	6.3	8.3	10.1	11.8	13.9	16.5	20.1	25.9	37.2	71.6	96.0
			120	–	1.4	2.0	2.5	3.0	3.7	4.6	5.8	7.8	11.8	22.7	–
			160	–	–	–	–	–	–	–	–	0.1	0.9	1.8	–
				($A)											
Profits (change in total farm gross margin) relative to deterministic base model					1136	1339	1520	1695	1907	2175	2544	3130	4233	7645	10342

established role in the optimal plan for the given soil types and treatment levels. Where the probability of meeting the malting grade standards did have an impact was on the dryland low-fertility and medium-fertility soils. The impact involved a substitution of feed barley activities for malting barley activities as the constraint was relaxed and, to the extent allowed by the rotational constraints in the model, not a substitution out of the other crop activities such as wheat and sorghum.

The substitution from feed barley to malting barley varieties as the probability of meeting the malting grade standards is relaxed is shown in figure 2. In the deterministic or base model, where the malting grade standards had to be met in all cases, the optimal farm plan included 24 hectares of malting barley and 214 hectares of feed barley. Conversely, where the malting grade standards had to be met only 50 per cent of the time, optimal malting barley area increased to 202 hectares at the expense of feed barley with 36 hectares. Table 1 reveals that the changes involved a substitution of feed barley varieties on low and medium-fertility soils under relatively high rates of nitrogen application with malting barley varieties using various rates of nitrogen application. These changes were limited to the dryland situation as malting barley generally is not an optimal choice for irrigated soils for the reasons outlined at the start of this section.

The results concur with expectations that at high levels or probabilities of meeting the malting grade standard, which entails a higher standard

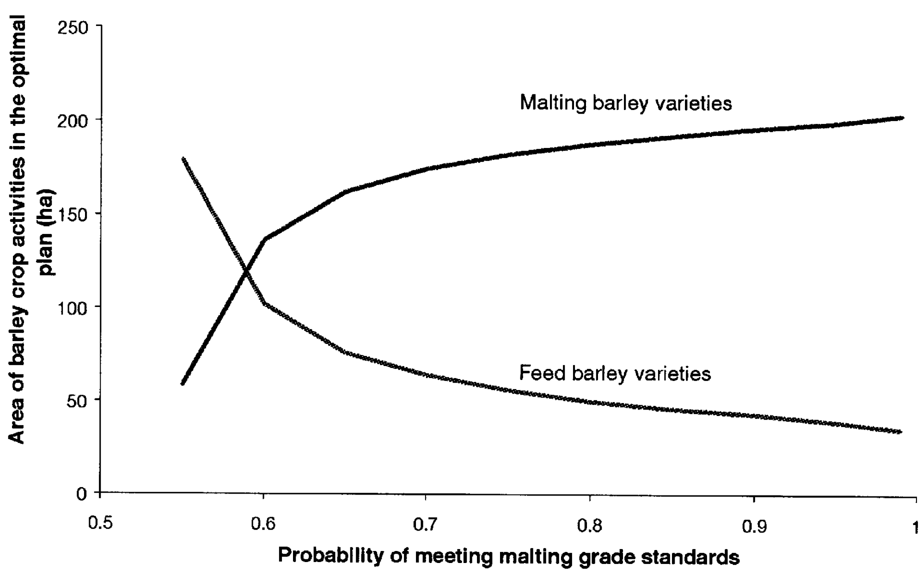

Figure 2 Impact of risk in meeting malting grade standards on optimal barley activities

normal distribution value in equations 11 and 12, the protein range for the malting barley crop activities increases and so their opportunity to meet the protein constraints and to enter the optimal farm plan diminishes. As the constraint is relaxed, some of the malting barley activities, which were not in the optimal plan of the deterministic model, come into the optimal plan of the chance-constrained model resulting in an increase in the value of the objective function or higher grain farm profits. However, relaxing the constraint does not guarantee that all malting crop activities will be in the specified protein range. Furthermore, even if they do fall within the specified protein range, it is the relative gross margins and input–output coefficients that determine whether they will enter the optimal solution.

The final row in table 1 indicates the change in total farm gross margin, relative to the base deterministic model, as the probability of meeting the malting grade standards falls. The suitability of the optimal plans reported in table 1 depends on the attitudes or beliefs of the barley grower towards the probability of meeting the malting grade standards. That is, advice to barley growers on optimal farm plans comes from reading down the columns of table 1. Growers with an optimistic view of meeting the malting grade standards, or prepared to accept the higher risks of doing so, should be directed to the farm plans and higher gross margins in the right-hand columns of this table, while growers with a more pessimistic outlook are better served by the plans on the left-hand side of the table. Although the higher returns associated with the lower probabilities of meeting the malting grade standards appear modest, they may be significant at the margin for the small and relatively low income grain growers on the Darling Downs, and may be substantial in aggregate.

The model enables examination of the relative disadvantage of barley activities not in the optimal solution. Table 2, for instance, illustrates the costs of forcing these non-basis activities into the solution for the case of the grower who requires that the standards be met in almost all cases (99 per cent of the time). The results reinforce the discussion of the barley and crop activities that did enter the optimal solution. That is, large opportunity costs were incurred in growing barley on dryland high-fertility soils, reflecting the profitability of growing wheat on these soils. Malting barley activities, in particular, would lead to significant adjustments and costs in the optimal plan to meet the strict protein levels implied in the malting grade standards. Conversely, dryland malting barley activities on low- and medium-fertility soils with high rates of nitrogen application that entered the optimal plan as the protein constraint was relaxed had relatively small opportunity costs.

A priori, protein variability is an important component in meeting the malting grade standards. Variability of protein levels arises due to soil, agronomic, yield and seasonal factors. Protein variance in this model of

Table 2 Costs of forcing feed and malting barley activities into the optimal solution ($\alpha = 0.99$)

Irrigation status	Soil fertility	Nitrogen application (kg/ha)	Opportunity cost ($A/ha)	
			Malting barley	Feed barley
Irrigated	High	0	138.1	132.7
		40	414.6	58.0
		80	227.4	158.9
		120	117.0	102.9
		160	85.5	98.0
	Medium	0	295.0	397.1
		40	152.3	–
		80	312.6	98.8
		120	125.6	49.1
		160	98.4	48.4
	Low	0	141.4	276.6
		40	–	12.6
		80	198.1	96.8
		120	123.7	59.6
		160	102.9	60.9
Dryland	High	0	250.7	238.1
		40	429.7	303.1
		80	312.7	169.9
		120	219.7	108.1
		160	241.3	210.2
	Medium	0	140.3	82.1
		40	–	145.1
		80	144.3	26.4
		120	–	–
		160	13.0	100.0
	Low	0	360.5	242.1
		40	221.1	196.9
		80	–	98.9
		120	–	53.8
		160	11.1	–

between 0.2 to 4.2 per cent protein came from experimental data (see note 12). However, barley receival dockets from GRAINCO indicated that the actual variance can be much larger, and in the case of the 1992–93 season reported in figure 1, up to 9.7 per cent protein. Variability of protein levels from experimental data is often less than field variability because experiments are usually confined to small plots and more often the soils are roughly homogeneous. Table 3 reports the results of some sensitivity analysis of protein variance. Protein variability seemingly has an impact similar to that of increasing the risk of meeting the malting grade standard, with higher

Table 3 Impact of risk levels and variance of protein on optimal farm plan returns

Protein variance (percentage of experimental variance)	Probability of meeting the malting grade standards					
	0.55	0.65	0.75	0.85	0.995	0.998
	values relative to base deterministic model ($A)					
0	7645.14	3130.055	2175.02	1695.05	1083.28	996.1
60	5194.8	2315.34	1680.18	1351.21	905.62	836.5
120	4068.9	1928.87	1440.7	1180.55	812.03	750.03
180	3422.33	1700.11	1295.9	1076.2	751.77	692.3

levels of protein variability associated with lower farm profits. However, the magnitude of the impact of protein variability is less. Furthermore, protein variability has a larger impact at lower probabilities of meeting the malting grade standards.

5. Conclusion

Barley growers have long been attracted to the premiums attached to malting grade barley even though there is a substantial risk in meeting the associated standards. However, the rise in demand and price for feed barley, along with the higher yields of feed barley varieties, have led some barley growers to re-evaluate their decision to focus primarily on malting barley varieties.

Results from the CCP model highlighted how the level of risk that growers were prepared to accept in not meeting the malting grade standards has a major impact on the optimal mix of feed and malting barley varieties. Given the different beliefs of individual barley growers about their ability to meet the standards, and varying capacities to cope with not meeting them, information based on simple deterministic models may be of limited value. The CCP approach enhances the relevance of the advice to barley growers by tailoring the advice to their beliefs about the chance of meeting the malting grade standards.

The results also emphasised the high costs of growing unprofitable malting barley activities when the chance of these activities meeting the malting grade standards is low. As a corollary, the ongoing focus on malting barley varieties by growers and by plant breeders may not be appropriate unless there is a high chance that they will meet the malting grade standards under the soil types and fertiliser treatments being considered.

The CCP approach adds an extra dimension to the deterministic farm planning tools. But how does it compare with other types of stochastic programming? In general, where sequential decision stages are involved and a rich specification of adjustment responses in each stage is required, other approaches such as discrete stochastic programming are more rigorous and useful. However, in the specific single-stage decision problem considered here, with the behavioural chance constraint closely mimicking the decision problem as perceived by barley growers, the sometimes-overlooked CCP can yield insights on this complex decision problem that its more rigorous counterparts cannot.

References

Berbel, J. 1993, 'Risk programming in agricultural systems: a multiple criteria analysis', *Agricultural Systems,* vol. 41, pp. 275–88.

Birch, C,J., Fukai, S., Cox, H. and Broad, I.J. 1993, 'Executive summary', *The Response of Different Barley Varieties to Nitrogen under Contrasting Conditions of Water Availability*, the Department of Agriculture, the University of Queensland, Brisbane.

Birch, C.J. and Long, K.E. 1990, 'Effect of nitrogen on the growth, yield and grain protein content of barley', *Australian Journal of Experimental Agriculture,* vol. 30, pp. 237–42.

Brown, C.G. and Drynan, R.G. 1986, 'Plant location analysis using discrete stochastic programming', *Australian Journal of Agricultural Economics*, vol. 30, pp. 1–22.

Charnes, A. and Cooper, W.W. 1959, 'Chance constrained programming', *Management Science,* vol. 6, pp. 73–9.

Chen, J. 1973, 'Quadratic programming for least cost feed formulations under probabilistic protein constraints', *American Journal of Agricultural Economics*, vol. 55, pp. 175–83.

Chen, J. and Baker, C.B. 1974, 'Marginal risk constraint linear programming for activity analysis', *American Journal of Agricultural Economics,* vol. 56, pp. 622–7.

Chirchir, N.J. 1994, 'Effect of nitrogen and water stress on the grain yield and grain protein of wheat and contrasting barley cultivars', Masters of Agricultural Studies thesis, the University of Queensland, Brisbane.

Cocks, K.D. 1968, 'Discrete stochastic programming', *Management Science,* vol. 15, pp. 72–9.

Dowling, C. and Vaschina, B. 1996, 'Grain protein as an index of soils nitrogen supply and value in grain sorghum', paper presented at the Australian Sorghum Conference 1996, February 20–22, Toowoomba.

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,* vol. 27, pp. 12–30.

Freund, R.J. 1956, 'The introduction of risk into a programming model', *Econometrica*, vol. 23, pp. 253–63.

Gali, V.J. 1998, 'Integrated demand, supply and market analysis for Queensland barley', PhD thesis, the University of Queensland, St Lucia, Brisbane.

Gali, V.J., Brown, C. and Wegener, M. 1998, 'The value of barley protein in livestock feeding in Queensland', *Australasian Agribusiness Review,* vol. 6, Paper 15.

Goyne, P.J. 1995, *Environmental Influences on Grain Size and Protein Content of Barley: Forward Estimates of Production to Target Niche Malting Markets*, GRDC Ref. No. DAQ 192, Queensland Department of Primary Industries, Brisbane.

Hardaker, J.B., Pandey, S. and Patten, L.H. 1991, 'Farm planning under uncertainty: a review of alternative programming models,' *Review of Marketing and Agricultural Economics*, vol. 59, pp. 9–22.

Hazell, P.B.R. 1971, 'A linear alternative to quadratic and semi-variance programming for farm planning under uncertainty', *Journal of Agricultural Economics,* vol. 27, pp. 239–52.
Hazell, P.B.R. and Norton, R.D. 1986, *Mathematical Programming for Economic Analysis in Agriculture*, Macmillan Publishing, New York.
Johnson, P.N. and Segarra, E. 1995, 'An evaluation of post conservation reserve program alternatives in the Texas high plains', *Journal of Agricultural and Applied Economics*, vol. 27, pp. 556–64.
Kingwell, R. 1994, 'Effects of tactical responses and risk aversion on farm wheat supply', *Review of Marketing and Agricultural Economics*, vol. 62, pp. 29–42.
Okunev, J. and Dillon, J.L. 1988, 'A linear programming algorithm for determining mean-gini efficient farm plans', *Agricultural Economics,* vol. 2, pp. 273–85.
Paris, Q. 1989, 'Stochastic technology and prices: reply', *American Journal of Agricultural Economics,* vol. 71, pp. 817–19.
Paris, Q. and Easter, C.D. 1985, 'A programming model with stochastic technology and prices: the case of Australian agriculture', *American Journal of Agricultural Economics,* vol. 67, pp. 120–9.
Patten, L.H., Hardaker, J.B. and Pannell, D.J. 1988, 'Utility-efficient programming for whole farm planning', *Australian Journal of Agricultural Economics,* vol. 32, pp. 88–97.
QDPI (Queensland Department of Primary Industries) 1995, *Summer Crop Management Notes*, *Darling Downs,* QDPI, Brisbane.
QDPI (Queensland Department of Primary Industries) 1996, *Winter Crop Management Notes*, *Darling Downs,* QDPI, Brisbane.
Rae, A.N. 1971a, 'Stochastic programming, utility and sequential decision problems in farm management', *American Journal of Agricultural Economics,* vol. 53, pp. 268–75.
Rae, A.N. 1971b, 'An empirical application and evaluation of discrete stochastic programming in farm management', *American Journal of Agricultural Economics,* vol. 53, pp. 625–38.
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.
Strong, W.M. 1981, 'Nitrogen requirements of irrigated wheat on the Darling Downs', *Australian Journal of Experimental Agriculture Animal Husbandry,* vol. 21, pp. 424–31.
Strong, W.M. 1989, 'Short-term fertilization of winter crops', in Vallis, I. and Thomas, G.A. (eds), proceedings of a workshop of Long-term Fertilization of Crops, Queensland Department of Primary Industries, Brisbane.
Taha, H.A. 1992, *Operations Research: An Introduction,* 5th edition, Macmillan Publishing Company, Sydney.
Tauer, L.W. 1983, 'Target MOTAD', *American Journal of Agricultural Economics,* vol. 65, pp. 606–14.
Wicks, J.A. and Guise, J.W.B. 1978, 'An alternative solution to linear programming problems with stochastic input-output coefficients', *Australian Journal of Agricultural Economics,* vol. 22, pp. 22–40.
Zhu, M.K., Taylor, D.B., Sarin, S.C. and Kramer, R.A. 1994, 'Chance constrained programming models for risk based economic and policy analysis of soil conservation', *Agricultural and Resource Economics Review*, vol. 23, pp. 58–65.