Supply-Side Risks and Malting Barley Procurement and Storage

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Abstract

U.S. production of six-rowed malting barley has declined sharply over the last several years. Further, the quality of U.S. malting barley has suffered repeatedly due to disease. This has left the U.S. malting industry dependent on a single-desk seller of malting barley, the Canadian Wheat Board. In this paper, we develop a discrete stochastic programming model to analyze the procurement and storage decisions of the U.S. malting industry. We employ the model to investigate the impact that various sources of risk have on the industry's reliance on imported barley. The results indicate strategies that mitigate dependence on imports.

Keywords: barley; discrete stochastic programming; risk; international trade.

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1. Introduction

Agricultural processing industries face unique procurement decisions. Supplies of primary inputs (crops) can vary substantially from year to year, both in quantity and quality. In many cases, such as wheat milling and barley malting, the distribution of quality characteristics within a crop year is also of keen interest. Processors seek to meet their requirements or those of end-users at minimum cost, given market premiums and discounts for quality factors and opportunities for blending. Price risks can also be significant, particularly when no futures markets are available and inventory levels are large relative to annual use.

In the malting sector, procurement patterns are especially sensitive to barley quality characteristics. Beginning in 1993, an extended outbreak of fusarium head blight (FHB) occurred in the Upper Midwest, the traditional source of most six-rowed malting barley grown in the United States. A mycotoxin associated with FHB can make barley unsuitable for malting. Quality problems in the Midwestern crop coincided with increased U.S. imports of malting barley from Canada (GAO). Imports were facilitated by reduced barriers to trade under the Canadian-U.S. free trade agreement, and by commercial integration of the U.S. and Canadian grain handling and processing sectors. (See Buschena and Gray for an analysis of malting industry mergers after the Canadian-U.S. free trade agreement). The involvement of the Canadian Wheat Board (CWB), a state trading enterprise, has made imports an especially contentious issue for U.S. barley growers. The role of the CWB in the North American barley market has also been the subject of much study and debate among economists (Carter; Schmitz *et al*.; Veeman). Much less attention has been paid to the impact of U.S. supply conditions, including crop quality, on recent trade patterns.

In this paper, discrete stochastic programming (DSP) is developed and employed to analyze barley procurement decisions. The model is developed from the perspective of the U.S. malting industry, which seeks to satisfy demand for malt at least cost over a two-year planning horizon subject to supply constraints and quality requirements. Multiple sources of risk (price, crop size, and crop quality) are incorporated in the analysis. Simulations demonstrate the sensitivity of barley procurement and stockholding to key parameters. The model is used to analyze the diverse factors affecting U.S. imports of malting barley from Canada.

Gaussian quadrature (GQ) is used to approximate the probability distributions of parameters incorporated in the model. GQ is a numerical technique that allows a probability distribution to be represented by a small number of discrete points (DeVuyst, Liu and Preckel). In our analysis, we apply the GQ method to joint distribution of grain quality parameters and to the joint distribution of barley prices and production. This brings two major benefits: first, it allows us to limit the dimension of the DSP model (which nevertheless contains nearly 10,000 variables); and second, we represent the distribution of grain quality parameters in a way that preserves blending opportunities (DeVuyst, Johnson, and Nganje). As discussed below, blending grain to meet quality specifications (and capture blending margins) is a critical feature of our analysis.

The paper is organized as follows. The next section provides some background on the malting barley sector, grain quality factors, and related issues. The third section explains our use of the GQ technique and provides an overview of the DSP model. Simulation results are reported in the fourth section. The paper concludes with a short summary and discussion of implications.

2. Background on Malting Barley

Malting barley has traditionally been a major crop in North Dakota, Minnesota, and South Dakota. However, acreage has declined sharply in recent years due to the combined impacts of crop disease, quality problems, and low prices. As extended outbreak of fusarium head blight (FHB) began in 1993. FHB is a fungal disease that reduces yields and is associated with deoxynivalenol (DON), also known as vomitoxin. DON can render barley unsuitable for malting at relatively low concentrations, and large price discounts are applied by buyers (malt companies).[1] Other important barley quality factors include plump kernels (%), test weight (lbs/bu), and protein (%). The distribution of these factors varies through time, depending on growing conditions.

Barley supplies present the U.S. malting and brewing industries with several types of risk. Production of malting barley is geographically concentrated. North Dakota and Minnesota account for most U.S. production of six-rowed malting varieties, the type preferred by U.S. brewers. (Saskatchewan has also developed into an important source of supply for these varieties, particularly since the onset of major quality problems in the U.S. crop.) Prices paid for malting barley, expressed as a premium over feed barley values, are heavily influenced by the size of the Midwestern crop. Price risks cannot be hedged, as malting barley is not traded on any futures exchange. Crop quality in the Midwest also determines how much malting barley must be imported from Canada.

Malt companies and major brewers maintain safety stocks of malting barley, which can be drawn down if there is a supply shortage or inadequate quality in a given crop year. Thus, procurement and storage strategies are interdependent. Important factors affecting procurement are:

- price, quantity, and distribution of quality in the current crop;
- stocks available from previous crop years;
- prospective supplies, prices and qualities of future crops;

- costs of storage; and
- cost and availability of barley from alternative sources (*i.e*., Canada).

The last factor is of special interest: as procurement of six-rowed malting barley shifts north of the border, U.S. buyers become more vulnerable to discretionary pricing by Canada's single-desk seller. CWB selling prices are not publicly released; hence, the spread between Canadian and U.S. barley prices cannot be directly observed. Here, we vary this price spread in model simulations to gauge the impact on U.S. barley imports.

3. Methodology and Data Sources

DSP can be characterized as a 'programming formulation of a decision tree' (Anderson, Dillon, and Hardaker, p. 224), in which actions are sequential and random events intervene with discrete probabilities.[2] Each random event (or permutation of random events) represents a 'state of nature,' and actions taken in each period must be such that feasibility conditions are satisfied for all subsequent states. As Hazell and Norton note (p. 106),

> "A major difficulty of the approach is its hearty appetite for data, and the fact that models rapidly become very large because of the need to have separate rows and columns for many resources and activities in every state of nature."

With a rise in the number of random variables (or time periods), the dimension of decision variables must also increase, and constraint sets must be duplicated for each state of nature. This 'curse of dimensionality' can be partly mitigated by computer power. However, in some applications, the analyst may be forced to simplify the DSP model to ensure it is solvable.

Our problem is developed from the perspective of the U.S. malting industry. The industry requires 85 million bushels of six-rowed malting barley annually for processing.[3] At the outset of a two-year planning horizon, the industry must decide how much of the current domestic crop to purchase, how much to import from Canada, and how much to store. Barley supplies are heterogeneous, but quality standards can be satisfied through blending. Minimum limits apply for test weight and the percent of plump kernels; maximum limits apply for protein levels and DON. Blending can occur both within and across crop years. The model objective is to minimize the expected costs of procurement, storage, and the squared deviations from target inventories. (See the appendix for complete mathematical specification.)

Procurement and storage decisions are made in each of two years. From the standpoint of first-year decisions, there are several sources of uncertainty. These include prices of barley in the second year, as well as the size of the Midwestern crop and distribution of quality factors in the second year. Uncertainty is resolved in the second year, and ending inventories of barley are valued at the market price prevailing in each state of nature.

The dimension of the problem is driven by two factors: first, the number of states of nature; and second, the representation of grain quality distributions. In both cases, we use Gaussian quadrature to limit the size of the DSP model. GQ is a numerical method for representing probability distributions. It involves choosing a discrete set of points and probabilities that have lower-order moments that match the moments of the distribution to be approximated.[4] For a discrete representation of a joint distribution, the representative points can be chosen as a subset of the original distribution.

Distributions of grain quality factors were derived from annual crop quality surveys conducted by the Department of Cereal Science, North Dakota State University. In these surveys, barley samples are collected from the major growing regions in the Dakotas and Minnesota and evaluated for specific quality characteristics, including protein, test weight, plump kernels, and (since 1993) DON. For example, in the 1995 crop year, 147 samples of six-rowed malting barley were collected and analyzed. While these survey results are representative of crop quality conditions in 1995, there are far too many observations for purposes of our blending analysis. Instead, we use GQ to select 15 representative observations from the original survey data. With appropriate weights, these 15 points are sufficient to reproduce all first- and second-order moments of a four-variable distribution (*i.e.*, protein, test weight, plump, and DON). The weights can be interpreted as crop shares; that is, the proportion of the crop with given quality attributes. This approach allows a manageable analysis of blending and preserves distributional characteristics of the original data. Crop quality data for seven individual years, 1993-99, are summarized in this way for inclusion in the DSP model. These seven quality distributions are assumed to be equally likely in the second year of the planning horizon.

Barley prices and Midwestern production in the second year are unknown. To represent the distribution of possible prices and production, we develop two regression models. Changes in production of malting barley are regressed on lagged prices of feed barley and the malting price premium, using data from 1985 through 1999. T ratios are in parentheses.

Y(t)	=	-1.17260	+	0.00499 FP(t-1) +	0.00705 MP(t-1)
		(-2.896)		(1.909)	(1.920)
R-squared		0.538	DW	2.216	

where Y(t) is the ratio of year t production to year t-1 production of six-rowed malting barley in North Dakota, Minnesota, and South Dakota; FP(t) is the price of feed barley (c/bu, marketing year average) received by producers in North Dakota; and MP(t) is the malting premium in North Dakota (c/bu, marketing year average), defined as malting barley price minus feed barley price.[5] Barley that is of a malting variety but which fails to meet quality standards of the malting industry can be sold as feed barley. Hence, the (lagged) feed barley price and malting premium are both relevant for predicting changes in production.

The North Dakota malting premium is taken to be representative of premiums received by barley producers in the three-state region. (Comparable data for other states are not available.) The premium is regressed on regional production of malting barley and a time trend, using data from 1984 to 1999:

MP(t) =	153.9473	− 0.5569 R(t)	− 2.7097 T(t)
	(8.700)	(-7.067)	(-3.290)
R-squared	0.802	DW	2.347

where R(t) is the regional production of six-rowed malting barley in year t (million bu); and T(t) is a time trend (1984=1, 1985=2, etc.).

To represent production and price uncertainty, the residuals from the two regressions are combined with contemporaneous data on feed barley prices. Using GQ, we identify 10 representative observations which, with suitable probability weights, match all first- and second-order moments of the entire sample. These outcomes are incorporated in the DSP model as alternative states of nature. Combined with the 7 quality distributions, this means there are $10 \times 7 \times 15 = 1050$ possible outcomes in year two. Note that decisions in year one (*i.e.*, procurement, blending, and storage) must ensure feasibility in year two for all states of nature.

Barley purchases and barley removed from storage can be blended to meet quality specifications for DON, protein, test weight and plump. This blending introduces the possibility of cost savings, as low-quality barley is purchased at discounted prices. The discounts for DON, protein and plump are derived from Johnson and Nganje, and are reported in Tables 1 and 2.

Canada is treated as a residual supplier of barley in the model. By assumption, Canadian barley exactly meets the malting industry's minimum quality specifications,[6] and can be purchased at a fixed price spread relative to the Midwestern malting price. Canadian barley can be used immediately or stored for future use.

Also by assumption, the industry seeks to maintain inventories equivalent to two years of annual requirements. That is also the level of beginning stocks in year one. A quadratic penalty is applied in the objective function for deviations from a targeted inventory level. This follows a long tradition of quadratic cost functions in the management sciences literature (Holt *et al*., pp. 72-91). The sensitivity of model results to the size of the penalty is demonstrated below.

The DSP model includes 9,967 variables and 4,936 constraints. The objective function is nonlinear by virtue of the quadratic penalty on inventories, but all constraints are linear. The model is solved using GAMS/MINOS (Brooke *et al*.).

4. Model Results

Supply parameters in the base case are representative of the 1999 crop year. Midwestern production is limited to 64 million bushels,[7] and the quality distribution is derived from the 1999 barley quality survey. Beginning stocks are assumed to have the 1998 quality distribution. Given the shortfall of 1999 production relative to annual requirements (85 million bu), the U.S. malting industry can either import from Canada or run down its existing barley inventory—subject to quality constraints and blending opportunities.

Figure 1 shows how this choice is influenced by the price spread between Canadian and Midwestern six-rowed malting barley. The vertical axis measures the import cost differential: the additional (delivered) cost associated with importing Canadian barley, relative to Midwestern. With zero cost differential, the U.S. malting industry would import about 30 million bushels. Imports are only slightly reduced with positive cost differentials, owing to the short supply of Midwestern barley in the base period. Canadian barley would have to priced at a substantial discount, of about 30 cents per bushel, to induce imports of 40 million bushels. That is because the U.S. malting industry can capture blending margins when it purchases domestic barley. Margins can be earned when domestic barley is purchased at a discount because of quality deficiencies and blended with a higher-quality supply, either from the current or previous crop year. Figure 1 shows that changes in imports and domestic purchases are not completely offsetting; inventories can also respond to the import cost differential. With larger negative differentials, the rise in imports exceeds the drop in domestic purchases.

Midwestern production was abnormally low in 1999, the base year for our analysis. Figure 2 shows how import demand would shift under alternative assumptions about the Midwestern crop. With 25% higher production than assumed in the base case, import demand shifts to the left; assuming zero cost differential, imports are reduced approximately by half. On the other hand, if the Midwestern crop were 25% lower than assumed in the base case, import demand would shift to the right.

Figure 3 shows the impact of alternative assumptions about the size of beginning inventories. Recall that in the base case barley inventories are equivalent to two years' requirements. If beginning stocks were 50% higher than in the base case, import demand would shift to the left. Indeed, no barley would be imported unless discounted relative to the Midwestern crop. If beginning stocks were 50% lower than in the base case, import demand would shift to the right and become much less elastic. Demand for imports is inversely related to the size of beginning stocks.

A quadratic penalty applies to deviations from target inventories. To assess the importance of this parameter, simulations are conducted with alternative values. Results are shown in Figure 4. Demand for imports shifts to the left when the penalty is lower than assumed in the base case, and to the right when the penalty is higher. This illustrates that imports depend, in part, on the importance of safety stocks to the U.S. malting industry. If the industry is less willing to deviate from targeted inventory levels, demand for imports increases.

A critical feature of import demand is the industry specification for DON. Beginning in 1993, infestations of DON have rendered large fractions of the Midwestern crop unusable for malting purposes. Even in 1999, a year of relatively light infestations, only about half the crop had DON levels less than 0.5 ppm, the point at which commercial discounts begin. What would be the effect of a relaxed industry standard for DON? To answer this, simulations are conducted in which the industry allows 1.0 ppm (after blending) in barley prior to malting; this compares to a maximum of 0.5 ppm in the base case. Results for imports are shown in Figure 5. With a relaxed industry standard, steep discounts would be necessary to induce any imports from Canada. This reinforces the finding of the GAO that the influx of Canadian malting barley in recent years has been largely due to quality problems in the Midwestern crop, as well as stringent quality standards of the malt companies and brewers.[8]

The malting premium, or difference between malting and feed barley price, also plays an important role in our results. The malting premium in year one is known, while that in year two reflects (as yet unobserved) production levels. Production in year two is influenced by lagged values of the malting premium. Thus, a higher premium in year one can induce larger supplies in year two. How does this affect the demand for imports? An answer is suggested in Figure 6. When the year-one malting premium is increased by 50 cents relative to the base case, demand for imports is substantially reduced. That is because the malting industry, anticipating larger Midwestern supplies and lower prices in year two, has an incentive to postpone some of its procurement.

5. Summary and Implications

This paper integrates procurement, storage, and blending decisions in a model with multiple sources of supply risk. The mathematical programming model is developed from the perspective of the U.S. malting industry, which seeks to minimize costs of procurement and storage over a two year planning horizon. Apart from price risks, the industry faces uncertainty about available supplies and the distribution of crop quality factors. Lower quality barley is discounted in the analysis, and blending activities allow the industry to capture margins while meeting grain quality specifications.

The analysis focused on U.S. barley imports from Canada. By varying the import cost differential, we derive a demand function for Canadian six-rowed malting barley. Under base-case conditions (reflecting the 1999 crop year), U.S. import demand remains close to 30 million bushels even with large positive cost differentials. Given the inelasticity of demand, it appears that the Canadian Wheat Board could use its pricing discretion to considerable advantage in the U.S. malting barley market. For its part, the U.S. malting industry could reduce its dependence on Canadian supplies by bidding up the U.S. domestic price and so encouraging production. Production levels in the Upper Midwest have fallen sharply since the early 1990s, owing to the combined effects of crop disease and low prices. Substantially higher prices (*i.e.*, malting premiums) may now be required to recover the barley acres lost to other crops. By increasing malting premiums, the U.S. malting industry's demand would become more elasticity, and thereby reduce the industry's vulnerability to CWB discretionary pricing.

Quality factors are important determinants of grain trade patterns. In the malting barley sector, DON levels have been especially critical in the last several years. Model simulations indicate that a relatively small change in industry specifications (from 0.5 to 1.0 ppm allowable

DON) would virtually eliminate the need for malting barley imports.

Table 1. Discounts for DON (Vomitoxin) Contamination in Malt Barley

DON (ppm)	Discount (cents/bu.)
≤ 0.5	0.00
≤ 1.0	4.45
≤ 2.0	57.25
≤ 3.0	62.25
≤ 4.0	70.50
> 4.0	NA[1]

[1]Discounts for DON above 4 ppm are larger than premiums for malting barley, so producers receive a higher price selling their barley as feed.

Table 2. Discounts for Protein and Plump

Protein (%)	Discount Formula (cents/bu.)
≤ 13.5	0.00
≤ 14	(% protein - 13.5) * 20
> 14	(% protein -14) * 30 + 10
Plump (%)	**Discount Formula (cents/bu.)**
≥70	0.00
≥ 60	(70 - % plump) * 2
< 60	(60- % plump) * 4 + 20

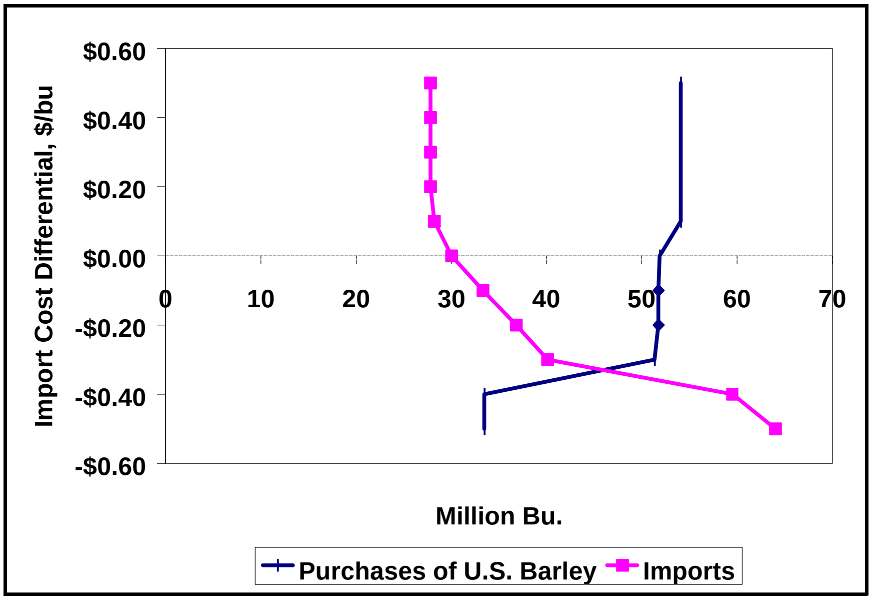

Figure 1. Base Case Results.

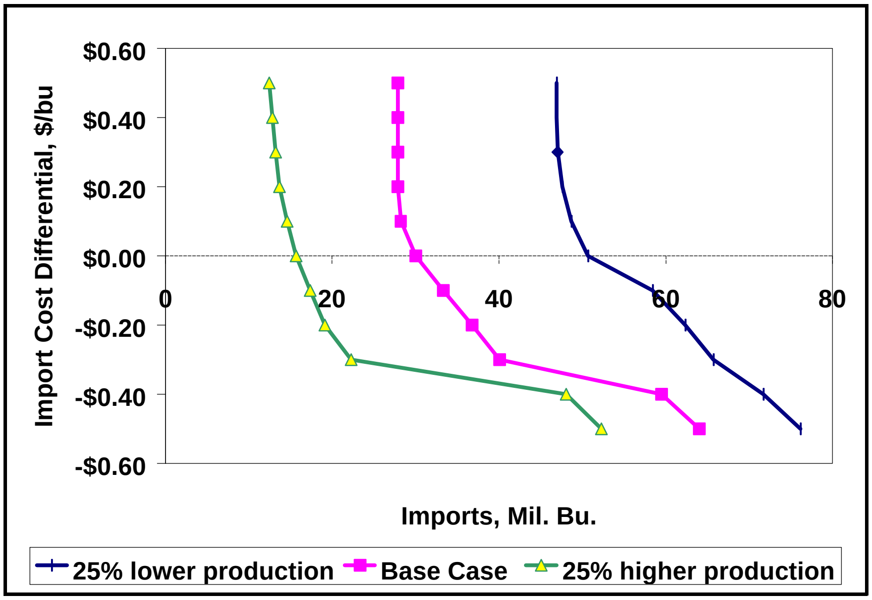

Figure 2. Impact of Midwestern Production on Imports.

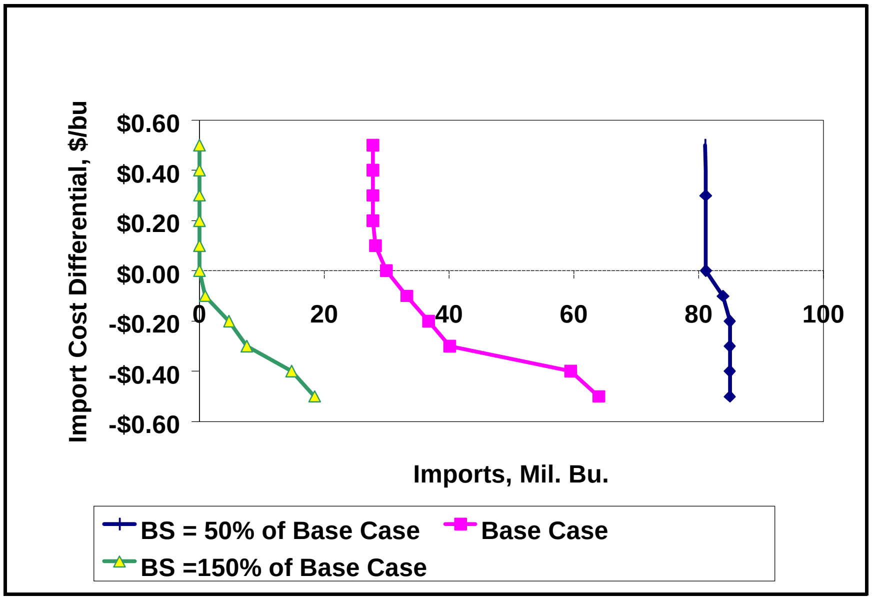

Figure 3. Impact of Beginning Stocks on Imports.

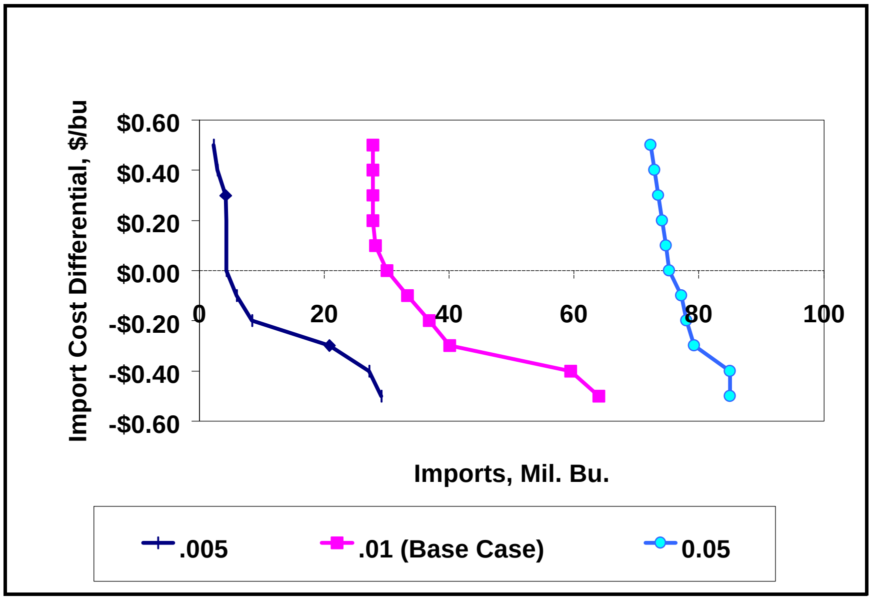

Figure 4. Impact of Penalty Parameter on Imports.

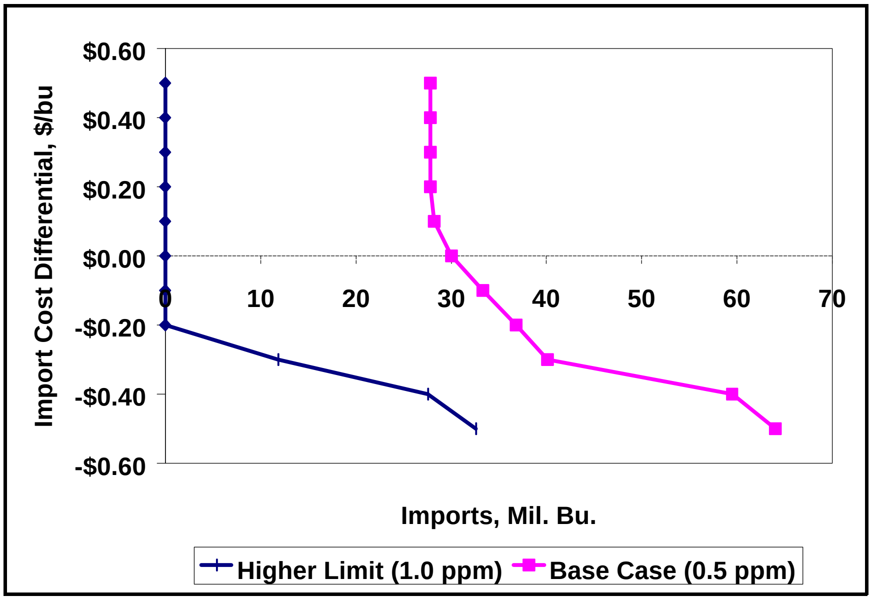

Figure 5. Impact of DON Limit on Imports.

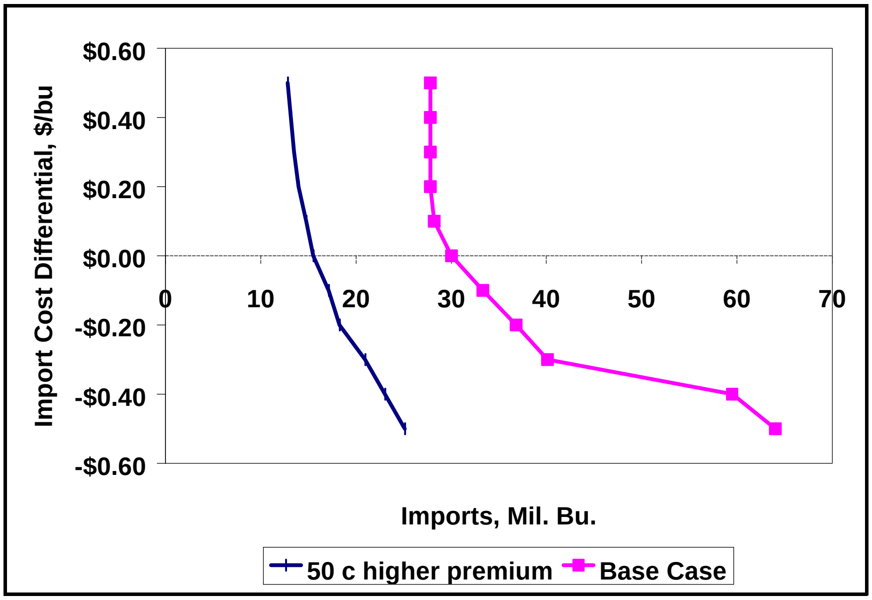

Figure 6. Impact of Malting Premium on Imports.

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Appendix

Notation

The notation used in the model below are as follows. Subscripted numbers denote the time period. For example, $begstk_0$ denotes the beginning or initial period stock of barley. Indices that are in parenthesis are used to denote states of quality or price. For example, $domestic_2(j, k, p)$ denotes domestic purchases of barley of quality type *j* given that quality distribution *k* and price state *p* are observed. All other notation are defined below.

á	quadratic penalty parameter;
$begstk_0(l)$	initial stocks of barley of quality *l*;
demand	annual quantity of malting barley demand by industry;
discount(·)	discounts applied to barley with quality (·);
$domestic_1(j)$	purchases of domestic barley in period 1 of quality *j*;
$domestic_2(j,k,p)$	purchases of domestic barley in period 2 of quality *j* given price outcome *p* and quality distribution *k* are observed;
$domstrd_1(j)$	period one domestic barley purchased for storage of quality *j*;
$domstrd_2(j,k,p)$	period two domestic barley purchased for storage of quality *j* by state;
$domprod_1(j)$	period one domestic barley production of quality *j*;
$domprod_2(j,k,p)$	period two domestic barley production of quality *j* by state;
DON(j)	ppm of DON in barley of *j* quality;
E[·]	mathematical expectations operator;
$Endstk_1$	period one total ending stocks of domestic barley;
$Endstk_2(j, k, p)$	period two total ending stocks of domestic barley by quality and state;
$Imports_1$	period one imports of Canadian malt barley;
$Imports_2(k,p)$	period two imports of Canadian malt barley;
$Importstrd_1$	period one imports stored;
$Importstrd_2(k ,p)$	period two imports stored by state;
plump(j)	percent plump of barley of *j* quality;
$price_0$	price of initial stocks of barley;
$price_1$	period one price of malt barley before discounts;
$price_2(p)$	period two price of malt barley by price *p*;
prob(k, p)	joint probability of realizing quality distribution *k* and price state *p;*
prot(j)	percent protein in barley of *j* quality;
r	discount rate;
strchg	storage charge for barley stored across time periods;
target	target storage quantity;
trans	cost of transporting barley from Canada to Minneapolis;
tw(j)	test weight of barley of *j* quality;

$util_{0,1}(l)$ initial stocks of barley of quality *l* utilized in period 1;
$util_{0,2}(l,k,p)$ initial stocks of barley of quality *l* utilized in period 2;
$util_{1,2}(j,k,p)$ barley of quality *j* stored in period 1 and utilized in period 2.

For simplicity, we represent the U.S. malt industry as a single buyer of U.S. six-rowed malting barley. The industry's objective, **(A1)**, is to minimize the sum of expected discounted cost of meeting the U.S. demand for malt and a quadratic penalty function for deviations around a target storage level. A two-year time horizon is assumed.

$$\begin{aligned}
&\min \sum_{l} begstk_0(l) * (price_0 - discount(l)) \\
&+ \sum_{j} domestic_1(j) * (price_1 - discount(j)) + Imports_1 * (price_1 + trans) \\
&+ \frac{1}{1+r} * \Big(\sum_{k} \sum_{p} prob(k,p) * \\
&\Big(\Big(\sum_{j} (domestic_2(j,k,p) - endstk_2(j,k,p)) * (price_2(j,k,p) - discount(k)) \\
&+ Imports_2(k,p) * (price_2(p) + trans) - Importstrd_2(k,p) * price_2(p)\Big)\Big)\Big) \\
&+ (Endstk_1 + Importstrd_1) * strchg \\
&+ \acute{a} * (Endstk_1 - target)^2 \\
&+ \acute{a} * \sum_{j} \sum_{k} \sum_{p} (Endstk_2(j,k,p) - target)^2
\end{aligned} \qquad \textbf{(A1)}$$

In **(A2)**, model constraints for quality are given. These quality constraints are derived from Johnson and Nganje. The constraints require that protein in utilized grain be equal to or less than 13.5% in both years and in all states of nature. The level of DON in utilized grain, in both years and all states of nature, is constrained to be equal to or less than 0.5 ppm. Plump is constrained to be at least 70% in utilized grain, and test weight is required to be at least 43 pounds.

Additional constraints, **(A3)**, are added to require that stored barley averages no more than 0.5 ppm DON. In addition to preventing the program from driving down the quality of

$$\sum_{l} util_{0,1}(l) * prot(l) + \sum_{j} util_{1,1}(j) * prot(j) + Imports_1 * 0.135 \le 0.135 * demand;$$

$$\sum_{l'} util_{0,2}(l,k,p) * prot(l) + \sum_{j} util_{1,2}(j,k,p) * prot(j) + \sum_{k} util_{2,2}(j,k,p) * prot(k) + Imports_2(k,p) * 0.135 \le 0.135 * demand \ \forall (k,p);$$

$$\sum_{l} util_{0,1}(l) * don(l) + \sum_{j} util_{1,1}(j) * don(j) + Imports_1 * 0.5 \le 0.5 * demand;$$

$$\sum_{l'} util_{0,2}(l,k,p) * don(l) + \sum_{j} util_{1,2}(j,k,p) * don(j) + \sum_{k} util_{2,2}(j,k,p) * don(k) + Imports_2(k,p) * 0.5 \le 0.5 * demand \ \forall (k,p);$$

$$\sum_{l} util_{0,1}(l) * plump(l) + \sum_{j} util_{1,1}(j) * plump(j) + Imports_1 * 0.70 \ge 0.70 * demand; \quad \textbf{(A2)}$$

$$\sum_{l'} util_{0,2}(l,k,p) * plump(l) + \sum_{j} util_{1,2}(j,k,p) * plump(j) + \sum_{k} util_{2,2}(j,k,p) * plump(k) + Imports_2(k,p) * 0.70 \ge 0.70 * demand \ \forall (k,p);$$

$$\sum_{l} util_{0,1}(l) * tw(l) + \sum_{j} util_{1,1}(j) * tw(j) + Imports_1 * 43 \ge 43 * demand;$$

$$\sum_{l'} util_{0,2}(l,k,p) * tw(l) + \sum_{j} util_{1,2}(j,k,p) * tw(j) + \sum_{k} util_{2,2}(j,k,p) * tw(k) + Imports_2(k,p) * 43 \ge 43 * demand \ \forall (k,p).$$

stored grain, this reflects the industry's uncertainty about effects of FSB infestations. (Even in 1999 which is considered a high-quality crop, 80 out 163 malt barley samples (49%) had DON higher than 0.5 ppm.)

$$\sum_{l} util_{0,2} * DON(l) + \sum_{j} domstrd_1(j) * DON(j) + Importstrd_1 * 0.5 \le 0.5 * Endstk_1;$$

$$\sum_{j} (domstrd_1(j) - util_{1,2}(j)) * DON(j) + \sum_{j} domstrd_2(j,k,p) * DON(j) + Importstrd_2(k,p) * 0.5 \le 0.5 * Endstk_2(k,p) \ \forall (k,p). \quad \textbf{(A3)}$$

Balance constraints, **(A4)**, are also imposed.

$$Imports_1 = Imputil_1 + Importstrd_1;$$
$$Imports_2(k,p) = Imputil_2(k,p) + Importstrd_2(k,p) \ \forall(j,k,p);$$
$$begstk_0(l) = util_{0,1}(l) + util_{0,2}(l,k,p) \ \forall(l,k,p);$$
$$domestic_1(j) = util_{1,1}(j) + domstrd_1(j) \ \forall j;$$
$$domestic_2(j,k,p) = util_{2,2}(j,k,p) + domstrd_2(j,k,p) \ \forall(j,k,p);$$
$$domestic_1(j) \le domprd_1(j) \ \forall j;$$
$$domestic_2(j,k,p) \le domprd_2(j,k,p) \ \forall(j,k,p);$$
$$domstrd_1(j) \ge util_{1,2}(j,k,p) \ \forall(k,p);$$

$$\sum_l util_{0,1}(l) + \sum_j util_{1,1}(j) + Imputil_1 = demand; \qquad \textbf{(A4)}$$

$$\sum_l util_{0,2}(l,k,p) + \sum_j util_{1,2}(j,k,p) + util_{2,2}(j,k,p) + Imputil_2(k,p) = demand \ \forall(k,p);$$

$$Endstk_1 = \sum_l (begstk_0(l) - util_{0,1}(l)) + \sum_j domstrd_1(j) + Importstrd_1;$$

$$Endstk_2(k,p) = \sum_j (domstrd_1(j) - util_{1,2}(j,k,p) + domstrd_2(j,k,p)) + Importstrd_2(k,p) \ \forall(k,p).$$

Footnotes

1. DON is water-soluble and heat-stable, so it survives throughout the malting and brewing process. DON in malt can cause unacceptable ‘gushing’ problems in beer. Discounts for detectable levels of DON in barley (practically, more than 0.5 ppm) have ranged between 35 and 55 cents per bushel in recent years. See Johnson and Nganje for discussion.

2. There have been numerous applications of DSP in agricultural economics. Examples include Rae; Featherstone, Baker, and Preckel; and Schroeder and Featherstone.

3. This estimate is based on discussion with industry sources.

4. Miller and Rice, and Preckel and DeVuyst applied GQ to univariate probability distributions; DeVuyst, Liu and Preckel extend the method to joint distributions.

5. An alternative specification with regional production R(t) as dependent variable had unacceptably large error terms. Errors larger than actual production in the base year (1999), when incorporated in the DSP model, would have allowed complete elimination of Midwestern production in some states of nature.

6. Comparable crop quality data for Canadian six-rowed barley are not available.

7. This is the authors’ estimate of six-rowed malting barley production in North Dakota, Minnesota, and South Dakota, based on acreage planted to malting and non-malting varieties.

8. Assessing the impact of the FHB epidemic, the GAO notes that “Canadian imports have somewhat moderated the blight’s impact on U.S. brewers and maltsters. Shortages of malting barley in the United States as a result of these diseases would normally tend to increase malting premiums and prices, but these increases have been tempered by the large imports of Canadian malting barley.” (p. 11). These price effects are not considered in our analysis.