Location, Planting Decisions, and the Marketing of Quality-Differentiated Agricultural Commodities

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Abstract

In a marketing environment, the demand conditions, the costs of shipping and storing grain varieties, the interest rate on farm loans, and the distribution of cropland in the area are important determinants of growers' planting decisions. In this article, I focus on a market for two quality-differentiated agricultural commodities: one produced with the use of biotechnology and the other, without. I develop a model for analyzing the equilibrium planting and marketing decisions made by geographically dispersed producers during the marketing year following harvest. I identify the types of marketing environments leading to a greater concentration of equilibrium acreage planted to a particular grain variety near the market and investigate the effects of the marketing environment on the spatial patterns of equilibrium land allocation among grain varieties.

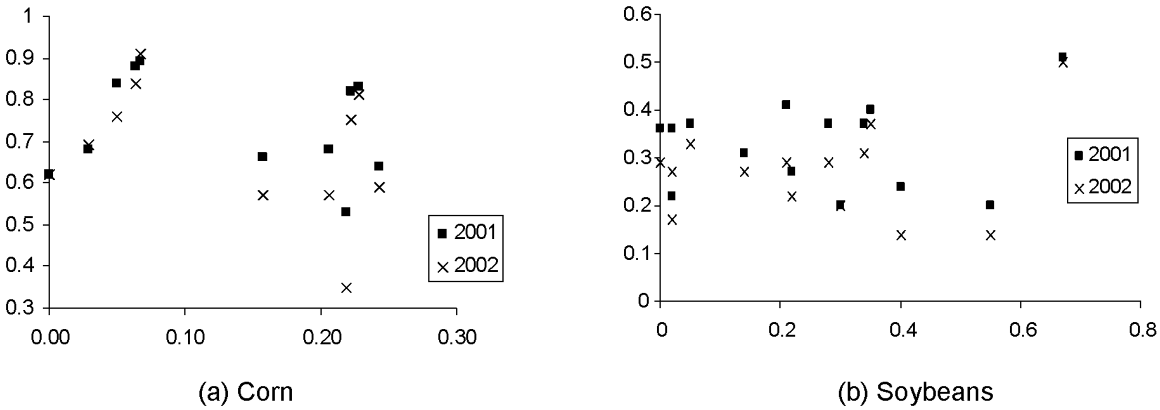
Keywords: commodity prices, grain storage, location, marketing, product quality, supermodularity.

LOCATION, PLANTING DECISIONS, AND THE MARKETING OF QUALITY-DIFFERENTIATED AGRICULTURAL COMMODITIES

Introduction

There is an ongoing transformation of many agricultural commodity markets toward greater product differentiation. The advent of genetically engineered crop varieties has raised a number of consumer concerns about food safety and has created an incentive for further product differentiation based on production characteristics. This trend posed a challenge for the U.S. bulk commodity marketing system and called for a better understanding of the economic reasons behind the adoption of new agricultural technologies. Differentiation of commodities based on the extent of genetic modification used in production is an important, though clearly not exclusive, example of differentiation in grain agriculture and will be of central interest in this study. The goal of this article is to investigate the effects that the marketing environment has on the spatial distribution of land allocated among quality differentiated grain varieties in a growing region.

Figure 1 presents some evidence on the variation in the shares of acreage planted to non-biotech corn and soybeans across different growing regions (major U.S. crop producing states). The shares of planted acreage are plotted against a proxy to the local transportation costs given by the adjustments made to the national loan rates for corn and soybeans for each state.[1] A list of factors influencing acreage allocation at a particular location may consist of soil characteristics, various area-specific pest management issues, growers' attitudes about the new technology and assessment of the potential benefits, traditional cultivation practices, and other considerations.[2] The marketing environment in a growing region constitutes another important set of factors determining the pattern of land allocation among different crops (e.g., see Lin, Chambers, and Harwood for a discussion of marketing biotech and non-biotech grain varieties). In addition to the local demand conditions, aspects of a regional marketing environment include the transportation costs to the terminal markets for different grain varieties, varietal storage



Source: U.S. Department of Agriculture

FIGURE 1. Shares of non-biotech corn and soybeans in producing states plotted against loan rate adjustments (cents/bushel), 2001 and 2002

costs, access to credit and credit market conditions, as well as the pattern of concentration of cropland in the area.[3]

The focus of this article is on the equilibrium spatial distribution of land farmed using a conventional process in the presence of a cost-saving technology in a market where consumers are willing to pay a premium for the commodity that is costlier to produce. Some examples of agricultural product differentiation that begins on the farm are products certified as organically grown and/or produced without the use of genetically modified seed varieties and which follow identity preservation methods. The issue of land allocation among competing crops may be important for policymakers because agricultural technologies and production practices, such as pesticide use patterns and soil management, may have significant environmental consequences, such as pest resistance, impacts on biodiversity and beneficial insects, and other types of externalities (see, e.g., Feedstuffs 2002a; Feedstuffs 2002b). These environmental impacts are likely to differ across and within producing regions, in part because of the variation in the adoption rates (Feedstuffs 2002c). An understanding of how marketing conditions in the area interact with the growers' planting decisions may help policymakers design better policies that promote environmentally friendly farming practices.

In particular, transportation costs in the region are likely to have a bearing on growers' marketing plans and, consequently, on planting decisions.[4] Therefore, accounting for the spatial heterogeneity among producers may shed some light on the differences in adoption rates across growing areas. Benirschka and Binkley demonstrate that in a single commodity market where suppliers are differentiated by location, transportation costs determine the optimal pattern of shipping during the marketing year. Firms with the lowest transportation costs supply the market first because “a producer close to the market has a relatively high opportunity cost of storage, [and] he will store commodities only for a short time” (Benirschka and Binkley, p. 515). Frechette and Fackler further refine this analysis to study commodity futures price backwardation and they introduce additive storage costs. With additive storage costs, the discounted market price may rise or fall over time depending on the relative magnitudes of the discount rate, the storage costs, and the transportation costs. In a forthcoming article, I use a similar model to analyze the distortions caused by government marketing loan programs and grower program choice (Saak). I use an extension of this model here to study marketing and land allocation decisions in a multi-product setting.

The rest of the article is organized as follows. First, I develop a formal model of a two-commodity, multi-period agricultural market with geographically dispersed seasonal production. After analyzing possible spatial production patterns, I examine in detail the case when the shipping costs are invariant across grain varieties. Next, I investigate the determinants of the spatial distribution of the equilibrium land allocation and identify conditions under which the concentration of the acreage planted to one variety is ordered in a monotone manner by distance to market. Then I study the problem of the monopolistic supplier of the cost-saving technology. I conclude with a formal analysis of the effects of demand-side uncertainty on the equilibrium spatial acreage allocation.

Model

Consider a market for two types of commodities: high- and low-quality grain, h and l, that are supplied by producers differentiated by their location $d \in [0,1]$ relative to the terminal market. The per unit transportation cost from any location is proportional to distance (location) d and is given by $e^h d$ and $e^l d$ for high- and low-quality varieties, $e^h \geq e^l$. The cumulative distribution of acres of cropland surrounding the market is given by $F(d)$ where $F(0) = 0$ and $F(1) = 1$. At planting, growers decide which variety to grow, and the fraction of acres located at distance d from the market and allocated to high-quality grain is denoted by $\alpha(d) \in [0,1]$. The yields are common across varieties and are normalized to unity. The per acre cost of growing the two varieties, c^h and c^l, is invariant to location, and $c^h > c^l$. The focus here is on the planting time growing decisions and the intra-year dynamics between the two harvests. Time between the harvests is discrete and indexed by $t = 0,...,T$, where $t = 0$ is the harvest time, and $t = T$ is the end of the marketing year. A producer who chooses to sell his crop after harvest at $t > 0$ incurs per unit, per period storage costs w^h and w^l for, respectively, high- and low-quality grain varieties, $w^h \geq w^l$.[5] There is no uncertainty, and producers discount future profits at $\beta = 1/(1+i) \in (0,1)$, where $i > 0$ is the per period risk-free interest rate.[6]

The inverse demand functions for two types of grain at the terminal market are given by $p_t^h = P^h(s_t^h, s_t^l)$ and $p_t^l = P^l(s_t^h, s_t^l)$, where s_t^h and s_t^l are grain supplies delivered to the market at time $t \geq 0$. We make the following assumptions about P^h and P^l:

ASSUMPTION 1. (*i*) $P^h(s^h, s^l) \geq P^l(s^h, s^l)$, $P^h(s,0) = P^l(s,0)$, $P^h(0,s) = \infty > P^l(0,s)$; (*ii*) $P^h_{s^h} \leq P^l_{s^h} < 0$ and $P^l_{s^l} \leq P^h_{s^l} < 0$.

Here the subscripts denote differentiation. The first condition in (*i*) says that higher-quality grain is valued more. The premium vanishes when the supply of low-quality grain is small, and the premium becomes very large when the supply of high-quality grain is small. Derivative conditions in (*ii*) state that the two grain varieties are substitutes in consumption. Also, the premium decreases with high-quality supply and increases with low-quality supply, which is consistent with condition (*i*).

Spatial Equilibrium

At harvest, the present value of the unit profit of the producer located at d who grows grain variety q and markets his crop at time t is given by

$$\pi(d,t,q) = \beta^t (p_t^q - e^q d) - W^q(t) - c^q, \tag{1}$$

where $W^q(t) = \sum_{i=1}^{t} \beta^i w^q = w^q \beta(1-\beta^t)/(1-\beta)$ is the harvest time value of the storage costs, $W^q(0) = 0$, $q = l,h$.

Each producer chooses the grain variety and the marketing time t to maximize the discounted profit $\pi(d,t,q)$:[7]

$$\pi(d) = \max_{q,t} \pi(d,t,q) . \tag{2}$$

The producer's problem is naturally decomposed into two steps: (*a*) the choice of variety q, and (*b*) the choice of the marketing time t. And so, the equilibrium is characterized by the function $\alpha^*(d)$, the share of acres that are sown to high-quality grain and located at distance d from the terminal market, and functions $t^h(d)$ and $t^l(d)$, the optimal timing of marketing for high- and low-quality grain growers.

Observe that $\pi(d,t,q)$ is supermodular in (d,t): $\Delta_t \Delta_d \pi(d,t,q) = \beta^t (1-\beta) e^q > 0$, where Δ denotes the difference operator.[8] Then, from Theorem 2.8.2 in Topkis (p. 77), it follows that for any price sequence $\{p_t^q\}$, $t^q(d) \le t^q(d')$ if $d < d'$, where $q = h,l$. This implies that the set of producers who market their crop at time $t > 0$ is given by $(d_{t-1}^q, d_t^q]$, where d_t^q is the location of the threshold variety q grower who is indifferent between marketing at t and $t+1$. Hence, per period supplies are given by $s_t^h = \int_{d_{t-1}^h}^{d_t^h} \alpha^*(s) dF(s)$ and $s_t^l = \int_{d_{t-1}^l}^{d_t^l} (1-\alpha^*(s)) dF(s)$ where $0 \le d_{-1}^q < d_T^q \le 1$. Note that conditions (*i*) in Assumption 1 assure that in equilibrium $d_{t-1}^q < d_t^q$, and $\alpha^*(d) > 0$ for some d in $(d_{t-1}^h, d_t^h]$ and $\alpha^*(d) < 1$ for some d in $(d_{t-1}^l, d_t^l]$, so that $s_t^h > 0$ and $s_t^l > 0$ for each $t = 0,..,T$.

Next, we ascertain the possible spatial patterns of high- and low-quality grain production. The locations of the threshold producers and the shares of acres sown to each variety can be found from equilibrium profit-maximization conditions

$$\pi(d, t^h(d), h) \ge \pi(d,t,l) \text{ for any } t \ge 0 \text{, if } \alpha^*(d) > 0 \tag{3a}$$

and

$$\pi(d,t^l(d),l) \geq \pi(d,t,h) \text{ for any } t \geq 0 \text{, if } \alpha^*(d) < 1. \tag{3b}$$

The producer profit function optimized with respect to the timing of marketing the crop, $\pi(d,t^q(d),q)$, is submodular in (d,q) for all d if $\Delta_q \Delta_d \pi(d,t^q(d),q) = -\beta^{t^l(d)}$ $(\beta^{t^h(d)-t^l(d)} e^h - e^l) < 0$, where the envelope theorem is used to perform the differentiation.[9] Consider two cases: (*a*) $\beta^T e^h > e^l$, and (*b*) $\beta^t e^h < e^l$ for some $t < T$.

In case (*a*), the required submodularity condition clearly holds for all locations, $\Delta_q \Delta_d \pi(d,t^q(d),q) < 0$. Therefore, high-quality grain is produced in the area close to the market, $\alpha^*(d) = 1$ for $d \leq d_T^h$, and low-quality grain is produced in the area far away from the market, $\alpha^*(d) = 0$ for $d > d_{-1}^l = d_T^h$. Equilibrium conditions in this case are given by

$$\pi(d_t^h,t,h) = \pi(d_t^h,t+1,h),\ t = 0,...,T-1,$$

$$\pi(d_T^h,T,h) = \pi(d_T^h,0,l),\ t = T$$

$$\pi(d_t^l,t,l) = \pi(d_t^l,t+1,l),\ t = 0,...,T-1,$$

where $s_0^h = F(d_0^h)$, $s_t^h = F(d_t^h) - F(d_{t-1}^h)$ for $t = 0,...,T$, $s_0^l = F(d_0^l) - F(d_T^h)$, and $s_t^l = F(d_t^l) - F(d_{t-1}^l)$ for $t = 1,...,T-1$, $s_T^l = 1 - F(d_{T-1}^l)$. The spatial supply and production patterns in the case are depicted in Figure 2. Above the line are the types of commodities q and the time periods when producers located in the interval $[d_{t-1}^q, d_t^q)$ supply the market, and below the line is the quantity supplied for each commodity, s_t^q, $q = l,h$.

In case (*b*), the areas of high- and low-quality grain production alternate in some range because the submodularity underlying the (weak) inverse relationship between the distance and grain quality produced in the area no longer holds. Let z = $\min\{t : \beta^t e^h < e^l\}$; then, $d_t^l \in (d_{t+z-1}^h, d_{t+z}^h)$ for $t = 0,...,T-z$. Here all acreage located near the market is planted to high-quality variety, $\alpha^*(d) = 1$ for $d \leq d_{z-1}^h$. However,

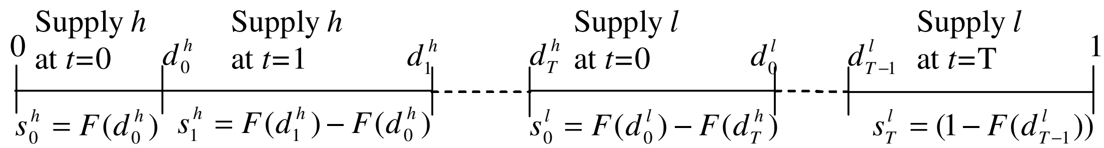


FIGURE 2. Spatial supply and production pattern of grain varieties

moving further from the market, the areas sown to each variety begin to alternate, $\alpha^*(d) = 0$ for $d \in (d_{t+z-1}^h, d_t^l]$, and $\alpha^*(d) = 1$ for $d \in (d_t^l, d_{t+z}^h]$, $t = 0,...,T-z$. As distance to the market increases, eventually the alternating pattern ceases giving way to the plantings of low-quality variety, $\alpha^*(d) = 0$ for $d > d_T^h$.[10] This follows from no-arbitrage and profit-maximization conditions (3) and the conditions that in equilibrium the supply of each grain variety must be strictly positive at each period. The equilibrium locations of the threshold producers $\{d_t^h\}$ and $\{d_t^l\}$ can be found from

$$\pi(d_t^h, t, h) = \pi(d_t^h, t+1, h),\ t = 0,...,z-2,$$

$$\pi(d_t^h, t, h) = \pi(d_t^h, t-z+1, l),\ t = z-1,...,T,$$

$$\pi(d_t^l, t, l) = \pi(d_t^l, t+z, h),\ t = 0,...,T-z,$$

$$\pi(d_t^l, t, l) = \pi(d_t^l, t+1, l),\ t = T-z+1,...,T-1,$$

where $s_t^h = F(d_t^h) - F(d_{t-1}^h)$ for $t = 0,...,z-2$, $s_t^h = F(d_t^h) - F(d_{t-z}^l)$ for $t = z-1,...,T$, $s_t^l = F(d_t^l) - F(d_{t+z-1}^h)$ for $t = 0,...,T-z+1$, and $s_t^l = F(d_t^l) - F(d_{t-1}^l)$ for $t = T-z+2$, ..., T. The spatial supply and production patterns in the case of $z = 1$ ($\beta e^h < e^l < e^h$) are depicted in Figure 3.

Consequently, when the difference in the transportation costs is not very large, namely, if $\beta^t e^h < e^l$ for some $t < T$, there is a range, $d \in [d_{z-1}^h, d_{T-z+1}^h]$, where areas producing high- and low-quality varieties alternate as the distance to the market increases. As the discount rate increases, this range narrows, until it disappears when $\beta^T e^h \geq e^l$. Summarizing, there are two distinct determinants of the spatial distribution of production. One is the difference in the transportation costs that makes the areas closer to the market more attractive for high-quality grain production. The other is intertemporal

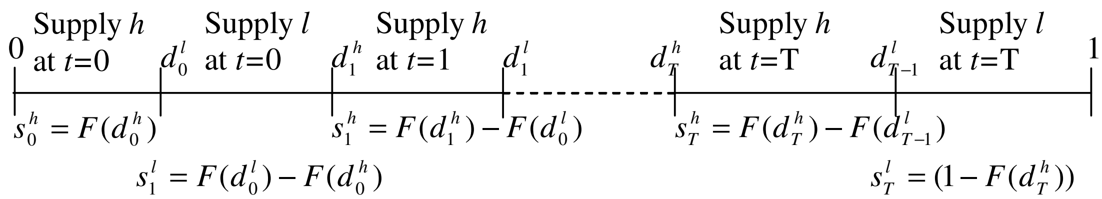


FIGURE 3. Alternating spatial pattern of varietal production

arbitrage opportunities that bring about the optimal marketing decisions (the timing of sales) for both types of growers. To better isolate the effects of intertemporal arbitrage on the equilibrium spatial distribution of high-quality grain production, consider a special but instructive case when the transportation costs from any location are invariant across grain varieties.

For the rest of the article, let $e^h = e^l = e$. Then conditions (3) imply that in equilibrium the range of locations that supply the market in a given period is the same for each variety: $t^h(d) = t^l(d) = t^*(d)$ for all d, and hence, $d_t^h = d_t^l = d_t^*$. Because in equilibrium the distribution of high-quality grain growers within the range $(d_{t-1}^*, d_t^*]$ is indeterminate, we can write $\alpha^*(d) = \alpha_t^* \in (0,1)$ where $d \in (d_{t-1}^*, d_t^*]$. This leads to the following:

DEFINITION. Spatial equilibrium is described by the sequences $\{d_t^*\}$ and $\{\alpha_t^*\}$ such that

$$p_t^h - ed_t^* - \beta(p_{t+1}^h - ed_t^* - w^h) = 0\,,\ t = 0,...,T-1\,, \tag{4a}$$

$$\beta^t(p_t^h - p_t^l) - (w^h - w^l)\beta(1-\beta^t)/(1-\beta) - (c^h - c^l) = 0\,,\ t = 0,...,T\,, \tag{4b}$$

where $p_t^q = P^q(\alpha_t^*(F(d_t^*) - F(d_{t-1}^*)), (1-\alpha_t^*)(F(d_t^*) - F(d_{t-1}^*)))$, $d_{-1}^* = 0$, $d_T^* = 1$, $t = 0,...,T$, $q = h,l$. Figure 4 depicts the spatial supply and production patterns in this case.

Difference equation (4a) has embedded in it the two initial conditions needed to determine the solution. A straightforward differentiation of (4b) establishes that each given pair of d_{t-1} and d_t uniquely determines α_t, which in turn can be used to establish

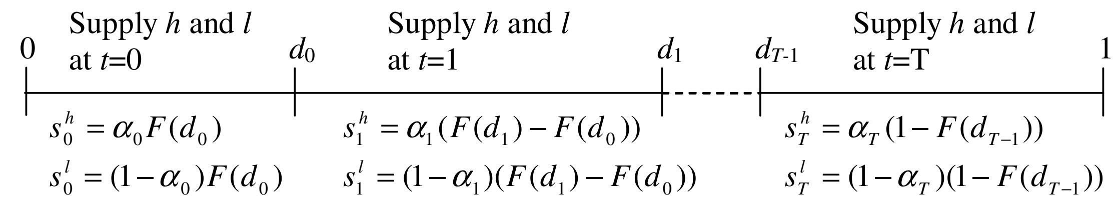


FIGURE 4. Spatial supply and production pattern of grain varieties

the monotonicity of the left-hand side of (4a) in d_{t+1}. Therefore, when Assumption 1 holds, the equilibrium sequences $\{d_t^*\}$ and $\{\alpha_t^*\}$ that satisfy (4) are uniquely determined by the boundary conditions. Furthermore, a plausible assumption is that $p_T^l \geq e^l + W^l(T) + c^l$, i.e., producers at all locations participate in production and supplying the terminal market. Note that this is always true if producers are considered in the interval $[0, \min[(p_T^l - W^l(T) - c^l)/e^l, 1]]$.

Spatial Production Patterns

It is important to understand how the distribution of acres allocated to high- and low-quality grain depends on location. As will be shown, in general, no monotone relationship between the planting decisions and location can be ascertained. Next is an investigation of the implications that equilibrium marketing decisions have for the amounts of grain varieties supplied each period. From (4a) it is clear that the market prices for both varieties increase over time, $p_t^q < p_{t+1}^q$, $q = h, l$. It is helpful to decompose the total change in prices as the share of high-quality grain and total supply change from (α, s) to (α', s') where $\alpha' < \alpha, s' < s$, as follows:

$$\begin{aligned}\Delta_{(\alpha,s)} P^q(\alpha s, (1-\alpha)s) &= [P^q(\alpha' s', (1-\alpha')s') - P^q(\alpha' s, (1-\alpha')s)] \\ &+ [P^q(\alpha' s, (1-\alpha')s) - P^q(\alpha s, (1-\alpha)s)]\end{aligned}, \quad q = h, l. \tag{5}$$

While the first square bracket is clearly positive, the sign of the second bracket is ambiguous because the supplies of high- and low-quality grain move in opposite directions. Suppose that $P_{s^h}^h \leq P_{s^l}^h$ and $P_{s^h}^l \geq P_{s^l}^l$, so that the price of high quality falls and the price of low quality rises as the share of high quality increases, $\partial p_t^h / \partial \alpha_t \leq 0$

$\leq \partial p_t^l / \partial \alpha_t$. Then the second bracket is negative for high-quality grain price, p_t^h, and positive for low-quality grain price, p_t^l. Therefore, in this case, the total amount of supply must decrease over time, $s_t = s_t^h + s_t^l > s_{t+1}^h + s_{t+1}^l = s_{t+1}$, in order for the market prices of both varieties to increase.

On the other hand, from (4b) it is clear that the premium for high quality increases over time: $\Delta_t(p_t^h - p_t^l) = (\beta^{-(t+1)} - \beta^{-t})((w^h - w^l)\beta/(1-\beta) + c^h - c^l) > 0$. To understand what can be inferred about the behavior of the supply of both varieties, decompose the total change in the premium in the manner of (5) into two components. One component is attributable to the change in the total amount supplied, and the other is attributable to the change in the share of high-quality grain in the total supply:

$$\begin{aligned}\Delta_{(\alpha,s)} R(\alpha s, (1-\alpha)s) = & [R(\alpha' s', (1-\alpha')s') - R(\alpha' s, (1-\alpha')s)] \\ & + [R(\alpha' s, (1-\alpha')s) - R(\alpha s, (1-\alpha)s)], \end{aligned} \tag{6}$$

where $R(\alpha s, (1-\alpha)) = P^h(\alpha s, (1-\alpha)s) - P^l(\alpha s, (1-\alpha)s)$. While the second square bracket is clearly positive when condition (*ii*) in Assumption 1 holds, the sign of the first bracket is ambiguous because supplies of both varieties fall and the premium may move in either direction. Consider a special case with $R_{s^h} = 0$ and $R_{s^l} > 0$, where the latter condition is necessary to assure the uniqueness of equilibrium. Then the sign of the first square bracket in (6) is negative because the premium decreases as low-quality grain supply falls, $(1-\alpha')s' < (1-\alpha')s$. Therefore, if the total amount of supply decreases over time, $s_t = s > s' = s_{t+1}$, the share of high-quality grain must decrease as well, $\alpha_t = \alpha > \alpha' = \alpha_{t+1}$, in order for the price premium to rise over time. Furthermore, the share of acreage planted to high-quality grain decreases with the distance to the market, $\alpha^*(d) = \alpha^*_{t^*(d)} \geq \alpha^*_{t^*(d')} = \alpha^*(d')$, because $t^*(d) \leq t^*(d')$ if $d < d'$.

From (5) and (6) it is clear that the change in the total grain supply gives rise to the possibility that the share of high-quality grain may rise over time. To isolate this effect, for convenience, make the following assumption:

ASSUMPTION 2. $P^h(s^h, s^l) - P^l(s^h, s^l) = R(s^h/(s^h + s^l))$ where $\partial R(x)/\partial x < 0$ for $x \in [0,1]$, $R(0) = \infty$, and $R(1) = 0$.

Equation (4b) implies that $\Delta_t(P^h(\alpha_t s_t, (1-\alpha_t)s_t) - P^l(\alpha_t s_t, (1-\alpha_t)s_t))$ $= \Delta_t R(\alpha_t) > 0$. Therefore, Assumption 2 guarantees that in equilibrium the share of high-quality grain marketed each period falls over time, $\alpha_t^* > \alpha_{t+1}^*$, and space, $\alpha^*(d)$ $\geq \alpha^*(d')$ where $d < d'$. Summarizing yields the following:

RESULT 1. (*a*) Let Assumption 2 hold, or (*b*) let $P_{s^h}^h \leq P_{s^l}^h$, $P_{s^h}^l \geq P_{s^l}^l$, $P_{s^h}^h - P_{s^h}^l = 0$, and $P_{s^l}^h - P_{s^l}^l > 0$. Then the share of high-quality grain marketed each period decreases over time, $\alpha_t^* > \alpha_{t+1}^*$, and the share of acreage at each location planted to high-quality grain (weakly) decreases with distance, $\alpha^*(d) \geq \alpha^*(d')$ where $d < d'$.

The following example illustrates that the share of high-quality grain supplied each period, α_t^*, may decrease or increase over time. Also, it is demonstrated that the effect of the discount rate on the share of high-quality grain produced at a given location, $\alpha^*(d)$, is non-monotone.

EXAMPLE. Let $T = 1$, $F(d) = d$, $c^h - c^l = 1$, $w^h = w^l = 1$, $e = 1$, $P^l(s^h, s^l) = g(s^h + s^l)$ and $P^h(s^h, s^l) = g(s^h + s^l) + (s^l)^{s^h}/s^h$, where $g' < -(s^l)^{s^h - 1}$, $g(s) = 1/s$.

Because here the price of low quality depends only on the total supply, the solution is simplified, as the share of high-quality grain and the location of the threshold producer can be found separately. Figure 5 depicts the relationship between the shares of acres planted to high quality close to ($d \leq d_0$) and far from the market ($d > d_0$) and the interest rate.

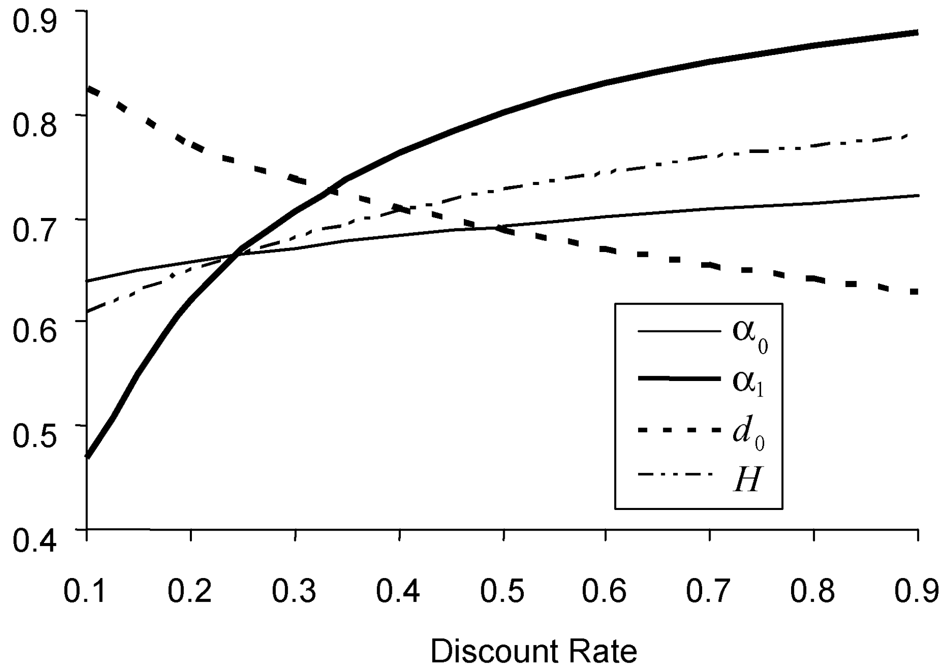


FIGURE 5. The shares of high-quality grain and the discount rate

When the discount rate is small $(\beta < 0.25)$, the share of high-quality grain supplied during the first period exceeds the share of high-quality grain supplied during the second period. The situation is reversed as the discount rate becomes larger. Even though the total quantity of high-quality grain produced monotonically increases with the discount rate, the effect on the share of high-quality grain at a particular location is non-monotone. For example, $\alpha^*(d = 0.8; \beta = 0.1) = 0.64 > 0.62 = \alpha^*(d = 0.8; \beta = 0.2)$.

From equation (4b), given that Assumption 2 holds, it is clear that the share of high-quality grain supplied each period, α_t^*, decreases with the production and storage cost differentials, $c^h - c^l$ and $w^h - w^l$, and increases with the discount rate, β. Some comparative statics results concerning the equilibrium distribution of high-quality grain production across space, $\alpha^*(d)$, are derived next. First is an investigation of the effects of the transportation and storage costs on planting decisions.

RESULT 2. Let Assumption 2 hold. Then (*a*) the share of high-quality grain produced at each location $\alpha^*(d)$ decreases with the transportation cost e, and (*b*) $\alpha^*(d)$ increases with a uniform increase in storage costs, $w^h \to w^h + w, w^l \to w^l + w$, $w > 0$.

If the equilibrium shares of high-quality grain supplied each period are determined in isolation from the total amount of grain supplied, the share and the cumulative quantity of high-quality grain at each location (weakly) declines as the transportation cost increases. The relationship is reversed if the storage costs for both varieties increase by the same amount, because of the different timing of the transportation and storage costs. While the transportation cost is typically incurred once (at the time immediately preceding the sale), the storage cost is incurred each period and accumulates over time. An increase in the transportation cost renders the option to delay sale more profitable, and the sets of producers supplying the market at a given period shift closer to the market. In contrast, an increase in the storage cost renders the option to delay sale less profitable. A subsequent increase in prices in the post-harvest period is required to re-establish an incentive to store. Therefore, the sets of producers supplying the market at a given period shift away from the market. Because the shares of high-quality grain supplied each period are unaffected, the share of high-quality grain produced at a given location changes accordingly: it decreases with the transportation cost and increases with the storage cost.

Next is an inquiry into the other determinants of the total amount of high-quality grain produced, $H(\beta, c^h - c^l, w^h - w^l, F) = \int_0^1 \alpha^*(z; \beta, c^h - c^l, w^h - w^l) dF(z)$, the discount rate, β, the production and storage cost differentials, $c^h - c^l$ and $w^h - w^l$, and the distribution of available cropland near the market, $F(d)$. Let the parameter γ parameterize a shift of the acreage, $F(d;\gamma)$, towards the market so that $F(d;\gamma) \leq F(d;\gamma')$ for all $d \in [0,1]$ if $\gamma < \gamma'$.

RESULT 3. (*a*) Let $P^h_{s^l} - P^l_{s^l} = 0$ and $P^h_{s^h} - P^l_{s^h} < 0$, or $P^h_{s^l} - P^l_{s^l} > 0$ and $P^h_{s^h} - P^l_{s^h} = 0$.

Then the total quantity of high-quality grain H increases with the discount rate β and decreases with the production and storage cost differentials $c^h - c^l$ and $w^h - w^l$. (*b*) Let $T = 1$ and let Assumption 2 hold. Then the quantity of high-quality grain H increases as acreage shifts toward the market.

In general, an increase in the discount rate or in the cost differentials has an ambiguous effect because both the locations of the equilibrium threshold producers, d_t^*, and the shares of high-quality grain supplied each period, α_t^*, are affected. Part (*a*) of the result focuses on special cases when the price premium depends on the supply of either high- or low-quality grain but not both. Then the share of high-quality grain produced in the region responds positively to an increase in the discount rate. In other words, under certain conditions, more acres will be planted to high-quality grain in an area with lower interest rates on farm loans, and these interest rates are linked to the conditions of local credit markets and banking systems. Furthermore, and very intuitively, in areas where the added storage and production expenses associated with high-quality grain are smaller, the acreage planted to high-quality grain will be greater.

For part (*b*) of the result, suppose that the marketing year consists of just two periods: harvest-time, $t = 0$, and post-harvest marketing, $t = 1$. Suppose also that the premium paid for high-quality grain is determined solely by the share of high-quality grain in the total supply. Then a shift of the cropland toward the market, possibly accompanied by an increase in the total acreage, will cause the number of acres allocated to high-quality grain to increase. Therefore, areas where most of the cropland is concentrated near the terminal market are likely to grow more high-quality grain than are similar areas where the acreage available for planting is distributed more uniformly.

Endogenous Production Cost Differential

The new agricultural technology (e.g., cost-saving genetically modified seeds) is often supplied by or patented and subsequently licensed to distributors by a single company.[11] In such cases, the cost differential is likely composed of two parts: $c^h - c^l = r^f - r$.[12] Here r is the price charged by the technology supplier, and $r^f > 0$ is the cost savings arising because of the use of the technology on farms and not (directly) controlled by the patent holder, $r \le r^f$. Both of these costs are taken to be common among all growers. The demand for the cost-saving seed is equal to the number of acres farmed using the new technology, $1-H$. Of interest is how the revenue of the technology supplier responds to the changes in the production and marketing environments. The monopolist's revenue gross of production costs (that are either sunk or normalized to zero) is

$$\Pi^M = \max_r \; r(1-H(r)) . \tag{7}$$

Results 2 and 3 can be readily used to infer the following regarding the revenue accrued to the new technology supplier:

RESULT 4. (*a*) Let $P^h_{s^l} - P^l_{s^l} = 0$ and $P^h_{s^h} - P^l_{s^h} < 0$, or $P^h_{s^l} - P^l_{s^l} > 0$ and $P^h_{s^h} - P^l_{s^h} = 0$.

Then the monopolist's revenue Π^M increases when the discount rate β falls, and the farm production and storage cost differentials, r^f and $w^h - w^l$, rise. For (*b*)-(*d*), let Assumption 2 hold. Then Π^M increases with (*b*) an increase in the transportation cost e , and with (*c*) a uniform decrease in the storage costs $w^h \to w^h - w, w^l \to w^l - w$, $w > 0$; (*d*) In addition, let $T = 1$. Then Π^M increases as the acreage shifts away from the market.

Therefore, it is likely that the cost-saving seed supplier will be more interested in promoting the new technology in a region with less-developed credit markets (a higher interest rate on farm loans), and where the cost-savings from the use of the technology are greater in both production and subsequent storing. While not modeled formally, this immediately implies that a greater probability of comingling of the two grain varieties that takes away the value of the high-quality commodity plays into the monopolist's hand, as it increases the difference in storage costs. Also, the cost-saving seed supplier may prefer an area with higher transportation costs and a greater (cheaper) storage capacity. In addition, an area where the concentration of cropland occurs relatively far from a terminal market is also more likely to be targeted by the new seed supplier.

In general, there is no guarantee that problem (7) is well behaved and has a unique solution. However, if one of the conditions in Result 4, part (*a*) holds, and in addition, if

$R_{s^h s^l} = P^h_{s^h s^l} - P^l_{s^h s^l} = 0$ and $R_{s^h s^h} = P^h_{s^h s^h} - P^l_{s^h s^h} > 0$, or $R_{s^h s^l} = 0$ and $R_{s^l s^l} = P^h_{s^l s^l}$ $- P^l_{s^l s^l} > 0$, respectively, it can be readily verified that there is a unique r^* that maximizes the monopolist's revenue. Consider some of the determinants of the cost differential set by the monopolistic technology supplier in this case:

RESULT 5. Let (*a*) $R_{s^h}(s^h, s^l) < 0$, $R_{s^l}(s^h, s^l) = 0$, $R_{s^h s^l}(s^h, s^l) = 0$, $R_{s^h s^h}(s^h, s^l) > 0$, or (*b*) $R_{s^l}(s^h, s^l) > 0$, $R_{s^h}(s^h, s^l) = 0$, $R_{s^h s^l}(s^h, s^l) = 0$, $R_{s^l s^l}(s^h, s^l) > 0$ for all $s^h, s^l > 0$.

Then the optimal technology fee charged by the monopolist r^* increases with the storage cost differential, $w^h - w^l$, and with the farm cost savings in production provided by the new technology, r^f.

Under certain conditions concerning the price premium for varieties produced using conventional farming practices, the price of the cost-saving seed is likely to be higher in a growing area where the benefits of the new technology are more pronounced relative to another, otherwise similar, growing area where the potential cost-savings are lower. Also, an increase in the added storage expense of the conventional grain variety leads to an optimal upward adjustment of the technology fee.

The next subsection inquires into how the introduction of the demand-side uncertainty affects the equilibrium planting and marketing decisions across space.

Uncertainty

In a general case, the analysis of the effects of uncertainty on equilibrium planting decisions is complicated because of the interaction between the marketing decisions and the uncertainty regarding the future demand conditions that unfold each period as the marketing year progresses. To simplify the analysis, consider a special but illustrative case with two marketing periods: harvest-time, $t = 0$, and post-harvest, $t = 1$. Furthermore, for the rest of this section, assume the following. The distribution of cropland in the growing area is concentrated in just two points: at $d = 0$, an area close to the market, and at $d = \bar{d}$, an area far away from the market, so that $F(d) = f$, $d < \bar{d}$, and $F(\bar{d}) = 1$. To focus on the effects of uncertainty arising because of intertemporal and spatial arbitrage and not because of the way the uncertainty enters the demand functions, it is held that $p_t^h = P^h(s_t^h, s_t^l) + \theta_t$ and $p_t^l = P^l(s_t^h, s_t^l)$, where θ_0 and θ_1 are identically independently distributed (i.i.d.) random shocks. The resolved uncertainty regarding θ_0 may affect the price of the low-quality variety p_t^l only through the marketing decisions of the high-quality variety growers made at harvest since the two grain varieties are substitutes in consumption. To simplify notation, let $e = 1$ and $w^h = w^l = w$.

It is instructive to first investigate the case with no uncertainty, $\Pr(\theta_0 = \hat{\theta})$ $= \Pr(\theta_1 = \hat{\theta}) = 1$. Consider equilibrium where all growers located near the market at $d = 0$ supply the market at harvest, $t = 0$, $\pi(d = 0, t = 0, q) > \pi(d = 0, t = 1, q)$, $q = l, h$, and all growers far away from the market at $d = \bar{d}$ supply the market after the harvest, $t = 1$, $\pi(d = \bar{d}, t = 1, q) > \pi(d = \bar{d}, t = 0, q)$, $q = l, h$. The shares of acres sown to high-quality grain at each location, α_0^* and α_1^*, adjust until producers are indifferent between growing either variety, $\pi(d = 0, t = 0, h) = \pi(d = 0, t = 0, l)$ and $\pi(d = \bar{d}, t = 1, h)$ $= \pi(d = \bar{d}, t = 1, l)$, or

$$p_t^h - p_t^l = (c^h - c^l)\beta^{-t}, \; t = 0,1, \tag{8}$$

$$\beta(p_1^q - w) \le p_0^q \le \beta(p_1^q - w) + (1-\beta)\bar{d}, \; q = l, h, \tag{9}$$

where $s_0^h = \alpha_0^* f$, $s_0^l = (1-\alpha_0^*) f$, $s_1^h = \alpha_1^*(1-f)$, and $s_1^l = (1-\alpha_1^*)(1-f)$. Clearly, one can always pick the storage cost, w, and the transportation cost, $\bar{d}$, such that these conditions hold.

Turning back to the analysis under uncertainty, let θ_0 and θ_1 be i.i.d. random variables with the expectations given by $E\theta_0 = E\theta_1 = \hat{\theta}$, and consider equilibrium marketing decisions made at $t = 0$ after the uncertainty regarding θ_0 is resolved. Denote by $\underline{\theta}(\alpha_0^*, \alpha_1^*)$ and $\bar{\theta}(\alpha_0^*, \alpha_1^*)$ the realizations of θ_0 such that the intertemporal arbitrage may take place:

$$P^h(\alpha_0^* f, (1-\alpha_0^*)f) + \underline{\theta} = \beta(P^h(\alpha_1^*(1-f), (1-\alpha_1^*)(1-f)) + \hat{\theta} - w)\text{, and}$$
$$P^h(\alpha_0^* f, (1-\alpha_0^*)f) + \overline{\theta} = \beta(P^h(\alpha_1^*(1-f), (1-\alpha_1^*)(1-f)) + \hat{\theta} - w) + (1-\beta)\overline{d}\,.$$

Then, at time 0, for any $\theta_0 < \underline{\theta}$, some of the high-quality growers at $d = 0$ will choose to supply at $t = 1$, and their number, $x_0 > 0$, is given by

$$P^h(\alpha_0^* f - x_0, (1-\alpha_0^*)f) + \theta_0 = \beta(P^h(\alpha_1^*(1-f) + x_0, (1-\alpha_1^*)(1-f)) + \hat{\theta} - w)\,,$$

where it is held that low-quality growers far away from the market at $d = \overline{d}$ have no incentive to market their crop at $t = 0$:

$$P^l(\alpha_0^* f - x_0, (1-\alpha_0^*)f) \le \beta(P^l(\alpha_1^*(1-f) + x_0, (1-\alpha_1^*)(1-f)) - w) + (1-\beta)\overline{d}\,. \quad (10)$$

While for any $\theta_0 > \overline{\theta}$, some of the high-quality growers at $d = \overline{d}$ will choose to supply at $t = 0$, and their number, $x_1 > 0$, is given by

$$P^h(\alpha_0^* f + x_1, (1-\alpha_0^*)f) + \theta_0 = \beta(P^h(\alpha_1^*(1-f) - x_1, (1-\alpha_1^*)(1-f)) + \hat{\theta} - w) + (1-\beta)\overline{d}$$

where it is held that low-quality growers near the market at $d = 0$ have no incentive to delay marketing their crop until $t = 1$:

$$P^l(\alpha_0^* f + x_1, (1-\alpha_0^*)f) \ge \beta(P^l(\alpha_1^*(1-f) - x_1, (1-\alpha_1^*)(1-f)) - w)\,. \quad (11)$$

Therefore, the resultant price premium for the high-quality variety looks as depicted in Figure 6 given that $R_{s^h s^h} = P^h_{s^h s^h} - P^l_{s^h s^h} = 0$, so that the change in the curvature is solely attributable to the intertemporal arbitrage opportunities exercised by high-quality growers. The effect of the random shock on the price of the high-quality variety at harvest is smoothed out because of the possibility of the intertemporal arbitrage by the high-quality grain growers at each location. Figure 6 suggests that an increase in uncertainty has an ambiguous effect on the expected price premium because the curvature of the premium is non-monotone in θ_0. On the one hand, the premium is (weakly) convex around $\underline{\theta}$, the lower bound of the "no-arbitrage" range of the values of the random shock θ_0, where some high-quality growers near the market may choose to delay marketing. On the other hand, the premium is (weakly) concave around the upper bound

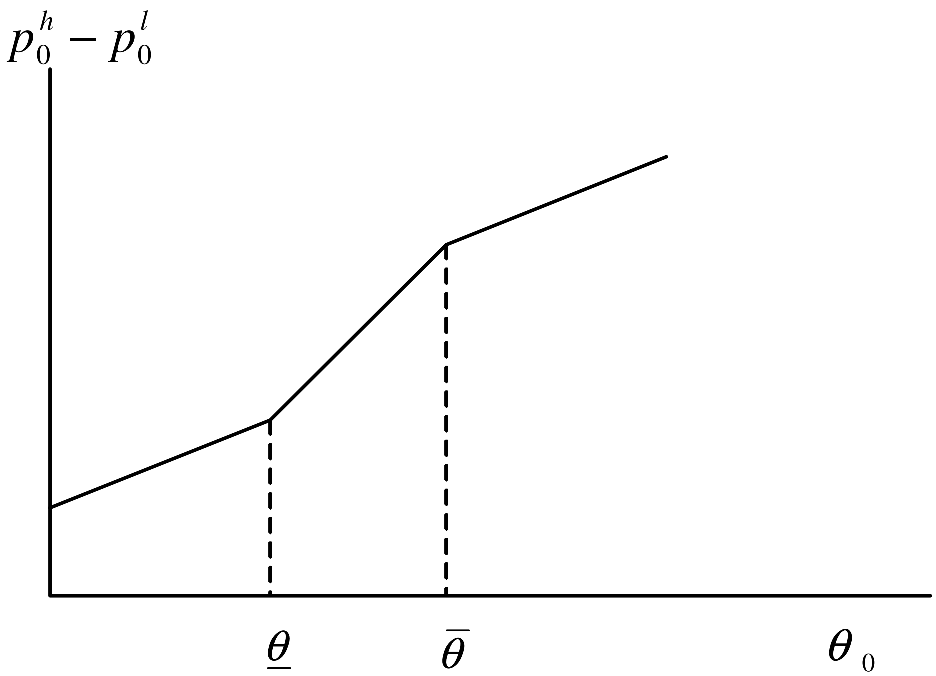


FIGURE 6. Price premium under uncertainty

of the "no-arbitrage" range, $\overline{\theta}$, where some high-quality growers far away from the market may choose to market their crop at harvest. The following verifies this intuition.

For simplicity, it is held that the random demand shocks have a two-point distribution: $\theta_t = \hat{\theta} - \varepsilon$ with probability 0.5, and $\theta_t = \hat{\theta} + \varepsilon$ with probability 0.5, $t = 0,1$, where $\varepsilon \geq 0$. Then an increase in ε constitutes an increase in uncertainty regarding the demand for the high-quality variety. When $\underline{\theta} + \varepsilon \leq \hat{\theta} \leq \overline{\theta} - \varepsilon$, a small increase in uncertainty has no effect on the equilibrium planting decisions. Suppose that $\hat{\theta} - \underline{\theta} < \varepsilon < \overline{\theta} - \hat{\theta}$, so that the negative shock to the demand for high-quality variety at harvest renders it profitable (in expectation) for the high-quality grain growers near the market to delay marketing until after the harvest. In planting time equilibrium, the shares of high-quality grain produced at each location adjust until $E \max_t \pi(d,t,h) = E \max_t \pi(d,t,l)$, for $d = 0, \overline{d}$, where the expectation is based on the information available at planting. Then, equilibrium is given by $(\alpha_0^*, \alpha_1^*, x_0^*)$ such that

$$E\{p_t^h - p_t^l\} = (c^h - c^l)\beta^{-t},\ t = 0,1, \tag{12}$$

$$P^h(\alpha_0^* f - x_0^*, (1-\alpha_0^*) f) + \hat{\theta} - \varepsilon = \beta(P^h(\alpha_1^*(1-f) + x_0^*, (1-\alpha_1^*)(1-f)) + \hat{\theta} - w), \tag{13}$$

where $\hat{\theta} - \underline{\theta}(\alpha_0^*, \alpha_1^*) < \varepsilon < \overline{\theta}(\alpha_0^*, \alpha_1^*) - \hat{\theta}$, $E\{p_0^h - p_0^l\} = 0.5[R(\alpha_0^* f - x_0^*, (1-\alpha_0^*) f)$ $+ \hat{\theta} - \varepsilon] + 0.5[R(\alpha_0^* f, (1-\alpha_0^*) f) + \hat{\theta} + \varepsilon]$, $E\{p_1^h - p_1^l\} = 0.5R(\alpha_1^*(1-f) + x_0^*, (1-\alpha_0^*) f)$ $+ 0.5R(\alpha_1^*(1-f), (1-\alpha_1^*)(1-f)) + \hat{\theta}$, and condition (10) holds.

From (12) it follows that the equilibrium share of high-quality acres near (far from) the market increases (decreases) with the extent of the intertemporal arbitrage by the high-quality growers near the market, x_0: $\partial\alpha_0^* / \partial x_0 \geq 0$ and $\partial\alpha_1^* / \partial x_0 \leq 0$. This, upon differentiating (13), yields $\partial x_0 / \partial\varepsilon > 0$ if $P_{s^h}^h(s^h, s^l) > P_{s^l}^h(s^h, s^l)$ for all $s^h, s^l > 0$. In other words, an increase in the magnitude of the negative demand shock will cause a greater share of high-quality growers near the market to delay marketing until after the harvest. Consequently, the shares of high-quality grain production in the areas close to the market and far away from the market move in opposite directions as uncertainty increases, $\partial\alpha_0^* / \partial\varepsilon \geq 0$ and $\partial\alpha_1^* / \partial\varepsilon \leq 0$. Next, consider the case with $\overline{\theta} - \hat{\theta} < \varepsilon < \hat{\theta} - \underline{\theta}$ when the positive shock to the demand for high-quality variety at harvest renders it profitable (in expectation) for the high-quality grain growers located far away from the market to market their crop at harvest-time. An analysis similar to that in the previous case shows that the response of equilibrium shares of acres planted to high-quality grain in the areas near and far from the market is reversed: $\partial\alpha_0^* / \partial\varepsilon \leq 0$ and $\partial\alpha_1^* / \partial\varepsilon \geq 0$ if $P_{s^h}^h(s^h, s^l) > P_{s^l}^h(s^h, s^l)$ for all $s^h, s^l > 0$. Summarizing gives the following:

RESULT 6. An increase in uncertainty may increase or decrease the share acres sown to high-quality grain variety at each location. Namely, let $P_{s^h}^h(s^h, s^l) > P_{s^l}^h(s^h, s^l)$ for all $s^h, s^l > 0$.

Suppose there is an increase in uncertainty regarding the value of θ_t. Then the share of acres allocated to high-quality variety near (far away from) the market increases (decreases) $\partial\alpha_0^* / \partial\varepsilon \geq 0$ and $\partial\alpha_1^* / \partial\varepsilon \leq 0$ if $\hat{\theta} - \underline{\theta} < \varepsilon < \overline{\theta} - \hat{\theta}$, and conversely, $\partial\alpha_0^* / \partial\varepsilon \leq 0$ and $\partial\alpha_1^* / \partial\varepsilon \geq 0$ if $\overline{\theta} - \hat{\theta} < \varepsilon < \hat{\theta} - \underline{\theta}$.

Conclusions

This article presents an investigation of the effects of the marketing environment on the acreage allocation among multiple crops in a growing area. The study analyzes equilibrium planting and marketing decisions during the marketing year between the two harvests in a market for two quality differentiated agricultural commodities with geographically dispersed producers. The study includes the important case of a market for grains differentiated based on the genetically modified (GM) content present in the seed. Such differentiation typically requires additional expenses in grain processing, including storing and transportation, in order to assure identity preservation of the non-GM crop. The elements of the marketing environment studied here are demand conditions, the costs of shipping and storing grain varieties, the state of agricultural credit markets (summarized by the interest rate on farm loans), and the distribution of cropland in the area.

While most statements about the precise spatial pattern of equilibrium land allocation among the grain varieties require a detailed knowledge about the environment, it is interesting that a higher cost of shipping or storing a non-GM crop (high-quality grain variety) will not necessarily cause all of non-GM acreage to concentrate near the market. Several conditions on the behavior of demand for grain varieties under which the concentration of non-GM acreage occurs near the market are identified. Also, the study illustrates that the costs of shipping and storing grain may have counteracting effects on the spatial pattern of equilibrium planting decisions because of the different timing within the marketing year for these two types of expenses. Some of the determinants of the revenue and the price of (GM) cost-saving seeds charged by the monopolistic seed supplier are investigated. Upon the introduction of demand uncertainty, the study demonstrates that the equilibrium effects of uncertainty on the extent of the concentration of non-GM acreage near the market are ambiguous.

Whereas this article emphasized the spatial heterogeneity among producers, the producer heterogeneities in varietal storage and transportation costs, planting costs, benefits derived from using a particular variety and past farming practices, risk attitudes, discount rates, and access to credit are other essential features of the agricultural environment. For example, in light of the previous analysis, the incentives to invest in additional on-farm or off-farm storage capacity required for a cost-effective product differentiation may differ across locations. In particular, it may turn out that farmers located in the middle of the growing area where transportation costs are moderate will have the greatest incentive to expand storage capacity, allowing for better crop identity preservation. Both theoretical and empirical understanding of marketing and planting decisions in the presence of producer heterogeneities is likely to provide valuable policy insights.

Endnotes

1. This measure of transportation costs ignores the variability in the cost of shipping grain within a state.

2. There is a large literature concerned with the motives behind the adoption of agricultural biotechnology. For example, the effects of uncertainty about consumer attitudes toward genetically modified foods on equilibrium acreage planted to non-modified varieties are studied in Saak and Hennessy. The motives based on the added flexibility in pest management in the context of heterogeneous susceptibility to infestation across farms are investigated in Hennessy and Saak. Hubbell, Marra, and Carlson, and Lapan and Moschini study grower adoption of biotechnology in other contexts.

3. For example, Bullock, Desquilbet, and Nitsi discuss and provide many empirical estimates of price premiums and identity preservation costs for non-biotech grain varieties, including the costs of purity testing, shipping, and segregation in various stages of the food supply chain.

4. To better focus on the interaction between the marketing environment and planting decisions, the planting costs are assumed to be invariant across locations in what follows.

5. Under a typical commercial storage contract, a producer is charged a fee accrued during the first three to six months even if the grain is removed from storage before that. This and other kinds of fixed storage costs are not considered explicitly. Accounting for them would complicate the notation without changing the nature of the results.

6. The likely heterogeneity in the discount rates among producers is potentially important but is not modeled here.

7. For simplicity, I ignore the time elapsed between planting and harvesting the crop.

8. The theory of comparative statics that relies on properties such as supermodularity and single crossing is developed in Topkis, Milgrom and Shannon, and Athey, among others. A function on a suitable domain is supermodular if increasing one variable increases the incremental return to another variable. This concept is intimately related to the important economic notion of complementarity.

9. If a function $-f$ is supermodular, then f is said to be submodular.

10. I exclude the case with $\beta^z e^h = e^l$ for some $z > 0$ as a zero probability event except for the case with $e^h = e^l$. The analysis in these cases is parallel to the analysis when $e^h = e^l$ because there is also $d^h_{t+z} = d^l_t$ for $t = 0,...,T - z$.

11. According to some estimates, the Animal and Plant Health Inspection Service—the arm of the U.S. Department of Agriculture responsible for regulating transgenic plants—reviews about 1,000 applications from biotechnology companies each year (Feedstuffs 2002a).

12. The case in which agricultural technology improves the output characteristics of the product can be analyzed in a similar manner. Then one can write $c^h - c^l = r^f + r$, and the technology supplier's revenue is $\Pi^M = rH(r)$.

Appendix

Proof of Result 2. (*a*) First, establish that $\alpha^*(d;e) \geq \alpha^*(d;e')$ for all d if $e \leq e'$. From Assumption 2 it follows that $\partial\alpha_t^* / \partial e = 0$. Suppose that $d_t' > d_t$ for some t. Let $t = i \geq 0$ be the first time that this happens. Then $s_i^h = \alpha_i(F(d_i) - F(d_{i-1})) <$ $\alpha_i(F(d_i') - F(d_{i-1}') = s_i^{h'}$ and $s_i^l = (1-\alpha_i)(F(d_i) - F(d_{i-1})) <$ $(1-\alpha_i)(F(d_i') - F(d_{i-1}')$ $= s_i^{l'}$, and hence $p_i^h = P^h(s_i^h, s_i^l) > p_i^{h,'} = P^h(s_i^{h'}, s_i^{l'})$, because $d_{i-1}' \leq d_{i-1}$ by assumption.

Also, from equilibrium conditions at $t = i$ it follows that $e'd_i'(1-\beta) = p_i^{h,'} - \beta p_{i+1}^{h,'} + \beta w^h$ $> p_i^h - \beta p_{i+1}^{h,'} + \beta w^h$ $= ed_i(1-\beta)$, which, rearranging, yields $\beta(p_{i+1}^h - p_{i+1}^{h,'}) > p_i^h - p_i^{h,'}$ > 0. Because p_{i+1}^h $= P(s_{i+1}^h, s_{i+1}^l) > p_{i+1}^{h,'} = P(s_{i+1}^{h'}, s_{i+1}^{l'})$, and hence, $s_{i+1}^h = \alpha_{i+1}(F(d_{i+1}) - F(d_i)) < \alpha_{i+1}(F(d_{i+1}') - F(d_i') = s_{i+1}^{h'}$ and s_{i+1}^l $= (1-\alpha_{i+1})(F(d_{i+1}) - F(d_i)) < (1-\alpha_{i+1})(F(d_{i+1}') - F(d_i') = s_{i+1}^{l'}$, along with $d_i' > d_i$, it follows that $d_{i+1}' > d_{i+1}$. From equilibrium conditions at $t = i+1$ it follows that $e'd_{i+1}'(1-\beta) = p_{i+1}' - \beta p_{i+2}' + \beta w^h$ $> p_{i+1} - \beta p_{i+2} + \beta w^h = ed_{i+1}(1-\beta)$, and $\beta(p_{i+2}^h - p_{i+2}^{h,'}) > p_{i+1}^h - p_{i+1}^{h,'} > 0$. Continuing in this fashion, $d_{T-1}' > d_{T-1}$ is obtained and $p_T^h = P^h(\alpha_T(1 - F(d_{T-1})), (1-\alpha_T)(1 - F(d_{T-1})))$ $> p_T^{h,'} = P^h(\alpha_T(1 - F(d_{T-1}')),$ $(1-\alpha_T)(1 - F(d_{T-1}')))$ which is impossible. Therefore, it follows that $d_t' \leq d_t$ for all t when $e \leq e'$. Consequently, $\alpha^*(d;e) = \alpha^*_{t^*(d;e)} \geq \alpha^*_{t^*(d;e')}$ $= \alpha^*(d;e')$ because $t^*(d;e) \leq t^*(d;e')$ for all d, and $\alpha_t^* > \alpha_{t+1}^*$ from Result 1, part (*a*).

(*b*) Next, establish that $\alpha^*(d;w^h,w^l) \leq \alpha^*(d;w^h+w,w^l+w)$ for all d if $w > 0$. The proof is similar to that of part (*a*). From Assumption 2 it follows that $\partial\alpha_t^* / \partial w = 0$. It can also be shown that an increase in storage costs, $w^{h,'} = w^h + w$ and $w^{l,'} = w^l + w$, implies that $d_t' \geq d_t$ for all t, and hence $t^*(d; w^h, w^l) \geq t^*(d; w^{h,'}, w^{l,'})$ for all d. And so, $\alpha^*(d; w^h, w^l) \leq \alpha^*(d; w^{h,'}, w^{l,'})$.

Proof of Result 3. (*a*) First, establish that $H(\beta) < H(\beta')$ if $\beta < \beta'$ and $H(\phi) > H(\phi')$ if $\phi < \phi'$, where $\phi = c^h - c^l, w^h - w^l$. Suppose that $P^h_{s^l} - P^l_{s^l} = 0$ and $P^h_{s^h} - P^l_{s^h} < 0$. Differentiating (4b) it follows that
$\partial s^h_t / \partial \beta = -[(w^h - w^l)(\beta^{-t}(t(1-\beta)-1)+1)/(1-\beta)^2 \; + (c^h - c^l)t\beta^{-t-1} / (P^h_{s^h} - P^l_{s^h}) > 0$,
$\partial s^h_t / \partial (c^h - c^l) = \beta^{-t} / (P^h_{s^h} - P^l_{s^h}) < 0$, and $\partial s^h_t / \partial (w^h - w^l)$
$= \beta(1-\beta^t)/[(1-\beta)(P^h_{s^h} - P^l_{s^h})] < 0$, where $s^h_t = \alpha^*_t (F(d^*_t) - F(d^*_{t-1})$. And so,
$H(\beta) = \sum_{t=0}^{T} s^h_t(\beta) < \sum_{t=0}^{T} s^h_t(\beta') = H(\beta')$, and $H(\phi) = \sum_{t=0}^{T} s^h_t(\phi)$
$> \sum_{t=0}^{T} s^h_t(\phi') = H(\phi')$. Now suppose that $P^h_{s^l} - P^l_{s^l} > 0$ and $P^h_{s^h} - P^l_{s^h} = 0$. Following the same steps yields $\partial s^l_t / \partial \beta < 0$, $\partial s^l_t / \partial (c^h - c^l) > 0$, and $\partial s^l_t / \partial (w^h - w^l) > 0$.
Consequently, $H(\beta) = 1 - \sum_{t=0}^{T} s^l_t(\beta) \; < 1 - \sum_{t=0}^{T} s^l_t(\beta') = H(\beta')$, and
$H(\phi) = 1 - \sum_{t=0}^{T} s^l_t(\phi) \; > 1 - \sum_{t=0}^{T} s^l_t(\phi') = H(\phi')$.

(*b*) Next, establish that $H(\gamma) \leq H(\gamma')$ if $\gamma < \gamma'$. Differentiating (4a) when $T = 1$ yields: $\partial d^*_0 / \partial \gamma = -G_\gamma / G_{d_0}$, where $G_\gamma = ([\partial p^q_0 / \partial s^h]\alpha^*_t + [\partial p^q_0 / \partial s^l](1-\alpha^*_t))$
$+ \beta([\partial p^q_1 / \partial s^h]\alpha^*_1 + [\partial p^q_1 / \partial s^l](1-\alpha^*_1)))F_\gamma(d^*_0) \leq 0$, $G_{d_0} = G_\gamma f(d^*_0)/F_\gamma(d^*_0) - (1-\beta)$
< 0. And so, $\partial F(d^*_0(\gamma);\gamma)/\partial\gamma = -(1-\beta)F_\gamma / G_{d_0} \; \geq 0$. Write the quantity of high quality grain as $H(\gamma) = (\alpha^*_0 - \alpha^*_1)F(d^*_0(\gamma)) + \alpha^*_1$. Hence, $\partial H(\gamma)/\partial\gamma \; = (\alpha^*_0 - \alpha^*_1)$
$\partial\{F(d^*_0(\gamma);\gamma)/\partial\gamma \geq 0$.

Proof of Result 4. All parts are proved similar and follow from Results 2 and 3, and the possibility of choosing a new price of the technology, r, after the change in the environment. Let ϕ denote the parameter in question, $\phi = \beta, r^f, w^h - w^l, e, w, \gamma$. Then, write $\Pi^M(\phi) = r^*(\phi)(1-H(r^*(\phi),\phi)) \le r^*(\phi)(1-H(r^*(\phi),\phi')) \le r^*(\phi')$ $(1-H(r^*(\phi'),\phi')) = \Pi^M(\phi')$.

Proof of Result 5. To show that (*a*) $\partial r^* / \partial(w^h - w^l) > 0$; (b) $\partial r^* / \partial r^f > 0$, it must be established that $\Pi^M(r, w^h - w^l, r^f) = r(1-H) = r(1-\sum_{t=0}^{T} s_t^h) = r\sum_{t=0}^{T} s_t^l$ is supermodular in $(r, w^h - w^l)$ and (r, r^f). Differentiating (4b) twice under condition (1) and using Result 3 yields $\partial^2 s_t^h / \partial(w^h - w^l)\partial r = \beta^{-t} R_{s^h}^{-2} R_{s^h s^h} \partial s_t^h / \partial(w^h - w^l) < 0$ and $\partial^2(1-H)/\partial(w^h - w^l)\partial r = -\sum_{t=0}^{T} \partial^2 s_t^h / \partial(w^h - w^l)\partial r > 0$, while using condition (2) and Result 3 yields $\partial^2 s_t^l / \partial(w^h - w^l)\partial r = \beta^{-t} R_{s^l}^{-2} R_{s^l s^l} \partial s_t^l / \partial(w^h - w^l) > 0$ and $\partial^2(1-H)/\partial(w^h - w^l)\partial r > 0$. And so, if either condition (1) or (2) holds, then $\partial^2 \Pi / \partial r \partial(w^h - w^l) = \partial(1-H)/\partial(w^h - w^l) + r\partial^2(1-H)/\partial r \partial(w^h - w^l) > 0$. The supermodularity of the profit function in (r, r^f) follows immediately from the second-order conditions of the maximization problem.

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