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Economic Hysteresis and the Effects of Output Regulation

Timothy J. Richards

Economic hysteresis, the continuation of a phenomenon after its initial cause has disappeared, represents an alternative theoretical explanation for the fixed-asset problem. When a set of fixed assets includes quota licenses, hysteresis in license investment leads to distortions that have not been measured in the policy analysis literature. A model of economic "friction" tests the effect of hysteresis in Alberta dairy investment. Estimates of investment functions show that desired investment (disinvestment) must be significantly greater (less) than zero before any action is taken. Because cattle and quota are often purchased together, the relatively long periods of no change in quota holdings that result from hysteresis cause similar periods in which herds neither grow nor contract.

Key words: Alberta, dairy, dynamic duality, fixed asset, hysteresis, option value, supply management

Introduction

Economists often blame the periodic overproduction of agricultural commodities on inputs that become "locked in" to production or the fixed-asset problem. Several explanations for the fixed-asset phenomenon exist, but few consider output regulation's role. The usual rationale uses Johnson's argument that agricultural inputs have low salvage values relative to production values, so large price reductions must occur to cause disinvestment. More recently, Hsu and Chang show that, when investment is costly, a difference between the costs of investment and disinvestment will cause asset fixity.

Though these and other studies establish a strong theoretical basis for the fixed-asset problem, there is only limited empirical evidence that it indeed exists. For example, Chambers and Vasavada fail to find any fixity in the aggregate use of capital, materials, and energy in U.S. agriculture. On the other hand, Nelson, Braden, and Roh find that farmers are more reluctant to part with tractors than to acquire them in response to price changes. Although Chang and Stefanou's study of Pennsylvania dairy shows that investment and disinvestment occur at significantly different rates, their inputs are quasi-fixed, or adjust slowly, rather than truly fixed. Clearly, there is a need to both explain and test for true asset fixity within a single theoretical framework.

A better empirical approach to studying the fixed-asset problem will help determine the effects of farm policy on the reluctance of farm inputs to leave production. In particular, this problem may prove to be most acute in the case of Canadian dairy policy. If U.S. challenges to Canada's tariffication of its dairy import quotas are successful, then the Canadian industry will face intense international competition. The consequent ratio-

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The author is an assistant professor in the School of Agribusiness and Environmental Resources, Arizona State University.
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nalization of the Canadian dairy industry will be especially difficult if herd sizes are slower to adjust as a result of supply management. Therefore, this study considers the possibility that the quota licenses used in conjunction with Canadian dairy supply management are indeed fixed inputs and, through their complementarity with other inputs, slow the rate of cattle disinvestment and operator exit.

This treatment of quota licenses is unlike previous work in which quota is regarded as a strict limit to output (Moschini; Stefanou et al.). Rather, supply management simply creates another asset in which farmers must invest. For example, Alberta dairy farmers accumulate licenses gradually through the quota exchange.[1] Once purchased, producers are reluctant to sell licenses to meet short-term production fluctuations, because it takes too long to repurchase them should the need arise in the future. Despite managing milk supply, both production and net returns to dairy in Alberta remain highly variable.

Given the uncertainty in input costs and milk production, this study develops a test for quota fixity based on recent innovations in the investment-under-uncertainty literature. Research by Dixit (1992) and Chavas suggests that the fixed-asset problem may result from economic hysteresis. Hysteresis, or the continuation of a phenomenon after its initial cause has disappeared, means that investments in dairy cows, quota, or other fixed inputs are slow to exit once returns have fallen. This is due to the possibility, however remote, that returns will one day rise enough to justify owning the asset once again. In fact, several authors (Brennan and Schwartz; McDonald and Siegel; Dixit 1989, 1991a, b, 1992; Pindyck; Chavas; and many others) argue that classical investment decision rules no longer apply when investment returns are inherently unstable and there are sunk or transaction costs of investment. When returns in the future are uncertain, an opportunity to wait and see what the future will bring has some value. This is the option value of an opportunity to make an investment. Once the investment is made, its option value disappears, so the returns to an investment must cover both its financial cost and the option value. This extra hurdle means that returns will vary over a far broader range than the classical rules suggest before investment (or disinvestment) is a rational decision. As potential investors wait for the higher (or lower) return levels to be reached, observed investment or disinvestment will not respond to small changes in returns. This is the phenomenon of hysteresis or the fixed-asset problem.

The objectives of this study are to determine both the direct effect of hysteresis on quota license investment and the indirect effect of quota hysteresis on investments in other quasi-fixed inputs. Farm-level data from Alberta dairy producers show how hysteresis in quota investment can result in unexpected economic consequences. This empirical problem is of interest to economists studying agricultural investment since most previous research about hysteresis in investment has been on a theoretical level using ex ante simulations instead of applied (for example, Dixit 1989; Purvis et al.).

Estimates of a system of interrelated investment functions measure the indirect effects of requiring investment in quota licenses. Other empirical dairy studies (Weersink and Howard; Chang and Stefanou; Tsigas and Hertel) all show that investment in one quasi-fixed input will affect investment in all other inputs. As a result of this interaction, hysteresis in quota investment causes slow adjustment in the other inputs.

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[1] In Canada, fluid milk production is regulated on a provincial basis. Marketing quotas limit provincial supply to an amount that will allow the market to clear at a formula determined price. Although the system is under revision, quota is currently traded in a formal, monthly, mail-based exchange. Quota purchased through the exchange is allocated on a pro rata basis to all bidders meeting the ask price. Often, this means that buyers only obtain a fraction of the amount they require so it may take significant time to accumulate the desired amount.

Theoretical Model of Hysteresis in Investment

According to standard investment theory, a firm should only invest in a project when the discounted value of cash flows exceeds the initial investment costs. So, expansion or entry will only occur if the net present value of doing so is positive. If the price (cash flow) rises above the minimum average total cost (cost of entry), then a firm enters the industry or exits the industry in the short run if price falls below the minimum of average variable cost. In a perfectly competitive industry, this means that free entry to and exit from an industry causes the price to equal the minimum of long-run average cost.

These classical rules of entry and exit are misleading when the cash flows are inherently uncertain, and the entry or exit decision entails significant sunk costs. Specifically, when cash flows are uncertain and an investment or disinvestment involves a sunk cost, then there is a positive value to waiting to take advantage of an opportunity to do either. This value is an option value akin to the value of an option on a financial stock. For example, if there is a 50% chance that returns to an investment next period will cause the net present value to be $10, and a 50% chance that it will be −$10, the ability to delay the investment allows the investor to avoid the downside risk. In this simple example, the expected value of waiting to commit, or the option value, is $5. This logic is clear in Dixit's (1989) entry/exit example.

Assume that a firm is the only one with an entry opportunity. For simplicity's sake, also assume that once the firm enters it cannot exit. If entry entails a fixed cost of k and returns net revenues of R, then, assuming an interest rate of r, the classical rule implies that entry is profitable when the value of an active firm is merely greater than the entry costs. Or, if $V(R)$ is the maximized net present value of the firm as a function of net revenues, entry occurs when this value is positive: $V(R) = R/r - k > 0$. This rule no longer applies under uncertainty and sunk costs.

Uncertainty enters the model by letting net revenues be random. Following the derivation of Dixit (1992), R follows a geometric Brownian motion with a trend growth rate (μ) and a variance ($\sigma^2 t$) proportional to the level of revenues as in:

$$(1) \qquad \frac{dR}{R} = u\, dt + \sigma\, d\Omega.$$

Through $V(R)$, equation (1) defines how firm value changes over time.

An investor will be indifferent to investing or waiting to invest in a firm only if the value of waiting is equal to the return from owning an active firm over that period.[2] Applying Ito's lemma to equation (1) provides an expression for expected gain to owning an active firm:

$$(2) \qquad E[dV] = V'(R)\mu R\, dt + (1/2)V''(R)\sigma^2 R^2\, dt + o\, dt,$$

where the higher order terms of the Taylor expansion, $o\, dt$, are subsequently ignored.

In equilibrium, the expected capital gain, $E[dV]$, is equal to the annual return on the value of the firm, $rV(R)\, dt$. Dividing the equilibrium expression by dt and taking the limit as $dt \to 0$ provides a differential equation that describes the behavior of firm value in net revenues:

[2] This derivation closely follows Dixit (1992), where the appendix provides greater detail on the solution method.

(3) $$V'(R)\mu R + (½)V''(R)\sigma^2R^2 - rV(R) = 0.$$

The expression for $V(R)$ that solves this differential equation will be of the form $V(R) = R^x$. Substituting this expression for $V(R)$ in (3) yields a quadratic equation in x:

(4) $$x\mu + (½)x(x - 1)\sigma^2 - r = 0.$$

Equation (4) has two possible solutions for x—let them be a and b. The solution a must be negative and b must be greater than one to ensure that the firm value has an upper bound. Therefore, the solution for $V(R)$ becomes $V(R) = AR^a + BR^b$, but as R goes to zero, the value of waiting must go to zero, so $A = 0$ and the only possible solution becomes $V(R) = BR^b$. Using (4) to solve for b gives

(5) $$b = (½)[1 + \sqrt{1 + 8r/\sigma^2}] > 1.$$

This solution for b shows the difference between the level of returns that would cause investment under the usual rules, M, and the "trigger" level of returns that includes the option value, H. An investor will enter if revenues are above H but not enter if they are below H. If the value of the firm is given by the value of waiting when the firm is idle and the value of investing when the firm enters, then it must be true that

(6) $$V(R) = \begin{cases} BR^b, & R \leq H \\ R/r - k, & R \geq H \end{cases}.$$

Because the value of the firm must be continuous in net revenues, the slope of each component of the function $V(R)$ in (6) must be the same at the trigger price, H. This is known as the smooth pasting condition. Intuitively, the smooth-pasting condition means that, in order to maximize the value of the firm, the potential entrant must wait until R is high enough to cause the marginal value of waiting to equal the marginal value of current profits forgone, or $1/r = bBH^{b-1}$. Furthermore, the value of a firm that does enter can only differ from one that does not by the amount of entry costs, k, so $H/r = BR^b + k$. Solving these two equations for H produces

(7) $$H = kr\frac{b}{(b - 1)},$$

while $M = kr$. Because $b > 1$ by assumption, this result means the true entry level of R must be greater than the usual level, M, by a factor of $b/(b - 1)$.

This logic is shown through a simple diagram. Figure 1 shows how the option value causes the hysteresis. At the level of returns, H, traditional investment rules indicate that I_M should be the appropriate level of investment. However, if the total costs of investing include the option value,[3] H is the threshold above which investment begins. The difference between I_M and 0 is, therefore, a graphical measure of the effect of hysteresis. While the option value is unobserved, its effect on the "hysteresis gap" is readily observable.

Although the above illustration shows that hysteresis can theoretically affect the decision to invest in a dairy farm, substituting representative values of b into (7) shows that the expected effect is far from trivial. Using realistic values of net revenue variance and the discount rate into the solution for b above yields a value of 2.66. This means

[3] If the total costs of investment include the option value, they are termed the "full costs" of investing.

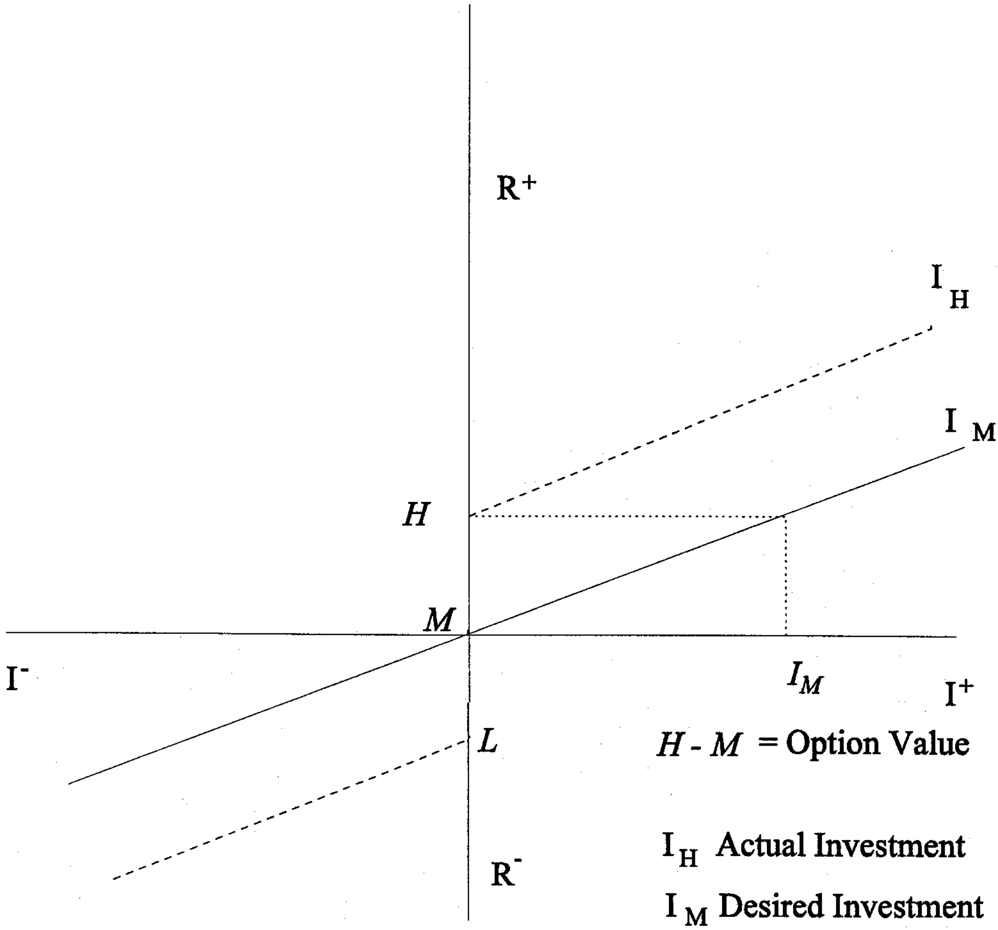

Figure 1. Hysteresis effect on quota license investment

that the value of H must be over twice that of M in order to justify entry into the dairy industry and, thereby, to justify investment in quota.[4]

The size of this difference means that returns can vary over a wide range before actual investment or disinvestment takes place. It is this sluggishness in the face of significant revenue variation that we observe and interpret as hysteresis. On a theoretical level, the above example shows that the value of b can significantly influence investment rates, but it is an empirical question as to whether it can be interpreted as an explanation for quota fixity.[5]

Previous empirical analyses of dairy investment behavior typically estimate smooth, symmetric investment demand functions derived from a cost-of-adjustment framework (for example, Howard and Shumway; Weersink and Howard; Chang and Stefanou). The

[4] The rate of return is assumed to be the average return on equity to dairy farms over the sample period chosen for this study (1975–91) which was 11.7%. The proportional standard deviation of fluid quota prices over this period was 23%.

[5] Most of the analysis conducted with respect to investment or capacity choice has used the example of an individual firm with a unique opportunity to invest. However, if many identical firms hold the same right to invest in an industry producing a homogeneous output, then the time value of waiting to invest is bid to zero. However, this does not invalidate the hysteresis result. As shown by Leahy, a competitive firm contemplating entry at the upper-bound price will still wait to invest because the expected value of operating returns at that level is still negative—the price cannot go above the upper threshold but can go below.

following section develops an empirical model of Alberta fluid milk production which, while retaining the cost-of-adjustment approach as its basis, relaxes the usual assumptions of smooth and symmetric investment. Without these restrictions, this approach is able to estimate the effect of hysteresis on quota investment.

Empirical Model of Hysteresis

To estimate the actual quota investment demand function shown in figure 1, the empirical procedure must differentiate between regimes of positive investment, negative investment, and no change in quota holdings. While this will measure the direct effect of hysteresis, the approach must also be able to estimate the indirect effects of quota's interaction with the other inputs. These requirements suggest a two-stage procedure. In the first stage, partitioning the data set into regimes of positive, negative, and zero quota investment permits consistent estimation of the hysteresis gap ($I_M - 0$) for both investment and disinvestment. In the second stage, simultaneous estimation of output supply, variable input demand, and investment demand measure the effect of quota adjustment on changes in the other quasi-fixed inputs, including the hysteresis gap. Partitioning the data in this way also allows for the possibility that the investment demand parameters differ between quota investment and disinvestment regimes. Despite these modifications, the cost-of-adjustment assumption remains at the core of the procedure.

Lucas and Mortensen, among others, develop the cost-of-adjustment model of investment. This model assumes that investing in certain inputs is costly. Installing capital equipment, hiring and training skilled labor, or breeding and raising dairy cattle are all examples of milk production inputs with high acquisition costs. Because the costs of investing rise in the rate of investment,[6] it is rarely optimal to instantaneously adjust the levels of these inputs to their desired levels, so they are called quasi-fixed.

Early empirical applications of the cost-of-adjustment model use a primal estimation method that restricts the analysis to a single investment demand equation. The dynamic dual method of Epstein avoids this limitation. The dynamic dual approach uses an intertemporal analogue of Hotelling's lemma to derive a system of output supply, investment demand, and variable input demand equations from a dual value function. Simultaneously estimating this system provides estimates of the effect of investment in any quasi-fixed input upon any other.

Previous studies use either a quadratic or generalized Leontief functional form for the value function. Based upon the findings of Howard and Shumway, this study uses the generalized Leontief functional form to estimate the output supply, input demand, and investment demand parameters:[7]

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[6] In other words, the investment cost function is assumed to be convex. If $C(I)$ is the cost of an investment rate I, then convexity implies that $C(I) > 0$, and $C''(I) > 0$.

[7] As suggested by Larson, this value function describes a problem that is dependent upon time (nonautonomous) where the producer expects continuous technical change over the entire period. Although producers expect technology to be continually changing, they do not form expectations of future prices. Such price expectations imply that "current relative prices . . . are expected to persist indefinitely. As the base period changes and new prices . . . are observed, the firm revises its expectations and its previous plans. Thus only the $t = 0$ portion of the plan . . . is carried out in general." (Epstein and Denny, p. 650). Moreover, the generalized Leontief value function maintains an assumption that the shadow value of each quasi-fixed input does not change as more is acquired ($V_{zz} = 0$, which implies that the shadow value of each quasi-fixed input does not change over time.

$$(8)\quad V(z, p, w, R, r, t_0) = [p' \ \ w'] \begin{bmatrix} A_{pz} \\ A_{wz} \end{bmatrix} [z] + [R'][B_{Rz}]^{-1}[z] + [p^{1/2'}]C_{pR}[R^{1/2}]$$
$$+ [R^{1/2'}]D_{RR}[R^{1/2}] + [p^{1/2'}]E_{pp}[p^{1/2}] + T \begin{bmatrix} G_{Tp} \\ G_{Tw} \\ G_{TR} \end{bmatrix} [p \ \ w \ \ R].$$

In equation (8), p is the output price; w is the input price vector; R is the quasi-fixed input rental price vector; z is the quasi-fixed input vector; T is a time-trend variable; and A_{pz}, A_{wz}, B_{rz}, C_{pR}, D_{RR}, E_{pp}, G_{tp}, G_{tw}, and G_{TR} are conformable parameter matrices.

Applying Hotelling's lemma to (8) produces specifications for the output supply:

$$(9)\qquad y(z, p, w, R, r, t_0) = \sum_j A_{pj}(rz_{t-1,j} - \dot{z}_j) + (r/2) \sum_j C_{pj}\left(\frac{R_j}{p}\right)^{1/2}$$
$$+ r \sum_i E_{ip}\left(\frac{w_i}{p}\right)^{1/2} + (rT - 1)G_p,$$

and input demand:

$$(10)\qquad a_i(z, p, w, R, r, t_0) = \sum_j A_{ij}(\dot{z}_j - rz_{t-1,j}) - r \sum_{k \neq i} E_{ki}\left(\frac{p_k}{w_i}\right)^{1/2} + E_{ii}$$
$$- (r/2) \sum_j C_{ij}\left(\frac{R_j}{w_i}\right)^{1/2} + (1 - rT)G_i,$$

and investment demand equations:

$$(11)\quad \dot{z}_j(z, p, w, R, r, t_0) = rz_{t-1,j} + \sum_m B_{jm}\left(z_{t-1,m} + (r/2)\left(C_{pm}\left(\frac{p}{R_m}\right)^{1/2}\right)\right.$$
$$\left. + \sum_i C_{im}\left(\frac{w_i}{R_m}\right)^{1/2} + 2 \sum_{m \neq j}\left(D_{jm}\left(\frac{R_j}{R_m}\right)^{1/2} + D_{mm}\right)\right)$$
$$+ \sum_m B_{jm}G_m(rT - 1),$$

where $\dot{z}_j$ is the rate of change of quasi-fixed input j.

Because the generalized Leontief value function yields adjustment-cost expressions (V_z) that are linear in rental prices, the investment demand functions (11) are consistent with a multivariable flexible accelerator (MVFA) interpretation. Including additive, independently, and identically distributed disturbance terms, the MVFA form of the investment demand functions are of the form:

$$(12)\qquad \dot{z}_i = (r + B_{ii})(z_i - z_i^*) + \sum_j B_{ij}(z_j - z_j^*) + u_i = M(Z - Z^*) + u_i,$$

where z_i^* is the steady state of the ith quasi-fixed input, and Z^* is a vector of all steady-state values.

In the terminology of the MVFA model, the matrix $M = (rI + B)$ is called the speed-of-adjustment or adjustment-coefficient matrix, where r is the annual interest rate, and I is an $n \times n$ identity matrix for n quasi-fixed inputs. The parameters of the speed-of-adjustment matrix show the proportion each quasi-fixed input adjusts towards its long-run equilibrium in response to short-run disequilibria in its own and all other quasi-fixed input stocks. However, the basic MVFA specification in (12) only allows for one of the three practical concerns this article addresses. Namely, the investment demand functions in (12) do produce estimates of the interrelatedness of investment, but they are symmetric and do not allow for the periods of no change in input stocks that hysteresis predicts.

In the first stage of the two-stage procedure, the hysteresis gap in both quota investment and disinvestment is estimated. Hysteresis in quota is likely to be significant because prolonged periods of no change in quota holdings occur often in the Alberta data. In fact, 40% of the dairy farms did not change their quota license holdings from one year to the next. Consequently, ordinary least squares estimates of the system parameters are biased due to the censored quota investment data (Amemiya, p. 367).

Rosett develops an approach to solve a similar estimation problem. In his case, Rosett attempts to explain the observation that small changes in financial asset yields do not appear to cause the expected changes in holdings. As a result of the costs of buying and selling financial assets, investors will wait until the expected returns rise above their required (or threshold) level before investment occurs, or fall below the disinvestment threshold before assets are sold. Similar to the hysteresis result, therefore, returns can vary within a wide range before actual investment changes.[8] Whereas Rosett's approach estimates the range of returns over which no change in holdings occurs, or the option value, it is the quantity effect that is of interest here.

The theoretical model above estimates the size of the option value in terms of the cost-of-adjustment parameters. Investment will only be positive when the discounted value of all future net revenues are greater than the sunk costs of investing today. In terms of the quota license cost-of-adjustment model, this is simply the condition that the price of quota licenses must be greater than the annualized equilibrium cost of adjusting quota:

$$R_{zq} \geq V_{zq}r. \tag{13}$$

However, the condition for investing in quota licenses under sunk costs and uncertainty must include the option value:

$$R_{zq} \geq \frac{b}{(b-1)} V_{zq}r. \tag{14}$$

Because the option value is unobservable, estimates of the effect of hysteresis use the quantity dependent investment demand equations to indirectly measure the size of the effect. Estimation of this effect requires partitioning the cost-of-adjustment model into regimes of investment, no investment, and disinvestment. Specifically, quota investment can be either negative, positive, or zero depending upon whether the return to holding quota is (*a*) less than the total cost of selling quota holdings net of the option value, (*b*) greater than the full costs of investing, and (*c*) between the upper and lower boundary defined by the option values. In terms of figure 1, the latter case means that returns fall between *H* and *L*. The option value for investment is, therefore, the difference between the intercept of the actual and the desired investment functions. A similar argument holds for the value of an option to disinvest. Because both option values result in a range of

[8] Shonkwiler and Taylor apply Rosett's method to explain the effect of direct and indirect costs of price changes on the observed rigidity of monthly FCOJ prices.

investment inactivity (hysteresis), these types of models are known as "friction" models (Maddala).[9]

In the dairy friction model, the upper and lower values of the dependent variable must be estimated. If $a_1 < 0$ represents a desired decrease in holdings and $a_2 > 0$ represents a desired increase, then the function that describes the latent desired investment variable becomes

$$(15)\qquad \dot{z}_q = \begin{cases} \dot{z}^*_{q_1} - a_1 - u; & \dot{z}^*_{q_1} - a_1 - u < 0; \\ 0; & \dot{z}^*_{q_1} - a_1 - u > 0 \\ & \quad > \dot{z}^*_{q_2} - a_2 - u; \\ \dot{z}^*_{q_2} - a_2 - u; & \dot{z}^*_{q_2} - a_2 - u > 0 \end{cases} \qquad a_1 < 0;\ a_2 > 0,$$

where $\dot{z}_q$ is the actual investment in quota; $\dot{z}^*_{q_1}$ is the desired disinvestment; and $\dot{z}^*_{q_2}$ is the desired rate of investment.

Assuming the error term u is normally distributed, Φ is the unit-normal cumulative density function and ϕ is the probability density function, so the probability function for the above problem is

$$(16)\qquad \begin{aligned} \mathrm{Prob}(\dot{z}_q > x, x > 0 \mid x) &= \mathrm{Prob}(\dot{z}^*_{q_2} - a_2 - x > u) \\ &= \Phi\left(\frac{\dot{z}^*_{q_2} - a_2 - x}{\sigma}\right); \\ \mathrm{Prob}(\dot{z}_q = 0 \mid x) &= \mathrm{Prob}(\dot{z}^*_{q_1} - a_1 > u > \dot{z}^*_{q_2} - a_2) \\ &= \Phi\left(\frac{\dot{z}^*_{q_1} - a_1}{\sigma}\right) - \Phi\left(\frac{\dot{z}^*_{q_2} - a_2}{\sigma}\right); \\ \mathrm{Prob}(x < 0, x > \dot{z}_q \mid x) &= \mathrm{Prob}(\dot{z}^*_{q_1} - a_1 - x < u) = 1 - \Phi\left(\frac{\dot{z}^*_{q_1} - a_1 - x}{\sigma}\right). \end{aligned}$$

Assuming that the effect of hysteresis, as measured by the a_i parameters, is the same for each observation, the likelihood function for the dairy friction model is

$$(17)\qquad L(a_i, \sigma \mid \dot{z}_q) = \prod_k \left(\frac{1}{\sigma}\right)\phi\left(\frac{\dot{z}_{q_1k} - \dot{z}^*_{q_1k} + a_1}{\sigma}\right)\prod_l \left[\Phi\left(\frac{a_2 - \dot{z}^*_{q_2l}}{\sigma}\right) - \Phi\left(\frac{a_1 - \dot{z}^*_{q_1l}}{\sigma}\right)\right] \cdot \prod_m \left(\frac{1}{\sigma}\right)\phi\left(\frac{\dot{z}_{q_2m} - \dot{z}^*_{q_2m} + a_2}{\sigma}\right),$$

where

$$(18)\qquad \dot{z}^*_{qi} = M_i(z_{qi} - z^*_{qi}),$$

for the ith investment regime in terms of the multivariate flexible accelerator model.

Maximizing the log of (17) with respect to the parameters of $\dot{z}^*_i$ and a_i produces consistent estimates of the effect of hysteresis on quota investment. Adjusting the inter-

[9] Note that the dynamic dual framework of Epstein requires the policy functions to be continuous and differentiable. The approach used herein is not inconsistent with this requirement if the functions are interpreted as the result of a two-stage optimization procedure. In a similar model of asymmetrical investment demand, Chang and Stefanou use this justification to support their estimation method. Once the first-stage decision to invest or disinvest is made, the functions estimated in the second stage are continuous for the subproblem of how much to invest or to disinvest.

cepts of the quota investment demand equations in (15) by a_i and reestimating the entire system (9)–(11) for each investment regime constitutes the second stage of the estimation procedure. This method produces consistent estimates of the effect of hysteresis, the asymmetrical investment parameters, and the interaction between rates of investment. Estimating this large number of parameters, however, requires a large data set. The following section describes the data used to estimate these three effects on dairy investment in Alberta.

Data and Methods

This study uses observations on a sample of 270 members of the Alberta Milk Producers' Society (AMPS) over the 1975–91 period, which provides a total of 720 time-series and cross-sectional observations.[10] Designed by Alberta Agriculture to monitor changes in costs of production, the sample provides price and quantity data on total milk output, quasi-fixed inputs, and variable inputs.

Variable production inputs include forage, grain and concentrates, and hired labor.[11] Dividing each producer's reported total feed value by the quantities fed gives the price of forage. Feed values are available for both homegrown and purchased feed, but to keep the model as parsimonious as possible, the study uses an average forage cost variable. A similar procedure provides the price and quantity of grain and concentrates. The sample producers report the wages paid for hired labor but do not provide sufficient data to adjust the labor variable for training or experience. Because of the geographical diversity in a large province such as Alberta and the marked differences in local feed markets, substantial cross-sectional and time-series price variation exists.

Quasi-fixed inputs include the amount of family labor, the value of capital structures, the stock of quota licenses, and the size of the "effective" dairy herd. Family labor is quasi-fixed because of the social difficulties of disinvestment and the biological lags in investing in more family members. Previous empirical studies of dairy find these facts to cause family labor to adjust slowly (for example, Weersink and Howard). As with hired labor, farmers report the wages paid to family members but do not indicate the amount of unskilled or child labor.

Capital consists of the value of buildings and equipment specific to the dairy enterprise. From the value data, Ball's method provides a capital rental price series. This rental price then defines an annual flow of capital services.

Deflating cattle numbers by an index of genetic improvement adjusts herd size for embodied technological change. The index consists of an average of all Alberta Holstein cows' breed class average (BCA) scores for each year.[12] Although it would be preferable to use an index that is independent of actual milking performance, as in Howard and Shumway (1988), this index is the only one available on a consistent basis throughout the sample period. The cattle rental price is derived with Howard and Shumway's (1988) method. Their approach consists of calculating the annual rental price that equates the

[10] This panel is unbalanced in the sense that producers remain in the sample for an average of four years. This turnover is due both to industry exit and the farmer's choice to stop participation. Despite this fact, Alberta Agriculture officials select replacements in order to maintain the stratification of the sample by both region and farm size.

[11] Forage consists of hay, silage, and an estimate of the value of pasture consumed.

[12] The breed class average is itself a national average production index for all cattle of that breed and age. A provincial average BCA is, therefore, an average BCA score.

cost of buying a heifer to be milked for three lactations and then sold into slaughter and renting her for three lactations.

Quota licenses are quasi-fixed because of the aforementioned illiquidities build into its exchange. Multiplying the annual average weighted-average cost of capital across all producers by the prevailing fluid quota price provides an annual quota rental price series.

Although the fluid milk price is formula determined, significant output price variation still exists as producers ship milk of differing fat content. This fact and the significant regional variation in feed, labor, and cattle prices provide sufficient price variation to allow dual estimation with pooled cross-sectional and time-series data. However, it is necessary to assume a constant cross-sectional effect across producers in order to ensure convergence of the entire model.

Duality requires several other restrictive conditions be met. Namely, duality requires the value function to be linearly homogeneous and concave in the quasi-fixed inputs. The generalized Leontief functional form automatically satisfies both of these conditions. Empirical tests of the remaining restrictions use the initial form of the model as in (9)–(11) to evaluate the symmetry, convexity, and monotonicity of the value function. Symmetry in prices requires that $D_{ij} = D_{ji}$ and $E_{ij} = E_{ji}$ for all i and j. Maintaining symmetry as the null hypothesis, Gallant and Jorgenson's quasi-likelihood ratio method produces a chi-squared test statistic of 25.324. With twelve degrees of freedom, the critical chi-squared value at a 1% level is 26.217. Although this test rejects symmetry at the usual level of significance (5%), subsequent estimates maintain symmetry to maintain theoretical consistency.

Monotonicity requires the value function to be increasing in output price ($V_p > 0$), decreasing in variable input prices ($V_{wi} < 0$), decreasing in quasi-fixed input rental rates ($V_{Ri} < 0$), increasing in quasi-fixed input stocks when investment is positive ($V_{zi} > 0$; $\dot{Z}_i > 0$), and decreasing in quasi-fixed input stocks when investment is negative ($V_{zi} < 0$; $\dot{Z}_i < 0$). Monotonicity in variable input prices, output prices, and quasi-fixed input stocks is met by all observations, while violations occur in approximately 4% of the observations of V_{Ri}.

Convexity in prices requires all elements of the C matrix to be negative ($C_{ij} < 0$ for all i, j) and the off-diagonal elements of the D and E matrices to be negative (D_{ij}, $E_{ij} < 0$ for all $i \neq j$). The model does not converge with the imposition of convexity, but of the twenty-eight parameters involved, only three violations of convexity are statistically significant on an individual basis. As a result of these convergence problems, subsequent estimates maintain only symmetry in prices. Convergence also requires restricting the technical change coefficients to be equal across all equations.

Estimating the first-stage friction model uses the maximum-likelihood procedure in TSP. In the second stage, estimating the full dynamic system, including the investment demand equations, uses the nonlinear three-stage least squares procedure in TSP. Simultaneous estimation is necessary because each input's rate of investment appears on the right-hand side of all other investment equations. The next section presents and discusses the results of this estimation.

Results and Discussion

Table 1 presents the results of testing for symmetry of the investment parameters between investment, disinvestment, and no change in quasi-fixed input stocks. Statistical tests

Table 1. Tests for Alberta Fluid Milk Quota Investment Symmetry: 1975–91

Null hypothesis:
H_0: Parameters for nonzero quota adjustment equal full set parameters
$\chi^2 = 298.4509$*
H_0: Parameters for zero quota adjustment equal full data set parameters
$\chi^2 = 298.4509$*
H_0: Parameters for negative and positive quota adjustment are equal
$\chi^2 = 337.2403$*
H_0: Parameters for negative quota adjustment equal full data set parameters
$\chi^2 = 372.4590$*
H_0: Parameters for positive quota adjustment equal full data set parameters
$\chi^2 = 709.6993$*

Note: Asterisk denotes significance at the 5% level. For each test, there are 69 degrees of freedom so the critical chi-squared value is 93.52.

reject the null hypothesis that the investment demand parameters are the same for quota investment and disinvestment. The first set of tests consists of modified Chow tests that use the quasi-likelihood ratio method of Gallant and Jorgensen. With the Gallant and Jorgensen method, the difference between the three-stage least squares distance function under the null and alternative hypotheses is chi-squared distributed. Alternatives to the null hypothesis of equal parameters in every regime include parameter differences by positive license investment, negative investment, or no change in license holdings. The number of parameters that are left to vary between the two investment regimes determines the number of degrees of freedom. Given that there are 69 parameters in the model, the critical chi-squared value for each test, assuming 69 degrees of freedom, is 93.52. Clearly, these tests reject the null hypothesis of parameter equality in each case.

The first-stage maximum-likelihood estimates provide a second (joint) test of the friction model specification and the significance of the hysteresis effect. If the deviations of actual contraction or expansion from their desired levels (a_1 and a_2) are statistically significant, then the friction model does indeed capture the effect of hysteresis. The maximum-likelihood estimate of a_1, the amount by which desired quota divestiture must fall below zero before actual quota license selling occurs, is -135.136 with a t-statistic of -3.66. On the other hand, the amount by which desired purchases must rise above zero before investing in quota licenses (a_2) is 37.309 with a t-statistic of 2.02. Given that the average fluid quota holding in the sample for 1991 is only 650 liters, hysteresis in Alberta dairy is not only statistically but also economically significant.

In other words, hysteresis causes the full-cost quota investment curve (I_H) to rise above the traditional curve by 5.7%, while quota disinvestments average almost 21% below what the traditional model predicts. In other words, producers are reluctant to sell quota licenses that they will find difficult to reacquire, should the need arise. Because producers retain their quota licenses, they must maintain production sufficient to fill their quota. If they do not, their quota will revert to the board.[13] While the first-stage estimates provide evidence of hysteresis in quota investment, the second-stage estimates show the effect of quota on investments in other quasi-fixed inputs. Such interactions may indeed distort investment more than the hysteresis effect of quota.

[13] This prediction of the model agrees with casual observation of producer behavior. Often, producers will maintain a given level of production, or even postpone exit from the industry, based upon speculation over quota prices.

Table 2. Investment Substitution Matrix under Fluid Milk Quota Expansion

	Disequilibrium Variable			
	Capital	Quota	Cattle	Family Labor
Response variable:				
Capital	−0.036*	−0.021**	0.002*	0.001
	(−2.215)	(−4.994)	(2.554)	(0.742)
Quota	−0.275**	−0.065**	0.005*	0.007*
	(−4.363)	(−4.095)	(2.254)	(2.091)
Cattle	2.538**	0.416*	−0.035**	0.174**
	(5.402)	(2.526)	(−8.896)	(9.216)
Family labor	−2.027**	−0.666**	0.133**	−0.122**
	(−3.500)	(−4.592)	(8.672)	(−11.303)

Note: Two asterisks indicate significance at the 1% level and single asterisk indicates significance at the 5% level. A negative off-diagonal coefficient indicates a complementary relationship, while a positive coefficient indicates a substitute relationship. The numbers in parentheses are t-values.

Details of the parameter estimates of the full model are available in Richards, so this discussion concerns only the speed-of-adjustment parameters. Tables 2 and 3 present the parameter estimates for the regimes of quota investment and disinvestment, respectively. In these tables, the off-diagonal elements indicate whether the inputs are dynamic substitutes or complements. Specifically, quasi-fixed inputs are dynamic substitutes if positive investment in one causes a negative adjustment in the other and vice versa for complements.[14] In terms of the empirical model, inputs i and j are substitutes if it is found that the B_{ij} parameter in the speed-of-adjustment matrix is positive. Conversely, if B_{ij} is negative, the inputs are dynamic complements.

Given a constant rate of discount of 8%, capital adjusts away from its long-run equilibrium at a rate of 4.4% per year when quota holdings are increasing. In other words,

[14] This definition is not directly analogous to static theory. In terms of adjustment costs, if the V_{ij} element of the B^{-1} matrix is positive, then the cost of adjusting i rises in the price of j—a complementary relationship. However, this may lead to a positive B_{ij} element, defined as substitutes in terms of quantity movements.

Table 3. Investment Substitution Matrix under Fluid Milk Quota Contraction

	Disequilibrium Variable			
	Capital	Quota	Cattle	Family Labor
Response variable:				
Capital	0.005	0.017*	−0.003**	0.006**
	(1.434)	(1.837)	(−3.673)	(4.487)
Quota	0.014	−0.275**	0.015**	0.007
	(1.369)	(−4.625)	(2.825)	(0.851)
Cattle	0.145	1.003*	−0.127**	0.209**
	(1.266)	(2.136)	(−4.277)	(5.592)
Family labor	−0.238	−0.652*	0.132**	−0.295**
	(−1.517)	(−1.816)	(5.377)	(−9.593)

Note: Refer to table 2 footnote.

when quota is bought and when the stock of capital is less than desired, the capital stock falls rather than rises as we would expect in a static model. The B_{kq} parameter indicates quota's effect on the net rate of capital adjustment. The B_{kq} value of -2.1% suggests that capital and quota are dynamic complements—a rise in quota investment will cause the rate of capital investment to rise. On the other hand, quota disinvestment does not affect the rate of capital adjustment (table 3)—a finding that provides indirect evidence of fixity in capital holdings.

Under quota expansion, the rate of quota adjustment ($r + B_{qq}$) indicates that quota adjusts away from the long-run equilibrium at a rate of 1.5% per year. Further, a weak substitute relationship with both cattle and family labor supports the movement away from the steady state. However, the strength of the complementary relationship with capital causes the net adjustment of quota to be 25% towards the equilibrium. When selling quota, producers move towards the desired stock level at a rate of 19.5% per year. In this case, the complementary effect disappears, and quota adjustments move toward the steady state.

Notice further that quota's effect on investment in capital is not symmetric for investments and disinvestments. Whereas quota expansions support the growth of farm capital, quota disinvestments do not affect the rate of capital adjustment and vice versa.

Preliminary estimates with a continuous quota investment model, also reported in Richards, show that the cattle own speed-of-adjustment parameter is only 0.8% at an 8% interest rate—herd size responds very slowly to disequilibria in current herd size. Furthermore, the interaction effect of quota license adjustment causes the cattle herd to adjust 31% per year away from the long-run equilibrium. The adjustment parameters in table 2 indicate that, when quota license investment is positive, herd sizes adjust 3.5% per year towards the optimal, but the substitute relationship with quota leaves the herd 38% further away from the steady-state herd size.[15] Similar substitute relationships with family labor and capital further slow the adjustment of the cattle herd. These results suggest that the introduction of supply management, which causes producers to invest in quota licenses, significantly distorts the pattern of cattle investment.

On the other hand, when quota license investment is negative, herds move toward their long-run optimum by 4.7% per year. Similar to the case of expansion, quota substitution slows herd size adjustments considerably. In fact, the effects of quota and family labor, taken together, are sufficiently strong to raise herd sizes. This phenomenon may reflect further institutional problems with trading fluid quotas. Since the sample does not include producers that completely sell out, this model measures only incremental changes in quota holdings. With the rapid rise in fluid quota values throughout the 1980s, many producers sold fluid quota and bought industrial or market share quota. Because the law of one price often does not hold across the fluid and market share quota markets, these arbitrageurs were able to profit from moving from the fluid to the industrial market. Taking advantage of these opportunities to arbitrage the two markets, the proceeds of these transactions were often used to expand herd size and sell more milk into the lower price industrial market. While these results imply that quota investment worsens the fixity of dairy cattle in Alberta, the same argument does not hold for family labor.

Many believe that quota licenses provide producers with a golden handshake—a store

[15] Note that herd size is defined as the number of effective cattle or cattle numbers of a standard genetic ability to produce milk, using 1975 as a base period.

of value to ease their exit from the industry. The results here support this argument. Tables 2 and 3 provide evidence to suggest that quota acquisitions are associated with increasing family labor usage while selling hastens exit. For example, the family labor of farmers that purchase quota adjusts independent of the other inputs at a rate of 12.2% per year, while those selling licenses have a labor adjustment rate of 21.5% per year. Family labor's interaction with quota causes adjustments to accelerate by 65%, while interactions with herd size causes adjustments to slow by 13%. This latter result is precisely what the golden handshake effect predicts—when quota is sold, family labor exits as well.

Conclusions

This study shows that supply management in the Alberta dairy industry affects farm production decisions in two ways. First, uncertainty in the returns to dairy production, in combination with the sunk costs involved in adjusting quota stocks, creates an option value. This option value is the value of waiting to make an investment in quota licenses. Standard capital budgeting criteria, investing when the net present value of the project is positive, are no longer valid as returns must now cover the cost of investment plus the option value. Postponing quota investment in the hopes that returns either rise above the higher threshold, or fall below the lower, is responsible for hysteresis arising with respect to adjustments in quota licenses. In practical terms, hysteresis means that quota, once purchased, will not be sold as readily as a neoclassical model would predict. In fact, this study shows that desired quota purchases must rise 137 liters above current levels before purchases are made or fall 35 liters below prevailing levels before divestiture occurs.

Second, the sensitivity of investment to input prices for capital, quota licenses, cattle, and family labor differs between investment and disinvestment. For example quota investment causes capital to adjust more rapidly, while quota investment slows herd size adjustments. In fact, these distortions to cattle investment are so strong that they cause herd size to expand when a static model would suggest that they should contract.

These results imply that supply management is likely to adversely affect dairy efficiency. Dairy regulators, and any other regulators that use supply management should consider these unintended economic effects when assessing the cost of their programs. First, despite the golden handshake effect, hysteresis creates overinvestment in Alberta dairy. Inputs that would otherwise exit the industry, instead, remain in production in hopes of better times. Given the rise in quota values in recent years, quota investors appear to expect much better times despite a series of negative GATT rulings against supply management, the signing of the GATT agreement, and the passage of NAFTA.

Moreover, because the policy causes producers to invest in an input whose only value is in capturing rents, farmers invest less to increase the physical productivity of the firm. As a result, overinvestment in dairy cattle likely leads to lower productivity growth in Alberta dairy. Given the newly competitive dairy market promised for North America, the Alberta dairy industry could find itself unable to compete with imported milk products and many of the least efficient producers would be forced from the industry.

These results apply to many industries besides dairy. Many industries have output regulations through some type of licensing program—the forest industry, for example.

Once thought to be neutral in their effect on productivity, efficiency, and investment as simply rent transfer devices, stumpage fees can worsen any existing hysteresis in forestry investments. The airline industry represents another interesting example of this problem. The purchase of landing rights at designated airports is a form of output regulation that represents a significant investment by airline companies. Given the history of firms that hold airport rights far beyond the point of zero returns, an empirical determination of hysteresis in this industry would not be surprising.

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References

Amemiya, T. *Advanced Econometrics.* Cambridge: Harvard University Press, 1985.

Ball, V. E. "Output, Input, and Productivity Measurement in U.S. Agriculture, 1948–79." *Amer. J. Agr. Econ.* 67(1985):475–86.

Brennan, M. J., and E. S. Schwartz. "Evaluating Natural Resource Investments." *J. Business* 58(1985):135–57.

Chambers, R. G., and U. Vasavada. "Testing Asset Fixity for U.S. Agriculture." *Amer. J. Agr. Econ.* 65(1983): 761–69.

Chambers, R. G., and R. E. Lopez. "A General, Dynamic, Supply-Response Model." *Northeast. J. Agr. and Resour. Econ.* 11(1984):142–54.

Chang, C. C., and S. E. Stefanou. "Specification and Estimation of Asymmetric Adjustment Rates for Quasi-Fixed Factors of Production." *J. Econ. Dynamics and Control* 12(1988):145–51.

Chavas, J.-P. "Production and Investment Decisions under Sunk Cost and Temporal Uncertainty." *Amer. J. Agr. Econ.* 76(1994):114–27.

Dixit, A. "Entry and Exit Decisions under Uncertainty." *J. Polit. Econ.* 97(1989):620–38.

———. "Irreversible Investment with Price Ceilings." *J. Polit. Econ.* 99(1991a):541–57.

———. "Irreversible Investment and Competition under Uncertainty." Work. Pap., Dept. of Econ., Princeton University, May, 1991b.

———. "Investment and Hysteresis." *J. Econ. Perspectives* 6(1992):107–32.

Epstein, L. G. "Duality Theory and Functional Forms for Dynamic Factor Demands." *Rev. Econ. Stud.* 48(1981):81–95.

Epstein, L. G., and M. Denny. "The Multivariate Flexible Accelerator Model: Its Empirical Restrictions and Application to U.S. Manufacturing." *Econometrica* 51(1983):647–74.

Gallant, A. R., and D. W. Jorgensen. "Statistical Inference for a System of Simultaneous, Non-linear, Implicit Equations in the Context of Instrumental Variables Estimation." *J. Econometrics* 4(1979):275–302.

Howard, W. H., and C. R. Shumway. "Dynamic Adjustment in the U.S. Dairy Industry." *Amer. J. Agr. Econ.* 70(1988):837–47.

———. "Nonrobustness of Dynamic Dual Models of the U.S. Dairy Industry." *Northeast J. Agr. and Resour. Econ.* 18(1989):18–25.

Hsu, S.-H., and C.-C. Chang. "An Adjustment-Cost Rationalization of Asset Fixity Theory." *Amer. J. Agr. Econ.* 72(1990):298–308.

Johnson, G. L. "Supply Functions—Some Facts and Notions." In *Agricultural Adjustment Problems in a Growing Economy,* eds., Earl Heady et al., pp. 74–93. Ames: Iowa State University Press, 1956.

Larson, B. A. "Technical Change and Applications of Dynamic Duality to Agriculture: Comment." *Amer. J. Agr. Econ.* 71(1989):799–802.

Leahy, J. "Optimality, Competitive Equilibrium, and the Entry and Exit Decisions of Firms." Discus. Pap. No. 1566, Harvard Institute of Economic Research, Harvard University, August, 1991.

Lucas, R. E. "Adjustment Costs and the Theory of Supply." *J. Polit. Econ.* 75(1967):321–34.

Maddala, G. S. *Limited-Dependent and Qualitative Variables in Econometrics.* Cambridge: Cambridge University Press, 1983.

McDonald, R. L., and D. R. Siegel. "Investment and the Valuation of Firms When There Is an Option to Shut Down." *Internat. Econ. Rev.* 26(1986):331–49.

Mortensen, D. T. "Generalized Costs of Adjustment and Dynamic Factor Demand Theory." *Econometrica* 41(1973):657–65.

Moschini, G. "A Model of Production with Supply Management for the Canadian Agricultural Sector." *Amer. J. Agr. Econ.* 70(1988):318–29.

Nelson, C. H., J. B. Braden, and J. S. Roh. "Asset Fixity and Investment Asymmetry in Agriculture." *Amer. J. Agr. Econ.* 71(1989):970–79.

Pindyck, R. "Irreversible Investment, Capacity Choice, and the Value of the Firm." *Amer. Econ. Rev.* 78(1988):969–85.

Purvis, A., W. G. Boggess, C. B. Moss, and J. Holt. "Technology Adoption Decisions under Irreversibility and Uncertainty: An *Ex Ante* Approach." *Amer. J. Agr. Econ.* 77(1995):541–51.

Richards, T. J. "Supply Management and Productivity Growth in Alberta Dairy." Unpub. Ph.D. diss., Stanford University, 1994.

Rosett, R. N. "A Statistical Model of Friction in Economics." *Econometrica* 27(1959):263–67.

Shonkwiler, J. S., and T. G. Taylor. "Food Processor Price Behavior: Firm-Level Evidence of Sticky Prices." *Amer. J. Agr. Econ.* 70(1988):239–44.

Stefanou, S. E., J. Fernandez-Cornejo, C. M. Gempesaw II, and J. G. Elterich. "Dynamic Structure of Production under a Quota: The Case of Milk Production in the Federal Republic of Germany." *Eur. Rev. Agr. Econ.* 19(1992):283–99.

Tsigas, M. E., and T. W. Hertel. "Testing Dynamic Models of the Farm Firm." *West. J. Agr. Econ.* 14(1989): 20–9.

Weersink, A., and W. Howard. "Regional Adjustment Response in the U.S. Dairy Sector to Changes in Milk Support Price." *West. J. Agr. Econ.* 15(1990):13–21.