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Economic Hysteresis in Variety Selection

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Investing in a new perennial crop variety involves an irreversible commitment of capital and generates an uncertain return stream. As a result, the decision to adopt a new variety includes a significant real option value. Waiting for returns to rise above this real option causes a delay in adoption because of economic hysteresis. This study tests for hysteresis in the adoption of wine grape varieties using a sample of district-level data from the state of California. The empirical results show a significant hysteretic effect in wine grape investment, which might be reduced by activities that smooth earnings over time.

Key Words: California, grapes, hysteresis, investment, jump diffusion, real options, variety adoption, wine

JEL Classifications: Q14, Q11, D92, C34

For growers of cereal crops and annual fruits and vegetables, variety selection is an important decision, but one that can be reversed after a single growing season at relatively little cost. However, for growers of perennial crops such as tree and vine fruit, variety choice becomes more critical because their investment is generally much greater, the commitment is for a longer period, and the returns are slower to arrive and, for crops that cannot be stored from one year to the next, tend to be more volatile. Growers and plant breeders are faced with the difficult task of anticipating consumer tastes and demand, not only one harvest season forward, but often for several years into the future. Faced with this problem, many larger fruit growers regularly turn over from 10% to 20% of their orchard each year in anticipation of new consumer tastes and new varieties (J. Hein, personal communication). Despite the dynamic nature of variety selection, it is not uncommon to see the majority of shelf space in the produce aisle allocated to what many regard as substandard varieties—varieties that sell at prices far below those of newer, more appealing varieties of the same type of fruit. Although this could be partially explained by the inertia inherent in consumers' choice among products whose attributes are only discovered after considerable trial and experimentation, it does not explain growers' tendency to grow crops that appear to have become uneconomical; rather, this phenomenon is more likely an example of economic hysteresis.

Hysteresis, or the perpetuation of an economic activity long after its initial cause has disappeared, suggests that growers continue to grow crops that have apparently become uneconomical simply because of the small probability that returns will become favorable again at some time in the future. In general, hysteresis results when establishing a certain variety of fruit gives rise to a real option that must be taken into account in evaluating whether to either establish a new variety or to

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remove an older one. Such investment or disinvestment decisions create real options when they require an irreversible financial commitment, when the periodic returns are subject to ongoing uncertainty, and when there is a unique opportunity to make the investment (Dixit 1992).

Research has shown that real options can arise in a number of agricultural applications, including capacity choice in the anhydrous ammonia industry (Stiegert and Hertel) and technology adoption by Texas dairy farmers (Purvis et al.). More closely related to the subject matter of this study, Price and Wetzstein show that uncertainty and sunk investment costs can combine to cause the hurdle returns to establishing or removing a peach orchard to diverge significantly from what traditional net present value analysis would suggest. However, these studies each conduct *ex ante* analyses of investment or supply decisions taken under uncertainty and demonstrate, using plausible parameter assumptions, how large the "zone of inaction" or difference between the neoclassical and real-option investment and disinvestment hurdle rates can be. Although this is certainly of interest and a valid research question, studies such as these leave open the empirical question of whether growers appear to make supply decisions as if they do indeed behave according to the logic of real options. If we believe that decision makers are rational, then they should behave according to investment decision rules that recognize the value of the real options implicit in their decision, but empirical evidence of this type of behavior does not yet exist. Furthermore, given the assumed exogeneity of the returns process, we do not directly observe the gap between full-cost and neoclassical hurdle rates in aggregate data. Rather, we observe periods during which neither investment nor disinvestment occurs despite considerable variability in returns (Abel and Eberly; Oude Lansink and Stefanou). Consequently, in this study, we do not intend to estimate unobservable real option values, but rather the effect of hysteresis on rates of investment.

The nature and extent of hysteresis is also likely to depend on the exact form of volatility governing returns to a new investment. Although the studies cited above assume continuous returns processes, there is considerable evidence that real-world investments instead produce returns that are more typically discrete, or at least follow composite processes consisting of both discrete and continuous elements (Ball and Torous 1983, 1985; Bates; Hilliard and Reiss; Merton; Naik and Lee). For this reason, we test for the possibility that returns to a real investment follow a jump diffusion, rather than a continuous Brownian-motion process. Such an approach is particularly important given that our empirical example involves a class of investment that is subject not only to market volatility, but uncertainty from the weather and environment as well.

Namely, we demonstrate the importance of economic hysteresis in new variety investment by focusing on the case of growers adopting new varieties of wine grapes. The distribution of wine varieties represents a good example of economic hysteresis, because consumer tastes tend to evolve relatively rapidly; establishing a new variety entails a large investment of capital, land, and expertise; and a monopolistically competitive market structure means that individual vintners tend to have at least some market power because of the highly differentiated nature of their product. Because of rapid growth in wine consumption, it is also critically important for vintners to be able to meet the market demand for varieties that are currently in vogue. In general, developing a better understanding of the factors that drive investments in new varieties, and by corollary disinvestments in older ones, is important to a number of different decision makers involved in producing and marketing perennial crops.

Indeed, the potential effect of hysteresis is critical not only for growers who are immediately responsible for the planting or removal decision, but also the shippers and retailers at the consumer end, plant breeders and nurseries upstream from growers, and commodity boards and commissions responsible for marketing and promoting the product.[1] The central

[1] This is not to suggest that growers are unconstrained in variety choice because many varieties are

implication of the real option model is that hysteresis, or the observed sluggishness in adjustment, increases with the volatility of grower returns. Therefore, any activity that reduces the uncertainty of returns, such as contracting or generic promotion, is likely to speed the adjustment process from declining varieties to new, potentially more profitable ones.

The objectives of this research are to develop a theoretical explanation for the observed inertia in variety selection and to test whether wine grape growers recognize the real option values inherent in their decisions to switch among varieties. We then estimate the extent of the hysteresis that arises. Furthermore, this study seeks to determine whether discrete events or shocks to returns cause a significant change in the rate at which growers move between varieties. In doing so, we offer both a conceptual and empirical contribution to the literature on discontinuous supply response.

Econometric Model

In order to estimate the effect of uncertainty and sunk investment costs on variety choice, the econometric model seeks to explain growers' planned output decisions. Before developing this model in detail, we summarize the empirical implications of the real option approach. Each of these implications represents a testable hypothesis as to the existence of a hysteretic effect on variety choice. First, the existence of real options in variety choice gives rise to an "adoption hurdle" level of returns that is higher than the neoclassical (or net present value greater than zero) case and an "abandonment hurdle" that is below its neoclassical counterpart. Second, the degree to which the full-cost variety-adoption returns differs from the traditional hurdle rate is hypothesized to rise with the variability of returns, the growth rate of returns, and the cost of establishing a new variety. Third, if the nature of the uncertainty is such that the volatility of returns is subject to both continuous and discrete parts, the occurrence of a shock to returns is likely to have a statistically significant, and possibly counterintuitive, effect on planned output. Because our interest is not in estimating the size of option values, but rather their effect on planned output behavior, we develop the model in terms of the dual problem, namely of estimating the effect of changes in returns on bearing acreage. Therefore, in aggregate, the rate of movement either into or out of a given variety is measured by the net change in planned output of a variety, or the rate at which bearing acreage is falling or rising.

Ideally, if farm-level data were available on the timing of removals and replantings, the effect of real option values on the duration between variety switches suggests a natural test for the presence of hysteresis. However, in aggregate data, the available information must be assumed to describe a representative grower with a large portfolio of varieties who continually changes from one to the other each period. Whereas the theory underlying the notion of hysteresis suggests that an individual firm will exhibit a period of inaction and then a discrete change in the composition of output when the full cost hurdle is attained, in aggregate this effect appears as acreage allocations among varieties that respond slower to changes in relative returns than would be expected under traditional economic rules. Once either the upper or lower hurdle is reached, however, the decision to replace exhibits an inertia or irreversibility in the face of adverse changes in revenue because of the small probability that returns will once again become favorable.

A formal test of the hysteresis hypothesis thus has two components: (1) a test of the null hypothesis that real option values are equal to zero or that growers respond to neoclassical trigger levels and (2) a test of the statistical significance of the effect option values have on the rate at which growers allocate acreage to new varieties. To ensure that these tests reflect optimal choices, we begin by specifying the profit maximization problem facing a representative grower. Because yield variation among growers operating under best practice technol-

suited to specific regions or appellation. Furthermore, much vineyard redevelopment is done for reasons of disease infestation and disease control.

ogies are due more to random than grower-specific effects, we assume that planned output is indicated by the amount of acreage planted to a given variety. Following Varian, we define a vector of netputs ($\mathbf{y}$) used in the production of multiple grape varieties, where y_{it} is the planned output (acreage) of variety i in year t, y_{jt} is the acreage of variety j in year t, and $-y_{kt}$ is the amount of input k used in the production of each. With planned output (acreage) endogenous and both price and yield per acre assumed to be exogenous, the appropriate "price" variable is defined as per-acre revenue, R. Each netput can be sold or purchased at this value, defined on a per-acre basis for each. Furthermore, we allow for a vector of m exogenous variables, $\mathbf{z}$. The vector $\mathbf{z}$ consists of both the total acreage of all varieties in each district, as well as a set of factors that give rise to a real option value, namely the variability of revenue and the presence of discrete shocks to the revenue series. Given these assumptions, and suppressing the time subscript, a generalized Leontief dual-profit function is a plausible representation of the solution to a grower's maximization problem,

$$(1)\quad \pi(R;\mathbf{z}) = \sum_{i=1}^{n_1}\sum_{j=1}^{n_2} \beta_{ij}(R_iR_j)^{1/2} + \sum_{i=1}^{n_1}\sum_{k=1}^{n_2} \gamma_{ik}(R_iR_k)^{1/2} + \sum_{i=1}^{n_1}\sum_{l=1}^{m} \alpha_{il}(R_iz_l),$$

for n_1 grape varieties and n_2 production inputs, where β_{ij}, γ_{ik}, and α_{il} are parameters to be estimated. Applying Hotelling's Lemma to Equation (1) gives output supply equations for each variety i as a function of the return to alternative varieties j, variable inputs k, and l fixed factors

$$(2)\quad \frac{\partial \pi}{\partial R_i} = y_i = \beta_{ii} + \sum_{j=1}^{n_1} \beta_{ij}\left(\frac{R_j}{R_i}\right)^{1/2} + \sum_{k=1}^{n_2} \gamma_{ik}\left(\frac{R_k}{R_i}\right)^{1/2} + \sum_{l=1}^{m} \alpha_l z_l \quad \forall i = 1, 2, \ldots, n_1.$$

This specification, however, is a simplification because it does not address the way in which growers form their revenue expectations, nor does it consider that $\mathbf{z}$ must also include either the value of an option to adopt a new variety or to abandon an existing variety. In order to focus our attention on the effects of option values on variety choice, we assume a simple expectations process. Because most fruits take approximately 3 years to attain bearing status after planting (or grafting), the revenue that is relevant for y_{it} is the expectation of R_{it} formed at $t - 3$, which we assume to be the realized value at that time. Specification of the option value implicit in $\mathbf{z}$, however, requires more extensive modification of the basic output response model.

There are several alternatives for capturing the effect of option values in Equation (2). Richards uses the existence of real options, which create a gap between the "adoption trigger" (R_H) and "abandonment trigger" (R_L), and estimates the size of this gap using the Tobit-like friction model of Rosett. Azzam suggests that this approach is a theoretically consistent way to explain the cause of a wide variety of irreversible phenomenon. Similarly, Richards and Patterson estimate an endogenous option value in agricultural labor movement through a simple spatial arbitrage model. Others use the logic of the existence of a real option value to motivate a discontinuous investment demand function but do not explicitly estimate the size of the zone of inaction that results (Oude Lansink and Stefanou).[2] Although Richards and Richards and Patterson are able to estimate the size of the option value–induced discontinuity, neither is able to directly test for the presence of hysteresis or the inertia growers exhibit in remaining with an existing variety or their reluctance to adopt a new one. Vande Kamp and Kaiser and Parsley and Wei suggest a modification of the method developed by Wolffram and Houck in which the apparent irreversibility of a dependent var-

[2] These authors develop a dynamic dual model to explain discontinuous investment response. Although a dynamic dual model is theoretically preferred, the required data do not exist for the problem at hand.

iable is explained as a function of either cumulative increases (irreversible growth) or decreases (irreversible decline) in a key explanatory variable. These authors suggest that this method explains hysteresis in a more direct way.[3] However, their justification for using this approach is purely empirical and is, therefore, *ad hoc*. Moreover, their application is appropriate only for problems where the regressor does not necessarily exhibit a range of inaction. Implicitly, therefore, their approach assumes that the regressor could have a continuous effect through zero, and the difference between an upper and lower threshold is not endogenous to the model structure itself.

A synthesis of the two modeling approaches—the endogenous option value gap and irreversibility—requires two modifications to the behavioral Equation (2). First, we recognize that if the underlying returns are inherently uncertain, there will exist an upper hurdle in the level of returns (R_H), above which the change in planned supply is positive, and a lower hurdle (R_L), below which the change in planned output becomes negative. Second, we also know that there will be a significant gap between these two values for even small amounts of uncertainty and fixed investment costs. If the marginal value of producing a particular variety lies between these levels, there is no incentive to either increase or decrease acreage, so we observe no new varieties being planted nor any net removals of existing varieties. The formal proof of this result is well understood by now, so we will state here only the somewhat unique features of our basic assumptions underlying the process governing wine grape returns and its implication for the magnitude of this option value gap (Dixit and Pindyck). Specifically, we assume that revenue uncertainty is due to both random yields and prices—prices from market factors and yields from climatic and other biological factors such as disease, drought, and pests. Rather than assume Brownian motion for both processes, however, we specify yields in terms of a jump diffusion process, where uncertainty consists of both discrete, or one-time extreme events, and continuous elements. As the product of price and quantity, the process for revenue given this assumption is as shown in Equation (3).

$$(3) \quad dR = \mu_R R dt + \sigma_P R dz_P + \sigma_Q R dz_Q + R d\phi,$$

where μ_R is the drift, or annual rate of increase of revenue; σ_i is the standard deviation of the process governing i; and dz is the increment of a standard Weiner process, where $E[dz] = 0$; $E[dz^2] = dt$; and $E[dz_P, dz_Q] = \rho dt$, where ρ is the correlation between price and quantity, $d\phi$ is the increment of a Poisson process with mean arrival rate λ, and

$$(4) \quad d\phi = \begin{bmatrix} 0 & \text{with probability } 1 - \lambda dt \\ \eta & \text{with probability } \lambda dt \end{bmatrix},$$

where $E[dz_P, d\phi] = E[dz_Q, d\phi] = 0$, $E[d\phi] = \eta\lambda dt$, and η is the percent change in output. Given this process governing revenues, contingent claim valuation methods can be used to solve for the value of an option growers have to either defer the decision to remove an existing variety or to plant a new one. Dixit (1989) shows that the difference between the upper, or entry-inducing, threshold level of returns (R_H) and the traditional or "Marshallian" measure (M_H) can be expressed as

$$(5) \quad R_H = \Omega M_H = C + r_k K,$$

where K is the cost of establishment, r_k is the firm's cost of capital, C is operating cost, and $\Omega > 1$ is a nonlinear function of the parameters of the stochastic process governing revenue and the cost of capital. Again, a similar argument shows that the lower, or exit-inducing, threshold is strictly less than the Marshallian hurdle level, which is the annualized cost of removing an existing variety. Although analytical solutions for the difference between the real-option and traditional hurdles is not possible, Dixit (1989) shows the gap to be sig-

[3] Specifically, Vande Kamp and Kaiser's modification involves restricting the period of cumulative increases or decreases to n, rather than $T - 2$ periods, where n is determined by the researcher. This allows for both short-term irreversibility and, by including contemporaneous values of the regressor, long-term reversibility in the dependent variable.

nificant for even small fixed costs and levels of uncertainty. Therefore, the real options model provides a theoretical justification for specifying a discontinuous planned output response function, where reductions in acreage of a particular variety respond only to movements in revenue below a certain point and increasing acreage only to movements above the investment hurdle.

Consequently, segmenting the revenue variable in the manner suggested by Wolffram and Houck is no longer *ad hoc,* as suggested above, but is consistent with optimal grower behavior. With this approach, a new variable is created that consists only of the sum of previous increases in revenue from the previous period to, using Vande Kamp and Kaiser's extension, T years in the past, and another is defined to consist of the sum of previous decreases in revenue [Equation (6)]

$$(6) \qquad R_i^+ = \sum_{\tau=0}^{T} \max[\Delta R_{t-\tau}, 0]$$

$$R_i^- = \sum_{\tau=0}^{T} \min[\Delta R_{t-\tau}, 0],$$

where T is to be determined by the data through any readily acceptable goodness of fit criteria such as Schwartz' AIC. To avoid the multicollinearity problems reported by Vande Kamp and Kaiser that result from including each of the $\tau = 0, 1, 2, \ldots, T$ segmented regressors in the same regression, we restrict our analysis to one value of T, consisting of the entire sample period. This assumption is useful for two reasons. First, allowing for permanent effects of transient phenomena is consistent with the notion of hysteresis used here. Second, the relatively short sample period means that "permanent" effects persist for a length of time that is easily within a grower's likely investment horizon. To test for the possibility of long-term reversibility, Vande Kamp and Kaiser include current values of revenue in the expression as well so that the composite acreage response model becomes

$$(7) \qquad y_i = \beta_{ii} + \sum_{j=1}^{n_2}\left[\beta_{ij}^0\left(\frac{R_j}{R_i^0}\right)^{1/2} + \beta_{ij}^+\left(\frac{R_j}{R_i^+}\right)^{1/2} + \beta_{ij}^-\left(\frac{R_j}{R_i^-}\right)^{1/2} + O_{ij}(\sigma_{i,R}, \lambda_i^+, \lambda_i^-, A_i)\right] + \sum_{k=1}^{n_3}\left[\gamma_{ik}^0\left(\frac{R_k}{R_i^0}\right)^{1/2} + \gamma_{ik}^+\left(\frac{R_k}{R_i^+}\right)^{1/2} + \gamma_{ik}^-\left(\frac{R_k}{R_i^-}\right)^{1/2} + O_{ik}(\sigma_{i,R}, \lambda_i^+, \lambda_i^-, A_i)\right],$$

where $R_i^0 = R_{i,t}$ and $\beta_{ii} = \beta_{i,0} + \Sigma_{i=1}^{n_1} \beta_{ij}^0 R_1$ and R_1 is the revenue prevailing in the first period of the data set. This expression also allows us to test for the significance of both revenue volatility ($\sigma_{i,R}$) and the upward (λ^+) or downward (λ^-) revenue shocks on the investment option value (O_{ij}) and, hence, the hysteresis gap while controlling for the total bearing acreage in each district (A_i). In Equation (7), the option value is modeled as a simple linear-separable function of volatility, discrete changes in revenue, and total acreage,

$$(8) \qquad O_i = \alpha_{i,0} + \alpha_{i,1}\sigma_{i,R} + \alpha_{i,2}\lambda_i^- + \alpha_{i,3}\lambda_i^+ + \alpha_{i,4}A_i,$$

but could plausibly assume any of a number of more complex forms. Because this specification is chosen arbitrarily, we test the maintained linear form against log and quadratic models. However, to account for the likely endogeneity of the gap between the minimum investment threshold of R and the maximum disinvestment threshold of R, the estimation method must also reflect that the distribution of y is not likely to be continuous but, rather, is truncated at the upper and lower entry thresholds.

Although this approach is only strictly correct when variety acreage does not change when revenue is between the upper and lower thresholds, this characteristic is likely to be violated in aggregate data. However, we approximate this distribution by assuming that changes in acreage that are not statistically significantly different from zero represent regimes of no effective change. Therefore, we can divide the data set into regimes of falling acreage, rising acreage, and no effective change in acreage and estimate the parameters of Equation (7) in each of these regimes [Equation (9)]

$$(9)\quad \Delta y = \begin{bmatrix} \Delta y_1^* - O_1 - u; & \Delta y_1^* - O_1 - u < 0; \\ 0; & \Delta y_1^* - O_1 - u > 0 \\ & > \Delta y_2^* - O_2 - u; \\ \Delta y_2^* - O_2 - u; & \Delta y_2^* - O_2 - u > 0 \end{bmatrix}$$

$$O_1 < 0; \qquad O_2 > 0,$$

where O_1 is the value of an option to remove an existing variety, and O_2 is the value of an option to adopt a new variety. Assuming the error term u is normally distributed, Φ is the unit-normal cumulative density function, and ϕ is the probability density function, the density function for the above problem is

$$\begin{aligned}(10)\quad & \Pr(\Delta y > x, x > 0 \mid x) \\ &= \Pr(\Delta y_2^* - O_2 - x > u) \\ &= \Phi\left(\frac{\Delta y_2^* - O_2 - x}{\sigma}\right); \\ & \Pr(\Delta y = 0 \mid x) \\ &= \Pr(\Delta y_1^* - O_1 > u > \Delta y_2^* - O_2) \\ &= \Phi\left(\frac{\Delta y_1^* - O_1}{\sigma}\right) - \Phi\left(\frac{\Delta y_2^* - O_2}{\sigma}\right); \\ & \Pr(x < 0, x > \Delta y \mid x) \\ &= \Pr(\Delta y_1^* - O_1 - x < u) \\ &= 1 - \Phi\left(\frac{\Delta y_1^* - O_1 - x}{\sigma}\right).\end{aligned}$$

Assuming that the effect of hysteresis, as estimated by the O_m parameters, is the same for each observation, the likelihood function for the variety friction model is

$$\begin{aligned}(11)\quad & L(\Delta y \mid O_m, \sigma) \\ &= \prod_d \left(\frac{1}{\sigma}\right)\phi\left(\frac{\Delta y_d - \Delta y_d^* + O_1}{\sigma}\right) \\ &\times \prod_g \left[\Phi\left(\frac{O_2 - \Delta y_g^*}{\sigma}\right) - \Phi\left(\frac{O_1 - \Delta y_g^*}{\sigma}\right)\right] \\ &\times \prod_r \left(\frac{1}{\sigma}\right)\phi\left(\frac{\Delta y_r - \Delta y_r^* + O_2}{\sigma}\right)\end{aligned}$$

defined over regimes of d observations of declining acreage, r observations of rising acreage, and g observations with no significant change. With this model, we are able to estimate both the endogenous gap between the lower and the upper thresholds and the potentially persistent effect of changes in revenue on the acreage of each variety.

Data and Methods

The example used to demonstrate the applicability of this model is from California wine grape production. Specifically, the sample used in this study consists of wine grape–bearing acreage, prices, and yields for eight crush reporting districts in the state of California over the 1976–1998 period. All acreage data are from *California Grape Acreage,* which is published annually by the California Department of Food and Agriculture (CDFA). This document provides a complete description of the data-gathering methods used to compile grape acreage and variety information. Varieties are reported at a high level of disaggregation and are exhaustive of all counties. For the model described above, returns are defined as per-acre gross revenue, or yield multiplied by price. Prices are reported by the CDFA on a reporting district basis and are defined as weighted average grower returns on a per-ton, delivered basis, where the weighted average is calculated over quantities delivered at various degrees Brix, or quality standard. Reported this way, returns are adjusted for either premiums or discounts to the standard Brix content. The full schedule of Brix adjustment factors and the associated premiums or discounts are reported in the annual CDFA *Final Grape Crush Report.* However, because prices are reported on a crush district basis and acreage on a county basis, the acreage data are aggregated up to the district level. Furthermore, changes to crush reporting district boundaries and descriptions during the sample period require the definition of a set of equivalencies between old and new districts. Grape varieties are chosen to represent the top five in each county by acreage. Given the diversity of growing conditions, the local nature of many wine markets, and the large number of varieties available, this means including 15 varieties in the final sample. Virtually all varieties, however, are grown to a certain extent in each district. Where a variety is not grown, the missing price is calculated from the state average for that year from all other districts. By pooling these data over a 23 year period and eight reporting districts, 184 combined time series and cross-sectional observations are available for each variety, for a total of 2,760 observations in all. Table 1 provides a summary of each variable used in the econometric model.

To estimate the option value inherent in both investment and disinvestment decisions, estimates of both the volatility of revenue and the nature, in terms of size and frequency, of discrete shocks to revenue are found for each variety and district. Before estimating these values, however, it is first necessary to establish whether a jump diffusion or continuous Brownian motion process is a better representation of the revenue series. To accomplish this, we use the maximum likelihood approach developed by Ball and Torous (1983, 1985) and Jarrow and Rosenfeld to test the Poisson-normal mixture model originally suggested by Merton.[4] We then use a likelihood ratio test to select between the jump diffusion and Brownian motion specifications with the unrestricted log-likelihood function,

$$(12)\quad L(r|\lambda, \mu_R, \sigma_R^2, \delta^2) = \sum_{i=1}^{M} \ln\left(\sum_{n=0}^{N} \frac{e^{-\lambda}\lambda^n}{n!}\phi(r_i|\mu_R, \sigma_R^2 + n\delta^2)\right),$$

for M observations of annual changes in revenue $[r_i = \ln(R_{i,t}/R_{i,t-1})]$, where λ is the Poisson intensity parameter, σ_R^2 is the volatility of the continuous part, δ^2 is the volatility of the discrete part, and ϕ is the normal density function. The null hypothesis of continuous Brownian motion implies $\lambda = 0$. With two restrictions and a significance level of 5%, we easily reject the continuous model in favor of a jump diffusion specification.[5] Our goal in estimating this model, however, is not only to determine which specification provides a better fit to the data but also to recover the value of λ so that we can define what constitutes a shock to the revenue series. With $\lambda = 0.073$, this implies a total of 174 shocks over all districts and sample years. Therefore, we rank the deviations from district and variety mean returns and define the largest 174 in absolute value as shocks. Although this procedure is but one of many ways to define a discontinuity, allowing the data to determine the presence or absence of a shock means that this approach is less *ad hoc* than alternative means of accomplishing what is regarded as an inherently difficult task (Ball and Torous 1983). Indeed, because of the difficulty in obtaining convergence of Equation (12) around a unique value of λ, we estimate constant values for each of the conditional volatilities. To find a district and variety-varying continuous volatility for the option value in Equation (11), therefore, we calculate volatility empirically as

$$\sigma_{i,R}^2 = V[\log(R_{i,t}/R_{i,t-1})],$$

using only the observations that do not exhibit a discontinuity. This procedure is consistent with the definition of conditional volatility as estimated in Equation (12) but provides a measure that varies by district and variety. Whether either of these variables represents a significant effect on investment, however, must be formally tested against a nonhysteretic model of investment.

We estimated the likelihood function [Equation (11)] by pooling the district–variety data over all time periods. Because of the large number of varieties involved, we created a single alternative variety revenue variable as an index of the annual revenue from all competing varieties for each district, where the weights in this index are annual bearing acreages. Starting values for all variables are from a single-regime ordinary least squares regression, but the reported results are robust to a

[4] Hilliard and Reis estimate the parameters of a similar process for soybeans using an implied estimation technique with observed soybean option prices. However, in the absence of a "wine option" market, we cannot use this approach.

[5] Detailed parameter estimates for Equation (12) are available from the authors.

Table 1. Descriptive Statistics of Wine Grape Variety Distribution: 1986–1998

Variety Number	Variety Name	Mean Revenue (\$/acre)	Mean Acreage[a]	Mean Investment $(A_t - A_{t-1})$
1	Barbera	3,457.988	1,757.395	−56.805
2	Cabernet Sauvignon	2,367.672	3,476.557	120.801
3	Carignane	1,457.873	2,006.313	−87.045
4	Chardonnay	2,930.808	4,726.791	403.641
5	Chenin Blanc	1,787.216	3,932.807	6.193
6	French Colombard	1,692.121	6,647.420	109.642
7	Grenache	2,214.653	1,727.068	−36.943
8	Merlot	2,219.824	1,094.511	187.778
9	Petite Sirah	1,440.099	736.511	−60.665
10	Pinot Noir	2,445.143	1,130.653	6.510
11	Ruby Red	1,527.375	1,083.501	−9.841
12	Ruby Cabernet	1,303.449	1,345.251	−59.869
13	Sauvignon Blanc	2,933.403	1,292.628	42.051
14	White Riesling	2,392.537	834.528	−29.051
15	Zinfandel	2,839.404	3,538.506	110.521

Sources: California Department of Food and Agriculture. *California Grape Acreage.* Various issues; California Department of Agriculture *Grape Crush Report.* Various issues.
[a] Mean acreage is defined over all districts and sample years.

relatively wide range of initial values. Standard testing procedures (F-test) allowed us to compare a fixed county effects model to a single constant-term alternative. Because we reject the null hypothesis at the 5% level of significance, all subsequent hypothesis tests maintain a fixed county effects specification.

Results and Discussion

These tests include (1) the significance of growers' investment decisions in response to upward and downward relative revenue movements within investment and disinvestment regimes, (2) the significance of long-term reversibility, (3) the significance of option values as a cause of investment hysteresis, (4) the significance of volatility and discrete shocks to revenue in determining option values, and (5) the symmetry of growers' response to changes in relative variety revenue in variety selection. The first two of these tests determine the appropriate model of wine grape variety investment, whereas the latter three test the central hypotheses regarding investment hysteresis.

Specifically, recall that the irreversible investment model in Equation (10) allows for upward- and downward-segmented revenue variables in both investment and disinvestment regimes. However, there is some question as to whether a more appropriate, and parsimonious, model might consist of only downward revenue movements in the disinvestment regime and upward movements during periods of positive investment. Because the simpler model is nested within the more complete specification, a likelihood ratio test of the joint significance of all the possibly superfluous revenue variables is used to select between these models. The maintained model restricts each of these coefficients to zero and produces a log-likelihood function (LLF) value of −1,024.635, whereas the unrestricted model is −1,018.016, yielding a likelihood ratio statistic of 13.238. At a 5% significance level and 30 degrees of freedom, the critical chi-square value is 43.773, so we fail to reject the null hypothesis and use the simpler model in subsequent tests.

The second specification test has also been interpreted as a test of hysteresis (Parsley and Wei; Vande Kamp and Kaiser) in that this phenomenon implies a permanent effect of a transient cause and so is, by definition, not long-term reversible. Therefore, failure to reject the

Table 2. Wine Grape Variety Choice Hysteresis Estimates: 1986–1998

Negative Investment			Positive Investment			Symmetry H_o: $\beta_{1i} = \beta_{2i}$
Parameter	Estimate	t-ratio	Parameter	Estimate	*t*-ratio	*t*-ratio
β_{11}	−38.751*	−3.226	β_{21}	−49.361*	−24.080	0.871
β_{12}	−112.370*	−99.031	β_{22}	−86.622*	−20.824	−5.972*
β_{13}	−53.751*	−13.973	β_{23}	−92.805*	−46.275	9.002*
β_{14}	−189.980*	−24.737	β_{24}	−197.370*	−79.476	0.916
β_{15}	−206.460*	−51.212	β_{25}	−221.230*	−44.114	2.295*
β_{16}	−67.509*	−12.884	β_{26}	−111.100*	−33.769	7.046*
β_{17}	−14.294*	−2.562	β_{27}	−22.396*	−10.472	1.356
β_{18}	−68.078*	−62.808	β_{28}	−67.825*	−27.173	−0.093
β_{19}	−56.613*	−21.024	β_{29}	−73.875*	−13.605	2.848*
β_{110}	−66.148*	−50.942	β_{210}	−58.919*	−27.855	−2.913*
β_{111}	−65.490*	−21.664	β_{211}	−68.544*	−17.621	0.620
β_{112}	−48.487*	−20.193	β_{212}	−68.819*	−34.027	6.476*
β_{113}	−27.273	−1.745	β_{213}	−12.690*	−4.173	−0.916
β_{114}	14.446*	4.341	β_{214}	−35.944*	−3.848	5.082*
β_{115}	−89.654*	−12.538	β_{215}	−88.564*	−42.075	−0.146
α_{10}	−21.885*	−3.149	α_{20}	55.009*	18.121	
α_{11}	−31.362*	−2.059	α_{21}	28.926*	8.586	
α_{12}	7.539*	2.065	α_{22}	36.881*	17.416	
α_{13}	−64.528*	−8.076	α_{23}	−21.465*	−8.004	
α_{14}	−0.004*	−7.316	α_{24}	0.011	1.089	

Notes: In this table, β_{mi} refers to the generalized Leontief revenue-response parameter of variety *i* acreage in investment regime *m*, where $m = 1$ indicates negative investment (disinvestment), and $m = 2$ indicates positive investment, and α_{mi} refers to the option value parameter *l* in regime *m*. A single asterisk indicates significance at a 5% level. The value of the log-likelihood function is −1,024.635.

The t-ratio is calculated under the null hypothesis of response symmetry $\beta_{1i} = \beta_{2i}$. A single asterisk suggests rejection of the null hypothesis of response symmetry.

null hypothesis that the current-period effect of revenue is equal to zero provides support for, but not conclusive evidence of, a hysteretic revenue effect. Comparing a model that includes current-period revenues to the preferred model from hypothesis test 1 above produces a likelihood ratio test statistic of 10.358, which is again chi-square distributed with 30 degrees of freedom. Consequently, this test suggests a preference for the more parsimonious model and for the existence of hysteresis in wine grape investment. Direct estimates of the option value and, hence, the gap between Marshallian and full-cost investment and disinvestment trigger revenue levels provide more direct evidence of this phenomenon.

Tests for nonzero option values involve joint tests of the α_i parameters above. If all of these parameters are equal to zero, then O_m must be zero as well. Rejecting the null hypothesis of zero option values means that there is a significant gap between the revenue value that would induce investment under Marshallian rules and under full recognition of the option value inherent in adopting a new variety. Given the assumed stochastic process for revenues, therefore, it will take a longer time for revenues to drift above the higher option value threshold or below the lower exit threshold, unless driven beyond the threshold by a discrete shock to revenue. This is the nature of hysteresis in this market. Based on the estimates in Table 2, the chi-square test statistic for joint significance of the α parameters in both regimes is 28.468. With eight degrees of freedom and at a 5% level of significance, we can easily reject the null hypothesis of zero option values. This result, therefore, implies that adoption of new varieties and removal of the old are both significantly delayed because of the uncertainty to returns and the fixed costs of switching varieties. Furthermore, likelihood ratio tests are used to determine whether non-linear option value terms are preferred to the maintained linear versions. Comparing the linear model to one that includes log-volatility, jump terms, and total acreage produces a likelihood ratio statistic of 28.982 (LLF = −1,039.126), whereas a similar comparison to a quadratic option value terms gives a likelihood ratio statistic of 25.994 (LLF = −1,037.632). At a 5% level and eight degrees of freedom, the critical chi-square value is 15.507, so we reject the null, nonlinear alternative in either case. Of perhaps greater interest than the nature of the specification is the value and sign of each component of the option value.

In the disinvestment regime, a higher option value means a larger negative gap between actual and desired levels of disinvestment. Consequently, factors that cause higher values of O_1 are expected to have a negative effect on vine removals. Indeed, the constant term α_{10} is significantly less than zero, so all else constant, planned removals are 21.89 acres lower because of the existence of a real option value. Equivalently, expected returns would have to fall by an amount sufficient to cause an additional removal of 21.89 acres before instantaneous action is optimal. Similarly, a rise in the variability of revenue of one dollar causes the option value to rise, so removals fall by over 31 acres. Although these effects are intuitively clear, the effect of discrete shocks to revenue are less so. In the disinvestment regime, a negative jump in revenue makes it more likely that the grower's option will be exercised immediately, thus lowering its value and increasing the rate of disinvestment. Conversely, a positive shock to revenue while removing a variety creates some doubt that revenues will fall below the lower threshold, thus increasing the option value and slowing the rate of disinvestment. Compare this effect to an equivalent revenue shock in the investment regime. A positive jump in revenue reduces the uncertainty that the threshold will be crossed in the future, so the option value falls and the gap between desired and actual investment falls. On the other hand, a sharp reduction in revenue increases the uncertainty of ever moving above the investment trigger, so the option value rises. Similarly, the intercept value (α_{20}) and the effect of revenue volatility (α_{21}) suggest that returns to a new variety must rise sufficient to justify an additional 55 acres of investment in order to induce immediate adoption and that this hurdle rises by 29 acres for every one dollar rise in the variance of revenue. Whereas previous simulated theoretical models of hysteresis (Dixit 1989; Price and Wetzstein) suggest that variability is the key determinant of option values, and hence hysteresis, this analysis shows that discrete shocks can be nearly as important in a quantitative sense. Finally, Table 2 also reports the results of testing for symmetry on a parameter-by-parameter basis. In 8 of 15 cases, we reject the null hypothesis of a symmetric response to upward and downward movements, although the differences are not always of the same sign. Although virtually all of the revenue-response parameters are significant and all are of the expected sign, they are difficult to interpret because of the generalized Leontief functional form and their reliance on the specific units of measurement used here.

Consequently, Table 3 presents own-revenue response elasticities for each variety. Three points are apparent from inspecting these elasticities. First, whether removing or planting vines, the response is uniformly inelastic, as is to be expected for any long-lived asset. Second, comparing the elasticities between regimes confirms the asymmetry tests reported above as growers' responsiveness to revenue changes appears to be roughly double when disinvesting relative to when they are investing. This is perhaps not surprising given the costs of each decision. Compared to establishing a new variety, removal is relatively less expensive, whereas establishment can mean capital expenditures of more than $10,000 per acre in addition to the investment in new, variety-specific knowledge. Although the hysteretic effect is likely to influence both types of

Table 3. Acreage Response Elasticities by Variety and Investment Regime

Negative Investment			Positive Investment		
Elasticity	Estimate	*t*-ratio	Elasticity	Estimate	*t*-ratio
η_{11}	0.175*	3.226	η_{21}	0.148*	47.015
η_{12}	0.334*	99.031	η_{22}	0.098*	74.745
η_{13}	0.229*	13.973	η_{23}	0.105*	92.297
η_{14}	0.443*	112.091	η_{24}	0.217*	133.057
η_{15}	0.292*	200.158	η_{25}	0.069*	217.888
η_{16}	0.162*	12.884	η_{26}	0.032*	111.051
η_{17}	0.104*	2.562	η_{27}	0.088*	19.669
η_{18}	0.254*	62.810	η_{28}	0.117*	45.337
η_{19}	0.327*	21.023	η_{29}	0.259*	72.758
η_{110}	0.427*	50.941	η_{210}	0.137*	52.833
η_{111}	0.357*	64.034	η_{211}	0.112*	66.495
η_{112}	0.218*	20.193	η_{212}	0.104*	67.308
η_{113}	0.172	1.745	η_{213}	0.047*	6.213
η_{114}	−0.104*	−4.341	η_{214}	0.106*	34.750
η_{115}	0.207*	12.538	η_{215}	0.110*	80.153

Note: The elasticities in this table, η_{ij}, show the response in variety j to its own revenue in investment regime i. A single asterisk indicates the elasticity is significantly different from zero at a 5% level.

decision, this suggests that the effect is less severe for disinvestment than investment. Third, once we control for the difference between rising and falling acreage, the investment elasticity does not appear to differ between those varieties that the market currently favors and those that are losing market share. For example, Table 1 shows strong acreage growth in Merlot, Chardonnay, Cabernet Sauvignon, and Zinfandel, yet their sensitivity to changes in revenue do not differ from the other, less favored varieties. If anything, growers are more sensitive to revenue reductions in removing these varieties. Given that the volatility of per-acre revenue is similar for each variety, the hysteresis model leads us to expect little difference in the sensitivity of each variety's acreage to changes in revenue. Indeed, if we account for asymmetries due to cost, the remaining sluggishness in either adoption or removal is likely to be similar for varieties of equal volatility.

Given the strong inertia in variety choice that these results demonstrate, it is perhaps not surprising that we continue to see varieties being grown despite the decline in demand for them relative to alternative varieties. In fact, such inertia is a rational economic response to uncertainty and fixed costs. If private nurseries, rootstock providers, University extension agents, or wine makers want to increase the rate at which new varieties are adopted, then this suggests two solutions, one of which is obvious and the other not. Clearly, by reducing the fixed cost of establishment, both the financial and the true economic costs of adoption will be reduced, so the rate of investment will increase. However, reducing the volatility of wine grape revenue will lower the real option value inherent in both adoption and removal and, thus, accelerate the process of variety propagation. Greater stability can be achieved through either revenue-based insurance products, such as the federally underwritten Crop Revenue Coverage (CRC), or through growers' participation in long-term production contracts with price guarantees from wine makers (Goodhue, Heien, and Lee). In fact, although the rise of contracting in wine grapes is more likely due to a problem of asymmetric information in grape quality, the development of this trading institution might also allow consumer demand to translate more rapidly into growers' variety investment decisions.

Conclusions and Implications

Although consumer preferences for different varieties of a particular commodity seem to undergo continual and rapid change, growers are often reluctant to switch to new varieties even though transient market signals suggest that a change would be immediately rational. Given the high costs of establishing a new variety, including not only the agronomic costs of planting but also the human capital costs of learning the idiosyncrasies of a new crop and the inherent variability of returns, we expect that decisions to switch varieties should entail significant real option values. Moreover, given the theoretical importance of discrete events in real option values, it is likely that shocks to a returns process are either likely to represent precipitating events that cause change or sources of greater uncertainty that exacerbate the extent of hysteresis. In this research, we develop an empirical test of hysteresis in variety choice and apply it to a time series, cross-sectional sample of wine grape–producing regions in California.

Our results provide three pieces of statistical evidence that, taken together, constitute strong support for the existence of a hysteretic effect in wine grape variety choice. First, we find statistically significant real option values, which are defined as the difference between the level of returns that would trigger an investment under neoclassical investment rules and the full-cost returns threshold that includes a real option value. Second, we find that these option values have a significant effect on the rate of investment in new grape variety acreage. Third, our results show that once an investment is made, it exhibits considerable inertia, or irreversibility. This is a key implication of the hysteresis model. In addition, we show that discrete shocks to the returns series in a positive direction accelerate investment but slow the rate of disinvestment and vice versa.

These results provide many implications for producing and marketing both agricultural commodities specifically and consumer products more generally. In the case of wine grapes, growers could become faster to adopt new varieties if they face lower establishment costs or if the expected returns to growing wine grapes become more stable. Greater stability could, in turn, arise as a result of growers' taking advantage of new innovations in federally underwritten revenue insurance products or through greater use of production contracts. Although contracting in wine grapes likely arose out of a need to address a more fundamental principal agent problem between growers and wine makers, it might indeed have the unintended side effect of increasing the rate of new variety adoption. Although we apply this model to the case of wine grape variety choice, its implications are far more general than this. For example, when a consumer goods manufacturer develops a new product, the research and development expenditure can be substantial, yet the outcome far from assured. In this case, we would expect to see firms attempt to sustain existing brands much longer than would be the case if they follow strict Marshallian investment rules.

Although we use aggregate, county-level data, future research in this area might provide a more precise test of our thesis by using farm-level panel data. By accounting for firm-specific discrete events, we would be better able to understand the relative effects of ongoing volatility and idiosyncratic events in causing variety change. Furthermore, we assume a very simple jump diffusion model in order to ensure that our econometric model remains relatively tractable, but the financial economics literature has become far more sophisticated in modeling composite distributions caused by the existence of discrete events.

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