What Can We Learn from Spatial and Vertical Price Transmission Studies?
Empirical Examples from U.S. Meat Markets*

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Abstract
We provide an overview of the empirical literature that has addressed vertical and spatial price transmission in meat markets. We address several criticisms offered in the literature and point out additional shortcomings that may be relevant to the techniques often used to evaluate price transmission. A fundamental point stressed in our discussion is that the results of price-based evaluations of price transmission are not likely to be very informative without a deeper understanding of the structures and institutions relevant to the markets in question. Implications of spatial price linkages are less vulnerable in this regard in that the simple mechanism underlying such evaluations—spatial arbitrage—is generally straightforward. Evaluations of vertical price transmission are more troubling in that the results can be consistent with a variety of different structural explanations. Absent information about the economic structure of the problem, such empirical evidence is not likely to be especially informative. Finally, we consider a brief application of recently developed nonlinear time-series models to a consideration of vertical price linkages in meat markets. The aforementioned cautions apply to our results in that the methods and results, while interesting to the applied econometrician, cannot be used to make structural inferences without a deeper understanding of the markets.

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Introduction

The degree to which market shocks are transmitted up and down the marketing chain and across spatially-distinct markets has long been considered to be an important indicator of the performance of the market. A rich empirical literature has investigated the extent to which markets are linked across space and throughout the marketing chain, and meat and livestock markets have played an important role in this literature. Vertical price linkages are often considered to be relevant to structure, conduct, and performance issues. In particular, the extent to which shocks at one level of the market are realized at other market levels is often taken to be an important indicator of the exercise of market power. In meat and livestock markets, this issue has been of particular interest in light of the considerable consolidation and concentration of the industry by packers and processors.

A closely related though distinct set of issues has been addressed through a consideration of spatial price linkages. In particular, these relationships have been used to address a variety of economic issues. In a fashion similar to that underlying vertical price linkage evaluations, economists often consider the degree of spatial price linkages to be an important indicator of market power and a factor often used to define the extent of a market. Transactions costs may allow buyers or sellers to enjoy a degree of localized market power. Spatial price linkages are often interpreted as providing insights into the efficiency of the infrastructure of a market. This is especially true in developing economy applications, where infrastructure issues such as road systems, market development, transportation, and so forth may be especially pertinent.

Much of this empirical literature is concerned with the application of time-series modeling techniques to price data alone. This line of research, though extensive, has been challenged for its lack of structural models. In particular, several authors have questioned the extent to which insights into the nature and performance of markets can be gained from an analysis based solely on price data. Perhaps the harshest criticisms have been applied to tests of
market integration (spatial price linkages). See, for example, Barrett (2001) who makes a persuasive argument that price data alone, in lieu of corresponding quantity or trade flows, may not provide especially informative inferences regarding spatial price linkages.

The goal of this article is to provide an overview of the empirical literature that has addressed spatial and vertical price linkages for meat and livestock products. We will attempt to address perceived shortcomings of some empirical methodologies. Likewise, we will attempt to point out additional shortcomings that have not received a great deal of attention in the existing literature. As will be made clear, there is ample room for both agreement and disagreement with the conclusions reached in this large empirical literature and the commentaries that have been applied to it. The plan of this paper is as follows. The next section provides an overview of the empirical literature that has addressed vertical and spatial price linkages for agricultural products. In this overview, we attempt to point out perceived shortcomings in individual studies. Underlying this review is a central question—Are the results informative? We hope to make the point that an understanding of the fundamental structure of the markets under consideration is essential to the proper interpretation of the results. As is true with almost any empirical analysis, different structural stories may be consistent with the results and thus any proper inferences must be made conditional on a complete comprehension of the structures and institutions underlying the market. In the final part of this paper, we offer an empirical evaluation of vertical price linkages for the three principle U.S. meat products—beef, pork, and chicken. These markets have been evaluated in earlier studies and we introduce a new approach to considering the nonlinearities that may be inherent in the dynamic adjustments to exogenous shocks in these markets.
The Current State of Research

Vertical Price Transmission

As we have noted, a very large literature has examined price transmission issues in agricultural commodity markets.¹ Much of this literature has been concerned with linkages among farm, wholesale, and retail prices. Three aspects of vertical price transmission have been of particular importance in the applied literature—the extent of adjustment (i.e., how big of a response is triggered by a shock of a given size), the timing of the adjustment (i.e., are there significant lags in adjustment), and the extent to which adjustments are asymmetric (i.e., do positive shocks trigger different adjustments than negative shocks).

Much of the motivation underlying this line of research has involved concerns about market power and the potential effects that increased market concentration may have on price adjustment processes. Many applications in the empirical literature have been directed toward meat commodities. This reflects the substantially increased degree of concentration that has been experienced in these markets as a result of a number of mergers and consolidation of the industry. A comprehensive review of the theoretical and empirical issues underlying this literature has been provided by Wohlgenant (2001). In addition, the recent paper of Weldegebriel (2004) considers the empirical implications for various modeling approaches and the actual competitive standing of a particular industry. He concludes with a very important point—that a range of empirical results regarding price transmission among different levels of the market can be consistent with a variety of competitive structures, from perfect competition to monopoly.

A seminal paper in the study of price transmission issues is the study of Heien (1980). Heien considered the transmission of price shocks from free-on-board (fob) to retail prices. Using a simple dynamic, time series model, his results indicated that retail prices responded to fob price shocks but that fob prices did not respond to retail price shocks. In other words, the direction of causality ran from wholesale to retail markets and not in reverse.

Recent research has focused on the potential asymmetry for price adjustments. In par-

¹There are a number of recent literature reviews that provide a comprehensive review of the vertical price transmission literature. The motivated reader is referred to Meyer and von Cramon-Taubadel (2004), Conforti (2004), and Weldegebriel (2004) for more comprehensive reviews.
ticular, it is often argued that positive shocks at one level of the market may elicit different responses at other levels that negative shocks. Pelzman (2000) noted that most standard theoretical models that explain market linkages do not incorporate factors that would explain the existence of asymmetric responses. He thus concludes that existing theoretical models are incomplete or invalid. Most recent studies use a modeling approach first introduced by Wolffram (1971) and later modified by Houck (1979). These specifications typically involve a regression of price differences on lagged price differences, where the lagged differences are segregated according to sign such that positive changes are allowed to have a different effect than negative changes.

Recent research has given more careful consideration to the time-series properties of the price data. In particular, nonstationarity and the potential for cointegration relationships among prices at various levels of the market have been made an important part of price transmission models. Von Cramon-Taubadel (1998) was one of the first to incorporate the concept of cointegration into models of asymmetric price transmission. His research used a particular form of an error correction model that recognized the potential for asymmetric adjustments. He found that wholesale prices in German hog markets reacted more rapidly to positive shocks than to negative shocks originating at the farm level.

Goodwin and Holt (1999) argued that the adjustments to exogenous shocks at various levels of the market may be nonlinear as well as asymmetric. They estimated a full vector error correction (VEC) model of monthly beef price relationships at the farm, wholesale, and retail levels. Their results were consistent with causality running from farm to wholesale to retail levels. They also found evidence of statistically significant thresholds and asymmetries in price adjustments. This line of research was later extended to a consideration of hog price relationships by Goodwin and Harper (2000).

A number of institutional and theoretical explanations for the existence of asymmetries have been offered. Ward (1982) pointed out that agents in possession of perishable commodities may be hesitant to raise prices for fear of being left with spoiled product. Ball and Mankiw (1994) note that the use of menu costs by agents may lead to more resistance to lower prices than to increase prices since the adjustment to a new pricing structure may be costly for agents.
Bailey and Brorsen (1989) pointed out that asymmetries in price adjustments may be caused by asymmetries in the underlying costs of adjustments. Kinnucan and Forker (1987) argued that government policies may lead to asymmetric price adjustments if agents believe that price movements in one direction may be more likely to trigger government intervention than movements in another direction. In particular, the government may be more likely to intervene if market shocks permanently lower farm prices than if farm prices increase.

Implicit in many considerations of asymmetric adjustment are suspicions that agents in concentrated industries may practice price discrimination such that price increases are passed along to buyers more frequently and to a greater extent than price decreases. Likewise, when one considers linkages between highly concentrated processors and farmers, the conventional wisdom is that processors may be more likely to pass along price decreases than price increases. In both cases, the asymmetric adjustments result from the concentrated agents’ exploitation of their market power.

In all, a large literature has argued in favor of asymmetries in price transmission studies. While it is difficult to generalize this entire literature, most studies that have looked for asymmetries have found them. A wide variety of explanations for these asymmetric price relationships have been offered. We have attempted to provide a broad overview of this literature.

**Spatial Price Transmission**

A closely related concept involves the degree to which price shocks tend to be transmitted across spatially distinct markets. An even broader literature has been directed toward a variety of issues that pertain to spatial price transmission. Many studies of spatial price transmission have appeared in the international trade literature. The notion of a condition of price equilibration known as the “Law of One Price” plays a central role in most models of international trade and has been the focus of trade research over the past one-hundred years or longer. The extent to which spatially distinct markets within a given economy are linked is often investigated within the context of tests of “spatial market integration.” As we noted above, many of these investigations have involved developing country markets, where the infrastructure that links spatially separated markets may be in question. Likewise,
the degree of spatial price transmission has also played an important role in the anti-trust literature, where the spatial definition of a market is often an issue.

The empirical literature that has addressed spatial price transmission issues is immense. A comprehensive review of this literature is contained in Fackler and Goodwin (2001). We limit our consideration here to a handful of papers that have considered spatial price relationships important to livestock and meat markets. However, several points raised in the review of Fackler and Goodwin are worth repeating here. First of all, the spatial price transmission literature has suffered from a rather loose terminology that has resulted in confusion when comparing results across alternative studies. In particular, the degree of price transmission is often characterized in terms of spatial market integration, spatial efficiency, the law of one price (or, at an aggregate level, purchasing power parity), and spatial arbitrage conditions. The conditions required for markets to be considered to be “integrated” may vary substantially across different studies. Fackler and Goodwin (2001) argue that different authors invoke different definitions of these concepts and that their empirical tests therefore involve different hypotheses about the market conditions implied by integration. For example, spatial integration may imply perfect price transmission (i.e., that a price change in one market is provokes an identical adjustment in another market) or, alternatively, may only require only that prices do not wander arbitrarily far apart. Fackler and Goodwin (2001) note that the literature must be examined with careful attention to the specific conditions being evaluated and used to construct empirical tests. Evidence consistent with one author’s view of integration may be taken as evidence against integration by another. Indeed, this caution is also pertinent to the literature on vertical price transmission. One must be careful to recognize the conditions being evaluated and how the institutional details that underlie the empirical analysis frame the results.

Several studies of market integration have been directed toward livestock commodities. Goodwin and Schroeder (1990a, 1990b) examined spatial price linkages among regional cattle markets. They presented tests of spatial market integration and considered the dynamic patterns of adjustment to exogenous shocks in regionally distinct markets. Their analysis was based upon vector autoregression models involving prices at individual markets as well as explicit tests of the arbitrage conditions that underlie linkages among spatially separate
cattle markets. They concluded that there was a substantial degree of integration among markets and that shocks to a specific market tended to elicit responses in other markets.

Goodwin and Schroeder (1991) used a variety of cointegration tests to evaluate spatial linkages among regional U.S. cattle markets. Their results revealed strong linkages among weekly prices. Cointegrating parameter estimates were also consistent with a reasonably strong tendency toward price equalization. They also considered an investigation of the factors that tended to influence the extent of integration integration among pairs of markets. Their results revealed that an increased distance between markets tended to moderate the degree of price transmission. They also found that increased industry concentration tended to increase market linkages. Such a finding could be consistent less spatial price discrimination (perhaps implying less market power) or, alternatively, with efficiency gains that tended to decrease the costs associated with spatial transactions.

A key criticism (among the many that have been directed toward this literature) involves the omission of transactions costs. Spatially distinct markets are linked by spatial arbitrage (either actual trade or the threat of trade). Standard regression-based tests of spatial linkages typically consider some version of the following price relationship:

$$P_{1t} = \alpha + P_{2t}$$  \hspace{1cm} (1)

where $P_{1t}$ represents the price of a commodity at location $i$ in time period $t$ and $\alpha$ is a parameter that is often taken to represent transactions costs. Of course, transactions costs are likely to be significant when one is considering the movement of meat or livestock commodities across regions. This relationship may be flawed by the fact that, unless markets are linked by a continuous flow of the commodity (implying that the expected price differences are exactly equal to the costs of trade), this condition may not hold as an equality but rather as

$$P_{1t} \leq \alpha + P_{2t}.$$  \hspace{1cm} (2)

To address this point, recent research on spatial price linkages has focused on the potential for nonlinearities which may be relevant in models of integration. These nonlinearities may reflect the role of unobservable transactions costs. Two specific types of models have been adopted to address these nonlinearities. The parity bounds models of Spiller and Wood
Sexton, Kling, and Carman (1991), and Baulch (1997) applied endogenous switching models which account for the multiple regimes that may result from transactions costs. In another line of research, Goodwin and Piggott (2001) used threshold autoregression models to examine market integration. Such models recognize thresholds, caused by transactions costs, that deviations must exceed before provoking equilibrating price adjustments which lead to market integration. Threshold effects occur when larger shocks (i.e., shocks above some threshold) bring about a different response than do smaller shocks. The resulting dynamic responses may involve various combinations of adjustments from alternative regimes defined by the thresholds. Goodwin and Piggott (2001) evaluated spatial price linkages for corn and soybean markets dispersed at various point in North Carolina. They also confirmed the statistical significance of thresholds and asymmetries in price linkages. They argued that processing and handling facilities may be geared toward adjustments in only one direction. As an example, they discussed transportation infrastructure, which may be suited to exporting a product but not importing. Such issues may result in asymmetric responses to market shocks.

What Can We Learn From Price-Based Models?

The preceding review of literature demonstrates that the vast majority of the studies of price transmission are based solely on price data. This reflects the fact that other variables that may be pertinent to the measure of price transmission (e.g., transactions costs) may be difficult or even impossible to measure. Many criticisms raised in the existing literature have been based upon this lack of important information and resulting ignorance of potentially important factors in empirical tests.

A significant criticism of price-based tests of spatial market linkages has involved this ignorance of transactions costs and the implications for nonlinearities in the price relationships. Barrett (page 26, 2001) recently reviewed these criticisms and argued that “...price data alone offer a fragile base for inferences about market efficiency.” He makes a persuasive case for considering “flow-based” indicators of market integration. These points are certainly valid though, as he notes, such indicators are typically difficult or even impossible to measure. However, a counter to this argument recognizes the fact that actual flows (whether
of commodity, services, etc.) are not always necessary in order for markets to be efficiently linked. Consider, for example, the case of two livestock producers located in relatively close proximity to one another. A pure flow-based measure of market integration would seem to require that a direct flow of commodity between these two producers would be necessary in order for the markets to be considered to be integrated. However, the fact that two such sellers may market their product to a common buyer could be sufficient to "efficiently" link the markets and thus form some version of "integrated" markets. Such examples are everywhere—consider two financial institutions servicing a common set of borrowers. No direct linkage in terms of a flow of funds or services is needed to discipline these institutions to keep their lending rates tightly linked.

With these criticisms in mind, one must ask the question "What can be learned about market behavior from price-based tests?" We would argue that one must view the results of any such test (and, indeed, any empirical analysis) within the framework of a wider understanding of the structure and institutions underlying the price data. For example, it is certainly the case that, as Barrett (2001) argues, nonstationarity of transactions costs may imply that cointegration-based tests of market integration may fail even if prices are tightly linked by efficient arbitrage. Such an argument is unassailable. However, we would argue that such a finding suggests additional steps for the analyst and for the user of any such inferences. An investigation of the behavior of transactions costs or reasonable proxy measures (i.e., fuel prices) would seem a natural next step in an evaluation of spatial price linkages. Such an application is presented by Bekkerman, Goodwin, and Piggott (2009), who revisit the earlier analysis of Goodwin and Piggott (2001) and consider the extent to which the threshold parameters that represent transactions costs may themselves be endogenous to other factors. They consider fuel costs and seasonality as factors that may shift transactions costs and thus result in thresholds that are non-constant or are themselves nonstationary.

The important point is an obvious one. Any conclusions about price transmission made in a vacuum regarding an understanding of the basic characteristics of the market being evaluated are questionable. This fundamental point applies not just to studies of price transmission (though it seems especially pertinent there) but rather to and empirical analysis meant to inform the researcher about some economic phenomena of interest. The old
adage that “no theory is bad theory” should perhaps be broadened to the wider view that “numbers without theory and institutional knowledge may be bad numbers.” In an age where ever-faster computers and empirical and econometric techniques are being developed at an unprecedented rate, it is easy to succumb to the temptation to apply the next latest and greatest technique to yet another set of numbers (i.e., price series) without thinking about the exact behavior and phenomenon being modeled.

This fundamental point—that the results of price transmission tests must be viewed within a framework defined by one’s understanding of the basic process being modeled—is equally applicable to tests of vertical price transmission. As the preceding discussions have noted, many different aspects of market behavior may be reflected in a common set of findings regarding farm-to-retail price transmission. For example, asymmetric adjustments may reflect the exercise of market power by processors or may reflect asymmetric adjustment or government policies that inhibit adjustment in a particular direction. Without an prior understanding of the economic phenomena being modeled, it is unclear exactly what definitive information can be gleaned from test results alone. Take, for example, the aforementioned case of asymmetric adjustment between farm and retail meat markets. What does such a finding imply? In the absence of a deeper understanding of the structure of the meat markets in question, very little beyond the conclusion that the adjustments are asymmetric. This is not to say that such information is not valuable but only that the value may not extend beyond a simple demonstration of the fact that positive price shocks elicit a response that differs from negative shocks.

In summary, the criticisms of price-based tests of spatial and vertical price transmission are well-founded but, in some cases, perhaps misplaced. It is incumbent upon any user of empirical research results to understand the institutional setting underlying the results as well as the assumptions and empirical methods used to arrive at the results. This responsibility is especially relevant to price-based evaluations since many different structures and institutions may be consistent with a particular set of findings. One should be wary of making strong conclusions regarding the factors behind a set of findings if such factors are, themselves, unknown or difficult to measure.
An Application of Nonlinear Models to U.S. Meat Prices

With the aforementioned cautions in mind, we present an example intended to demonstrate some of the more recent advances in time-series techniques used to model vertical price transmission. This analysis is intended to illustrate the techniques associated with nonlinear time-series modeling and is not intended to provide definitive evidence regarding market power, adjustment costs, or other structural phenomena that may underlie price transmission in these markets.

Monthly price data for U.S. farm, wholesale, and retail markets were collected for beef, chicken, and pork from USDA sources. In particular, selected versions of the Red Meats Yearbook and the Poultry Yearbook were used to obtain data. We utilized logarithmic transformations of all price variables in the analyses that follow. The price data were collected from January 1985 through December 2003 for beef and pork and December 2002 for chicken.

We hypothesize that structural changes and various nonlinearities may be relevant to price relationships in these markets. In such a case, standard time-series tests may be inconsistent or potentially misleading. With this in mind, we considered standard Dickey-Fuller and Phillips-Perron tests of the stationarity of the logarithmic prices. The results are presented in Table 1. The results are somewhat mixed, though in most cases the evidence favors a finding of nonstationarity. Again, it is relevant to note that these testing results may be sensitive to asymmetries and nonlinearities that are not explicitly recognized by the tests. We conducted standard Johansen cointegration tests for each commodity. The trace test statistic for cointegration are presented in Table 2. In every case, the results are consistent with one or two cointegrating vectors among the three prices.

Table 3 presents OLS estimates of the cointegrating relationship regressions. The cointegration relationships were normalized on the retail price, such that the retail prices were regressed on wholesale and farm-level prices. The results are surprising in that the coefficients on farm prices for all three of the meat commodities are negative. A similar finding was found for pork markets by Goodwin and Harper (2000). However, these results are in contrast to those obtained using weekly beef price data over the 1981-1998 period by Goodwin and Holt (1999). This may reflect structural changes that could have occurred in these
industries over the period of study. In particular, the industries have become considerably more concentrated and the chicken and pork industries have become much more dependent upon contract production and vertical integration. Differences between the beef results and those presented by Goodwin and Holt (1999) likely reflect the different time period, the use of monthly instead of weekly data, and different definitions of the prices. We re-estimated the beef model for the 1981-1998 period and obtained very similar results to those presented by Goodwin and Holt (1999). These results highlight another important modeling issue that should be addressed in any such investigation. One must give some consideration to the timing of the relationships under consideration. If one believes that adjustments to shocks take place within a year, the use of annual data may not reveal the important dynamics of interest. Likewise, some relationships may be more accurately modeled using weekly rather than monthly price data. Of course, weekly price data are often rare and thus one must balance data availability issues against modeling considerations. Having acknowledged this point, it is also important to note that a lack of data does not justify an inappropriately specified model.

Goodwin and Holt (1999) and Goodwin and Harper (2000) used nonlinear time series models to consider vertical price linkages among meat markets. Tong (1978) originally introduced nonlinear threshold time series models. Balke and Fomby (1997), noting the correspondence between error correction models representing cointegration relationships and autoregressive models of an error correction term, extended the threshold autoregressive models to a cointegration framework. Balke and Fomby (1997) also showed that standard methods for evaluating unit roots and cointegration work reasonably well when threshold cointegration is present.

Consider a standard cointegration relationship representing an economic equilibrium

\[ y_{1t} - \beta_1 y_{2t} - \beta_2 y_{3t} - \ldots - \beta_k y_{kt} = \nu_t, \quad \text{where} \quad \nu_t = \rho \nu_{t-1} + e_t. \quad (3) \]

Cointegration of the \( y_{it} \) variables depends upon the nature of the autoregressive process for

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2 To see this correspondence, consider a simple equilibrium relationship of the form \( y_t = \alpha + \beta x_t + e_t \). The extent of cointegration between \( y_t \) and \( x_t \) depends upon the autoregressive root \( \rho \) in \( e_t = \rho e_{t-1} + v_t \). As \( \rho \) approaches 1, deviations from the equilibrium become nonstationary and thus the series are not cointegrated.

3 Balke and Fomby (1997) and Enders and Granger (1998) have also shown, however, that standard tests may lack power in the presence of asymmetric adjustment.
\( \nu_t \). As \( \rho \) approaches one, deviations from the equilibrium become nonstationary and thus the \( y_{it} \) variables are not cointegrated. Balke and Fomby extend this simple framework to the case where \( \nu_t \) follows a threshold autoregression:

\[
\rho = \begin{cases} 
\rho^{(1)} & \text{if } |\nu_{t-1}| \leq c \\
\rho^{(2)} & \text{if } |\nu_{t-1}| > c,
\end{cases}
\]

where \( c \) represents the threshold which delineates alternative regimes. An equivalent vector error correction representation of the threshold model can be written as:

\[
\Delta y_t = \begin{cases} 
\sum_{i=1}^{p} \gamma_i^{(1)} \Delta y_{t-i} + \theta^{(1)} \nu_{t-1} + \epsilon_t^{(1)} & \text{if } |\nu_{t-1}| \leq c \\
\sum_{i=1}^{q} \gamma_i^{(2)} \Delta y_{t-i} + \theta^{(2)} \nu_{t-1} + \epsilon_t^{(2)} & \text{if } |\nu_{t-1}| > c,
\end{cases}
\]

where \( \epsilon_t \) is a mean zero residual. Balke and Fomby (1997) discuss a number of extensions to this framework, including models with multiple thresholds which imply multiple parametric regimes and thus allow asymmetric adjustment.

Following the general approach of Goodwin and Holt (1998) and Goodwin and Harper (2000), we applied standard and threshold vector error correction (VEC) models to the prices for beef, pork, and chicken at retail, wholesale, and farm levels. In the case of a standard threshold vector error correction model, we use standard impulse responses to evaluate the dynamic relationships the characterize price transmission among the various market levels for these three meat products. Note that these standard linear models do not allow for asymmetric responses to shocks. Likewise, the impulse responses are fully transparent with regard to the size and timing of the shocks. In light of the nonstationary nature of the price data and the error correction properties of the system of equations, shocks may elicit either transitory or permanent responses. In particular, nonstationarity implies that shocks may permanently alter the time path of variables.

Figure 1 illustrates impulse responses over the 24 month period following a one-unit (cents per pound) shock to prices. The diagrams suggest that adjustments at the retail market level to shocks tend to be smaller than corresponding adjustments at farm and

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4More generally, thresholds pertain to some delay parameter \( d \) in adjustment to \( \nu_t \), such that \( |\nu_{t-d}| \leq c \) defines the threshold. Most applications assume a delay of \( d = 1 \).

5In the case of \( k \) thresholds, \( k + 1 \) different regimes are implied, each of which may imply its own set of dynamics for the system. Extensions to this framework include ‘band-TAR’ models in which adjustment is toward the edge of the threshold and ‘returning-drift’ TAR models which model the processes as random walks with drift toward the thresholds.
wholesale market levels. In particular, the three left-hand side diagrams illustrate retail price responses to shocks to each of the market levels. The responses are relatively modest, especially in the case of shocks to wholesale and farm level markets, where almost no response is discernable. In contrast, responses of farm-level prices to shocks at the various market levels are more substantial. It is interesting to note that positive retail price shocks tend to correspond to negative farm price responses for beef and pork. As we have noted, such a response, though puzzling, is consistent with the cointegrating regression estimates and with the results obtained in other research (e.g., Goodwin and Harper (2000)).

We next consider a nonlinear version of the vector error correction models. In particular, we allow for asymmetric responses and threshold behavior by adopting the threshold VEC models that were introduced by Balke and Fomby (1997). Our particular model allows for two thresholds which define three regimes. We constrain our grid search for thresholds to ensure that one regime corresponds to negative shocks to equilibrium (by concentrating our search from across negative residuals from the cointegrating regression) and another regime that corresponds to positive deviations from equilibrium. The third regime is defined for cointegration residual values that fall between the thresholds. This particular specification corresponds to a vector error correction model of the form:

\[ \Delta y_t = \begin{cases} 
\sum_{i=1}^{p} \gamma_i^{(1)} \Delta y_{t-i} + \theta^{(1)} \nu_{t-1} + \epsilon_t^{(1)} & \text{if } \nu_{t-1} \leq c_1 \\
\sum_{i=1}^{q} \gamma_i^{(2)} \Delta y_{t-i} + \theta^{(2)} \nu_{t-1} + \epsilon_t^{(2)} & \text{if } c_1 < \nu_{t-1} \leq c_2, \\
\sum_{i=1}^{q} \gamma_i^{(3)} \Delta y_{t-i} + \theta^{(3)} \nu_{t-1} + \epsilon_t^{(3)} & \text{if } \nu_{t-1} > c_2, 
\end{cases} \tag{6} \]

In contrast to the linear model case, the response to a shock is dependent upon the history of the series and the possibility of asymmetric responses implies that the size and sign of the shock will influence the nature of the response. Consequently, there are many different possible impulse response functions. We chose to evaluate the impulse responses at the final observation in our data and considered one-unit positive and negative shocks. We adopt the nonlinear impulse response function approach of Potter and Koop, Pesaran, and Potter, which defines responses (denoted \( I_{t+k} \)) on the basis of observed data \( (z_t, z_{t-1}, \ldots) \) and a shock \( (\nu) \) as:

\[ I_{t+k}(v, Z_t, Z_{t-1}, \ldots) = E[Z_{t+k} | Z_t = z_t + v, Z_{t-1} = z_{t-1}, \ldots] - E[Z_{t+k} | Z_t = z_t, Z_{t-1} = z_{t-1}, \ldots]. \tag{7} \]
Figures 2-4 present the nonlinear asymmetric threshold impulse responses for beef, pork, and chicken, respectively. While the impulse responses are similar to the linear model results presented in Figure 1, several differences are notable. First, responses to exogenous shocks tend to be more modest in retail markets than those experienced at wholesale and farm levels. The nonlinear models tend to imply a greater degree of reaction to exogenous shocks than was the case for the linear models. Short-run reactions often involve a degree of volatility which may take 12 or more months to die out. Finally, the results imply the presence of substantial asymmetries in the adjustments to positive and negative shocks. An interesting result applies to retail price adjustments to farm and wholesale level shocks. In every case, positive farm-level price shocks are passed along to retail level prices. However, negative farm-level price shocks tend to have very little effect on retail level prices. Such asymmetric adjustment is often revealed and has been an issue of concern to observers of the industry. The results also suggest that farm-level prices do not tend to respond to shocks in retail markets. In almost every case where adjustments occur in response to market shocks, the adjustments are involve permanent changes in prices. This reflects the nonstationary nature of the price data and the fact that shocks tend to evoke permanent changes.

More recent research has focused on nonlinear models that provide even greater flexibility in terms of the degree of structure imposed on the adjustment process. Mancuso, Goodwin, and Grennes (2003) considered nonparametric (local linear) regressions in nonlinear models of real interest parity conditions. In a similar line of research, Baghli (2005) considered polynomial expansions and nonparametric regression models relating the error correction terms to adjustments in the VEC model variables.

Baghli (2005) notes the “curse of dimensionality” problem that characterizes multivariate nonparametric regression problems and suggests a simplification to the basic VEC model that allows one to overcome this problem. In particular, he considers a standard VEC model similar to equation 5 above (absent thresholds) under the assumption that

\[ E(\epsilon_t|\nu_{t-1} = \nu_t, \Delta P_t = 0) = 0. \] (8)

This assumption essentially wipes out any short-run dynamics and instead focuses on the long-run response of \( \Delta P \). This, in turn, implies a nonlinear error-correction process that is
characterized by
\[ E(\Delta P^i_t | \nu_{t-1} = \nu_t, \Delta P^j_t = 0) = F(z_{t-1}). \] (9)

We estimated Nadaraya-Watson kernel regression estimates of equation 9 for each of the three market level price adjustments for the three meat commodities. The Nadaraya-Watson estimator is given by
\[ F(z_{t-1}) = \frac{(hT)^{-1} \sum_{t=2}^{T} \Delta P_t K(\frac{z - z_{t-1}}{h})}{(hT)^{-1} \sum_{t=2}^{T} K(\frac{z - z_{t-1}}{h})}, \] (10)
where \( K() \) is a univariate kernel function and \( h \) is a bandwidth parameter. We use a normal kernel and the Silverman “rule of thumb” bandwidth parameter.

Figure 5 illustrates the resulting nonparametric error-correction processes. The estimated regressions suggest even richer patterns of nonlinear adjustment. The results generally conform to expectations based upon the cointegrating regression estimates in that the responses tend to “correct” the departures from equilibrium implied by the lagged error term. For example, this is reflected in the negative slope of the retail price adjustments to departures from equilibrium.

In short, the nonparametric regressions suggest richer dynamics than what may be captured by simple VEC models, even when such models include thresholds to capture nonlinearities. Interpretation of the dynamics implied by these error correction processes is a topic for future research. In particular, a range of impulse responses would seem to be implied by these responses and thus greater attention to the particular patterns of adjustment implied by the nonparametric regressions is merited.

**Conclusions**

We have attempted to provide an overview of the current state of research addressing vertical and spatial price transmission in meat markets. A substantial literature has addressed this topic and the results have been used to infer a number of conclusions regarding the behavior of market linkages across space and across different levels of the marketing chain.

We have also noted the significant criticisms that have been directed toward this general line of inquiry. A central question is fundamental to the interpretation of any empirical research results addressing questions of price transmission—“What can be learned about
the behavior and performance of the markets from such tests?” We argue here that the many criticisms of price-based tests of spatial and vertical market linkages, while valid, are sometimes misplaced because they assume that such tests are conducted without regard to the overall institutional and structural characteristics of the market and the economic conditions being evaluated. Price-based tests of spatial market linkages are less problematic in that they address a rather simple question—“To what extent do localized price shocks tend to affect other regional markets?” It is certainly the case that a variety of limitations apply to the tests often used to assess market integration. Users of any such test should be aware of these limitations and condition their interpretation of results on these caveats.

Price-based studies of vertical price transmission may be more troubling in that there is a wide range of structural and institutional explanations that may underlie any particular set of findings. For example, a finding of asymmetric price adjustments could imply a number of different things about the market—from nonlinear adjustment costs to the exercise of market power. Absent any knowledge of the structure of the market and the institutional details underlying market linkages, price-based studies of vertical price linkages may not be very informative. Thus, we would challenge applied researchers to use care in forming conclusions about market structure and behavior on the basis of price transmission studies alone.

We conclude with an empirical example of recent nonlinear modeling techniques that have been applied to studies of price transmission. We apply these techniques to a consideration of vertical price transmission among farm, wholesale, and retail markets for beef, pork, and chicken. Monthly data dating from 1985 are used to evaluate dynamic patterns of adjustment. Our results are consistent with those revealed in other studies of this form. Significant differences in the degree of adjustment to exogenous shocks at individual market levels are revealed. In general, retail markets tend to adjust less to shocks than is the case for wholesale and farm markets. The results also reveal patterns of asymmetric adjustment in several cases. We also introduce a fully nonlinear regression model of the error correction process and provide suggestions for future research in this area.
Table 1. Unit Root Tests

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Table 2. Johansen Cointegration Tests

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Table 3. Cointegrating Regression Estimates (Normalized on Retail Price)

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<th>Estimate</th>
<th>Standard Error</th>
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Figure 1: Standard VEC Model Impulse Responses for Meat Prices

(a) Beef Retail
(b) Beef Wholesale
(c) Beef Farm
(d) Pork Retail
(e) Pork Wholesale
(f) Pork Farm
(g) Chicken Retail
(h) Chicken Wholesale
(i) Chicken Farm
Figure 2: Asymmetric Threshold VEC Model Impulse Responses for Beef Prices

(a) Retail to Retail
(b) Retail to Wholesale
(c) Retail to Farm
(d) Wholesale to Retail
(e) Wholesale to Wholesale
(f) Wholesale to Farm
(g) Farm to Retail
(h) Farm to Wholesale
(i) Farm to Farm
Figure 3: Asymmetric Threshold VEC Model Impulse Responses for Pork Prices
Figure 4: Asymmetric Threshold VEC Model Impulse Responses for Chicken Prices
Figure 5: Nadaraya-Watson Nonparametric Error Correction Models
References


