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Abstract

We study price discovery in the U.S. fed cattle market, examining the interaction among weekly live cattle futures, negotiated cash fed cattle, and boxed beef cutout prices. Extensive testing and innovation accounting based on directed acyclic graphs of error-correction residuals indicates that the futures price continues as the dominant source of information in the fed cattle market. While the cash cattle price has a strong predictive influence on the boxed beef price, the boxed beef price plays only a marginal role in price discovery.

Keywords: Price discovery, U.S. fed cattle market, cointegration, directed acyclic graphs, innovation accounting.

Introduction

In recent decades the U.S. cattle industry has experienced added vertical integration and concentration, raising concerns about thin cash markets and the reliability of market information. These structural trends have heightened the debate on economic and policy issues related to price discovery in the cattle markets (Koontz and Ward 2011). Effective price discovery is critical as it facilitates pricing quantity and quality of a commodity at a specified time and place. Recently, there have been concerns that the decline in the volume of negotiated fed cattle cash market transactions could reduce the representativeness of these prices, lead to market manipulation and other distortions, and lower the quality of the pricing process in the marketing chain.

In an effort to improve price transparency in livestock markets, Congress passed the Livestock Mandatory Reporting Act (LMRA). This Act directed the United States Department of Agriculture (USDA)–Agricultural Marketing Service (AMS) to implement a mandatory system of price reporting for livestock and meat products. Research suggests that there have been improvements in price transparency (Ward 2006) since the implementation of the LMRA in April 2001. Recently, Lee et. al. (2012) report that causality and cointegration between the negotiated cash trade prices and other alternative marketing arrangement (AMA) prices for fed cattle have not been affected by the thin negotiated cash market for fed cattle. However, concerns continue to increase as more negotiated cash price transactions are replaced by contracts, marketing agreements, alliances, formula-pricing arrangements, and packer-owned cattle. In 1988 cash market transactions in which buyers and sellers negotiated the price and other terms of the transaction accounted for 79.5% of packer procurement. By 2009-2010 these negotiated transactions had declined to 34.1% of packer procurement (Ward, 2010). The threat to price transparency exists as packers and producers continue to choose other non-negotiated cash methods to transfer cattle ownership. The market may be forced to look at new alternate sources of information to perform its price discovery function.

While the fed cattle cash markets have been studied extensively after 2001, there has been

less recent focus on the Chicago Mercantile Exchange (CME) live cattle futures contract and on negotiated boxed beef prices as tools for price discovery. Prior research finds that cash and futures prices are well linked and indicates that the futures price leads the cash price movements (Oellermann et. al. 1985; Koontz, Garcia, and Hudson 1990; Yang et. al. 2002). Lee, Ward, and Brorsen (2012), report that negotiated cash prices lead all AMA prices except forward contracts, which according to Koontz, Garcia, and Hudson (1990) are closely tied to futures prices. Futures contracts are traded daily and the large volumes allow information to be reflected rapidly in the market. Several studies (Garcia et. al. 1988; McKenzie and Holt 2002) have found the live cattle futures markets to be efficient in incorporating new supply and demand information quickly into prices. In addition, the CME live cattle futures contract has undergone many changes in an effort to represent the cash market more closely and thereby reduce basis risks in hedging. From a different perspective, the increased use of non-negotiated procurement methods may have a direct impact on the role of the futures market in the price discovery process. It is also uncertain whether the thinly traded negotiated cash market has affected futures market price discovery. While we anticipate that the futures price has maintained its critical role in price discovery, it is unclear whether recent developments such as increased financialization, changes in the composition of traders, and the move to electronic trading have influenced the transmission of futures prices to the cash market.

The wholesale boxed beef cutout value, which reflects the price that packers receive for beef products, is also appealing as an alternate source of price discovery (Schroeder and Mintert 2000). Many researchers have investigated price transmission in the U.S. fed cattle markets from farm level to the wholesale level. Early work by Boyd and Brorsen (1985) and Shroeder and Hayenga (1987) indicate that the farm price of beef unidirectionally causes the wholesale beef price, as the changes in farm price lead wholesale prices by more than a week. Marsh and Brester (1989) indicate that boxed beef prices and fed cattle prices are closely related and may respond jointly to changes in economic information. Hahn (1990) differs from other contemporary researchers and rules out farm centered price discovery in short run beef markets, pointing to wholesale and retail beef markets as other potential sources of price discovery. Using more recent data, Goodwin and Holt (1999) find that information flows up the marketing channel from farm to wholesale level and that farm markets show adjustments to shocks from the wholesale markets, reflecting the enhanced price transmission between markets over time. Nonetheless, the market environment in which these studies were performed is different from the current one. In a recent review of literature, (Koontz and Ward 2011) cite unpublished work (Koontz 2007), suggesting that post LMRA, a change in the boxed beef cutout value leads to a larger change in the fed cattle price and faster adjustment to the boxed beef price. This raises an important question on the role of boxed beef prices in the price discovery process and its use as a base price for pricing cattle. Schroeder and Mintert (2000) suggest that the difference between boxed beef wholesale prices and cash fed cattle prices may vary depending on processing margins, making its use difficult for formula pricing. Research by Cai, Stiegert, and Koontz (2011a) indicates that packers switch between cooperative and non-cooperative regimes of pricing fed cattle leading to variations in the marketing margin. In related work Cai, Stiegert, and Koontz (2011b) find a decreased duration of non-cooperative regimes, reflecting more market power in the fed cattle market

post LMRA. While several challenges exist, researchers have not ruled out the use of boxed beef prices in establishing base prices for contracts. The role of boxed beef prices in the price discovery process, and its interaction with futures and cash fed cattle prices, is uncertain and warrants attention.

Most studies that examine price discovery in the cattle markets were performed in a market environment that differs greatly from the current environment. While the link among the negotiated cash fed cattle prices and other AMA prices has been established (Lee, Ward, and Brorsen 2012), there is less clarity on the role of futures and boxed beef prices as alternative sources of price discovery. The interactions among these prices are assessed using time series procedures which involve testing for non-stationarity, structural breaks, and then employing vector autoregressions, or cointegration and vector error-correction models. The Garbade and Silber (1983) approach is used to estimate the proportional contribution of each of these markets in the price discovery process. The short-run dynamics are also based on Granger type causality tests using the Toda and Yamamoto (1995) lag augmented procedure. The lead-lag relationships that exist are identified, and in the presence of cointegration weak exogeneity testing is applied. We also use directed acyclic graphs (DAG) on the residuals of the estimated models to assess the contemporaneous relationships that may exist among the markets. Finally, forecast error variance decompositions and impulse response analysis summarize the short-run dynamic linkages among the markets. We perform the analysis for the full sample (5/4/2001 through 8/3/2012), and for sub-periods before and after the financial market crash in October 2008. The findings of this study provide insight into the behavior of these markets, the price discovery process, and how it has evolved in the face of changing market environments post LMRA.

Our paper is organized as follows. The first section outlines the data and the empirical procedures used in the study. In the next section we present the empirical results and its economic significance. Finally our conclusions are presented.

Data and Empirical Procedures

Data

The data used in the analysis come from multiple sources. We use weekly average futures settlement prices for the nearby CME live cattle futures contract from the Commodity Research Bureau (CRB) database. For the cash fed cattle price, we use the 5 Area Weekly Weighted Average Direct Slaughter Cattle report (LM_CT150) for 35 to 65% Choice live steers. We also use the weekly average cutout value from the National Weekly Boxed Beef Cutout and Boxed Beef Cuts-Negotiated Sales report (LM_XB459), with the Choice: 600-900 lbs. prices weighted 55% and the Select: 600-900 lbs. prices weighted 45% to match the par quality grade specification for the CME live cattle futures contract. To more closely match the futures par delivery specification, which is on live animal basis, we adjust the actual boxed beef cutout value by the expected average hot yield of 63% (CME Rulebook, Chapter 101 Live Cattle Futures) and use this adjusted value as our boxed beef price. Both cash fed cattle and boxed beef prices are downloaded from the Livestock Marketing Information Center (LMIC).

All price series are expressed in cents/lbs., and are converted into their natural logarithms consistent with procedures used in previous research. Figure 1 presents the futures price, cash fed cattle price, and boxed beef price for the 5/4/2001-8/3/2012 period used in the analysis.

Unit Root Testing

We conduct unit root tests to identify the order of integration in futures, cash fed cattle, and boxed beef prices. Augmented Dickey Fuller (ADF) type tests are performed with the number of lags chosen using the Schwarz Bayesian Information Criterion (SBIC). We use multiple specifications for the test, including a model with a trend component to account for any possible deterministic trend in the price series. ADF-GLS tests (Elliot, Rothenberg, and Stock 1996) are also used, which are ADF tests on GLS de-trended data. Ng and Perron (1995, 2001) show that the use of too short lag lengths lowers power for ADF tests and makes DF-GLS tests oversized. They recommend a general-to-specific procedure for ADF tests and a modified Akaike information criterion (MAIC) for DF-GLS tests. In addition, the Zivot-Andrews (ZA) test which allows for one possible shift in the mean, trend or both mean and trend is also used (Zivot and Andrews 1992). The ZA test has a null hypothesis of a unit root process with drift that excludes exogenous structural change. The alternative hypothesis is a trend stationary process that allows for a one time break in the level, the trend or both depending on the model variant. All prices are tested for stationarity in levels as well as in first differences. This analysis is done for the full sample of 587 observations spanning twelve years.

The Garbade and Silber Measure of Price Discovery

Garbade and Silber (1983) use an econometric model to measure the proportional contribution of each market in the price discovery process. The Garbade and Silber procedure is specified for storable commodities where the variables included in the model are the cash price for a commodity and its cash equivalent futures price (futures price discounted for interest costs). For non-storable commodities, prior research (Oellerman et.al. 1989 (feeder cattle); Bessler and Covey 1991(live cattle); Schroeder and Goodwin 1991 (live hogs)) has examined the relationship between futures settlement price and the cash price assuming an equilibrium each day. We apply this bivariate model in a pairwise context to futures, cash fed cattle, and boxed beef prices that are closely interrelated. The model of price behavior is specified as follows

$$\begin{bmatrix} X_t \\ Y_t \end{bmatrix} = \begin{bmatrix} \alpha_x \\ \alpha_y \end{bmatrix} \begin{bmatrix} 1 - \beta_x & \beta_x \\ \beta_y & 1 - \beta_y \end{bmatrix} \begin{bmatrix} X_{t-1} \\ Y_{t-1} \end{bmatrix} + \begin{bmatrix} U_t^x \\ U_t^y \end{bmatrix} \quad (1).$$

In equation (1) above, X_t and Y_t are the logarithm of prices in each market respectively on day t . The coefficients β_x and β_y reflect the effect of a one period lagged price in one market on the current price in the other market. Equation (1) can be algebraically rearranged and estimated using OLS, requiring only that the first difference of each price series and the cross difference between the series lagged one period be stationary.¹ In this

specification, the market that initiates the change (has the lowest coefficient β_x or β_y) is most important in price discovery. Since these markets are closely interrelated, $\beta_x \geq 0$ and $\beta_y \geq 0$ seems reasonable and the ratio $\beta_x/(\beta_x + \beta_y)$, designated here as θ , is used to measure the proportional contribution of market Y in the price discovery process. The value of θ is theoretically bound between zero and one. If $\beta_y = 0$, then $\theta = 1$, and market X is a pure satellite of market Y . On the other hand, if $\beta_x = 0$, then $\theta = 0$, which implies that market Y is a satellite of X , and market Y reacts to market X . A θ value of .5 indicates equal contribution to price discovery from both markets. While the Garbade and Silber approach is valuable in deriving economic relationships between markets, its application is limited to the bivariate framework and it assumes that an equilibrium is established each day.

Causality Testing

Granger causality tests are usually performed on VAR models to summarize the dynamic interactions that each market price has with other market prices. Toda and Yamamoto (1995) suggest that if the coefficients are from a VAR equation and if any of the variables are non-stationary (whether or not they are cointegrated) the usual Wald test statistic for this testing will not have an asymptotic Chi-Square distribution. An alternate way to deal with this is to use a procedure proposed by Toda and Yamamoto (1995) and Dolado and Lutkepohl (1996). Toda and Yamamoto (1995) showed that in integrated and cointegrated systems, the Wald test for linear restrictions on the parameters of a VAR (k) has an asymptotic distribution for the estimated VAR ($k + d_{max}$), where d_{max} is the maximum order of integration in the system. The value of k can be determined using SBIC. Suppose SBIC chooses a VAR (3), since $d_{max} = 1$, we estimate a VAR (4) model and test the coefficients of the first three lagged terms for each variable. A detailed description of Granger causality testing using the Toda and Yamamoto lag augmented procedure is available in Rambaldi and Doran (1996).

Cointegration and Error Correction Modeling

Since we are interested in the interaction among the futures price, the cash fed cattle price, and the boxed beef price, we examine the cointegration relationships among them to identify how information is transmitted. A description of the Johansen's test for cointegration in the matrix form is given below. We start with the general K^{th} order VAR model as follows

$$\Delta Y_t = D + \Pi Y_{t-1} + \sum_{i=1}^{k-1} \Gamma_i \Delta Y_{t-i} + \epsilon_t \quad (t = 1, \dots, T) \quad (2),$$

where Y_t is an $(n \times 1)$ vector to be tested for cointegration, and $\Delta Y_t = Y_t - Y_{t-1}$; D is the deterministic term which may take different forms such as a vector of zeros or non-zero constants depending on properties of the data; Π and Γ are matrices of coefficients, $\Pi = \alpha\beta'$; and k is chosen so that ϵ_t is a multivariate normal white noise process with mean zero and finite covariance matrix ($\epsilon_t \sim iid(0, \Sigma)$).

We first test whether the vector Y_t is trend stationary rather than a multivariate unit root

with drift process. Under the trend stationary hypothesis the matrix Π has full rank (k). One of Johansen's cointegration tests, the trace test, has this alternative hypothesis (Johansen and Juselius 1990; Johansen 1992). Since the Johansen's test is sensitive to the number of lags, the SBIC is used to select the lag order. The long-run pattern of price transmission is examined by testing the number of cointegration relations (r). Trace tests and λ -max tests (Johansen and Juselius 1990; Johansen 1991) test this hypothesis. The cointegrating relationships explain the long-run equilibrium in prices, facilitated by the transmission of information among markets. The rank of Π determines the number of cointegrating vectors, tested as follows

$$H(r) : \Pi = \alpha\beta' \quad (3).$$

A vector error correction model (VECM) imposing the cointegrating relationships is estimated to examine how prices adjust interactively under the constraint of the identified long-run equilibrium price relationships. The short-run dynamic pattern of price transmission can be observed from both α and $(\Gamma_i, \dots, \Gamma_{k-1})$. The α parameter defines short-run adjustments to the long-run relationship between variables, and the parameters $(\Gamma_i, \dots, \Gamma_{k-1})$ define the short-run adjustment to changes of the process. Weak exogeneity tests for each price series Y_t relative to the long-run equilibrium (Johansen and Juselius 1990; Johansen 1992) are also performed as they allow us to identify the market that dominates in price discovery in the long run. This hypothesis is framed as

$$B'\alpha = 0 \quad (4).$$

The null hypothesis is that each price does not respond to disturbances in the long-run relationship i.e., the i^{th} row of the Π matrix is zero (Johansen and Juselius 1990, 1992; Johansen 1991). In other words, we test whether the i^{th} row of α has its elements equal to zero. If any row of α equals zero, then that price does not respond to the disequilibrium among the prices.

Innovation Accounting Analysis

It is well recognized that the individual coefficients of the VECM like the standard VAR are difficult to interpret, making it challenging to explain the short-run dynamic structure. Hence, we also investigate the dynamic relationships among the series through innovation accounting, as recommended by Sims (1980) and Swanson and Granger (1997). Impulse response functions and forecast error variance decompositions are then conducted on the innovations from the VECM converted into its equivalent level VAR, to summarize the short-run dynamic linkages among various markets. The equivalent level VAR representation of the VECM with the cointegration constraints imposed yields consistent results on forecast error variance decompositions and impulse response functions (Phillips 1998). When performing innovation accounting it is important to account for the contemporaneous innovation correlation (Lutkepohl 2006; Enders 2008). VAR type analysis generally relies on a Choleski factorization to achieve a just-identified system in contemporaneous time. The main problem

with the Choleski factorization is that the direct imposition of (contemporaneous) recursive causation may not always be valid (Sims 1986; Bernanke 1986; Swanson and Granger 1997). A better approach for dealing with the contemporaneous correlation problem is the structural factorization approach followed by Bernanke (1986), and Sims (1986) allowing for a non-recursive (contemporaneous) structure of causation.

Following Swanson and Granger (1997), a data-determined approach—the DAG technique—is used to explore contemporaneous causal structure of innovations, which also provides information on the instantaneous price discovery process. DAG techniques have been used by many studies (Bessler, Yang, and Wongcharupan 2003; Babula et. al. 2004; Haigh and Bessler 2004; Yang and Bessler 2004; Wang and Bessler 2006; and Bryant et. al. 2009) to explore the contemporaneous relationships among variables. The observed residuals (innovations) from the VECM are used as the input in the directed graph algorithm (PC and GES). A directed graph is an assignment of causal flows among a set of variables based on their observed correlations and partial correlations. Each pair of variable has a characteristic edge relationship that represents the causal relationship between them. Since edges or orientations that are robust across different algorithms provide higher confidence levels, we use both the PC algorithm and the GES algorithm (TETRAD IV) to study causal behavior. The PC algorithm is based on the standard Neyman-Pearson hypothesis testing. Beginning with a complete undirected graph, it removes edges based on zero correlations or partial correlations. Conversely, GES begins with a complete independence graph and adds edges (or reverses their orientation) based on score functions. A more detailed description of the PC and GES algorithms and DAG analysis can be found in Wang and Bessler (2006). The DAG combined with prior knowledge about the markets allows us to order variables in our model for further innovation analysis. Once the recursive order is identified and its structure imposed on the VECM, the model is converted to its equivalent level VAR form and impulse response functions and forecast error variance decompositions are generated.

Empirical Results

Table 1 presents the results of unit-root tests. Both futures and boxed beef prices are trend stationary whereas cash fed cattle price is non-stationary. The first differences of all three price series are stationary. The ZA test is significant at the .05 level for the futures price, indicating that futures price is stationary. The test indicates a break in level and trend on 10/3/2008, which coincides with the financial crash of October 2008. For cash fed cattle and boxed beef prices, the ZA tests with a single break in both level and trend are not significant at the .05 level, indicating no structural break and non-stationarity. In the wake of recent financialization in the futures markets, it is not surprising that events in the financial markets have a greater impact on the futures markets. A visual inspection of Figure 1 reveals that the markets move together closely and the relationships among the markets may not have varied substantially over time. Nonetheless, based on the structural change in the futures price series identified by the ZA test, we break the data into sub-periods and assess how price discovery has evolved over time in addition to assessing the relationships for the entire period. The data were split into two parts, one before the financial crash and the other after the financial crash. We drop the observation on the week of the crash (10/3/2008) from the

analysis.²

The Garbade and Silber (1983) price discovery approach is used to explore the lead-lag relationships between the markets. Unit root tests on the difference between the one period lagged price combinations for all three series indicate that they are stationary. The first differences of individual price series are also stationary. Hence, the Garbade and Silber model can be consistently estimated using the Newey-West estimator. The estimated coefficients β_x , β_y , and the value of θ in the futures and cash fed cattle, futures and boxed beef, and cash fed cattle and boxed beef relationships for the full sample (Panel A), sub-period 1 (Panel B), and sub-period 2 (Panel C) are presented in Table 2. For Panel A, the β_x coefficients are positive and significant at the .01 level. This indicates that the one period lagged futures price can explain both cash fed cattle and boxed beef prices and that the one period lagged cash fed cattle price can explain the boxed beef price. The coefficients for β_y in the relationships between futures and boxed beef price, and cash fed cattle and boxed beef price are not significant even at the .10 level. This shows that there is very little feedback of information in the reverse direction i.e., from the boxed beef market to the futures market and from the boxed beef market to the cash fed cattle market. Moreover, the θ values from Panel A are close to one, indicating that the live cattle futures price dominates the cash fed cattle price and boxed beef price and that the cash fed cattle price dominates the boxed beef price in incorporating new information.³ The results from Panels B and C are similar to those in the full sample. The θ values are also close to one for all bivariate relationships in all samples. The tests indicate that the futures market completely dominates the cash fed cattle market in price discovery and the boxed beef market is a pure satellite of the futures market and the cash fed cattle market. While we are able to establish the relationships between the markets using the Garbade and Silber approach, the bivariate framework limits our ability to reveal the complete interaction among all three markets.

We next examine the Granger causality among the price series. Since the cash fed cattle prices are non-stationary and the other two prices are stationary, the usual Wald test statistic for Granger causality testing may not have an asymptotic Chi-Square distribution (Sims, Stock, and Watson 1990; Toda and Phillips 1993a, 1993b). Hence, the Granger causality tests are performed on a VAR (4) model using the Toda and Yamamoto lag augmented approach. These results are presented in Table 3. Hamilton (1994) recommends that “Granger causality” be interpreted as whether one variable helps forecast another variable rather than one variable causes another. For the full sample, the coefficients for cash fed cattle and boxed beef prices in the futures equation are significant at the .05 and .10 level respectively i.e., the lagged values of both cash fed cattle and boxed beef prices help forecast the futures price. In the case of the cash fed cattle equation, both futures and the boxed beef price are found to be significant at the .01 and .05 level. For the boxed beef equation, the futures price is significant at the .05 level and the cash fed cattle price is significant at the .01 level. The results obtained from sub-period 1 are consistent with the full sample i.e., bidirectional causality could not be rejected across the markets for sub-period 1, revealing the interrelationship between the markets, and their ability to anticipate (forecast) and incorporate information from other markets. In contrast, for the post-crash period, the futures price and the boxed beef price are found to be detached in the short run. The boxed beef price does not help forecast the futures price or the cash price at the .10 significance level. Moreover,

the coefficient for the lagged values of the futures price in the boxed beef equation is not significant at the .10 level, indicating that the futures price does not help forecast the boxed beef price in the short run during this period. While the causality testing provides insights into the statistical significance of predictive relationships, it fails to specify the structure of pricing process, does not identify the magnitudes of the responses among prices nor the degree to which predictive errors among the series are related.

To further assess the price discovery process in the fed cattle market, the cointegration relationships among the futures, cash fed cattle, and boxed beef prices are evaluated. The Johansen's test is based on a data determined structure and the SBIC is used to choose the optimum number of lagged variables. Figure 1 indicates that there may be a trend (drift) in the level series which should be accounted for in the model. The maximum likelihood estimation procedure by Johansen and Juselius (1990) is performed with only a constant term to account for the trend (drift) in level series and the lags of variables chosen by SBIC. The results from the analysis of the full sample and the two sub periods are presented in Table 4. For the full sample (Panel A), both the trace test and the λ -max test indicates that there are two cointegrating vectors at the .10, .05, and .01 levels of significance. For the two sub-periods, the Johansen's test indicates a rank of two at the .10 and .05 significance levels for the trace test, and at all levels for the λ -max test. The results of the trace test indicate a multivariate unit root with drift process for the full period and the two sub-periods. The SBIC chooses a model with three lags for the full period and sub-period 1, and two lags for sub-period 2.⁴

A VECM is then estimated for the full period (Panel A), sub-period 1 (Panel B), and sub-period 2 (Panel C) imposing two cointegrating vectors.⁵ The results of weak exogeneity testing are summarized in Table 5. For the full sample, we fail to reject the null of weak exogeneity for futures at the .10 significance level ($\chi_2 = 1.8$) and we reject the null hypothesis of weak exogeneity for both cash fed cattle ($\chi_2 = 21.6$) and boxed beef ($\chi_2 = 42.2$) prices at the .01 significance level. The results from Panel B are similar to those from the full sample. The results indicate that the futures price does not make short-run adjustments to the long-run disequilibrium. Weak exogeneity of futures price is not surprising, owing to faster speed and accuracy in processing transactions and lower transaction costs, allowing information to be quickly incorporated in the futures market. This result is consistent with prior findings of Oellerman, Brorsen, and Farris (1985) and Yang, Bessler, and Leatham (2001) who indicate that the futures market dominates price discovery. For Panel C, weak exogeneity of the futures market is not rejected at the .01 and .05 levels ($\chi_2 = 5.5$), but is rejected at the .10 level. The change is likely attributable to the sharp drop in futures prices during the financial crash which was not reflected in the other two prices. It appears that the futures price subsequently rebounded to the longer-term relationship and resulted in the rejection.⁶ The weak exogeneity of cash fed cattle and boxed beef markets are rejected at the 0.01 level, indicating that they strongly adjust to the disequilibrium.

Innovation accounting using forecast error variance decompositions and impulse response functions are employed to reveal the magnitude of short-run linkages among markets. Enders (2008) and Luthkepohl (2006) note that the ordering of the variables can influence forecast error variance decompositions and impulse response functions particularly if the correlations between the innovations exceed 0.20. Various procedures exist to identify an appropriate

structure for analysis. Here, the DAG technique is used to find and assign the causal ordering of prices. The innovations from the VECM are used to generate the contemporaneous innovation correlation matrix (Σ). Equation (5) below represents the lower triangular elements of the correlation matrix on innovations for the full sample, represented in order, futures, cash fed cattle, and boxed beef in both rows and columns

$$\Sigma = \begin{bmatrix} 1.0 & 0.0 & 0.0 \\ 0.68 & 1.0 & 0.0 \\ 0.29 & 0.51 & 1.0 \end{bmatrix} \quad (5).$$

The correlation between futures and cash fed cattle price (0.68) is the highest followed by cash fed cattle and boxed beef price (0.51). The correlation between futures and boxed beef price (0.29) is the lowest among all three correlations. All correlations are found to be significant at the .01 significance level. The above contemporaneous correlation matrix (Σ) is the initial step of DAG analysis using TETRAD IV.

We use both PC and GES algorithms on the VECM innovations. Figure 2, Panel A represents the causal pattern indicated by the PC algorithm. Analysis using the PC algorithm with a pre-specified α of 0.01 indicates a direction of causality from boxed beef \rightarrow cash fed cattle \rightarrow futures, with -1.58 as the loss metric score. On the other hand, the direction of causality changes to futures \rightarrow cash fed cattle \rightarrow boxed beef when using the GES algorithm (see Figure 2, Panel B). The same variables enter the model for both algorithms and the loss metric scores are exactly identical. The GES causal ordering futures \rightarrow cash fed cattle \rightarrow boxed beef is chosen for the innovation accounting as it consistent with prior research, and corresponds more closely to the workings of the market.⁷ The results for both sub-periods are consistent with the full sample and are not reported.

The structural factorization of Bernanke (1986) and Sims (1986) is employed to assign the causal ordering. The innovation vector from the estimated equivalent level VAR model can be written as $A\epsilon_t = v_t$ where A is a (3×3) matrix and v_t is a vector of orthogonal shocks. The DAG obtained from our method is used to place zeros on the A matrix and gives the following representation on innovations in contemporaneous time⁸

$$\Sigma = \begin{bmatrix} 1.0 & 0.0 & 0.0 \\ a_{21} & 1.0 & 0.0 \\ a_{31} & a_{32} & 1.0 \end{bmatrix} \times \begin{bmatrix} v_{f,t} \\ v_{c,t} \\ v_{b,t} \end{bmatrix} = \begin{bmatrix} \epsilon_{f,t} \\ \epsilon_{c,t} \\ \epsilon_{b,t} \end{bmatrix} \quad (6),$$

where $\epsilon_{i,t}$ terms are the observed innovations from VECM, $v_{i,t}$ are the orthogonal innovations from each market, and $i = f$ (futures), c (cash fed cattle), b (boxed beef) respectively.

The 15-week forecast error variance decompositions for the full sample are reported in table 6. The forecast error variance decompositions identify the proportion of the movement in a particular sequence due to its “own” shocks versus shocks to other variables (Enders, 2008). Enders (2008) points out that it is common for a variable to explain almost all of its own forecast error variance at short horizons and smaller proportions at longer horizons. The real test in terms of market dominance lies at longer horizons. The futures price contributes 100% of its own forecast error variance at the first-week horizon and 98% of its own forecast

error variance at the longer 15-week horizon. This implies that the futures market is highly exogenous; the futures price evolves independently of the forecast error shocks from the other two markets. In the case of the cash fed cattle market, the forecast error in the first-week horizon is partly explained by its own innovations (54.5%) and partly by the futures market (45.5%). However, at longer horizons the futures market dominates. The cash fed cattle market also operates independently of the boxed beef market shocks at all horizons. The forecast errors for the boxed beef market in the first week horizon (73.3%) are largely attributable to its own innovations followed by the cash fed cattle market (18.4%) and the futures market (8.3%). In longer horizons the futures market dominates both the boxed beef and cash markets. In contrast, the boxed beef market is found to be a weak predictor of the futures market as well as the cash fed cattle market. The results are also found to be consistent across both sub-periods and not reported.

The impulse response functions are plotted with 95% bootstrapped confidence intervals (1000 runs) for the 15-week horizon and presented in Figure 3. Impulse response functions allow us to trace the time path of the various shocks on the three prices included in the VAR system. The causal ordering consistent with the DAG analysis isolates the impulse responses from the effect of contemporaneous correlations and imposes a recursive structure for the dynamic structural equation model. The responses obtained are consistent with the results observed from forecast error variance decompositions. The responses to a 1% shock in the futures market are presented in the first column, followed by responses to shocks in the cash fed cattle market and the boxed beef market. The futures, cash fed cattle, and boxed beef markets respond significantly to the shocks from the futures markets i.e., a unit change in innovations from the futures market produces responses that are significantly different from zero at the .05 level in the other markets at all horizons. A unit shock in the futures market shock influences the futures, cash fed cattle, and boxed beef market similarly, with an immediate positive effect in the first-week horizon. The shocks from the cash fed cattle market influences the futures market in the second and third horizon, but the magnitude of these effects is very small. A unit shock in the cash fed cattle market also causes substantial responses in its own market as well as in the boxed beef market. The boxed beef market shocks do not cause any significant changes in the futures market or the cash fed cattle market at any horizon. In contrast, substantial responses are caused in the boxed beef market from impulses in the other two markets at all horizons. The results are consistent across both sub-periods analyzed and are not reported. Both impulse response functions and forecast error variance decompositions confirm the dominant status of the futures market. It can be inferred that the cash fed cattle prices lead the boxed beef price, and that the boxed beef market is not a price leader in the U.S. fed cattle market.⁹

Conclusions

We investigate price discovery in the U.S. fed cattle market by examining the interactions among the live cattle futures price, the cash price for fed cattle, and the boxed beef price. Weekly average futures prices from the CME live cattle contract, weekly negotiated 5-market cash prices for fed steers, and boxed beef cutout values adjusted by average hot yield are used to assess price discovery in the 2001-2012 post-LMRA period.

For the full sample, the bivariate Garbade and Silber (1983) approach identifies that the futures market dominates cash fed cattle and boxed beef markets in price discovery, and the cash fed cattle market dominates the boxed beef market.¹⁰ The Toda and Yamamoto (1995) lag augmented approach revealed bidirectional causality among all markets, but the statistical significance of the one-period ahead predictive tests varied. Cash fed cattle prices strongly caused box beef prices for the entire sample, but the reverse did hold particularly in the post-financial crash period when the boxed beef price had no effect on the cash fed cattle price. Futures prices strongly caused cash fed cattle prices throughout the sample, but cash prices causing futures prices was less significant. Causality between boxed beef and futures prices was least well established, particularly in the post-financial crash period where neither seemed to affect the other. On balance, consistent with Garbade and Silber findings, boxed beef seems to be playing a marginal role in the pricing process, losing its importance in the later part of the sample. The estimated cointegrating relationships identify two long-run vectors for the three markets. The dominance of the futures price in the long-run relationships is supported using weak exogeneity tests which indicate that the futures price does not adjust to long-run disequilibrium. In contrast, cash fed cattle and boxed beef prices are not weakly exogenous and adjust back to long-run disequilibrium.

Innovation accounting based on DAG contemporaneous causality indicates an ordering from futures to cash fed cattle to boxed beef prices (futures \rightarrow cash fed cattle \rightarrow boxed beef), and strengthened the relationships established earlier. Forecast error variance decompositions reveal that the futures market is a strongly exogenous market, and plays a dominant role in the cash and boxed beef decompositions at distant horizons. Shocks to the future price innovations also exhibit a relatively strong and lasting effect in the other markets. In contrast, shocks to the boxed beef innovations do not influence either futures or cash prices, and boxed beef forecast errors contribute practically nothing to the error variance in other markets. While cash prices do not affect futures prices, their effect on boxed beef prices both in terms of the error decomposition and impulse response is much larger than the boxed beef effect on the cash price.

The findings support earlier research that identified the dominance of the futures prices in the live cattle price discovery process. In light of Lee, Ward, and Brorsen's (2012) discovery that cash fed cattle negotiated prices are cointegrated with a number of other reported AMA prices, our results suggest that the cash fed cattle prices and the futures prices are well connected. While we do find that the boxed beef price enters into the long-run cointegrating relationships, its limited importance in short-run dynamics and price discovery was somewhat unexpected. Marsh and Brester (1989) indicate that boxed beef and fed cattle prices are closely related and respond jointly to changes in economic information, leading to small variability in their price differences. Also, Koontz and Ward (2011) citing an unpublished work (Koontz 2007) suggest that changes in boxed beef values post LMRA lead to large changes in fed cattle prices, but with more uncertainty in the relationship. Our findings appear to be more consistent with Schroeder and Mintert (2000) who mention that the difference between boxed beef prices and cash fed cattle prices may vary depending on processing margins. Koontz and his colleagues (Cai, Stiegert, and Koontz 2011a; Cai, Stiegert, and Koontz 2011b) in other work also find that packer processing margins may vary between periods of competitive and oligopsonistic pricing. This seems to fit more easily with the

notion of an average relationship that exists in the long run, but which exhibits less stable short-run dynamics through time. Regardless of the source of the short-run variability, the role of boxed beef cutout value as an alternative source of information appears questionable.

Endnotes

1. The Garbade and Silber (1983) model in equation (1) can be represented after algebraic rearrangement as follows

$$\begin{bmatrix} X_t - X_{t-1} \\ Y_t - Y_{t-1} \end{bmatrix} = \begin{bmatrix} \alpha_x \\ \alpha_y \end{bmatrix} + \begin{bmatrix} \beta_x \\ -\beta_y \end{bmatrix} [Y_{t-1} - X_{t-1}] + \begin{bmatrix} U_t^x \\ U_t^y \end{bmatrix}.$$

2. The results for the two sub-periods are reported and discussed when their implications differ from those obtained using the full sample.

3. The value of θ is higher than the Garbade and Silber bound of $[0, 1]$, which assumes β_x and β_y to be positive.

4. The robustness of the Johansen's test is assessed using models with different lags (two to six lags) and specifications (trend, constant, or both trend and constant) in the cointegrating vector. The results are found to be consistent across different specifications.

5. There is no serial correlation in the residuals up to 3 lags. While GARCH effects are present in the residuals of the equivalent level VAR with the cointegration restriction imposed, Gonzalo (1994) demonstrates that cointegration conclusions based on Johansen's maximum-likelihood estimation procedure are robust.

6. A smaller sample (11/7/2008-8/3/2012) was used to assess the sensitivity of the weak exogeneity tests to the events near the financial market crash. We fail to reject weak exogeneity for the futures market at all normal levels of significance, while weak exogeneity is rejected in cash fed cattle and boxed beef markets.

7. DAG analysis using innovations from a VAR (3) model also gave similar results.

8. The particular ordering in our case can be conveniently implemented using a Cholesky factorization of variables ordered recursively as futures, cash fed cattle, and boxed beef.

9. Forecast error variance decompositions and impulse response functions are also generated ordering futures first followed by boxed beef and cash fed cattle prices. While the boxed beef prices affects the cash fed cattle prices marginally in the impulse response analysis in the nearby horizons, its effect soon disappears. The cash error decomposition at distant horizons does not change, but the boxed beef decomposition at distant horizons shows slightly more of an own effect and less of an influence of cash prices. The relative importance of futures prices does not change.

10. The bivariate relationships between these markets are also assessed using the Gonzalo and Granger price discovery measure (Gonzalo and Granger 1995) and the Hasbrouck information shares measure (Hasbrouck 1995) for the full sample. The results based on bivariate cointegration between the three price pairs are consistent with those obtained from the Garbade and Silber approach.

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Table 1. Unit Root Tests: Weekly U.S. Cattle Prices

Market	Test	Level			First Difference		
		Lags	Test Statistic		Lags	Test Statistic	
Panel A.							
Futures	ADF (CT)	1	3.40	*	1	-17.36	***
	ADF GLS (T)	18	-2.54		18	-3.03	***
	ZA (CT)	3	-5.58	**	2	-13.15	***
Cash	ADF (CT)	2	-2.77		1	-21.05	***
	ADF GLS (T)	18	-2.06		18	-2.70	***
	ZA (CT)	3	-4.64		2	-15.12	***
Boxed Beef	ADF (CT)	2	-3.24	*	1	-23.71	***
	ADF GLS (T)	3	-3.43	**	7	-8.20	***
	ZA (CT)	3	-4.70		2	-15.36	***
Panel B.							
Futures	ADF (CT)	1	-3.90	**	1	-14.08	***
	ADF GLS (T)	2	-3.41	**	9	-4.65	***
Cash	ADF (CT)	2	-2.93		1	-17.34	***
	ADF GLS (T)	16	-2.43		7	-4.75	***
Boxed Beef	ADF (CT)	2	-2.94		1	-20.54	***
	ADF GLS (T)	3	-2.95	**	9	-5.58	***
Panel C.							
Futures	ADF (CT)	1	-3.40	*	1	-10.46	***
	ADF GLS (T)	4	-1.50		14	-1.73	
Cash	ADF (CT)	1	-3.29	*	1	-11.73	***
	ADF GLS (T)	2	-1.52		14	-1.43	
Boxed Beef	ADF (CT)	2	-2.95		1	-11.04	***
	ADF GLS (T)	4	-1.50		12	-1.74	

Notes: Panel A: 5/4/2001 through 8/3/2012, Panel B: 5/4/2001 through 9/26/2008, and Panel C: From 10/10/2008 through 8/3/2012. Futures denotes CME live cattle futures price. Cash denotes negotiated cash fed cattle price. Boxed Beef denotes the boxed beef cutout values multiplied by 63% to reflect the average hot yield. CT: constant and trend. We use SBIC criterion for choosing lag order for the ADF test. ADF-GLS (T): Trend (stationary around a linear time trend). Lag order for ADF-GLS is chosen based on the Modified Akaike Information Criterion (MAIC). τ -stat is the test statistic for the ADF tests. ZA test with one time break in both level and trend. For the ZA test, the test statistic is t-stat. ***Significant at $\alpha = 0.01$, **Significant at $\alpha = 0.05$, *Significant at $\alpha = 0.10$.

Table 2. The Garbade and Silber Approach

Coefficients	Cash (X)/ Futures (Y)		Boxed Beef (X)/ Futures (Y)		Boxed Beef (X)/ Cash (Y)	
Panel A.						
β_x	0.14 *** (0.00)		0.11 *** (0.00)		0.22 *** (0.00)	
β_y	-0.04 * (0.09)		-0.003 (0.85)		-0.01 (0.46)	
θ	1.40		1.03		1.05	
Panel B.						
β_x	0.12 *** (0.00)		0.12 *** (0.00)		0.28 *** (0.00)	
β_y	-0.03 (0.26)		0.0004 (0.98)		-0.02 (0.39)	
θ	1.33		1.00		1.08	
Panel C.						
β_x	0.29 *** (0.00)		0.12 *** (0.00)		0.15 *** (0.00)	
β_y	-0.12 ** (0.02)		-0.02 (0.44)		-0.003 (0.90)	
θ	1.71		1.20		1.02	

Notes: Panel A: 5/4/2001 through 8/3/2012, Panel B: 5/4/2001 through 9/26/2008, and Panel C: From 10/10/2008 through 8/3/2012. Futures denotes CME live cattle futures price. Cash denotes negotiated cash fed cattle price. Boxed Beef denotes the boxed beef cutout values multiplied by 63% to reflect the average hot yield. Both β_x and β_y are rounded to two decimal places and the θ values may have rounding error. Schwarz Bayesian Information Criterion (SBIC) chosen lags are, 3, 3, and 2 for models in panels A, B, and C respectively. ***Significant at $\alpha = 0.01$, ** Significant at $\alpha = 0.05$, *Significant at $\alpha = 0.10$. P-values are presented in parenthesis.

Table 3. Toda and Yamamoto Test of Granger Causality

Dependent Variable	F (t)	C (t)	B (t)
Panel A.			
All Cash = 0	9.30 (0.03)	24.57 (0.00)	10.18 (0.02)
	**	***	**
All Boxed Beef = 0	7.06 (0.07)	8.38 (0.04)	93.56 (0.00)
	*	**	***
Panel B.			
All Cash = 0	6.83 (0.08)	9.34 (0.03)	7.08 (0.07)
	*	**	*
All Boxed Beef = 0	6.30 (0.10)	10.42 (0.02)	65.91 (0.00)
	*	**	***
Panel C.			
All Cash = 0	5.31 (0.07)	9.90 (0.01)	4.14 (0.13)
	*	**	
All Boxed Beef = 0	2.91 (0.23)	1.07 (0.59)	22.94 (0.00)

Notes: Panel A: 5/4/2001 through 8/3/2012, Panel B: 5/4/2001 through 9/26/2008, and Panel C: From 10/10/2008 through 8/3/2012. F, C, and B represents futures, cash fed cattle, and boxed beef prices respectively. Futures denotes CME live cattle futures price. Cash denotes negotiated cash fed cattle price. Boxed Beef denotes the boxed beef cutout values multiplied by 63% to reflect the average hot yield. Schwarz Bayesian Information Criterion (SBIC) chosen lags are, 3, 3, and 2 for models in panels A, B, and C respectively. Maximum order of Integration = 1. ***Significant at $\alpha = 0.01$, ** Significant at $\alpha = 0.05$, *Significant at $\alpha = 0.10$. P-values are presented in parentheses.

Table 4. Johansen Test for Cointegration

	Panel A.	Panel B.	Panel C.	Critical Values		
Rank	λ -Trace	λ -Trace	λ -Trace	10%	5%	1%
≤ 2	1.93	2.77	0.29	6.50	8.18	11.65
≤ 1	37.91	23.15	23.89	15.66	17.95	23.52
0	105.20	67.97	85.16	28.71	31.52	37.22
Rank	λ -Max	λ -Max	λ Max	10%	5%	1%
≤ 2	1.93	2.77	0.29	6.50	8.18	11.65
≤ 1	35.99	20.37	23.59	12.91	14.9	19.19
0	67.29	44.83	61.28	18.90	21.07	25.75

Notes: Panel A: 5/4/2001 through 8/3/2012, Panel B: 5/4/2001 through 9/26/2008, and Panel C: From 10/10/2008 through 8/3/2012. Schwarz Bayesian Information Criterion (SBIC) chosen lags are, 3, 3, and 2 for models in panels A, B, and C respectively. LR test of the null hypothesis that there are at most “r” cointegrated vectors against the alternative that there are 3 cointegrated vectors (λ -Trace), and that there “r+1” cointegrated vectors (λ -Max). The model is specified with only a constant term in the equation to account for the trend (drift) in level series.

Table 5. Weak exogeneity Test (VECM)

Dependent Variable	ΔF (t)	ΔC (t)	ΔB (t)	
Panel A.				
Estimate of Coefficient (α_1)	0.02	0.13		-0.02
Estimate of Coefficient (α_2)	-0.05	-0.14		0.18
Weak Exogeneity	1.84 (0.40)	21.2 (0.00)	***	41.4 (0.00) ***
Panel B.				
Estimate of Coefficient (α_1)	0.01	0.11		-0.02
Estimate of Coefficient (α_2)	-0.06	-0.14		0.17
Weak Exogeneity	1.82 (0.40)	11.20 (0.00)	***	21.62 (0.00) ***
Panel C.				
Estimate of Coefficient (α_1)	0.13	0.32		-0.07
Estimate of Coefficient (α_2)	-0.17	-0.37		0.27
Weak Exogeneity ^a	5.52 (0.06)	* 25.01 (0.00)	***	45.18 (0.00) ***

Notes: Panel A: 5/4/2001 through 8/3/2012, Panel B: 5/4/2001 through 9/26/2008, and Panel C: From 10/10/2008 through 8/3/2012. F, C, and B represents futures, cash fed cattle, and boxed beef prices respectively. Schwarz Bayesian Information Criterion (SBIC) chosen lags are, 3, 3, and 2 for models in panels A, B, and C respectively. ***Significant at $\alpha = 0.01$, ** Significant at $\alpha = 0.05$, *Significant at $\alpha = 0.10$. P-values are presented in parentheses.

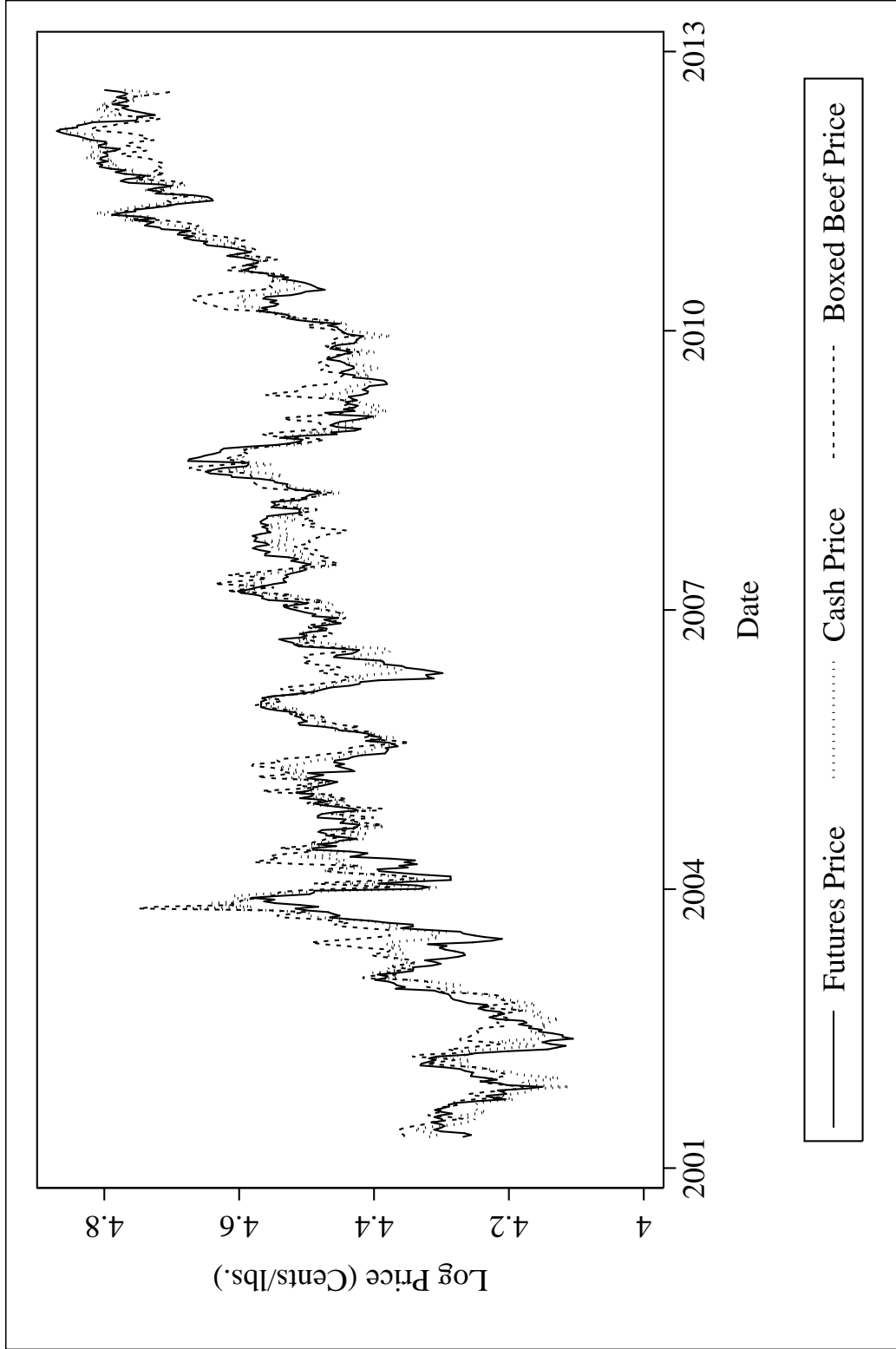
a. We fail to reject weak exogeneity of the futures market when observations from October 2008 are removed.

Table 6. Forecast Error Variance Decompositions (Level VAR)

	Weeks	Futures	Cash	Boxed Beef
Futures	1	99.78	0.01	0.20
	2	99.04	0.83	0.14
	5	98.33	1.22	0.45
	10	97.80	1.16	1.04
	15	97.54	0.93	1.53
Cash	1	45.54	54.46	0.00
	2	53.09	46.56	0.35
	5	66.74	32.80	0.46
	10	79.30	20.02	0.68
	15	85.30	13.65	1.05
Boxed Beef	1	8.25	18.43	73.31
	2	23.91	27.36	48.73
	5	38.44	28.26	33.30
	10	51.40	25.74	22.86
	15	61.85	20.94	17.21

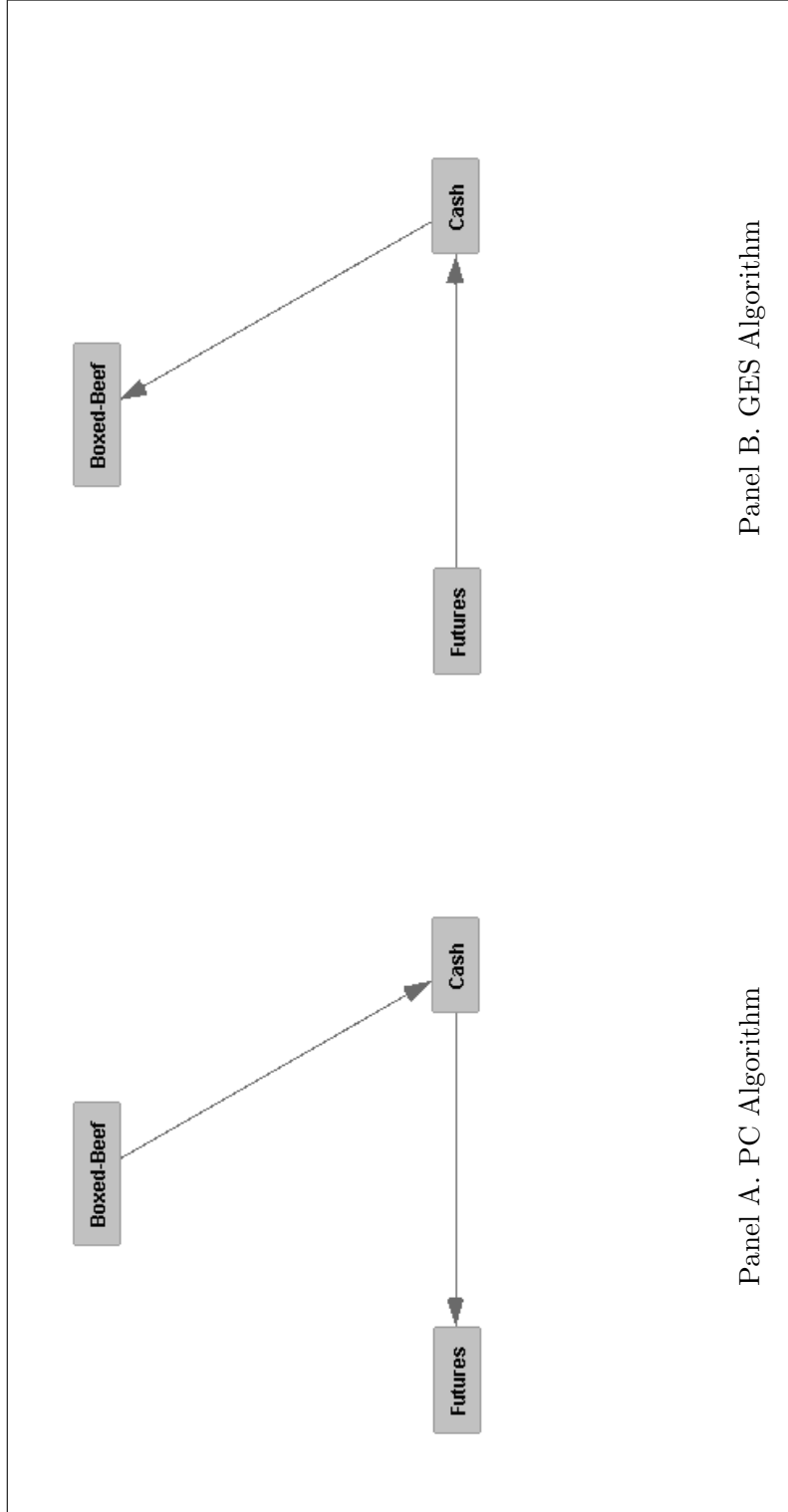
Notes: Data spans 5/4/2001 through 8/3/2012. The forecast error variance decompositions in each row sum to 100. Futures denotes CME live cattle futures price. Cash denotes negotiated cash fed cattle price. Boxed Beef denotes the boxed beef cutout values multiplied by 63% to reflect the average hot yield.

Figure 1. U.S. Fed Cattle Prices (May 2001-August 2012)



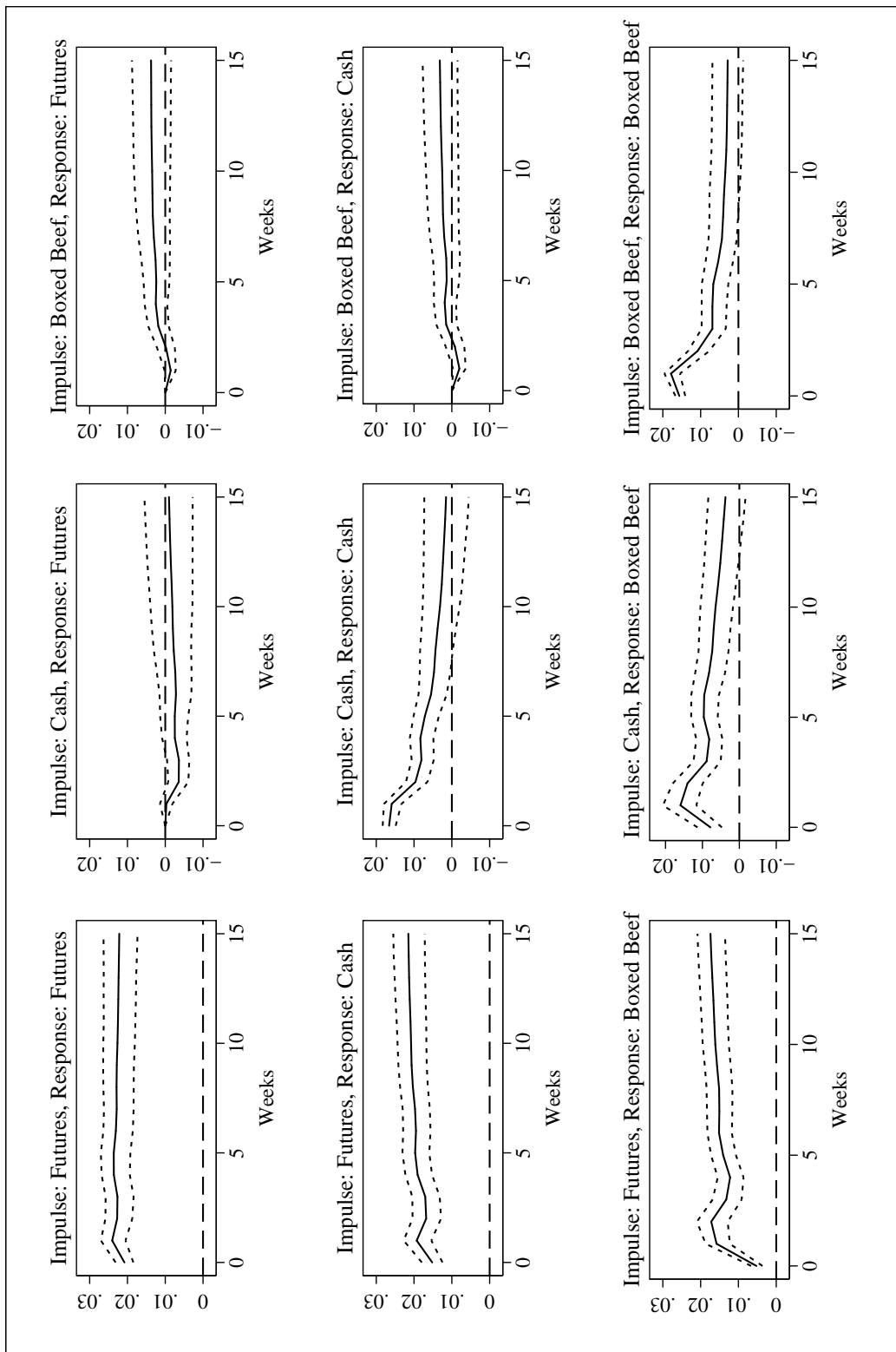
Notes: All prices are in natural logarithms. Futures price denotes CME live cattle futures price. Cash price denotes negotiated cash fed cattle price. Boxed Beef price denotes the boxed beef cutout values multiplied by 63% to reflect the average hot yield.

Figure 2. Directed Acyclic Graphs (DAG) of innovations from the VECM



Notes: DAG created using TETRAD IV. Futures denotes CME live cattle futures price. Cash denotes negotiated cash fed cattle price. Boxed Beef denotes the boxed beef cutout values multiplied by 63% to reflect the average hot yield.

Figure 3. Orthogonal Impulse Response to 1% Shock in Each Price Series



Notes: Impulse response with 95% bootstrapped confidence intervals from level VAR using the ordering inferred from DAG. Futures denotes CME live cattle futures price. Cash denotes negotiated cash fed cattle price. Boxed Beef denotes the boxed beef cutout values multiplied by 63% to reflect the average hot yield.