Two Essays on Market Interdependencies, Price Volatility and Volatility Spillovers in the Western Canadian Feed Barley, U.S. Corn and Alberta Cattle Markets

by

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Abstract

Over the last decade, Alberta cattle markets have experienced several extreme events, including the 2003 Canadian bovine spongiform encephalopathy (BSE) crisis and recent episodes of feed price surges. These events may have affected the price volatility of Alberta cattle and its interdependencies with the feed grain markets. This thesis consists of two essays that aim to assess market interdependencies, price volatility and volatility spillovers in the western Canadian feed barley, U.S. corn and Alberta cattle industries.

The first essay employed the asymmetric generalized dynamic conditional correlation (AG-DCC) generalized autoregressive conditional heteroskedasticity (GARCH) framework to quantify volatility changes and market interdependencies among relevant markets. The model results suggested that the fed cattle price volatility was higher than the feeder cattle price volatility during the BSE crisis, while the opposite was true during non-BSE periods. Furthermore, no evidence was found to prove that the cattle and feed barley price volatility changed during food price surges. Although strong market interdependencies were found throughout the cattle supply chain, these relationships were weakened at the beginning of the BSE crisis. In contrast, weak interdependencies between the cattle and the feed grain markets were found. Moreover, the market relationships exhibited only small changes during the BSE crisis and feed price surges.

The second essay assesses price volatility spillovers in the Alberta cattle supply chain and between the cattle and feed grain markets using the bivariate asymmetric BEKK-GARCH model. Although bidirectional price volatility spillovers were found throughout the Alberta cattle supply chain, spillovers between cattle and feed grain price volatility were found exclusively between the Alberta lighter feeder cattle and Lethbridge barley markets. Furthermore, model results indicated strong volatility spillovers from the U.S. corn market to the barley market. Interestingly,

volatility spillovers were not found between the Alberta fed cattle and barley markets. However, barley price volatility might still be transmitted to the fed cattle market through feeder cattle price volatility.

This thesis contributes to the relatively scarce literature on price volatility and market linkages in the western Canadian agricultural sector, providing useful information for agricultural producers managing market risks and for policy makers designing efficient price stabilization programs.

Dedication

To my family

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Chapter 1. Introduction

"The advantage of knowing about risks is that we can change our behavior to avoid them" (Engle 2003, 326).

1.1. Introduction

As the strongest provincial economy in Canada, Alberta's economy is mainly supported by energy, agriculture, and other industries (Alberta Canada 2014). In 2013, the total farm receipts for Alberta accounted for around 21.47% of Canada's total agricultural revenue (Statistics Canada 2013). As the most important component in Alberta's agricultural sector, the cattle industry has experienced many difficulties over the past decade: first with a border closure due to the discovery of bovine spongiform encephalopathy (BSE) and more recently because of feed grain price surges. Given these events, understanding potential market linkages and price volatility interactions in Alberta's cattle supply chain and those between the cattle and feed grain markets may better inform cattle producers, crop farmers and policy makers about potential market risks.

1.2. Background on the Alberta Cattle Industry

Highly specialized and efficient, the Alberta cattle industry is comprised of three stages: i) cow-calf, ii) backgrounding and iii) finishing (Viney 1995). At the cow-calf stage, the majority of calves are born in late winter and placed on summer pasture before being weaned (Viney 1995). Typically, calves are weaned when they reach the weight range of 180-270 kg (400-600 lbs.) (Deng 2006). Lighter weaned calves are fed (backgrounded) with a low energy ration during the winter and then been placed back on pasture (Viney 1995). Heavier weaned calves are put on a high energy ration throughout the winter and marketed in the spring (Deng 2006).

After backgrounding, most cattle enter the finishing stage. In Alberta, a feedlot is the main facility for finishing. In feedlots, cattle are fed high energy rations until they reach a desired slaughter weight range (Deng 2006); typically the weight is 550kg (1250 lbs.). Slaughter cattle are called fed cattle in Alberta and live cattle in the U.S.

1.3. Economic Problem

Agribusinesses face different types of risks including production, financial and market risks. Market risks, include price volatility, in input or output markets are important considerations for decision making (Buguk et al 2003). In this study, price volatility is defined as the extent to which price varies over time (Gilbert and Morgan 2010). In certain instances price volatility challenges producers' ability to retain profitability (Apergis and Rezitis 2003). While most researchers have focused their attention on price volatility of one particular market, volatility spillovers, measured by the extent to which price volatility transmits from one market to another, is an equally important consideration (Buguk et al 2003). Financial market volatility and volatility spillovers have attracted much more attention than similar concerns in agricultural markets (Buguk et al 2003). Despite this lack of attention, Natcher and Weaver (1999) emphasised that arbitrage transmits commodity price volatility across markets. As a consequence, more research is warranted with respect to agricultural commodity price volatility and volatility spillovers. Furthermore, there might be a policy spillovers as price volatility transmits through market channels. So complete supply chain analysis requires considering price volatility in input and output markets (Buguk et al 2003). Therefore, the determination of the sources and magnitude of price volatility and volatility spillovers is important for agribusiness owners, researchers and policy makers.

Aside from the investigations of price volatility and volatility spillovers, proper examination of market interdependencies is also necessary because price changes induced by market shocks travel throughout the entire agricultural production chain. For example, in the cattle supply chain, feed price levels and volatility directly affect the costs and profitability of cattle producers (Goodwin et al 2011). Therefore, an appropriate assessment of market interdependencies in agricultural commodity markets is essential. In this study, market interdependencies are represented by conditional correlations, which are commonly used to measure the linear dependence between variables over time (Serra 2011).

A common economic problem faced by policy makers, feed grains farmers and cattle producers is the question of how variable prices are in each market. How do the market interdependencies vary over time as a result of market shocks? Is price volatility transmitted through the entire supply chain, and if so, are the volatility spillovers between markets symmetric or asymmetric? This thesis is dedicated to answering these questions.

1.4. Objectives

This thesis aims to assess potential market interdependencies, price volatility and volatility spillovers in the Alberta feed/cattle supply chains. Five markets are considered in both essays. Alberta feeder steers (500-600 lbs.), feeder steers (800-900 lbs.) and fed steers (1250 lbs.) are chosen to represent the downstream cattle supply chain. While, Lethbridge feed barley and U.S. corn prices are selected to represent the upstream portion of the supply chain.

On the one hand, the assessment of market interdependencies could provide information on market relationships among the studied prices. On the other hand, the investigation of price volatility spillovers could reveal the potential interactions between market price volatility. By analyzing market interdependencies and price volatility spillovers together, a complete picture of the relationships among the studied market prices could be drawn.

This study contributes to a relatively sparse literature on price volatility in the western Canadian agricultural sector. The study should provide useful information to agricultural producers for managing market risks and to policy makers designing efficient stabilization programs.

1.5. Study Plan

This thesis consists of two essays. Both essays employ a generalized autoregressive conditional heteroskedatistic (GARCH) model developed by Bollerslev (1986). The GARCH model and its variations are the most widely used time series processes to explore price volatility. Chapter 2 provides the first essay that measures price volatility and market interdependences in the cattle and feed grain markets in western Canada. The approach used employs a model developed by Cappiello et al (2006), the diagonal asymmetric generalized dynamic conditional correlation (AG-DCC) GARCH model, to explore the conditional volatility and market interdependencies. The DCC-GARCH family is originally developed by Engle (2002) and it assumed dynamic conditional correlations are time-varying and dependent upon past information. Given the large number of markets to be studied in the first essay, the AG-DCC GARCH model is employed because it is able to model the effects from joint market shocks (i.e., cross-sectional terms) on the dynamic conditional correlations. While the traditional DCC-GARCH model only has two parameters to govern the dynamic conditional correlations regardless the number of market prices being modeled. A revised two-stage estimation process was utilized in the AG-DCC GARCH modeling. In the first stage, proper mean and GARCH models were determined for each market price studied. This study extended the original AG-DCC model by incorporating error correction and cross-effect terms in conditional mean models. Results from the first stage were incorporated into the second stage for dynamic conditional correlation estimation. This type of estimation process reduces the computational complexity in the parameter estimation of multivariate GARCH models (Engle 2002). Furthermore, the two-stage estimation provides the flexibility in selecting proper GARCH models to accurately describe conditional volatility of each studied market price.

Chapter 3 contains the second essay that aims to investigate price volatility spillovers in the studied markets. To assess potential price volatility spillovers, an asymmetric multivariate GARCH model, known as the asymmetric Baba-Engle-Kraft-Kroner (BEKK) GARCH model is applied (Engle and Kroner 1995; Grier et al 2004). The BEKK GARCH model has several attractive empirical properties. First, the model is constructed to enforce positive-definiteness on the conditional variance-covariance matrix of the regression model residuals. Second, the model parameters can provide full dynamics of price volatility spillovers including the size and direction.

Chapter 4 concludes this thesis and provides discussions on limitations and possible future extensions of this study.

Chapter 2. Analysis of Price Volatility and Market Interdependency in the Western Canadian Feed Barley, U.S. Corn and Alberta Cattle Markets

2.1. Introduction

Alberta accounts for approximately 60% of Canada's fed cattle production. Over the last decade, the Alberta cattle industry has experienced substantial turmoil, including the breakout of bovine spongiform encephalopathy (BSE) in 2003, which caused border closures, and price surges in the feed grain markets in 2006-2008 and 2011-2013. These events may have contributed to the increased price volatility of Alberta cattle and affected the potential interdependencies in the cattle and feed grain markets.

Price volatility is a vital economic phenomenon (Engle 1982). Investigating price volatility is important because it is considered to be a major source of risk in the production decision-making process and has a substantial impact on the price discovery process (Goodwin and Kastens 1993; Buguk et al 2003). Furthermore, with the information of price volatility, business owners could adopt risk management tools and in turn maintain their desired level of profitability (Buguk et al 2003).

Proper examination of market interdependencies is also necessary because price changes induced by market shocks may travel throughout the cattle production chain. Furthermore, through the feeding process, feed crop price levels and volatility directly affect the costs and profitability of cattle producers (Goodwin et al 2011). Therefore, an appropriate assessment of market interdependencies in the cattle markets and feed grain markets is essential.

The generalized autoregressive conditional heteroskedasticity (GARCH) model (Bollerslev 1986) and its variations are common tools for investigating price volatility (Bauwens et al 2012). As a commonly used measure to explore the interdependencies between price series, correlations have been comprehensively studied in the field of finance. To reveal the co-movement of short-run nominal exchange rates, Bollerslev (1990) proposed a new multivariate GARCH model, i.e., the constant conditional correlation (CCC) GARCH model, as a convenient way to approximate the conditional correlation matrix for a set of market price changes. However, this convenience comes at a cost because the CCC-GARCH model assumes that the conditional correlations among price changes are temporally constant, i.e., the CCC GARCH model assumes that market interdependency is static. To investigate potentially time-varying interdependencies between markets, Engle (2002) developed the dynamic conditional correlation (DCC) multivariate GARCH model, which assumes that the correlation matrix of a set of market price changes varies with time. Cappiello et al (2006) further generalized Engle's (2002) DCC GARCH model by adding parameters that account for asymmetric effects and market specificity in conditional correlation specifications, naming the model the asymmetric generalized (AG) – DCC GARCH model. Asymmetric effects represent the unequal influences of negative and positive price changes on price volatility. In the field of agricultural price analysis, the dynamic conditional correlations are sometimes employed to uncover market interdependencies between agricultural commodities (Serra 2011; Goodwin et al 2011).

The purpose of this study is to assess the evolution of price volatility and market interdependencies among price changes in the Alberta cattle, Lethbridge barley, and U.S. corn markets due to the effects of the BSE discovery and feed price surges. These markets were chosen because no previous research on price volatility and market linkages has been performed on the Alberta cattle and feed grain sectors. Furthermore, since imports of U.S. corn also play an increasingly important role in cattle feeding regimes, price uncertainties in the U.S. sector could also affect Alberta feed barley and cattle markets (Crawford et al 2012). The results of this study may provide market risk information to cattle and feed barley producers; furthermore, analysis on market interdependencies may reveal the extent to which these markets are related.

The AG-DCC GARCH model (Cappiello et al 2006) enables the exploration of price volatility and market interdependencies in a two-stage multivariate GARCH framework. To the author's best knowledge, the AG-DCC GARCH model has not been used in the field of agricultural economics. This model can reveal richer information, such as asymmetry and market-specific shock effects, especially in the context of market interdependencies.

The remainder of this chapter is organized as follows. Section 2.2 provides a brief review of the relevant literature. Section 2.3 outlines the method employed in this study. Section 2.4 describes the data used for the analysis. The empirical results and discussions are presented in Section 2.5. Lastly, the main conclusions are discussed in Section 2.6.

2.2. Literature Review

Asset price volatility and dynamic conditional correlations have been broadly studied in the field of finance to construct optimal portfolios and hedge ratios. However, only a few researchers have analyzed conditional volatility and/or conditional correlations of price changes in agricultural markets.

Kesavan et al (1992) estimated price volatility using a GARCH model for U.S. beef and pork products. Their findings indicated that the farm price volatility of beef and pork is dependent on information from the previous period(s). Buguk et al (2003) studied price volatility for six markets within the U.S. catfish supply chain: soybean, corn, menhaden, feed materials (i.e., primary feed materials for raising catfish) and farm/wholesale catfish markets. The authors estimated an exponential GARCH model and found that volatility was persistent in most markets except for menhaden.

Apergis and Rezitis (2003) analyzed price volatility in Greek agricultural (input and output) markets and retail food markets. Using augmented GARCH processes, the authors showed that agricultural output markets are the most volatile among all of the examined markets. Serra (2011) adopted a smooth transition conditional correlation GARCH model to investigate the effects of the Spanish BSE on producer and retailer beef price volatility and the dynamic conditional correlation between their price changes. The author concluded that price changes between the producer and retailer beef markets were negatively correlated during the food crises. Therefore, price stabilization programs designed to stabilize one market cannot stabilize the other.

Jin et al (2008) explored the effects of 16 North American BSE incidents on the volatility of settlement prices for daily live cattle futures in the U.S. from 1993 through 2008 using GARCH processes.[1] The authors found that the futures price volatility of live cattle increased significantly for more than one day during three BSE events. These three cases included the 2003 case in Canada and the 2003 and 2006 cases in the United States.

[1] Canadian cases: December 1, 1993; May 20, 2003; January 2 and 11, 2005; January 22, 2006; April 16, 2006; July 3 and 13, 2006; August 23, 2006; February 7, 2007; May 2, 2007; December 18, 2007; and February 26, 2008 (CDC 2013).
U.S. cases: December 23, 2003; May 24, 2004; and March 2006 (CDC 2013).

Goodwin et al (2011) employed a state-dependent regime-switching model of dynamic conditional correlations to explore the effects of U.S. corn and soybean prices and price volatility on the U.S. feeder and fed cattle markets. The authors found positive dynamic correlations between the corn and soybean markets. A similar relationship was found between the feeder cattle and live cattle markets. Furthermore, the authors found a negative dynamic conditional correlation between corn and feeder cattle prices after September 2003. However, Goodwin et al (2011) did not find any significant correlation between the corn and fed cattle market price changes. The authors attributed this finding to the potential existence of transaction costs between the corn and cattle markets.

2.3. Method

This study assesses the dynamic conditional correlations among price changes and the evolutions of price volatility in the Alberta cattle, Lethbridge barley and U.S. corn markets. The U.S. corn market was included in the analysis because feedlot owners in southern Alberta are beginning to import U.S. corn as a substitute for barley (Crawford et al 2012), which may create a direct market link between the Alberta cattle and U.S. corn markets.

The feeder cattle (500-600 lbs.), feeder cattle (800-900 lbs.) and fed cattle markets were included in the analysis. To achieve the study’s objectives, the diagonal AG-DCC GARCH model (Cappiello et al 2006) was used. The original model specification presented in Cappiello et al (2006) was expanded by incorporating long-run price equilibrium (if it exists) and short-run price dynamics via an error correction process in the conditional mean model.

The two-stage estimation procedure that was originally designed for the diagonal AG-DCC GARCH model was used in this study. First, univariate GARCH models were estimated with error correction and cross-effect terms that were incorporated into the conditional mean equation. Second, the parameters that govern the dynamics of the conditional correlation were estimated based on the parameters estimated in stage one.

Prior to any model estimation, the augmented Dickey-Fuller (ADF) stationary test was conducted on both the natural logarithmically transformed prices (i.e., $100 \times \log(p_t)$) and the price changes (i.e., $100 \times \Delta \log(p_t) = 100 \times \log(p_t / p_{t-1})$) in the studied markets. Furthermore, the Ljung-Box Q test was used to detect autocorrelation in the price changes.

The specific estimation steps used in this study were as follows:

Step 1: A cointegration test (Johansen 1988) was conducted on logged price pairs that have the same order of integration to detect the existence of any long-run price relationship in the studied markets. Furthermore, ordinary least squares (OLS) were estimated between cointegrated logged price pairs (if they existed) to obtain the residuals, which were used as error correction terms in the conditional mean estimations.

Step 2: A five-variate vector autoregressive (VAR)-GARCH model with error correction terms that could be incorporated when appropriate was estimated.

Step 3: Insignificant coefficients were removed from the VAR component of the model that was estimated in the previous step; the five-variate VAR-GARCH model was re-estimated using only the significant coefficients.

Step 4: Standardized residuals, which were obtained from the VAR-GARCH model determined in the previous step, were used to estimate the parameters in the dynamic conditional covariances.

Step 5: Dynamic conditional correlations were calculated based on the estimated conditional volatility and covariances.

2.3.1. Mean and Variance Equations

A VAR-GARCH model can be used to fully explore the long-run price equilibrium and short-run price dynamics. The lag length of the VAR model was determined using the Akaike Information Criterion (AIC). Within the AG-DCC GARCH framework, any univariate GARCH model that is covariance stationary and assumes normally distributed errors can be used to model the conditional variances of price changes.[2] In this study, both the exponential GARCH (Nelson 1991) and the GJR GARCH (Glosten et al 1993) models were estimated due to their popularity and flexibility in the univariate asymmetric GARCH family; the model with a smaller Bayesian Information Criterion (BIC) was selected. The GARCH models adopted in this study are illustrated below.

[2] One may raise the question that the error distributions could have fat tails. Cappiello et al (2006) concluded that this problem is minor because the results from their model included standard Quasi-Maximum Likelihood estimation (QMLE) interpretation.

Nelson (1991) proposed a GARCH-type model called the exponential GARCH (EGARCH) model, which incorporates asymmetries in the conditional variance equations and does not require non-negative parameters to obtain positive conditional variances. Assuming the mean equation follows an AR (*q*) process, the AR (*q*) - EGARCH model can be expressed as follows:

$$\begin{aligned}
&\Delta \log(p_{i,t}) = c + \sum_{s=1}^{q} A_s \Delta \log(p_{i,t-s}) + e_{i,t} \\
&e_{i,t} = z_t \sqrt{h_{ii,t}}, z_t \sim \text{i.i.d.}(0,1) \\
&\log(h_{ii,t}) = \alpha_o + \alpha \left| \frac{e_{ii,t-1}}{\sqrt{h_{ii,t-1}}} \right| + \beta \log(h_{ii,t-1}) + d\, e_{ii,t-1} / \sqrt{h_{ii,t-1}}
\end{aligned} \tag{1}$$

where e_t is the residual obtained from the mean equation and h_t is the conditional variance. The asymmetric proportion of the conditional variance equation in Eq. (1) is characterized by the last term; this term can be removed if necessary. For the conditional variance equation to be covariance stationary, β must be less than unity (Villar 2010). The sign of parameter d is negative if negative price changes affect price volatility more than positive price changes.

Glosten et al (1993) included a binary variable in the standard GARCH model that allows the conditional variance to respond asymmetrically to positive and negative price changes. Assuming the mean equation follows an AR (*q*) process, the AR (*q*) – GJR GARCH process is described by the following equations:

$$\begin{aligned}
&\Delta \log(p_{i,t}) = c + \sum_{s=1}^{q} A_s \Delta \log(p_{i,s-i}) + e_{i,t} \\
&e_{i,t} = z_t h_{ii,t}, z_t \sim \text{i.i.d.}(0,1) \\
&h_{ii,t} = \alpha_0 + \alpha e_{i,t-1}^2 + \gamma G e_{i,t-1}^2 + \beta h_{ii,t-1} \\
&where \begin{cases} G = 1\, if\, e_{i,t} < 0 \\ G = 0\, if\, e_{i,t} \geq 0 \end{cases}
\end{aligned} \tag{2}$$

These equations imply that negative price changes can render larger effects on conditional variances than positive price changes can. Hence, the expected sign of the estimated parameter γ is positive (Bauwens et al 2012).

The assumed AR (q) process presented above is provided herein solely for illustrative purposes and can be further extended by incorporating other variables, such as error correction terms, dummy variables and moving average (MA) terms, given that the remaining regression residuals are white noise (Engle 1982). The conditional mean and conditional variance specifications employed in this study are detailed in Appendix A.

2.3.2. Diagonal AG-DCC GARCH Model

The DCC multivariate GARCH family has been commonly used to investigate market interdependencies by estimating the time-varying correlations among studied price changes. This type of model is empirically convenient when analyzing more than two markets. The diagonal AG-DCC GARCH model, which was utilized in this study, can accommodate asymmetric effects and the effects from joint market shocks when estimating conditional correlations.

To estimate the diagonal AG-DCC GARCH model, the $k \times 1$ vector (k denotes the number of markets, which is five in this study) of the standardized residuals ε_t was obtained from the VAR-GARCH model (see the previous section) and was used in further estimation processes. The elements of vector ε_t were calculated as $\varepsilon_{i,t} = e_{i,t} / \sqrt{h_{ii,t}}$ $(\forall\, i = 1,...,k)$; moreover, ε_t can be represented as follows:

$$\varepsilon_t \mid \psi_{t-1} \sim N(0, H_t) \tag{3}$$

where ψ_{t-1} is information available at $t-1$ and H_t is the conditional variance-covariance matrix, which can be decomposed as

$$H_t = D_t R_t D_t \tag{4}$$

where D_t is a diagonal matrix with $\sqrt{h_{ii,t}}\,(\forall\, i = 1,\ldots,k)$ on the diagonals and R_t is the time-varying correlation matrix, R_t can be described as

$$R_t = D_t^{-1} H_t D_t^{-1} \tag{5}$$

Within the diagonal AG-DCC GARCH framework, the evaluation of the conditional correlation matrix R_t can be determined by H_t, which can be estimated as follows:

$$H_t = \bar{R} \circ (mm' - aa' - bb') - \bar{N} \circ gg' + aa' \circ \varepsilon_{t-1}\varepsilon_{t-1}' + gg' \circ n_{t-1}n_{t-1}' + bb' \circ H_{t-1} \quad (6)$$

where a, b and g are $k \times 1$ parameter vectors that are estimated in Eq. (6), m is a $k \times 1$ vector of ones, ε_t is the $k \times 1$ vector of the standardized residuals, n_t accounts for the asymmetric effects, in which $n_t = I[\varepsilon_t < 0] \circ \varepsilon_t$, $I[\bullet]$ is a $k \times 1$ indicator function, operator $\circ$ represents the element-wise product (i.e., Hadamard product), $\bar{R} = \frac{1}{T}\sum_{t=1}^{T} \varepsilon_t \varepsilon_t{}'$ and $\bar{N} = \frac{1}{T}\sum_{t=1}^{T} n_t n_t{}'$. For H_t to be positive definite, a sufficient condition is for $\bar{R} \circ (mm' - aa' - bb') - \bar{N} \circ gg'$ to be positive semi-definite. For this condition to hold, every element in vectors a, b and g must satisfy the following condition (Cappiello et al 2006):

$$a_{ii}^2 + b_{ii}^2 + \lambda g_{ii}^2 < 1 \quad (7)$$

where λ is the maximum eigenvalue of $\left[\bar{R}^{-1/2}\bar{N}\bar{R}^{-1/2}\right]$; $\bar{R}^{-1/2}$ denotes that every element in $\bar{R}$ is in the form of an inverse square root (e.g., $\bar{r}_{ii}^{-1/2}$).

Assuming $k = 3$, the dynamic conditional co-variances that are governed by the market-specific parameters in Eq. (6) can be demonstrated as follows:

$$\begin{bmatrix} h_{11,t} & h_{12,t} & h_{13,t} \\ h_{21,t} & h_{22,t} & h_{23,t} \\ h_{31,t} & h_{32,t} & h_{33,t} \end{bmatrix} = C + \begin{bmatrix} a_{11} \\ a_{22} \\ a_{33} \end{bmatrix} \begin{bmatrix} a_{11} & a_{22} & a_{33} \end{bmatrix} \circ \begin{bmatrix} \varepsilon_{1,t-1} \\ \varepsilon_{2,t-1} \\ \varepsilon_{3,t-1} \end{bmatrix} \begin{bmatrix} \varepsilon_{1,t-1} & \varepsilon_{2,t-1} & \varepsilon_{3,t-1} \end{bmatrix}$$
$$+ \begin{bmatrix} g_{11} \\ g_{22} \\ g_{33} \end{bmatrix} \begin{bmatrix} g_{11} & g_{22} & g_{33} \end{bmatrix} \circ \begin{bmatrix} n_{1,t-1} \\ n_{2,t-1} \\ n_{3,t-1} \end{bmatrix} \begin{bmatrix} n_{1,t-1} & n_{2,t-1} & n_{3,t-1} \end{bmatrix} \quad (8)$$
$$+ \begin{bmatrix} b_{11} \\ b_{22} \\ b_{33} \end{bmatrix} \begin{bmatrix} b_{11} & b_{22} & b_{33} \end{bmatrix} \circ \begin{bmatrix} h_{11,t-1} & h_{12,t-1} & h_{13,t-1} \\ h_{21,t-1} & h_{22,t-1} & h_{23,t-1} \\ h_{31,t-1} & h_{32,t-1} & h_{33,t-1} \end{bmatrix}$$

where a_{ii}, b_{ii} and g_{ii} are parameters that govern the evolutions of the conditional variance-covariance matrix H_t and C represents the matrix of constants. After matrix multiplication, the right hand side of Eq. (8) is transformed to

$$\begin{bmatrix} h_{11,t} & h_{12,t} & h_{13,t} \\ h_{21,t} & h_{22,t} & h_{23,t} \\ h_{31,t} & h_{32,t} & h_{33,t} \end{bmatrix} = C + \begin{bmatrix} a_{11}^2 \varepsilon_{1,t-1}^2 & a_{11} a_{22} \varepsilon_{1,t-1} \varepsilon_{2,t-1} & a_{11} a_{33} \varepsilon_{1,t-1} \varepsilon_{3,t-1} \\ a_{22} a_{11} \varepsilon_{2,t-1} \varepsilon_{1,t-1} & a_{22}^2 \varepsilon_{2,t-1}^2 & a_{22} a_{33} \varepsilon_{2,t-1} \varepsilon_{3,t-1} \\ a_{33} a_{11} \varepsilon_{3,t-1} \varepsilon_{1,t-1} & a_{33} a_{22} \varepsilon_{3,t-1} \varepsilon_{2,t-1} & a_{33,t-1}^2 \varepsilon_{2,t-1}^2 \end{bmatrix}$$
$$+ \begin{bmatrix} g_{11}^2 n_{1,t-1}^2 & g_{11} g_{22} n_{1,t-1} n_{2,t-1} & g_{11} g_{33} n_{1,t-1} n_{3,t-1} \\ g_{22} g_{11} n_{2,t-1} n_{1,t-1} & g_{22}^2 n_{2,t-1}^2 & g_{22} g_{33} n_{2,t-1} n_{3,t-1} \\ g_{33} g_{11} n_{3,t-1} n_{1,t-1} & g_{33} g_{22} n_{3,t-1} n_{2,t-1} & g_{33}^2 n_{2,t-1}^2 \end{bmatrix} \quad (9)$$
$$+ \begin{bmatrix} b_{11}^2 h_{11,t-1} & b_{11} b_{22} h_{12,t-1} & b_{11} b_{33} h_{13,t-1} \\ b_{22} b_{11} h_{21,t-1} & b_{22}^2 h_{22,t-1} & b_{22} b_{33} h_{23,t-1} \\ b_{33} b_{11} h_{31,t-1} & b_{33} b_{22} h_{32,t-1} & b_{33}^2 h_{33,t-1} \end{bmatrix}$$

For any conditional variance h_{ii} in Eq. (6), the following relationship holds:

$$h_{ii,t} = \left(1 - a_{ii}^2 - b_{ii}^2\right)\left(\frac{1}{T}\sum_{t=1}^{T} \varepsilon_{i,t}^2\right) - g_{ii}^2\left(\frac{1}{T}\sum_{t=1}^{T} n_{i,t}^2\right) + a_{ii}^2 \varepsilon_{i,t-1}^2 + g_{ii}^2 n_{i,t-1}^2 + b_{ii}^2 h_{ii,t-1} \quad (10)$$

Additionally, for any covariance $h_{ij,t} (\forall i \neq j)$ in Eq. (6), the following equation is valid:

$$\begin{aligned} h_{ij,t} &= \left(1 - a_{ii} a_{jj} - b_{ii} b_{jj}\right)\left(\frac{1}{T}\sum_{t=1}^{T} \varepsilon_{i,t} \varepsilon_{j,t}\right) - g_{ii} g_{jj}\left(\frac{1}{T}\sum_{t=1}^{T} n_{i,t} n_{j,t}\right) \\ &+ a_{ii} a_{jj} \varepsilon_{i,t-1} \varepsilon_{j,t-1} + g_{ii} g_{jj} n_{i,t-1} n_{j,t-1} + b_{ii} b_{jj} h_{ij,t-1} \end{aligned} \quad (11)$$

To calculate the dynamic conditional correlations for any market pair, the following correlation coefficient formula can be applied:

$$\rho_{ij,t} = \frac{h_{ij,t}}{\sqrt{h_{ii,t}}\sqrt{h_{jj,t}}} \forall i \neq j \quad (12)$$

where $h_{ii,t}$ and $h_{jj,t}$ are the conditional variances estimated in Eq. (9).

2.3.3. The Likelihood Function

Estimation of the diagonal AG-DCC GRACH model was performed using a maximum likelihood approach by assuming a conditional multivariate normal distribution. Despite the frequent violation of the assumption of conditional normality, a consistent and asymptotically normal quasi-maximum likelihood estimator still exists (Engle and Sheppard 2001). The joint quasi log-likelihood function (Gjika and Horvath 2013) is described as follows:

$$
\begin{aligned}
L(\Theta) &= -\frac{1}{2}\sum_{t=1}^{T}(k\log(2\pi)+\log(|H_t|)+e_t' H_t^{-1} e_t) \\
&= -\frac{1}{2}\sum_{t=1}^{T}(k\log(2\pi)+\log(|D_t R_t D_t|)+e_t' D_t^{-1} R_t^{-1} D_t^{-1} e_t) \\
&= -\frac{1}{2}\sum_{t=1}^{T}(k\log(2\pi)+2\log(|D_t|)+\log(|R_t|)+\varepsilon_t' R_t^{-1}\varepsilon_t)
\end{aligned} \tag{13}
$$

Eq. (13) can be separated into a volatility segment and a conditional correlation segment. This separation requires that the parameters in univariate GARCH models be denoted as Γ and that the parameters in the DCC model be denoted as Ψ . Thus, the quasi log-likelihood function can be written as follows:

$$
L(\Gamma,\Psi) = L_{vol}(\Gamma) + L_{corr}(\Gamma,\Psi) \tag{14}
$$

where $L_{vol}(\Gamma)$ represents the volatility segment and $L_{corr}(\Gamma,\Psi)$ corresponds to the conditional correlation segment. By replacing R_t with an identity matrix I_k in Eq. (13), the volatility segment becomes

$$
\begin{aligned}
L_{vol}(\Gamma) &= -\frac{1}{2}\sum_{t=1}^{T}(k\log(2\pi)+2\log(|D_t|)+\underbrace{\log(|I_k|)}_{0}+e_t' D_t^{-1} I_k D_t^{-1} e_t) \\
&= -\frac{1}{2}\sum_{t=1}^{T}(k\log(2\pi)+2\log(|D_t|)+e_t' D_t^{-2} e_t) \\
&= -\frac{1}{2}\sum_{t=1}^{T}(k\log(2\pi)+\sum_{i=1}^{k}(\log(h_{ii,t})+\frac{e_{i,t}^2}{h_{ii,t}})) \\
&= -\frac{1}{2}\sum_{i=1}^{k}\sum_{t=1}^{T}(\log(2\pi)+\log(h_{ii,t})+\frac{e_{i,t}^2}{h_{ii,t}})
\end{aligned} \tag{15}
$$

The quasi log-likelihood of the volatility segment is the sum of the individual quasi log-likelihoods from the univariate GARCH models. Conditioning on the univariate GARCH parameters, the quasi log-likelihood function of the conditional correlation segment can be written as follows:

$$
\begin{aligned}
L_{corr}(\Gamma,\Psi) &= -\frac{1}{2}\sum_{t=1}^{T}(k\log(2\pi)+2\log(|D_t|)+\log(|R_t|)+e_t{}'D_t^{-1}R_tD_t^{-1}e_t) \\
&= -\frac{1}{2}\sum_{t=1}^{T}(k\log(2\pi)+2\log(|D_t|)+\log(|R_t|)+\varepsilon_t{}'R_t\varepsilon_t)
\end{aligned} \tag{16}
$$

Because the term $k\log(2\pi)$ is a constant and the term $2\log(|D_t|)$ is given in Eq. (16), these terms do not enter the first-order condition and can be excluded. The term $2\log(|D_t|)$ is given in Eq. (16) because the quasi log-likelihood of the conditional correlation segment is conditioning on the parameters from the univariate GARCH models. Therefore, a simplified version of Eq. (16) can be written as

$$
L_{corr}(\Gamma,\Psi) = -\frac{1}{2}\sum_{t=1}^{T}(\log(|R_t| + \varepsilon_t{}'R_t\varepsilon_t) \tag{17}
$$

The first step in this two-stage method of maximizing the quasi likelihood is used to obtain the following:

$$
\hat{\Gamma} = \arg\max\{L_{vol}(\Gamma)\} \tag{18}
$$

After obtaining the values from Eq. (18), the equation uses the values provided by the second step, which is

$$
\underbrace{\max}_{\Psi}\{L_{corr}(\Gamma,\Psi)\} \tag{19}
$$

According to Engle (2002), the consistency of the second stage (i.e., Eq. (19)) is guaranteed by ensuring the consistency of the first stage (i.e., Eq. (18)) under reasonable regularity conditions.

2.4. Data

Weekly data from January 4, 1995, to July 24, 2013, were used in this study; this period provided a sample of 969 observations. Prices for Alberta fed steers (1200-1400 lbs.), feeder steers (500-600 lbs.), and feeder steers (800-900 lbs.) are obtained from CanFax (1994-2013). These three cattle markets were chosen because they represent three important stages, i.e., backgrounding, weaning, and finishing, in the Alberta cattle production chain. For fed cattle prices, data were unavailable from May 21, 2003, to June 4, 2003, because the first three weeks of the BSE crisis halted price quotations. These three data points were filled with the Chicago Mercantile Exchange (CME) live cattle futures prices from the U.S. because the Canadian federal government used these prices to design compensation programs for cattle producers who were affected by the 2003 BSE crisis (CanFax 2003). Fed cattle price data were lacking for three periods in 2013. These missing data were filled with predicted values using a linear regression between the Alberta fed cattle and the CME live cattle futures prices. The CME live cattle futures prices were obtained from the Global Financial Database (2013). Weekly prices of Lethbridge free on board (F.O.B.) barley and U.S. Chicago Board of Trade (CBOT) No. 2 yellow corn were obtained from the Alberta Canola Producers Commission (1994-2013) and the United States Department of Agriculture-Economic Research Service (USDA-ERS) (2013), respectively. All prices were in nominal terms, and the corn price was converted into Canadian dollars using exchange rates extracted from the Global Financial Database (2013).

[Table 1 is about here]

Table 1 presents summary statistics for the five natural logarithmically transformed market prices (i.e., $100 \times \log(p_{i,t})$) and weekly price changes (i.e., $100 \times \log(p_{i,t} / p_{i,t-1})$). The augmented Dickey-Fuller (ADF) test on the natural logarithmically transformed prices indicates that the two feeder cattle, barley and corn market prices were non-stationary, while the fed cattle price was stationary. ADF tests were also conducted; all price change series were found to be covariance stationary. The lag selections for the ADF tests were based on the BIC.

In summary, the logged fed cattle price may be considered as $I(0)$, while the other four logged market prices may be $I(1)$.[3]

The Ljung-Box test for autocorrelations was performed on the price changes in the studied markets; the results indicate a strong autocorrelation in all price changes, implying that the use of a VAR structure in the conditional mean estimation was necessary. Similarly, the Ljung-Box test

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[3] One might raise doubts regarding the logged fed cattle price being $I(0)$, therefore, the Philips-Perron (PP) and KPSS unit root tests were also performed on the logged fed cattle price as robustness checks. Results from the PP test and KPSS test confirmed that the logged fed cattle price was $I(0)$. The test statistics of the PP and KPSS unit root tests for the logged fed cattle price were -4.4462** and 0.4604, respectively, ** stand for significance level of 5%. The PP unit root test is testing the null hypothesis of the existence of a unit root, while the KPSS unit root test is testing the null hypothesis of the tested time series being stationary.

was also conducted on the squared price changes to check for ARCH effects. The results indicate strong ARCH effects in all market price changes, which validated the use of the GARCH model.

[Figure 1 is about here]

Figure 1 presents price levels in the cattle and feed grain markets. The fed cattle prices plummeted at the onset of the BSE crisis in 2003. The feeder cattle prices also decreased substantially; however, this decrease was smaller in magnitude than that of the fed cattle prices. Feed grain prices experienced two major increases during the past decade, which are highlighted by the bands in Figure 1. The first increase began in late 2006 and continued through mid-2008, while the second increase began in mid-2010 and is ongoing. In addition to these two periods of high commodity prices in the 2000s, the U.S. corn price also increased substantially in 1996, which coincides with a severe drought in the U.S. Midwest and a consequential large decrease in the corn inventory (Schwalm et al 2012).

Figures 2a and 2b present the price changes for the five markets. The price changes in all three cattle markets varied substantially during the 2003 BSE crisis. As for the feed grain markets, the price changes in the barley market did not vary substantially during the two periods of feed grain price spikes relative to the other periods. The price changes in the U.S. corn market exhibited larger fluctuations after mid-2006.

[Figure 2a is about here]

[Figure 2b is about here]

[Table 2a is about here]

[Table 2b is about here]

Table 2a summarizes the unconditional pairwise correlations among the logged prices of the five markets. Table 2b is the same as Table 2a except that the correlations are presented for the price changes in the five markets.

2.5. Empirical Results and Discussions

In this section, the empirical results are presented using several tables and figures; discussions are provided based on the presented findings.

2.5.1. Cointegration

Pairwise Johansen trace tests were performed on the four aforementioned logged market prices that were $I(1)$. The results in Table 3 provide evidence that the two feeder cattle prices and the two feed crop prices were cointegrated, each having one linear long-run equilibrium relationship.

[Table 3 is about here]

2.5.2. Conditional Mean Estimations

First, a five-variate VAR-GARCH model was estimated with a lag length of 13 for the autoregressive structure determined according to the AIC; furthermore, this model incorporated error correction terms when appropriate. Second, because of the large number of parameters (337 parameters) estimated in this five-variate VAR (13)-GARCH model, the statistically insignificant own and cross-equation autoregressive terms were removed; the VAR-GARCH model (as indicated in Appendix A.) was subsequently re-estimated. Table 4 and Table 5 (in the next section) are intended to be one table; however, these two tables are separated due to practical issues.

[Table 4 is about here]

Table 4 shows the estimation results for the conditional mean equation. In general, cattle price changes did not respond to feed price changes except for the 800- to 900-pound feeder cattle price changes, which responded to barley price changes in a slightly negative manner. This change was expected because feeder cattle (500-600 lbs.) are in the backgrounding stage in the Alberta cattle production chain and are mainly fed with forage. Therefore, the cost of barley was not an essential factor for determining feeder cattle (500-600 lbs.) prices. Furthermore, the fed cattle price changes were not affected by recent barley price changes, primarily because fed cattle are at the finishing stage in the Alberta cattle production chain; therefore, these cattle have already been fed with barley. As a result, recent barley prices were not an important component of fed cattle prices.

To measure the effects of BSE on market price changes, a dummy variable that was given a value of 1 on June 4, 2003, and 0 otherwise was included in all five conditional mean equations. This BSE dummy variable was significant only in the feeder cattle (500-600 lbs.) and fed cattle equations. However, the estimated coefficient of the BSE dummy variable in the feeder cattle

(500-600 lbs.) equation was positive, indicating that the beginning of the BSE crisis resulted in a positive effect on feeder cattle (500-600 lbs.) price changes. The raw data demonstrated that an increase in the lighter feeder cattle price occurred on the day of the BSE discovery; the price began to decrease during the following week, which may represent a lagging market response to the BSE crisis in the feeder cattle (500-600 lbs.) market because the feeder cattle (500-600 lbs.) are farther from the fed cattle market in the cattle supply chain.

Price changes in feed grains did not respond to cattle price changes. The results between the barley and corn equations indicate that barley price changes were largely affected by U.S. corn price changes in the short run. The error correction process suggests that a long-run price equilibrium occurred between the barley and corn price changes. However, the error correction coefficient was statistically significant only in the barley equation. This result implies that only the barley price changes adjusted toward the long-run equilibrium between the barley and corn markets; the adjustment occurred slowly.

2.5.3. Conditional Variance Estimations

Based on the BIC, the GJR GARCH specification was selected as the conditional variance equation for the feeder cattle (800-900 lbs.) price changes, while the exponential GARCH specification was chosen for the other four market price changes.

[Table 5 is about here]

Table 5 presents the estimation results for the exponential and GJR GARCH models. The results indicate that among the five commodity markets, the feeder cattle (800-900 lbs.) price volatility was the least susceptible to general market shocks and was characterized by an insignificant α. The reason for this insensitivity may be that feeder cattle (800-900 lbs.) are at the final stage of cattle fattening; therefore, limited action can be taken by feedlot owners against market shocks. The rigidities of production at this stage partially prevented the price volatility from responding to general market shocks.

In contrast, general market shocks had a large effect on the price volatility of the feeder cattle (500-600 lbs.) market. This effect may be due to the nature of inelastic derived demand in the lighter feeder cattle markets, increasing the sensitivity of their prices to market shocks relative to the heavier feeder cattle markets.

The estimated response of the fed cattle price volatility to general market shocks was statistically significant; however, the response was smaller than that in the feeder cattle (500-600 lbs.) market. This smaller response may be the result of a proportion of the fed cattle producers using forward pricing, such as contracting. In addition, the fed cattle market has relatively elastic derived demand, since the fed cattle market is closer to the final market (i.e., beef market) in the beef supply chain than the feeder cattle markets are. Therefore, own market shocks in the fed cattle market cannot raise price volatility as much as those in the feeder cattle markets.

The estimated volatility persistence, which was characterized by $\beta_i(s)$, where $\beta_i(s)=1$ corresponds to perfect persistence and $\beta_i(s)=0$ indicates no persistence, in all three cattle market was higher than the effects of market shocks on conditional volatility (represented by $\alpha_i(s)$ and $d_i(s)$).

The coefficients (i.e., $d_i(s)$ and γ_i) that were used to measure the asymmetric effects on price volatility were highly significant for all three cattle markets. Each estimated d_i or γ_i in the conditional variance equations for cattle price changes had the expected signs, i.e., negative in the exponential GARCH specification and positive in the GJR GARCH specification. The statistical significances of the estimated $d_i(s)$ and γ_i indicate that negative price shocks had larger effects on price volatility than positive price shocks. This phenomenon was interpreted based on the rationale provided by Stigler and Prakash (2011); the authors argued that livestock producers' production decisions primarily depend on current market prices. Following this logic, the fed cattle producers who are not under contract can hold their cattle in the feedlot longer when facing a price decrease. This behavior can create a supply shock, which in turn can generate more uncertainties in the market.

The aforementioned BSE dummy variable was also included in the conditional variance equations for all five market price changes; the dummy variable was significant only in the conditional variance equation of the fed cattle price changes.[4]

In regard to the feed grain markets, the barley price volatility was found to be the most susceptible to general market shocks among the studied markets, including the three cattle

[4] Initial effects of the BSE crisis on fed cattle price volatility were revealed by this dummy variable and then the remaining effects were accounted by the GARCH term.

markets. This effect is possibly related to the supply of feed barley in western Canada being determined after harvesting, in which case market agents may have insufficient time to form marketing strategies, resulting in market overreactions when facing a price shock.[5]

The estimated $\beta_i(s)$ (i.e., volatility persistence) were found to be higher than $\alpha_i(s)$ and $d_i(s)$ (i.e., the effects of market shocks on conditional volatility) in both conditional variance equations for feed grain price changes. No significant asymmetric effects were found in either feed grain price volatility.

The post-estimation diagnostics show that no remaining serial correlations and ARCH effects were found in the five univariate GARCH models (as shown in Table 5).

[Figure 3a is about here]

Figure 3a presents the fed and feeder cattle price volatility estimated from the univariate GARCH models for the entire study period. Compared to the non-BSE periods, the fed cattle price volatility increased by approximately twelve times when the 2003 Canadian BSE incident occurred.

The negative effects of the 2003 BSE crisis on the Canadian cattle industry triggered large and swift federal and provincial responses in terms of implementing compensation policies to BSE-affected agricultural and food producers. More than $3.7 billion was paid out by the federal and provincial governments to BSE-affected market agents during the second halves of 2003, 2004, 2005 and the first three quarters of 2006 (Klein and Le Roy 2010). According to CanFax (2003), LeBlanc (2008) and Klein and Le Roy (2010), the federal and provincial compensation packages comprised a variety of programs, such as deficiency payments, emergency loans and the fed cattle competitive bid program (primarily in Alberta).[6,7,8]

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[5] A proportion of feed barley produced in western Canada is barley that failed to meet the standards for human consumption (e.g., through malting); therefore, the amount of feed barley supplied in the local market must be determined after the malting companies make their selections.

[6] Please see details of the compensation packages in Klein and Le Roy (2010).

[7] The deficiency payment is designed as percentage coverage on a regressive sliding scale of price declines from a designated reference price (Canfax 2003).

[8] The competitive bid program was intended to ease the pressures on the Alberta slaughtering industry and the Alberta beef markets. This program provides compensation to fed cattle producers to sell their cattle at a lower price. Buyers who intended to pay the lowered price were required to hold the purchased live fed cattle in their facilities alive for at least eight weeks (Canfax 2003).

According to the fed cattle price volatility presented in Figure 3a, the compensation packages and the re-opening of the U.S. border to boneless beef cuts in September 2003 were effective in stabilizing the fed cattle market because the fed cattle price volatility gradually recovered to its average level by the end of 2004.

[Figure 3b is about here]

Figure 3b shows the fed and feeder cattle price volatility estimated with fed cattle price volatility in the BSE period excluded due to scale reason. Like the fed cattle price volatility, the feeder cattle (500-600 lbs.) price volatility also increased during the BSE incident; however, the increase had a smaller magnitude. The feeder cattle (800-900 lbs.) price volatility increased slightly at the beginning of the BSE crisis relative to the other two cattle price volatility. This result may be due to feeder cattle (800-900 lbs.) coinciding with the middle stage of cattle fattening (i.e., already in feedlots), which suggests that limited action can be taken by feedlot owners to counteract the BSE incident. The rigidities in production at this stage partially prevented the price volatility from increasing during the market crisis period.

Instead of increasing substantially at the beginning of the BSE crisis, the feeder cattle (800-900 lbs.) price volatility peaked at the beginning of 2004. Based on Canfax (2004), strong local demand combined with a lack of supply in the feeder cattle markets, particularly in the heavier feeder cattle (700+ lbs.) markets, may have caused the volatility peak.

In general, the results show that the fed cattle price volatility was higher than the feeder cattle price volatility during the BSE crisis; the opposite case occurred during the non-BSE periods. The fed cattle price volatility tends to respond to market shocks according to the Canadian and U.S. beef markets, while the feeder cattle price volatility tends to be determined primarily by own market conditions, e.g., quality issues and market agent behaviors.

[Figure 4 is about here]

Figure 4 presents the estimated price volatility for the barley and U.S. corn markets. The price volatility for Lethbridge barley did not change during the two price spike periods relative to previous periods (i.e., see Figure 4) despite the substantial increases in the price level.

In general, the results show that the corn price volatility was higher than the barley price volatility throughout the study period.[9] However, large volatility spikes appeared in the barley market.

One spike in the feed barley price volatility stands out in the 1990s (i.e., 1995). The elimination of the Western Grain Transportation Act (WGTA), which was formerly known as the Crow's Nest Freight Rate (CNFR), on August 1, 1995, is a potential reason for this spike because freight costs for western Canadian grain producers doubled or tripled in the 1995/1996 crop year due to the elimination of the WGTA (Schmitz et al 2002). The CNFR (before 1983) and the WGTA (after 1983) provided a transportation subsidy to encourage western Canadian grain producers to move their products to the east (Thunder Bay, Ontario) and west (Vancouver, British Columbia) export shipping terminals (Doan et al 2003). Furthermore, the U.S. corn market experienced several extremes during 1995/1996, mainly due to a severe drought in the Midwest. The fluctuations in the U.S. corn market could also potentially affect the western Canadian feed barley price though close market linkages.

Several spikes in feed barley price volatility also appeared in 2000 and 2004, which may be attributed to weather shocks because these two years marked the beginning and end of a protracted drought period in western Canada (Schwalm et al 2012). One volatility spike in the feed barley market was observed on August 8, 2012, which is shown in Figure 4. This spike may have been indirectly caused by the elimination of the Canadian Wheat Board's (CWB's) monopsony on August 1, 2012, which may have introduced short-term price uncertainties to market agents.[10]

2.5.4. The Diagonal AG-DCC GARCH Estimation

[Table 6 is about here]

Table 6 summarizes the parameters estimated from the diagonal AG-DCC GARCH model (i.e., Eq. (6)). However, these parameters were not used to directly interpret dynamic conditional

[9] The 2008 financial crisis did not seem to cause large volatility responses in the studied commodity markets. One of the potential reasons for this is that many speculators switched their investments from stock and bond markets to futures market, which involves physical products, due to the crisis. Based on the traditional view on economics, more speculations in the commodity markets would more likely stabilize them (Friedman 1953).

[10] Prior to this date, wheat and barley for human consumption and feed barley for export in the prairie provinces had to go through the CWB.

variances and covariances. These dynamic conditional covariance equations (see Eq. (11)) incorporate products of the estimated coefficients. Therefore, the standard errors for each of the conditional covariance equations were calculated based on the delta method. See details of the delta method in Appendix B. The products of the estimated parameters provide interpretations on effects of cross-sectional market shocks on the calculated conditional correlations in market pairs.

[Table 7 is about here]

Table 7 shows the products of the parameters. Parameters $a_{ii}a_{jj}$ and $g_{ii}g_{jj}$ were used to measure the effects of cross-sectional general shocks (i.e., $a_{ii}a_{jj}$, past negative and positive innovations that occurred in both markets) and the effects of cross-sectional negative shocks (i.e., $g_{ii}g_{jj}$, past negative innovations that occurred in both markets) on the conditional covariances between market price changes, respectively. For example, the product of the estimated parameters representing cross-sectional general shocks (i.e., $a_{11}a_{22}$) was found to be positive and statistically significant between the two feeder cattle price changes. This result suggests that the conditional covariance was positively affected if the general shocks in the two feeder cattle markets shared the same sign. This finding was not surprising because these two feeder cattle markets are closely connected within the cattle supply chain; moreover, their prices tend to respond in a similar manner to general market shocks. Furthermore, a statistically significant asymmetric effect of cross-sectional negative shocks was found in this case, indicating that the covariance (in absolute value) was more responsive to cross-sectional negative market shocks than to cross-sectional positive market shocks. Furthermore, $b_{ii}b_{jj}$ was used to measure the persistence of conditional covariance changes between market prices.

In summary, cross-sectional general shocks only affected the covariance between the two feeder cattle markets and the covariance between the feeder cattle and U.S. corn markets. In terms of estimating asymmetric effects on the covariances among the studied price changes, the results demonstrate that the covariances among all pairs of cattle price changes were more responsive to cross-sectional negative shocks than to cross-sectional positive shocks. Asymmetric effects were also found in all covariances between cattle and feed barley price changes.

The estimated parameters presented in Tables 6 and 7 were intended to explain the dynamics of covariances between price changes. Rather than focusing on conditional covariances, summary statistics and time plots of the dynamic conditional correlations calculated based on Eq. (12) were generated. In doing so, several common problems regarding covariance can be avoided. For example, covariance has units that can cause market covariance with other units (i.e., $CAN/cwt in cattle markets and $CAN/tonne in feed grain markets) to be incomparable.

[Table 8 is about here]

Table 8 presents summary statistics for the dynamic conditional correlations. In general, the dynamic conditional correlation between the two feeder cattle price changes had the highest mean value, while the dynamic conditional correlation between the fed cattle and barley price changes had the lowest mean value.

[Figure 5 is about here]

Figure 5 illustrates the dynamic conditional correlations estimated for all three pairs of cattle price changes. According to the first panel, the dynamic conditional correlation between the feeder cattle (500-600 lbs.) and the fed cattle price changes remained within a window of 0.1 to 0.3 for most of the study period. At the beginning of the 2003 Canadian BSE crisis, the dynamic conditional correlation between the two price changes plummeted to nearly zero (i.e., 0.0286); however, the correlation returned rapidly to its normal level by the end of 2003.

Compared to the dynamic conditional correlation between the feeder cattle (500-600 lbs.) and the fed cattle price changes, the dynamic conditional correlation between the feeder cattle (800-900 lbs.) and the fed cattle price changes (second panel) exhibited less temporal variability. The dynamic conditional correlation between the feeder cattle (800-900 lbs.) and the fed cattle price changes also instantaneously decreased (i.e., 0.0549) when the BSE crisis occurred.

The results presented in the first two panels of Figure 5 indicate that a market crisis likely weakened the market linkages between the feeder cattle and the fed cattle markets; therefore, the devastating effects of the BSE crisis on the fed cattle market were only partially transmitted to the feeder cattle markets.

According to the third panel in Figure 5, the dynamic conditional correlation estimated between the two feeder cattle price changes was positive with a mean of 0.449. Moreover, throughout the study period, the dynamic conditional correlation estimated between the feeder (500-600 lbs.)

and the feeder (800-900 lbs.) cattle price changes exhibited large variations; the highest standard deviation was 0.1204 (see Table 8) among the ten dynamic conditional correlations. This dynamic conditional correlation did not change substantially during the BSE crisis. Apart from the BSE period, two large variations in the estimated dynamic conditional correlation that occurred in 1997/1998 and 2011-2013 merit mentioning. Based on CanFax weekly summary reports (1997, 2011), quality issues combined with the different market conditions between the light and heavy feeder cattle markets were the primary causes of the two fluctuations in the dynamic conditional correlations between the price changes.

[Figure 6 is about here]

Figure 6 presents the estimated dynamic conditional correlations between the feeder cattle (500-600 lbs.) and feed barley price changes and the conditional correlations between the feeder cattle (800-900 lbs.) and feed barley price changes. In general, these two dynamic conditional correlations were negative and nearly zero, exhibiting similar patterns throughout the entire study period. Based on the results shown in Table 7, cross-sectional negative market shocks had a greater impact on the dynamic conditional correlation between the feeder cattle (500-600 lbs.) and the barley price changes than they did on the correlation between the feeder cattle (500-600 lbs.) and the barley price changes, which is particularly true during the BSE period. The market linkage between the feeder cattle (500-600 lbs.) and barley markets was stronger during the BSE period than in other periods, indicating that lighter feeder cattle producers may benefit from watching the barley market closely during periods of cattle market distress because lighter feeder cattle prices are more susceptible to barley price shocks.

[Figure 7 is about here]

Figure 7 presents the dynamic conditional correlations between the feeder cattle (500-600 lbs.) and U.S. corn price changes and the correlations between the feeder cattle (800-900 lbs.) and U.S. corn price changes. These two dynamic conditional correlations exhibited similar patterns over time. However, more variation was observed in the dynamic conditional correlation between the feeder cattle (800-900 lbs.) and the U.S. corn price changes. Similarly to the results shown in Figure 6, Figure 7 suggests that the dynamic conditional correlations were also negative and near zero. In general, this result indicates that the market interdependencies between the feeder cattle markets and the U.S. corn market were weak.

[Figure 8 is about here]

Figure 8 shows the estimated dynamic conditional correlations between the fed cattle and feed barley price changes and the correlations between the fed cattle and U.S. corn price changes. In general, the dynamic conditional correlations between the fed cattle and feed grain (i.e., barley and corn) price changes were nearly zero throughout the entire study period. Furthermore, these two dynamic conditional correlations did not change during BSE crisis periods and feed price spikes (i.e., the shaded areas in Figure 8). This result indicates that price reductions in the fed cattle market did not result in price reductions in the feed grain markets; moreover, price increases in the feed grain markets also did not result in price increases in the fed cattle market. Therefore, the profitability of the fed cattle producers decreased in both cases. One of the potential reasons for this phenomenon is that the Alberta fed cattle market plays an intermediary role between the feeder cattle and retail markets (i.e., Canadian and U.S. beef markets); therefore, the fed cattle producers are less likely to modify their cattle prices under high feed prices.

[Figure 9 is about here]

Figure 9 shows the dynamic conditional correlation estimated between the feed barley and U.S. corn price changes. This dynamic conditional correlation was positively correlated with an average of approximately 0.1. Furthermore, it fluctuated to a great degree over time. These variations may reflect the potential deviation of one price from the other during price peaks, which weakened the interdependence of the two markets. Because the conditional mean estimation results in Table 4 confirmed that the U.S. corn price greatly affected the barley price rather than vice versa, it is more likely that the barley price deviated from the U.S. corn price.

2.6. Concluding Remarks

This study assessed the price volatility and market interdependencies in the Alberta cattle, feed barley, and U.S. corn markets due to the effects of the 2003 Canadian BSE crisis and recent episodes of feed price surges. To achieve these objectives, the diagonal AG-DCC GARCH model was employed. Four key findings emerge.

First, the estimated fed cattle price volatility was found to be higher than the feeder cattle price volatility during the BSE crisis; the opposite was true during non-BSE periods. According to analyses of time plots of the estimated cattle price volatility, the fed cattle price volatility was more likely to respond to market shocks according to the Canadian and U.S. beef markets. Therefore, fed cattle producers may benefit by monitoring the Canadian and U.S. beef markets closely to manage potential market risks. Additionally, the feeder cattle price volatility tends to be determined by own market conditions, such as quality issues and market agent behaviors. To manage price risks, feeder cattle producers may do well to consider signing forward contracts with their consumers or increasing their market power through vertical integration. Furthermore, negative cattle price changes were found to affect the cattle price volatility more than positive cattle price changes. This indicated cattle producers could benefit from employing protective means during periods of market price drops. For example, cattle producers could include countercyclical measures, which could offset volatility induced by weather shocks, in their risk management plans.

The volatility estimation results for the feed grain markets revealed that corn price volatility was likely to be higher than barley price volatility. However, barley price volatility was more responsive to market shocks than corn price volatility was.

Second, a weakened market linkage was found at the beginning of the BSE crisis between the feeder cattle and the fed cattle markets, implying that feeder cattle producers were partially buffered against the market crisis and had more time to employ protective measures.

Third, very weak market interdependencies were found between the cattle and feed grain markets, indicating that the cattle producers may have had low market power because they could not affect the feed prices and also failed to pass the increased costs to the meat packers. One potential solution is for cattle producers to vertically integrate at various stages to gain more market power and, in turn, to maintain their profitability.

Finally, a positive dynamic conditional correlation was obtained between the barley and U.S. corn markets. The market linkage between these two feed grain markets was weakened during feed price surges; therefore, barley producers who intend to manage their market risks should pay extra attention to own market conditions during periods of high prices.

Chapter 3. Analysis of Price Volatility Spillovers in the Western Canadian Feed Barley, U.S. Corn and Alberta Cattle Markets

3.1. Introduction

Investigation of price volatility spillovers in agricultural markets has a wide range of implications. Within agricultural supply chains, food producers are very interested in price volatility because the added risks increase the difficulties for them to manage price risks. Unstable input markets further expose them to reduced profitability. While in downstream markets growing uncertainty, compels them to modify their marketing strategies to manage risks (Rabobank 2011). Understanding the size and direction of price volatility spillovers in agricultural supply chains is also important for policy makers in making informed decisions; given knowledge about price volatility spillovers in a particular supply chain, policy makers can design efficient market programs (e.g., price stabilization programs) at different stages of the supply chain (Newbery 1989; Serra 2011; Assefa et al 2014).

Several market shocks have occurred in the Alberta cattle industry over the past decade. Major shocks include the 2003 bovine spongiform encephalopathy (BSE) crisis and U.S. mandatory country of origin labeling (MCOOL). Additionally, recent episodes of feed price surges may have created greater difficulties for Alberta cattle producers. Agribusiness owners and policy makers are concerned about potential price volatility spillovers throughout the cattle supply chain and the effects of such shocks in generating price volatility spillovers between the cattle and feed grain markets.

This study aims to assess price volatility spillovers in the Alberta cattle supply chain and between three Alberta cattle markets (i.e., feeder cattle (500-600 lbs.), feeder cattle (800-900 lbs.) and fed cattle) and the feed grain (i.e., Lethbridge barley and U.S. corn) markets. Together, these markets constitute the five markets studied in this paper. Bivariate versions of the asymmetric BEKK-GARCH model (Grier et al 2004) are used to achieve these objectives.

The remainder of this chapter is organized as follows. Section 3.2 provides a brief review of the relevant literature. Section 3.3 outlines the method employed. Section 3.4 describes the data. Section 3.5 presents the empirical results and discussion. Section 3.6 concludes.

3.2. Literature Review

Bauwens et al (2006) provide a survey of major volatility spillover models. Some of the major models include the VECH GARCH model (Bollerslev et al 1988), the factor model (Engle et al 1990) and the BEKK-GARCH model (Engle and Kroner 1995). Among these, the BEKK-GARCH model has attracted the most attention in the fields of finance and energy economics. The BEKK-GARCH model is specified so that by construction, it enforces positive-definiteness on the estimated conditional variance-covariance matrix; thus, no extra restrictions are needed (Bauwens et al 2006). Furthermore, the parameters estimated in the BEKK-GARCH model reveal the full dynamics of volatility spillovers, including their sizes and directions.

Researchers in finance believe that stock and commodity market price volatility may be more responsive to price decreases than to price increases, a phenomenon referred to as the leverage effect (Black 1976). In contrast, the inventory effect (Ng and Pirrong 1994) has gained popularity in the field of agricultural economics. Under the inventory effect, agricultural commodity price volatility tends to respond more to price increases than to price decreases. Motivated by these two concepts, Grier et al (2004) developed an extended version of the BEKK-GARCH model, called the asymmetric BEKK-GARCH model, which incorporates an asymmetric component. The asymmetric BEKK-GARCH model can be used to measure asymmetric aspects of price volatility responses to price increases or decreases.

Although the literature on price volatility spillovers in the fields of finance and energy economics is extensive, studies on volatility spillovers in agricultural markets are limited. Assefa et al (2014) provide a comprehensive literature review on price volatility spillovers in food supply chains, identifying several studies that explicitly investigate price volatility spillovers in food supply chains (Khan and Helmers 1997; Natcher and Weaver; Buguk et al 2003; Apergis and Rezitis 2003; Zheng et al 2008; Uchezuba et al 2010).

Khan and Helmers (1997) investigate price volatility spillovers in the U.S. corn, beef and pork markets. Applying a vector autoregressive (VAR) model both on calculated rolling variances of beef and pork prices at the farm, wholesale and retail levels and on U.S. corn prices, they found volatility spillovers from corn prices to farm-level prices of beef and pork. Natcher and Weaver (1999) apply a VAR model of GARCH-estimated conditional price volatility to the U.S. beef supply chain, finding bidirectional price volatility spillovers throughout the U.S. beef supply chain. Buguk et al (2003) study price volatility spillovers in the U.S. catfish supply chain. Incorporating volatility spillover components into an exponential GARCH model, they find statistically significant evidence of the existence of unidirectional price volatility spillovers from the feed grain markets (i.e., corn, soybean and menhaden) to the catfish feed market and the farm and wholesale catfish markets. Apergis and Rezitis (2003) utilize a variation of the VECH GARCH model, finding volatility spillovers from agricultural input and retail food markets to agricultural output markets. Zheng et al (2008) conduct an analysis on the prices of 45 retail food items in the U.S. By using an exponential GARCH model (with spillover components), they find unidirectional price volatility spillovers from markets at the retail level to markets at the farm level. Uchezuba et al (2010) also apply an exponential GARCH model (with spillover components) to the South African broiler supply chain, finding unidirectional price volatility spillovers from retail markets to farm markets.

3.3. Method

This study attempts to identify volatility linkages in the Alberta cattle supply chain and between the Alberta cattle and feed grain markets. The U.S. corn market is included in this study because southern Alberta feedlot owners sometimes import U.S. corn as a substitute for barley (Crawford et al 2012). Moreover, the Canadian barley market is driven by the U.S. corn price because of the dominating position the U.S. corn industry holds in the North American and even worldwide agricultural markets. To achieve this objective, a bivariate asymmetric BEKK-GARCH model developed by Grier et al (2004) is employed. This asymmetric model originally proposed by Engel and Kroner (1995) as the BEKK-GARCH model, which is symmetric.

3.3.1. Conditional Mean Equations

To fit any multivariate GARCH model, an appropriate conditional mean model is needed. In this paper, the conditional mean model is specified as either a bivariate VAR model or a bivariate vector error correction (VEC) model based on the results of the Johansen cointegration test (Johansen 1988). Lag structures for the conditional mean models are selected based on the Akaike Information Criterion (AIC). After estimating the bivariate VAR or VEC models, insignificant coefficients are eliminated, and the conditional mean models are re-estimated. The cointegration tests were conducted on logged prices and all other modeling was performed on price changes (i.e., $\Delta \log(p_t) = \log\left({p_t}\big/{p_{t-1}} \right) \times 100$).

The bivariate VAR model can be specified as follows:

$$\begin{aligned} \Delta \log(P_t) &= c_0 + \sum_{j=1}^{n} \theta_j \Delta \log(P_{t-j}) + \omega \cdot bse + \varepsilon_t \\ \varepsilon_t \mid \Psi_{t-1} &\sim (0, H_t) \end{aligned} \tag{20}$$

where $\Delta \log(P_t)$ is a 2×1 vector of price changes for any two of the five studied markets, c_0 is a 2×1 vector of constants, $\theta_j \; \forall \; j = 1, \ldots, n$ are 2×2 parameter matrices, ω is a 2×1 parameter vector and bse is a dummy variable that takes on the value of one from May 28, 2003 to August 20, 2003 and zero otherwise. ε_t is a 2×1 vector of residuals that depends on past information Ψ_{t-1} and has zero mean and a conditional variance-covariance matrix H_t. If a pair of price changes is cointegrated, then the error correction term is included in Eq. (20), so that the VAR model extends to the VEC model:

$$\begin{aligned} \Delta \log(P_t) &= c_0 + \sum_{j=1}^{n} \theta_j \Delta \log(P_{t-j}) + \omega \cdot bse + \vartheta \cdot ect_{t-1} + \varepsilon_t \\ \varepsilon_t \mid \Psi_{t-1} &\sim (0, H_t) \end{aligned} \tag{21}$$

where ϑ is 2×1 parameter vector, and ect_{t-1} is the error correction term for cointegrated pairs.

3.3.2. Asymmetric BEKK-GARCH Model

Following the determination of the appropriate conditional mean model, the asymmetric BEKK-GARCH model is estimated with the aforementioned bse dummy variable.[11] Incorporation of the exogenous bse dummy in the asymmetric BEKK-GARCH model allows the determination of whether the BSE crisis influenced the conditional covariance (i.e. volatility linkage) among markets. The bivariate asymmetric BEKK-GARCH model with exogenous variables can be written as follows:

[11] Hereafter, the terms "asymmetric BEKK-GARCH" and "BEKK-GARCH" are used interchangeably.

$$H_t = (C + \Omega BSE)(C + \Omega BSE)' + A'\varepsilon_{t-1}\varepsilon_{t-1}^{'}A + B'H_{t-1}B + D'\epsilon_{t-1}\epsilon_{t-1}^{'}D$$

$$\begin{aligned} & H_t = \begin{bmatrix} h_{11} & h_{12} \\ h_{21} & h_{22} \end{bmatrix}, \\ & C = \begin{bmatrix} c_{11} & 0 \\ c_{21} & c_{22} \end{bmatrix}, \quad \Omega = \begin{bmatrix} \omega_{11} & 0 \\ \omega_{21} & \omega_{22} \end{bmatrix}, \quad A = \begin{bmatrix} a_{11} & a_{12} \\ a_{21} & a_{22} \end{bmatrix}, \\ & B = \begin{bmatrix} b_{11} & b_{12} \\ b_{21} & b_{22} \end{bmatrix}, \quad D = \begin{bmatrix} d_{11} & d_{12} \\ d_{21} & d_{22} \end{bmatrix} \end{aligned} \tag{22}$$

where H_t is the conditional variance-covariance matrix from Eqs. (20) or (21), C and Ω are 2×2 lower triangular matrices with constants for each entry and BSE is a 2×2 lower triangular matrix with the bse dummy variable for each entry. A, B, C, D and Ω are parameter matrices that will be estimated. A is a 2×2 parameter matrix, and $\varepsilon_{t-1}\varepsilon_{t-1}^{'}$ is the outer product of residuals from the conditional mean model. B is a 2×2 parameter matrix, and H_{t-1} is the conditional variance-covariance matrix from the previous period. D is a 2×2 parameter matrix; ϵ_{t-1} is a 2×1 vector with elements $\epsilon_{i,t-1} = I[\varepsilon_{i,t-1} < 0] \circ \varepsilon_{i,t-1}$ and/or $\epsilon_{i,t-1} = I[\varepsilon_{i,t-1} \geq 0] \circ \varepsilon_{i,t-1}$ $\forall\, i = 1,2$, where $I[\bullet]$ is a 2×1 indicator function, and the vector ϵ_{t-1} introduces asymmetric effects to the BEKK-GARCH specification. The operator $\circ$ denotes the Hadamard product (i.e., the element-wise product). The parameters in A and D capture the own- and cross-volatility spillovers caused by market shocks, respectively. Specifically, the parameters in D measure the asymmetric effects induced by positive or negative market shocks. The parameter matrix B quantifies the persistence of own conditional variances and volatility spillovers through the past conditional covariance between markets.

To gain a full understanding of the interactions between two market conditional variances, the conditional variances and conditional covariance equations are expressed in the following three equations:

$$\begin{aligned} h_{11,t} = & (c_{11} + \omega_{11} bse)^2 + a_{11}{}^2 \varepsilon_{1,t-1}^2 + a_{21}{}^2 \varepsilon_{2,t-1}^2 + 2a_{11}a_{21}\varepsilon_{1,t-1}\varepsilon_{2,t-1} \\ & + b_{11}{}^2 h_{11,t-1} + b_{21}{}^2 h_{22,t-1} + 2b_{11}b_{21}h_{12,t-1} \\ & + d_{11}^2 \epsilon_{1,t-1}^2 + 2d_{11}d_{21}\epsilon_{1,t-1}\epsilon_{2,t-1} + d_{21}^2 \epsilon_{2,t-1}^2 \end{aligned} \tag{23}$$

$$
\begin{aligned}
h_{12,t} &= \left(c_{11}+\omega_{11}bse\right)\left(c_{21}+\omega_{21}bse\right)+\alpha_{11}\alpha_{12}\varepsilon_{1,t-1}^{2}+\alpha_{21}\alpha_{22}\varepsilon_{2,t-1}^{2} \\
&+\left(\alpha_{11}\alpha_{22}+\alpha_{12}\alpha_{21}\right)\varepsilon_{1,t-1}\varepsilon_{2,t-1}+\beta_{11}\beta_{12}h_{11,t-1}+\beta_{21}\beta_{22}h_{22,t-1} \\
&+\left(\beta_{11}\beta_{22}+\beta_{12}\beta_{21}\right)h_{12,t-1}+\varphi_{11}\varphi_{12}\epsilon_{1,t-1}^{2}+\varphi_{21}\varphi_{22}\epsilon_{2,t-1}^{2} \\
&+\left(\varphi_{11}\varphi_{22}+\varphi_{12}\varphi_{21}\right)\epsilon_{1,t-1}\epsilon_{2,t-1}
\end{aligned} \tag{24}
$$

$$
\begin{aligned}
h_{22,t} &= \left(c_{21}+\omega_{21}bse\right)^{2}+\left(c_{22}+\omega_{22}bse\right)^{2}+{a_{12}}^{2}\varepsilon_{1,t-1}^{2}+{a_{22}}^{2}\varepsilon_{2,t-1}^{2} \\
&+2a_{12}a_{22}\varepsilon_{1,t-1}\varepsilon_{2,t-1}+{b_{12}}^{2}h_{11,t-1}+{b_{22}}^{2}h_{22,t-1} \\
&+2b_{12}b_{22}h_{12,t-1}+{d_{12}}^{2}\epsilon_{1,t-1}^{2}+{d_{22}}^{2}\epsilon_{2,t-1}^{2}+2d_{12}d_{22}\epsilon_{1,t-1}\epsilon_{2,t-1}
\end{aligned} \tag{25}
$$

where $h_{11,t}$ and $h_{22,t}$ are the conditional variances for markets 1 and 2, respectively, and $h_{12,t}$ is the conditional covariance between these two markets. Furthermore, because all parameters in Eqs. (23) to (25) are in squared or product forms, the parameters in Eqs. (23) to (25) are simplified by replacing the nonlinear combinations of parameters with Greek letters. The simplified equations are specified as follows:

$$
\begin{aligned}
h_{11,t} &= \gamma_{11}+\alpha_{11}\varepsilon_{1,t-1}^{2}+\alpha_{11}^{'}\varepsilon_{2,t-1}^{2}+\alpha_{11}^{''}\varepsilon_{1,t-1}\varepsilon_{2,t-1}+\beta_{11}h_{11,t-1}+\beta_{11}^{'}h_{22,t-1} \\
&+\beta_{11}^{''}h_{12,t-1}+\varphi_{11}\epsilon_{1,t-1}^{2}+\varphi_{11}^{'}\epsilon_{2,t-1}^{2}+\varphi_{11}^{''}\epsilon_{1,t-1}\epsilon_{2,t-1}
\end{aligned} \tag{26}
$$

$$
\begin{aligned}
h_{12,t} &= \gamma_{12}+\alpha_{12}\varepsilon_{1,t-1}^{2}+\alpha_{12}^{'}\varepsilon_{2,t-1}^{2}+\alpha_{12}^{''}\varepsilon_{1,t-1}\varepsilon_{2,t-1}+\beta_{12}h_{11,t-1}+\beta_{12}^{'}h_{22,t-1} \\
&+\beta_{12}^{''}h_{12,t-1}+\varphi_{12}\epsilon_{1,t-1}^{2}+\varphi_{12}^{'}\epsilon_{2,t-1}^{2}+\varphi_{12}^{''}\epsilon_{1,t-1}\epsilon_{2,t-1}
\end{aligned} \tag{27}
$$

$$
\begin{aligned}
h_{22,t} &= \gamma_{22}+\alpha_{22}\varepsilon_{2,t-1}^{2}+\alpha_{22}^{'}\varepsilon_{1,t-1}^{2}+\alpha_{22}^{''}\varepsilon_{1,t-1}\varepsilon_{2,t-1}+\beta_{22}h_{22,t-1}+\beta_{22}^{'}h_{11,t-1} \\
&+\beta_{22}^{''}h_{12,t-1}+\varphi_{22}\epsilon_{2,t-1}^{2}+\varphi_{22}^{'}\epsilon_{1,t-1}^{2}+\varphi_{22}^{''}\epsilon_{1,t-1}\epsilon_{2,t-1}
\end{aligned} \tag{28}
$$

[Table 9 is about here]

Table 9 provides the correspondence between the Greek letters in Eqs. (26) to (28) and the nonlinear combinations of parameters in Eqs. (23) to (25).

The parameter combinations $\alpha_{ii}, \varphi_{ii}$ measure the effects of own general market shocks (past innovations) and own asymmetric market shocks (past negative or positive innovations) on conditional variances. β_{ii} measures the persistence of volatility.

The parameter combinations $\alpha_{ii}^{'}, \varphi_{ii}^{'}$ quantify the volatility spillover effects directly from general shocks (past innovations) and asymmetric shocks (past negative or positive innovations) in the other market. $\beta_{ii}^{'}$ measures volatility spillover effects directly from volatility persistence in the other market. In this study, these three parameter combinations ($\alpha_{ii}^{'}, \varphi_{ii}^{'}$ and $\beta_{ii}^{'}$) are defined as the direct volatility spillover components because these three components measure how market shocks and volatility persistence in one market directly influence the other market.

Parameter combinations $\alpha_{ii}^{''}, \varphi_{ii}^{''}$ are used to assess volatility spillover effects indirectly through the product of general shocks (past innovations) and the product of asymmetric shocks (past negative or positive innovations) in both markets. $\beta_{ii}^{''}$ measures the effects of the previous conditional covariance on the conditional variances in each market. In this study, these three parameter combinations ($\alpha_{ii}^{''}, \varphi_{ii}^{''}$ and $\beta_{ii}^{''}$) are defined as indirect volatility spillover components because they measure how the covariance between both markets and joint market shocks affect price volatility in one market.

The parameters in matrices C, Ω, A, B and D are estimated using maximum likelihood methods, and the standard errors of the nonlinear combinations of parameters are calculated using the delta method. See details of the delta method in Appendix B. Descriptions of the likelihood function are provided in the following two sections.

3.3.3. The Likelihood Function

Estimations of bivariate asymmetric BEKK-GARCH models in this study are performed through maximum likelihood by assuming a conditional multivariate student t distribution or a conditional multivariate normal distribution. The conditional multivariate student t distribution is used to account for potentially leptokurtically distributed residuals in the conditional mean equations. The conditional multivariate normal distribution is employed as an alternative to the multivariate student t distribution in cases where the bivariate asymmetric t-BEKK-GARCH models fail to pass the post-estimation diagnostics for the remaining ARCH effects. Engle and Sheppard (2001) proved that although the assumption of conditional normality is often violated in GARCH modeling, parameters can be interpreted though a consistent and asymptotically normal Quasi-Maximum Likelihood (QML) estimator.

The general notation of the likelihood function for a vector of residuals is as follows:

$$f(\varepsilon_t, \varepsilon_{t-1}, ..., \varepsilon_T \mid \xi_{t-1}) = \prod_{t-1}^{T} f(\varepsilon_t \mid \xi_{t-1}) \quad (29)$$

where ε_t is a vector of residuals at time t, and ξ_{t-1} is the information available at time $t-1$. T is the sample size.

The log-likelihood function of the multivariate student t-distribution is as follows:

$$L(\Theta) = T \log\left[\frac{\Gamma(\frac{v+k}{2})}{\sqrt{\pi(v-2)}\Gamma(\frac{v}{2})}\right] - \frac{1}{2}\sum_{t=1}^{T}\log\left|H_t\right| - \frac{v+k}{2}\sum_{t-1}^{T}(1+\frac{\varepsilon_t^{'} H_t^{-1}\varepsilon_t}{v}) \quad (30)$$

where Θ is a parameter field, $\Gamma(\bullet)$ is a gamma function, v is degrees of freedom, and k is the number of markets in the model ($k=2$ in a bivariate case). Because the purpose of the multivariate student t distribution is to account for potentially leptokurtically distributed residuals, $v>2$ is set so that the distribution is characterized by fat tails.

As an alternative to the multivariate student t distribution, the log-likelihood function of the conditional multivariate normal distribution is denoted as follows:

$$L(\Theta) = -\frac{1}{2}\sum_{t=1}^{T}(k\log(2\pi) + \log\left|H_t\right| + \varepsilon_t^{'} H_t^{-1}\varepsilon_t) \quad (31)$$

The conditional multivariate normal distribution has the advantage of making estimation relatively convenient. However, even if the true multivariate distribution of the residual vector differs from multivariate normality, the parameters estimated by maximizing Eq. (31) retain the popular QML interpretation (Engle and Sheppard 2001).

3.4. Data

Weekly data from January 4, 1995, to July 24, 2013, yielding a sample of 969 observations, are used in this study. Nominal prices of Alberta fed steers (1200-1400 lbs.), feeder steers (500-600 lbs.) and feeder steers (800-900 lbs.) from CanFax (1994-2013) were obtained. The fed cattle prices from May 21, 2003, to June 4, 2003 were unavailable because there were no price quotations during the first three weeks of the BSE crisis. These three data points were filled with

Chicago Mercantile Exchange (CME) live cattle futures prices because these prices are reference prices used by the Canadian federal government in designing compensation programs for cattle producers (CanFax 2003). Three data points for fed cattle prices were also missing, primarily due to floods in Calgary, Alberta in 2013. To fix this problem, an OLS regression of the CME live cattle futures price on the Alberta fed cattle price was run, and predicted values were obtained to fill the three missing data points. CME live cattle futures prices are obtained from the Global Financial Database (2013). Weekly nominal prices of Lethbridge free on board (F.O.B.) barley and U.S. Chicago Board of Trade (CBOT) No. 2 yellow corn were obtained from the Alberta Canola Producers Commission (1994-2013) and the USDA-ERS (2013), respectively. The U.S. corn price is converted into Canadian dollars.

[Table 10 is about here]

Table 10 presents summary statistics for all five natural logarithmically transformed market prices and weekly price changes. The augmented Dickey-Fuller (ADF) test is used to check the stationarity of each of the logarithmically transformed prices. The results indicate that the two feeder cattle prices and the barley and corn prices are non-stationary, whereas the fed cattle price is covariance stationary. Furthermore, ADF tests were conducted on all series of price changes, finding all of them to be covariance stationary. Lag selections for ADF tests are based on the Bayesian information criterion (BIC).

In summary, the logged fed cattle price might be considered as $I(0)$, whereas the other four logged market prices might be $I(1)$. (see footnote 3 for details of the robust tests)

[Figure 10 is about here]

Figure 10 presents price levels in cattle and feed grain markets. Whereas the fed cattle price decreased substantially at the beginning of the 2003 BSE crisis, the feeder cattle prices also decreased, but the magnitudes were smaller than those of the fed cattle price. The feed grain prices exhibited two major increases in the past decade, as shown by the shaded areas. The first increase started in late 2006 and continued through mid-2008. The second increase started in mid-2010.

[Figures 11a and 11b are about here]

Figures 11a and 11b show price changes in the five markets. Price changes in all three cattle markets fluctuated greatly during the 2003 BSE crisis. In the feed grain markets, price changes in the barley market do not appear to have varied very much during the two periods of food price surges compared with other periods. The U.S. corn price changes tend to show greater fluctuations after mid-2006.

3.5. Empirical Results and Discussion

This section begins by providing the results of cointegration tests. Then, this section presents and discusses the results of the conditional mean equations, the estimated price volatility and the nonlinear combinations of the estimated parameters from the bivariate asymmetric BEKK-GARCH models of interest.

3.5.1. Cointegration

The results of cointegration tests are shown in Table 11. Johansen trace tests (Johansen 1988) were performed on logged market prices that were $I(1)$.

[Table 11 is about here]

As shown in Table 11, the results of the Johansen trace tests (Johansen 1988) yielded evidence of cointegration between the two feeder cattle prices and between the two feed grain prices. These results implied the existence of long-run price relationships between the feeder cattle (500-600 lbs.) market and the feeder cattle (800-900 lbs.) market and long-run price relationshipts between the Lethbridge barley market and the U.S. corn market.

3.5.2. Price Volatility and Volatility Spillovers in the Alberta Cattle Supply Chain

This section presents the estimation results for the bivariate asymmetric BEKK-GARCH models of (i) the two feeder cattle markets; (ii) the feeder cattle (500-600 lbs.) market and the fed cattle market; and (iii) the feeder cattle (800-900 lbs.) market and the fed cattle market. Asymmetric effects are defined as price decreases in both markets. The asymmetric effects were defined as price decreases based on the rationale provided by Stigler and Prakash (2011); the authors argued that livestock producers' production decisions primarily depend on current market prices. Following this logic, the fed cattle producers who are not under contract can hold their cattle in the feedlot longer when facing a price decrease. This behavior could potentially create a supply shock, which in turn can generate more uncertainties in the market.

3.5.2.1. Conditional Mean Equations

This section presents and discusses the results of the conditional mean equations estimated for the bivariate asymmetric BEKK-GARCH models in the Alberta cattle supply chain.

[Table 12 is about here]

Table 12 shows that price changes in the two feeder cattle markets were responsive to their own lags and to each other's lags. Furthermore, the error correction terms were highly significant in both feeder cattle conditional mean equations, which suggested that the price changes in each market would adjust towards their respective long-run equilibrium. The *bse* dummy variable was also included in both feeder cattle mean equations, and the results demonstrated that the BSE crisis had a negative influence on feeder cattle price changes.

[Table 13 is about here]

As shown in Table 13, the conditional mean estimations of prices changes in the feeder cattle (500-600 lbs.) and fed cattle markets indicated that cattle price changes in these markets were mainly responsive to their own lags. In addition, fed cattle price changes had a large positive influence on feeder cattle (500-600 lbs.) price changes, whereas feeder cattle (500-600 lbs.) price changes had a minor negative influence on fed cattle price changes. Furthermore, the results showed that the *bse* parameter in the fed cattle equation is negative (i.e., -9.9739) and highly significant, suggesting that the BSE crisis had an extremely negative effect.

[Table 14 is about here]

Table 14 shows the conditional mean estimations of feeder cattle (800-900 lbs.) and fed cattle price changes. Similar to the results presented in Table 13, these results showed that feeder cattle (800-900 lbs.) price changes responded negatively to lagged fed cattle price changes, whereas the fed cattle price changes responded positively to lagged feeder cattle (800-900 lbs.) price changes.

In summary, the conditional mean estimations indicated that positive price changes in the fed cattle market had a positive impact on price changes in feeder cattle markets, whereas positive price changes in feeder cattle markets had a mainly negative influence on price changes in the fed cattle market. This result is expected because feeder cattle are one of the major inputs in cattle production, and increases in input prices have a negative influence on output prices.

3.5.2.2. Price Volatility in the Alberta Cattle Supply Chain

This subsection addresses the results of price volatility estimations in the Alberta cattle supply chain.

[Figure 12 is about here]

The three panels in Figure 12 show time plots of the estimated price volatility of the feeder cattle (500-600 lbs.) and feeder cattle (800-900 lbs.) markets, as well as the covariance between price changes in these two markets. The time plots show that price volatility in the two feeder cattle markets displayed several spikes and shared similar patterns over the study period, which implied a close relationship between the price volatility of the two feeder cattle markets. This result was confirmed by the volatility spillovers estimation in the following section (i.e., section 3.5.2.3.).

The large price volatility spikes in both feeder cattle markets occurred mainly during the 2003 BSE crisis. At the beginning of the BSE crisis, the feeder cattle (500-600 lbs.) price volatility increased substantially, jumping from 2% to 8% in one week, and reached its highest level of the study period. Similarly, the feeder cattle (800-900 lbs.) price volatility also increased, primarily at the beginning of the BSE crisis, albeit to a lesser extent than feeder cattle (500-600 lbs.) price volatility did. In general, the market for feeder cattle (500-600 lbs.) appears to have been more volatile than the market for feeder cattle (800-900 lbs.), possibly because the feeder cattle (800-900 lbs.) are at the cattle-fattening stage in the cattle supply chain and thus are partially insulated against market turbulence by the rigidity of production at this stage.

[Figure 13 is about here]

Figure 13 provides time plots of the feeder cattle (500-600 lbs.) and fed cattle price volatility and the estimated covariance between price changes in these two markets. These data showed that the fed cattle price volatility increased substantially at the beginning of the 2003 BSE crisis but recovered to its average level after approximately six months, mainly because of the reopening of the U.S. border to Canadian boxed boneless beef that met certain standards combined with the swift implementation of market stabilization policies by the Canadian federal and provincial governments. Overall, the fed cattle price volatility was higher than that of the feeder cattle (500-600 lbs.) during the BSE period, whereas the reverse was true during other periods. In addition, the fed cattle market was more stable than the feeder cattle (500-600 lbs.) market during non-BSE periods.

[Figure 14 is about here]

Figure 14 presents time plots of estimated price volatility in the feeder cattle (800-900 lbs.) and fed cattle markets and the covariance between price changes in these markets. Similar to the results presented in Figure 13, the fed cattle price volatility was higher than that of the feeder cattle (800-900 lbs.) during the BSE crisis, whereas feeder cattle (800-900 lbs.) price volatility appears to have been slightly higher than the fed cattle price volatility during non-BSE periods.

The results presented in the estimated price volatility time plots revealed that feeder cattle price volatility exceeded the fed cattle price volatility during non-BSE periods, whereas the reverse was true during the BSE crisis. This finding suggested that the fed cattle market is more susceptible to market crises than the feeder cattle markets are and that fed cattle producers should adopt more comprehensive risk management tools, including production and price insurance and forward contracts.

3.5.2.3. Price Volatility Spillovers in the Alberta Cattle Supply Chain

This subsection presents and discusses the results of the price volatility spillover estimations of the bivariate asymmetric BEKK-GARCH models.

[Table 15 is about here]

Table 15, which presents the estimations of price volatility spillovers between the two feeder cattle markets, indicated that there were no direct volatility spillovers between these two markets (i.e., no significant $\alpha_{ii}^{'}, \beta_{ii}^{'}$ and $\varphi_{ii}^{'}$ are found). However, there was evidence of price volatility spillovers between the two markets through the product of past innovations (i.e., the parameter α_{ii}'' for variable $\varepsilon_{1,t-1}\varepsilon_{2,t-1}$ is statistically insignificant). Interestingly, the signs of the estimated parameters for $\varepsilon_{1,t-1}\varepsilon_{2,t-1}$ in both conditional variance equations are negative, suggesting that if the price shocks in each market had the same sign, the conditional volatility in these two markets would be negatively affected. The estimations also provided evidence of price volatility spillovers from the feeder cattle (800-900 lbs.) market to the feeder cattle (500-600 lbs.) market through the products of past innovations and past negative innovations (i.e., $\varepsilon_{1,t-1}\varepsilon_{2,t-1}$ and $\epsilon_{1,t-1}\epsilon_{2,t-1}$, respectively). This finding suggested that price decreases in both markets may have increased price volatility in the feeder cattle (500-600 lbs.) market. Moreover, price volatility spillovers from the feeder cattle (500-600 lbs.) market to the feeder cattle (800-900 lbs.) market through their past conditional covariance were observed.

The BSE parameter in the conditional covariance equation is statistically insignificant, which indicated that the apparent volatility linkage between the two feeder cattle markets was not influenced by the BSE crisis. This result was expected because neither market was directly affected by the BSE incident.

[Table 16 is about here]

Table 16 presents the estimated price volatility spillovers between the feeder cattle (500-600 lbs.) and fed cattle markets. The results in Table 16 provided evidence of direct and indirect price volatility spillovers from the fed cattle market to the feeder cattle (500-600 lbs.) market but no evidence of price volatility spillovers in the opposite direction. The direct volatility spillovers were through past negative innovations; thus, price decreases in the fed cattle market would increase price volatility in the feeder cattle (500-600 lbs.) market. Furthermore, this direct volatility spillover effect was enhanced when both markets experienced negative price shocks. Indirect price volatility spillovers from the fed cattle market to the feeder cattle (500-600 lbs.) market occurred through the past conditional covariance.

The BSE parameter in the equation for conditional covariance between these two markets was found to be negative and statistically significant at the 10% level, indicating that the volatility linkage between these two markets weakened during the first three months of the 2003 BSE crisis.

[Table 17 is about here]

Table 17 summarizes price volatility spillovers between the feeder cattle (800-900 lbs.) and fed cattle markets. The model estimations indicated the presence of bidirectional price volatility spillovers between these two markets. Specifically, the results showed minor price volatility spillovers from the fed cattle market to the feeder cattle (800-900 lbs.) market through the product of past negative price changes in both markets. This observation suggested that price volatility in the fed cattle market could influence price volatility in the feeder cattle (800-900 lbs.) market only if negative price shocks occurred in both markets.

In comparison, price volatility spillovers from the feeder cattle (800-900 lbs.) market to the fed cattle market were much larger in magnitude. Strong price volatility spillovers from the feeder cattle (800-900 lbs.) market to the fed cattle market occurred directly through past innovations, volatility persistence and past negative innovations in the feeder cattle (800-900 lbs.) market; in addition, weaker price volatility spillovers from the feeder cattle (800-900 lbs.) market to the fed cattle market occurred through the past conditional covariance, the product of past innovations and the product of past negative innovations in both markets.

The BSE parameter was not significant in the equation for conditional covariance between these two markets. This result was expected because, as noted above, the fed cattle price volatility had only a minimal influence on the feeder cattle (800-900 lbs.) price volatility. Therefore, the effects of the BSE crisis that originated in the fed cattle market were only weakly transmitted to the feeder cattle (800-900 lbs.) market.

In summary, the results showed bidirectional price volatility spillovers throughout the Alberta cattle supply chain. Moreover, the effects of price spillovers from upstream to downstream markets (i.e., from the feeder cattle markets to the fed cattle market) were much stronger than the effects of spillovers in the opposite direction. The BSE parameter in the conditional covariance equations revealed that the BSE crisis may have had no effects on the volatility linkages between the two feeder cattle markets and between the feeder cattle (800-900 lbs.) and fed cattle markets. However, there was evidence that the BSE crisis may have had a negative effect on the linkage between price volatility in the feeder cattle (500-600 lbs.) and fed cattle markets; this evidence suggested that the volatility linkage between these two markets was weakened at the beginning of the BSE crisis.

The results regarding price volatility spillovers implied that fed cattle producers should closely monitor feeder cattle markets and take note of factors that could affect feeder cattle price volatility. Such factors may include quality issues, market agent behaviors (e.g., cattle producers holding cow-calves in their facilities when facing price declines) and adverse weather conditions.

One example of how adverse weather conditions might affect feeder cattle price volatility is a cold winter that causes cow-calf producers to ship fewer animals to auction houses, thereby inducing a supply shock in feeder cattle markets. These results are relevant to policy makers because they suggested that market policies in feeder cattle markets might cause price uncertainty in the fed cattle market.

3.5.3. Price Volatility and Volatility Spillovers between the Feeder Cattle and Feed Grain Markets

This section presents estimation results for the bivariate asymmetric BEKK-GARCH models of interactions between the cattle and feed grain markets. Initially, asymmetric effects were defined as price decreases in both markets. However, one could argue that cattle price volatility might be more responsive to price increases than to price decreases in feed grain markets (possibly as a result of inventory effects). To account for this argument and to gain a fuller understanding of the channels of interaction between cattle and feed grain price volatility, asymmetric effects are also defined as price decreases in the cattle market and price increases in the feed grain market (i.e., $\epsilon_{1,t-1}\left(\epsilon_{1,t-1} < 0\right)\epsilon_{2,t-1}(\epsilon_{2,t-1} \geq 0)$), and the bivariate BEKK-GARCH models are re-estimated based on this new definition.

Figures illustrating the conditional volatility and covariances in the Alberta cattle and U.S. corn markets are presented in Appendix C. The bivariate asymmetric BEKK-GARCH results for the relationships between Alberta cattle markets and U.S. corn markets are presented in Appendix D. Detailed interpretations of cattle-corn market pairs are not provided because minor volatility spillovers from the corn market to the cattle market occur only in rare cases, a finding that may reflect the fact that Alberta cattle are primarily barley fed. Therefore, market linkages between the Alberta cattle and U.S. corn markets remain weak despite some Alberta cattle producers starting to import U.S. corn as a substitute for barley. However, the possibility remains that the price volatility of Alberta cattle is related to the price volatility of U.S. corn through the barley price volatility. Therefore, interpretations of the results of the bivariate asymmetric BEKK-GARCH models estimated for the barley and corn markets are provided.

3.5.3.1. Conditional Mean Equations

In this section, the results of the conditional mean estimations between the Alberta cattle and barley markets are presented and discussed. Table 18a shows the results of the conditional mean equations from the bivariate asymmetric BEKK-GARCH model with asymmetric effects defined as price decreases in both markets. Table 18b shows the results of the conditional mean equations from the bivariate asymmetric GARCH model with asymmetric effects defined as price decreases in the feeder cattle (500-600 lbs.) market and price increases in the barley market. Because the results presented in Tables 18a and 18b are similar, these two tables are treated as one for purposes of interpretation and discussion.

[Tables 18a and 18b are about here]

These two tables show that the barley price changes had a negative effect on the feeder cattle (500-600 lbs.) price changes. This finding is expected because barley is one of the main inputs in cattle production; accordingly, price increases in the barley market narrow the feeder cattle (500-600 lbs.) producers' profit margin. Feeder cattle (500-600 lbs.) price changes had no apparent effect on barley price changes.

[Tables 19a and 19b are about here]

Table 19a shows the conditional mean estimation between price changes in the feeder cattle (800-900 lbs.) and barley markets based on the bivariate asymmetric BEKK-GARCH model with asymmetric effects defined as price decreases in both markets. Table 19b shows the conditional mean estimation between price changes in these two markets based on the bivariate asymmetric BEKK-GARCH model with asymmetric effects defined as price decreases in the feeder cattle (800-900 lbs.) market and price increases in the barley market. Because the results shown in Tables 19a and 19b are similar, these tables are treated as one for purposes of interpretation.

Tables 19a and 19b show that the barley price changes had a negative influence on the feeder cattle (800-900 lbs.) price changes. This result implied that barley price increases/decreases affect the feeder cattle price (800-900 lbs.) negatively/positively, respectively.

[Tables 20a and 20b are about here.]

Table 20a shows the conditional mean estimation between the barley and fed cattle price changes based on the bivariate asymmetric BEKK-GARCH model with asymmetric effects defined as price decreases in both markets. Table 20b shows the conditional mean estimation between these two markets based on the asymmetric BEKK-GARCH model with asymmetric effects defined as price decreases in the fed cattle market and price increases in the barley. Because the results shown in Tables 20a and 20b are similar, these two tables are treated as one in the presentation of results.

According to the results in Tables 20a and 20b, fed cattle price changes did not respond to recent barley price changes. However, barley price changes that were 30 weeks old (i.e., lagged by 30) negatively affected current fed cattle price changes. This 30-week time frame is consistent with the backgrounding and finishing phases of the cattle production chain.[12] This information will help fed cattle producers by improving predictions regarding future fed cattle market prices.

3.5.3.2. Price Volatility in the Cattle and Barley Markets

In this section, the estimated price volatility in the Alberta cattle and feed barley markets are discussed and interpreted.

[Figure 15a and Figure 15b are about here]

Figures 15a and 15b present time plots of the estimated price volatility in the feeder cattle (500-600 lbs.) and barley markets and the covariance between these two markets. The plots in Figure 5a are generated by the bivariate asymmetric BEKK-GARCH model with asymmetric effects defined as price decreases in both markets, whereas the time plots in Figure 15b are generated by the bivariate asymmetric BEKK-GARCH model with asymmetric effects defined as price decreases in the feeder cattle (500-600 lbs.) market and price increases in the barley market.

[Figure 16a and Figure 16b are about here]

Figures 16a and 16b present plots of the estimated price volatility in the feeder cattle (800-900 lbs.) and barley markets and the covariance between these two markets. Figure 16a shows time plots generated by the asymmetric BEKK-GARCH model with asymmetric effects defined as

[12] The backgrounding and finishing phases of cattle production require approximately 240 days to feed barley to cow-calves until they become fed cattle.

price decreases in both markets, whereas Figure 16b shows time plots generated by the asymmetric BEKK-GARCH model with asymmetric effects defined as price decreases in the feeder cattle (800-900 lbs.) market and price increases in the barley market.

[Figure 17a and Figure 17b are about here]

Figures 17a and 17b show time plots of estimated price volatility in the fed cattle and barley markets and the covariance between these two markets. Figure 17a shows plots generated by the asymmetric BEKK-GARCH model with asymmetric effects defined as price decreases in both markets, and Figure 17b presents plots generated by the asymmetric BEKK-GARCH model with asymmetric effects defined as price decreases in the fed cattle market and price increases in the barley market.

Because the time plots of the estimated price volatility in the feeder cattle (500-600 lbs.), feeder cattle (800-900 lbs.) and fed cattle markets shown in Figures 15a, 15b to Figures 17a, 17b are the same as the plots shown in Figures 12 to 14, detailed interpretations of the time plots shown in Figures 15a, 15b to Figures 17a, 17b are not provided in this section. However, the results of the barley price volatility estimations are presented and discussed; then, these results are compared with the cattle price volatility estimations.

Two spikes that occurred in the barley market during the 1990s stand out, one that occurred at the end of 1995 and another that occurred at the end of 1999. One reason for the 1995 spike might be the elimination of the Western Grain Transportation Act (WGTA) (formerly, the crow rate) on August 1, 1995. According to Schmitz et al (2002), during the 1995/1996 crop year, freight costs doubled or tripled for western Canadian grain producers moving grain to export shipping terminals in Thunder Bay, Ontario and Vancouver, British Columbia. Furthermore, the U.S. corn market experienced several extremes during 1995/1996, mainly due to a severe drought in the Midwest. The fluctuations in the U.S. corn market could also potentially affect the western Canadian feed barley price though close market linkages.

The 1999 volatility spike in the barley market may have been due to adverse weather conditions, namely, a drought. As Schwalm et al (2012) noted, the end of 1999 marked the beginning of a prolonged drought in western Canada. Because the drought ended in 2004, this phenomenon is considered a potential reason for the volatility spikes in the barley market from 2003 to 2004.

These results suggested that the barley price volatility may have reflected an over-correction in response to market shocks; however, such market behavior would last only a short period (thus, volatility is less persistent), which suggests that barley producers need not panic when facing large-scale market turbulence, because the market may quickly return to normal.

A comparison of estimated price volatility in the barley market and in the cattle markets shows that the barley market experienced more volatility spikes than the cattle markets did. However, the volatility spikes in the barley market were less persistent than those in the cattle markets. On the one hand, these results suggested that the Alberta cattle markets are more stable than the barley market; on the other hand, they suggested that Alberta cattle markets took longer to absorb market shocks than the barley market did.

An analysis of the figures in this section (i.e., Figures 15a, 15b to Figures 17a, 17b) indicates that the barley price volatility had the largest effect on feeder cattle (500-600 lbs.) price volatility and that the effects weaken as feeder cattle gain weight. One potential reason for these results is that the influences of the U.S. cattle industry on Canadian cattle prices' increases as feeder cattle grow heavier. Another possible reason could be that less barley is required given the remaining feeding period got shorter as feeder cattle grow heavier.

3.5.3.3. Price Volatility Spillovers between the Feeder cattle (500-600 lbs.) and Barley Markets

This subsection presents two bivariate asymmetric BEKK-GARCH models. In the first model, asymmetric effects are defined as price decreases in both markets; in the second model, asymmetric effects are defined as price decreases in the feeder cattle (500-600 lbs.) market and price increases in the barley market.

[Table 21 is about here]

Table 21 shows the estimations of the asymmetric BEKK-GARCH model of interactions between the feeder cattle (500-600 lbs.) and barley markets with asymmetric effects defined as price decreases in both markets. The results provide evidence of bidirectional price volatility spillovers between the feeder cattle (500-600 lbs.) and barley markets. However, the spillovers were through indirect channels (i.e., the product of past innovations in both markets and/or the past conditional covariance). Specifically, barley price volatility spilled over into feeder cattle

(500-600 lbs.) price volatility through past conditional covariance, and the feeder cattle (500-600 lbs.) price volatility spilled over into barley price volatility through the product of past innovations (i.e., $\varepsilon_{1,t-1}\varepsilon_{2,t-1}$). The results did not indicate that price decreases in the barley market influenced price volatility in the feeder cattle (500-600 lbs.) market, or vice versa.

The bivariate asymmetric BEKK-GARCH model of the relationship between these two markets was also estimated with asymmetric effects defined as price decreases in the feeder cattle (500-600 lbs.) market and price increases in the barley market. Table 22 presents the results.

[Table 22 is about here]

The results in Table 22 are similar to those in Table 21. Again, there was no evidence of direct volatility spillovers between these two markets. However, there was evidence of indirect price volatility spillovers. Specifically, the barley price volatility spilled over into the feeder cattle (500-600 lbs.) price volatility only if there was a price decrease in the feeder cattle (500-600 lbs.) market and a price increase in the barley market. Thus, barley price volatility affected feeder cattle (500-600 lbs.) price volatility through the product of past negative innovations in the feeder cattle (500-600 lbs.) equation and past positive innovations in the barley equation (i.e., $\epsilon_{1,t-1}\left(\epsilon_{1,t-1} < 0\right)\epsilon_{2,t-1}(\epsilon_{2,t-1} \geq 0)$).

The BSE parameters in the conditional covariance equations were not statistically significant in either bivariate asymmetric BEKK-GARCH model, suggesting that the 2003 Canadian BSE crisis did not affect the potential volatility linkage between feeder cattle (500-600 lbs.) and barley prices.

To summarize, the results showed bidirectional price volatility spillovers between the feeder cattle (500-600 lbs.) and barley markets through indirect channels. The results also indicated that feeder cattle (500-600 lbs.) price volatility was likely to increase if there was an own-market price decrease and a barley market price increase. This finding implied a weak volatility linkage between these two markets. However, lighter feeder cattle producers and barley producers both would benefit from monitoring their price co-movements because the price volatility of each market tended to exert a greater influence on the price volatility of the other market during periods of market fluctuations, especially during periods of barley price surges.

3.5.3.4. Price Volatility Spillovers between the Feeder cattle (800-900 lbs.) and Barley Markets

This subsection presents two bivariate asymmetric BEKK-GARCH models. The first model defines asymmetric effects as price decreases in both markets, whereas the second model defines asymmetric effects as price decreases in the feeder cattle (800-900 lbs.) market and price increases in the barley market.

[Table 23 is about here]

Table 23 shows the bivariate BEKK-GARCH estimations of interactions between the feeder cattle (800-900 lbs.) and barley markets with asymmetric effects defined as price decreases in both markets. Only minor volatility spillovers from barley prices to feeder cattle (800-900 lbs.) prices were observed, and these spillovers occurred through the past conditional covariance. The results did not indicate that price decreases in the barley market affected the feeder cattle (800-900 lbs.) price volatility.

[Table 24 is about here]

Table 24 shows the bivariate BEKK-GARCH estimations of interactions between the feeder cattle (800-900 lbs.) and barley markets with asymmetric effects defined as price decreases in the feeder cattle (800-900 lbs.) market and price increases in the barley market. Similar to the previous model, the results show volatility spillovers from the barley prices to feeder cattle (800-900 lbs.) prices. However, the barley price volatility spilled over into feeder cattle (800-900 lbs.) price volatility through the product of past negative innovations in the feeder cattle (800-900 lbs.) equation and past positive innovations in the barley equation (i.e., $\epsilon_{1,t-1}\left(\epsilon_{1,t-1}<0\right)\epsilon_{2,t-1}(\epsilon_{2,t-1}\geq 0)$), rather than the past conditional covariance, as was the case in the previous model.

The BSE parameters were not found to be statistically significant in the conditional covariance equations in either model estimation of the interactions between the feeder cattle (800-900 lbs.) and barley markets. This observation suggested that the BSE crisis did not affect the potential volatility linkage between the feeder cattle (800-900 lbs.) and barley prices.

To summarize, the results demonstrated unidirectional price volatility spillovers from the barley market to the feeder cattle (800-900 lbs.) market. Similar to the findings in subsection 3.5.3.3., the results presented in this subsection indicate that feeder cattle (800-900 lbs.) price volatility was likely to increase if there was an own-market price decrease and a barley market price increase. The price volatility linkage between the feeder cattle (800-900 lbs.) and barley markets is relatively weak because volatility spillovers occurred only through indirect volatility spillover components (i.e., $\alpha", \beta"$ and $\varphi"$). An implication similar to the one drawn in the previous subsection (i.e., subsection 3.5.3.3.) can also be drawn here. Heavier feeder cattle producers may wish to closely observe the co-movements between heavier feeder cattle and barley prices because barley price volatility can potentially transmit to the heavier feeder cattle markets during periods of market fluctuations, especially barley price surges. In general, price volatility spillovers between the fed cattle and barley markets were not observed. This lack of spillovers may be due to fed cattle being the final products in the cattle supply chain; accordingly, recent barley prices are no longer a factor in fed cattle prices.

3.5.3.5. Price Volatility Spillovers between the Fed cattle and Barley Markets

This subsection presents two bivariate asymmetric BEKK-GARCH models. In the first model, asymmetric effects are defined as price decreases in both markets, whereas in the second model, asymmetric effects are defined as price decreases in the fed cattle market and price increases in the barley market.

[Table 25 is about here]

Table 25 summarizes the BEKK-GARCH estimations of interactions between the fed cattle and barley markets with asymmetric effects defined as price decreases in both markets. There is no evidence of price volatility spillovers between these two markets, indicating that the fed cattle price volatility may not be directly affected by the barley price volatility.

[Table 26 is about here]

Table 26 presents BEKK-GARCH estimations of interactions between the fed cattle and barley markets with asymmetric effects defined as price decreases in the fed cattle market and price increases in the barley market. Similar to the previous model, there is no evidence of price volatility spillovers between the two markets.

Furthermore, the BSE parameters in the conditional covariance equations were not statistically significant for either bivariate asymmetric BEKK-GARCH model.

Potential transmission of price volatility in the barley market to the fed cattle market is supported by the intermediary role played by feeder cattle price volatility. This relationship follows as a result of the finding in subsections 3.5.3.3 and 3.5.3.4 that the barley price volatility could affect the feeder cattle price volatility, which can in turn influence the fed cattle price volatility, as found in section 3.5.2. This evidence suggested that the fed cattle producers should closely observe market conditions in the feeder cattle and barley markets.

3.5.4. Price Volatility and Volatility Spillovers between the Barley and U.S. Corn markets

This section provides estimations of the bivariate asymmetric BEKK-GARCH model between the barley and U.S. corn price volatility with asymmetric effects defined as price decreases in both markets. The BSE dummy is excluded from this model because none of the feed grain markets were directly affected by the crisis. Initially, the model was estimated by assuming a conditional multivariate student t-distribution. However, the model failed to pass the post-estimation diagnostic tests for the remaining ARCH effects, implying that the BEKK-GARCH model could be misspecified. Therefore, the model is estimated by assuming a conditional multivariate normal distribution. Misspecification adjusted/robust standard errors are used to allow the estimated parameters to have standard QML interpretations.

3.5.4.1. Conditional Mean Equations

In this section, the estimation results of the conditional mean equations between the barley and U.S. corn markets are presented.

[Table 27 is about here]

Table 27 shows the results of the condition mean equation estimated within the bivariate asymmetric BEKK-GARCH frame with asymmetric effects defined as price decreases in both markets. The results show that the barley price changes were significantly affected by the U.S. corn price changes, but not vice versa. Furthermore, the error correction term was only statistically significant in the conditional mean equation of barley, which indicated that barley prices would adjust to their potential long-run equilibrium. This result implied that the Lethbridge barley prices closely followed the U.S. corn prices; this relationship was also reflected in Figure 10 (i.e., the figure showing price movements in the studied markets).

3.5.4.2. Price Volatility in the Barley and U.S. Corn Markets

This section presents time plots of estimated price volatility in the barley and U.S. corn markets and the covariance between the price changes in these two markets.

[Figure 18 is about here]

Figure 18 presents plots of estimated price volatility in the barley and U.S. corn markets and the covariance between the price changes in these two markets. Figure 18 shows that the corn price volatility was higher than the barley price volatility; however, price volatility in the barley market exhibited a greater number of large spikes than the U.S. corn market did. Furthermore, barley price volatility was observed to be responsive to the corn price volatility but not vice versa. This is also confirmed by the estimation results for price volatility spillovers between these two markets.

3.5.4.3. Price Volatility Spillovers between the Barley and U.S. Corn Markets

In this section, the results of the asymmetric BEKK-GARCH model are discussed.

[Table 28 is about here]

Table 28 presents the BEKK-GARCH estimations of interactions between the barley and U.S. corn markets. These estimations show strong unidirectional price volatility spillovers from the U.S. corn market to the barley market through all direct and indirect volatility spillover components with the exception of the general shock components measured by $\alpha(s)$. This observation indicated that the price volatility of barley was greatly affected by that of the U.S. corn. Furthermore, this result implied a potential volatility linkage between the U.S. corn and Alberta cattle markets.

3.6. Concluding Remarks

This study sought to assess price volatility spillovers within the Alberta cattle supply chain and between the Alberta cattle markets and feed grain markets affected by the 2003 Canadian BSE crisis and by recent episodes of feed price surges. The bivariate asymmetric BEKK-GARCH model (Grier et al 2004) was applied. Five key findings are presented below.

First, bidirectional price volatility spillovers were found throughout the Alberta cattle supply chain, which accords with Natcher and Weaver (1999). Furthermore, spillover effects from upstream markets (i.e., the feeder cattle markets) to the downstream market (i.e., the fed cattle market) were stronger than those in the reverse direction.

Second, only weak price volatility spillovers from the barley market to the feeder cattle markets were detected. In addition, the volatility spillover effects tended to be stronger during periods of price surges in the barley market. Therefore, feeder cattle producers should be mindful of barley market conditions to manage their market risk.

Third, there was no evidence of price volatility spillovers between the fed cattle and barley markets. These results indicated that the fed cattle market was potentially insulated from barley market fluctuations.

Fourth, barley price volatility was greatly affected by the U.S. corn price volatility. This result implied a strong volatility linkage between the barley and U.S. corn markets.

Finally, the combination of all of these results provides evidence of some price volatility spillovers from the U.S. corn market to the Alberta fed cattle market. The following figure illustrates the volatility spillover chain.

[Figure 19 is about here]

These results suggested that fed cattle producers should form comprehensive risk management plans that incorporate information from the feeder cattle and feed grain markets. Furthermore, fed cattle producers seeking to maintain their desired profitability should consider contracting with upstream suppliers and/or vertical integration.

These results also demonstrate to policy makers that policy implementation in the feed grain and feeder cattle markets that could potentially induce price volatility might also introduce market uncertainties into the fed cattle market. Therefore, individual efficient price stabilization programs may need to be designed for each market stage in the cattle supply chain (Serra 2011).

Chapter 4. Conclusions, limitations and Future Research

The province of Alberta currently has the strongest economy in Canada, its economy is mainly supported by energy, agriculture, and other industries (Alberta Canada 2014). In 2013, total Alberta farm receipts accounted for approximately 21% of Canada's total agricultural revenue (Statistics Canada 2013). As the most important component in the Alberta agricultural sector, the cattle industry has experienced many difficulties over the past decade. The first problem was the U.S. border closure due to the discovery of bovine spongiform encephalopathy (BSE). More recently feed grain price surges have challenged the financial viability of cattle producers. Because of these events, better understanding of market linkages and price volatility interactions throughout the feed grain/cattle supply chain is necessary for cattle producers, crop farmers and policy makers.

This thesis consisted of two essays on commodity market interdependencies, price volatility and volatility spillovers in the Alberta cattle supply chain, feed barley and the U.S. corn markets.

Three questions were asked in this thesis: i), how variable were market prices across the supply chain as result of market shocks over the study period? ii) How did the market interdependencies vary over time because of market crises? iii) Was price volatility transmitted through the supply chain, and if so, were the volatility spillovers asymmetric between market levels?

4.1. Conclusions

The first essay examined price volatility and market interdependencies in the Alberta cattle, western Canadian feed barley and U.S. corn markets by using a diagonal AG-DCC GARCH model. The estimated results revealed that during the 2003 BSE crisis that fed cattle price volatility was higher than feeder cattle price volatility. The opposite result held when BSE was not an issue. Estimated feed grain price volatility was higher for corn prices than for barley prices. Moreover, feed barley price volatility was found to be more responsive to own market shocks than corn price volatility was.

Dynamic conditional correlation was used to measure market price interdependencies. The results suggested that cattle price changes were positively correlated throughout the study period with the exception of the beginning of the 2003 BSE border closure. Dynamic conditional correlations between the feeder and fed cattle prices nearly dropped to zero at the beginning of the BSE event.

Positive dynamic conditional correlation was found between the western Canadian feed barley and U.S. corn prices. Furthermore, the dynamic conditional correlation tended to fluctuate more for the 2000s than it did in the 1990s.

The second essay investigated price volatility spillovers by utilizing a bivariate asymmetric BEKK-GARCH model. Estimations of price volatility spillovers provide evidence of bi-directional volatility spillovers in the Alberta cattle supply chain. Moreover, price volatility spillovers from upstream feeder cattle markets to the downstream fed cattle markets were found to be much stronger than in the reverse direction.

Bivariate asymmetric BEKK-GARCH models estimates between feeder cattle and feed barley markets revealed only weak price volatility spillovers from barley to feeder cattle markets. These volatility spillover effects tended to be stronger when barley prices surged. Furthermore, no evidence of price volatility spillovers was found between the fed cattle and feed barley markets.

Estimates of price volatility spillovers between western Canadian feed barley and U.S. corn markets showed strong volatility spillovers from the U.S. corn to feed barley markets. These results indicated the existence of a strong volatility linkage between the feed barley and U.S. corn markets. Combining all the price volatility spillovers results, a chain of volatility spillovers was identified (see Figure 19).

Figure 19 showed the dynamics of volatility interactions in the feed/cattle supply chain. These results implied that fed cattle producers should include risk information from the feeder cattle and feed grain markets in their risk management plans.

These results also provide policy makers with the information on volatility spillovers for evaluating existing policies and designing efficient market stabilization programs. For example, it has been argued that federal compensation policies may have placed too much emphasis on Alberta fed cattle producers in response to the 2003 Canadian BSE crisis. The results from this study could potentially serve as support to policies focusing on the fed cattle market. The study found that the BSE crisis had the greatest impact on the fed cattle price volatility within the Alberta cattle supply chain; furthermore, the fed cattle market was greatly exposed to price uncertainties in the feeder cattle markets, which was demonstrated by results from the volatility spillovers estimation. Given these results, the compensation programs' emphasis on Alberta fed cattle producers may have been appropriate.

4.2. Limitations

There were two main limitations in the first essay. First, the diagonal AG-DCC GARCH specification was restrictive. With this specification, the conditional covariances were driven only by cross-sectional terms, which could not account for specific market shock effects on the conditional covariances. The reason that the diagonal version of the model is employed is to accommodate the large number of markets studied in this thesis. Second, the normality assumption is violated because the distribution of price changes has fat tails. The estimators are inefficient despite the fact that they have consistent quasi-likelihood interpretations.

There was one main limitation for the second essay. To accommodate fat tails in the distribution of price changes, I have used a multivariate student t distribution for the maximum likelihood estimation. While the incorporation of the student t distribution addressed non-normality from fat tails, the distribution was not sufficiently flexible to account for other distributional anomalies (e.g., skewness). Therefore, the estimated parameters were interpreted using the quasi-likelihood framework, which rendered estimated parameters inefficient.

4.3. Future Research

Future research could extend this study by incorporating the U.S. live cattle market price changes into estimation to reveal the volatility interactions between Alberta and the U.S. Furthermore, based on results for conditional covariances obtained from this thesis, optimal hedge ratios could be calculated.

The distribution assumptions used in this thesis could be further relaxed. More flexible univariate and multivariate GARCH models could be employed. For example, multivariate skewed student t or copula based GARCH models are possible approaches.

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Tables

Table 1. Summary statistics for logged weekly prices and price changes (n=969)

Summary statistics for logged weekly prices (i.e., $100 \times \log(p_t)$)	Feeder Cattle (500 – 600 lbs.)	Feeder Cattle (800 – 900 lbs.)	Fed Cattle	Barley	Corn
Statistic					
Mean	481.605	464.217	450.162	502.091	499.474
Minimum	426.704	411.643	355.706	446.935	433.730
Maximum	521.428	496.459	480.974	569.541	580.329
Std. Dev.	19.154	15.662	15.217	26.895	34.125
ADF tests[1] for stationarity					
Test stats (lag = 0)	-1.763	-	-	-	-1.618
Test stats (lag = 1)	-	-2.296	-	-	-
Test stats (lag = 3)	-	-	-	-1.227	-
Test stats (lag = 11)	-	-	-3.554**	-	-
Summary statistics for weekly price changes (i.e., $100 \times \log(p_t / p_{t-1})$)					
Statistic					
Mean	0.025	0.032	0.031	0.087	0.079
Median	0.043	0.107	0.024	0.000	0.156
Minimum	-15.301	-14.60	-35.650	-15.778	-15.059
Maximum	12.258	9.389	51.128	17.984	16.299
Std. Dev.	2.366	2.119	3.333	2.544	4.238
Skewness	-0.411	-0.624	2.007	-0.150	-0.060
Kurtosis (excess)	6.094	5.423	75.914	9.223	1.550
Testing autocorrelations in price changes					
Ljung-Box Q-stats (6)	15.22**	56.54***	126.11***	32.61***	5.72
	(0.019)[2]	*(0.000)*	*(0.000)*	*(0.000)*	*(0.455)*
Ljung-Box Q-stats (12)	23.37**	96.61***	265.41***	37.67***	21.28**
	(0.025)	*(0.000)*	*(0.000)*	*(0.000)*	*(0.045)*
Testing ARCH effects in price changes					
Ljung-Box Q-stats (6)	108.80***	343.30***	37.29***	186.88***	62.52***
	(0.000)	*(0.000)*	*(0.000)*	*(0.000)*	*(0.000)*
Ljung-Box Q-stats (12)	245.92***	532.61***	238.20***	188.62***	105.90***
	(0.000)	*(0.000)*	*(0.000)*	*(0.000)*	*(0.000)*
ADF tests for stationarity					
Test stats (lag = 0)	-29.668***	-25.437***			-31.660***
Test stats (lag = 2)	-	-		-15.096***	-
Test stats (lag = 10)	-	-	-12.373***	-	-

***,**,* denote rejection of null hypothesis at the 1%, 5% and 10% significance levels, respectively.
[1]The critical values of the ADF test at 1%, 5% and 10% are -2.865, -2.569 and -3.440, respectively.
[2]p-values in parentheses.
Lags in ADF tests are based on Bayesian Information Criterion (BIC).

Table 2a. Unconditional pairwise correlations of logged weekly prices

	1995 - 2013				
Commodity	Feeder Cattle (500 – 600 lbs.)	Feeder Cattle (800 – 900 lbs.)	Fed Cattle	Barley	Corn
Feeder Cattle (500 – 600 lbs.)	1.000	0.946	0.674	0.150	0.039
Feeder Cattle (800 – 900 lbs.)		1.000	0.681	0.233	0.107
Fed Cattle			1.000	0.440	0.361
Barley				1.000	0.877
Corn					1.000

Table 2b. Unconditional pairwise correlations of weekly price changes

	1995 - 2013				
Commodity	Feeder Cattle (500 – 600 lbs.)	Feeder Cattle (800 – 900 lbs.)	Fed Cattle	Barley	Corn
Feeder Cattle (500 – 600 lbs.)	1.000	0.535	0.216	0.013	-0.027
Feeder Cattle (800 – 900 lbs.)		1.000	0.287	0.005	-0.030
Fed Cattle			1.000	0.054	0.023
Barley				1.000	0.091
Corn					1.000

Table 3. Johansen trace tests for cointegration

Market pairs	H_0	H_a	λ_{trace}	5% critical value
Barley – Corn	$r=0$	$r>0$	16.2371	15.41
	$r\le 1$	$r>1$	1.6097	3.76
Barley – Feeder Cattle (800 – 900 lbs.)	$r=0$	$r>0$	8.9476	15.41
	$r\le 1$	$r>1$	0.3667	3.76
Corn – Feeder Cattle (800 – 900 lbs.)	$r=0$	$r>0$	8.8601	15.41
	$r\le 1$	$r>1$	2.0391	3.76
Feeder Cattle (500 – 600 lbs.) – Feeder Cattle (800 – 900 lbs.)	$r=0$	$r>0$	32.0813	15.41
	$r\le 1$	$r>1$	3.6734	3.76
Barley – Feeder Cattle (500 – 600 lbs.)	$r=0$	$r>0$	9.6328	15.41
	$r\le 1$	$r>1$	1.8427	3.76
Corn – Feeder Cattle (500 – 600 lbs.)	$r=0$	$r>0$	8.8601	15.41
	$r\le 1$	$r>1$	2.0391	3.76

Cointegrating relationships

$$\log(p_{1t}) = -55.497 + 1.157\log(p_{2,t})$$
(5.920) (0.013)

$$\log(p_{4,t}) = 156.89 + 0.691\log(p_{5,t})$$
(6.091) (0.012)

Note: $\log(p_{1,t}), \log(p_{2,t}), \log(p_{4,t})$ and $\log(p_{5,t})$ are logged prices of feeder cattle (500 – 600 lbs.), feeder cattle (800 – 900 lbs.), barley and U.S. corn, each multiplied by 100, respectively.
Standard errors in parentheses.

Table 4. Conditional mean model estimation

	Feeder Cattle (500 – 600 lbs.)	Feeder Cattle (800 – 900 lbs.)	Fed Cattle	Barley	Corn
	(i = 1)	(i = 2)	(i = 3)	(i = 4)	(i = 5)
$AR(3)_{1i}$	0.0495** *(0.0204)*	-	-	-	-
$AR(4)_{1i}$	-	-	0.0961*** *(0.0282)*	-	-
$AR(5)_{1i}$	0.0560** *(0.0224)*	-	-	-	-
$AR(1)_{2i}$	0.1583*** *(0.0252)*	-	-0.1505*** *(0.0379)*	-	-
$AR(2)_{2i}$	-	0.0738** *(0.0297)*	-	-	-
$AR(4)_{2i}$	-	0.0873*** *(0.0301)*	-	-	-
$AR(6)_{2i}$	-	0.00802** *(0.0314)*	-	-	-
$FeederECT$	-0.0229*** *(0.0075)*	0.0340*** *(0.0086)*	-	-	-
$AR(1)_{3i}$	0.1421*** *(0.0144)*	0.2278*** *(0.0216)*	0.2613*** *(0.0314)*	-	-
$AR(2)_{3i}$	-	-	-0.0957*** *(0.0311)*	-	-
$AR(6)_{3i}$	-0.0832*** *(0.0133)*	-	-	-	-
$AR(7)_{3i}$	0.0786*** *(0.0176)*	-	-	-	-
$AR(9)_{3i}$	-	-	-0.0637** *(0.0273)*	-	-
$BSEcrash$	11.9096*** *(3.2081)*	-	-10.6225*** *(3.006)*	-	-
$AR(1)_{4i}$	-	-0.0717*** *(0.0201)*	-	-	-
$AR(2)_{4i}$	-	-	-	0.1838*** *(0.0145)*	-
$AR(3)_{4i}$	-	-	-	0.0856*** *(0.0221)*	-
$AR(1)_{5i}$	-	-	-	0.0803*** *(0.0137)*	-
$AR(2)_{5i}$	-	-	-	0.0595*** *(0.0128)*	-
$AR(3)_{5i}$	-	-	-	0.0600*** *(0.0137)*	-
$AR(5)_{5i}$	-	-	-	-	0.0878*** *(0.0269)*
$GrainECT$	-	-	-	-0.0070** *(0.0035)*	0.0143 *(0.0097)*

***,**,* denote rejection of null hypothesis at the 1%, 5% and 10% significance levels, respectively. Standard errors in parentheses. Note: $FeederECT$ and $GrainECT$ are the error correction terms taken from the two pairs of cointegrated price changes. $BSEcrash$ is a dummy variable that takes on the value of one on the day of June 4, 2003, when the Canadian BSE crisis was fully accounted for in the fed cattle market, and zero otherwise.

Table 5. GARCH estimations

	Feeder Cattle (500 – 600 lbs.)	Feeder Cattle (800 – 900 lbs.)	Fed Cattle	Barley	Corn
	(i = 1)	(i = 2)	(i = 3)	(i = 4)	(i = 5)
α_0	-0.0980**	0.2958	-0.0304	-0.0788	0.0914
	(0.0436)[1]	*(0.1918)*	*(0.0188)*	*(0.0968)*	*(0.1105)*
α_i	0.2735***	0.0759	0.0823***	0.6482***	0.2441***
	(0.0902)	*(0.0639)*	*(0.0212)*	*(0.0874)*	*(0.0542)*
β_i	0.9276***	0.7627***	0.9754***	0.7407***	0.9021***
	(0.0127)	*(0.1261)*	*(0.0056)*	*(0.0603)*	*(0.0403)*
d_i	-0.0810***	-	-0.0439***	-0.0192	-0.0350
	(0.0366)		*(0.0160)*	*(0.0207)*	*(0.0370)*
γ_i	-	0.1572**	-	-	-
		(0.0614)			
$BSEcrash$	-	-	4.7883***	-	-
			(1.0443)		
*Ljung – Box test for autocorrelation in **standardized residuals***					
LB-Q stats (6)	9.45	5.67	1.53	5.99	2.77
	(0.150)[2]	*(0.461)*	*(0.958)*	*(0.424)*	*(0.837)*
LB-Q stats (12)	11.33	16.02	8.20	11.02	15.93
	(0.501)	*(0.190)*	*(0.769)*	*(0.527)*	*(0.195)*
*Ljung – Box test for autocorrelation in **squared standardized residuals***					
LB-Q stats (6)	1.64	10.06	6.16	10.10	2.82
	(0.950)	*(0.122)*	*(0.405)*	*(0.120)*	*(0.831)*
LB-Q stats (12)	12.30	11.92	13.52	12.05	12.36
	(0.422)	*(0.452)*	*(0.332)*	*(0.442)*	*(0.418)*
Bayesian Information Crierion (BIC)	4.36	4.00	4.49	4.37	5.68

***,**,* denote rejection of null hypothesis at the 1%, 5% and 10% significance levels, respectively.
Note: $FeederECT$ and $GrainECT$ are the error correction terms taken from the two pairs of cointegrated price changes. $BSEcrash$ is a dummy variable that takes one on the day of June 4, 2003, when the Canadian BSE crisis was fully accounted for in the fed cattle market, and zero otherwise. The GJR-GARCH specification is used to model the conditional variance of feeder cattle (800 - 900 lbs.) price changes. The exponential-GARCH models are used to model the other four market price changes.
[1] standard errors in parentheses. [2] hereafter in this table, p-values in parentheses.

Table 6. AG-DCC GARCH model

	AG-DCC GARCH estimates		
	a_{ii}	g_{ii}	b_{ii}
Feeder Cattle (500 – 600 lbs.)	0.1716***	-0.5755***	0.8246***
	(0.0592)	*(0.0937)*	*(0.0470)*
Feeder Cattle (800 – 900 lbs.)	0.3517***	-0.3080***	0.6812***
	(0.0953)	*(0.0810)*	*(0.0907)*
Fed Cattle	0.0259	-0.1517***	0.9898***
	(0.0414)	*(0.0448)*	*(0.0030)*
Barley	-0.0989*	-0.2228***	0.9646***
	(0.0574)	*(0.0700)*	*(0.0346)*
Corn	-0.1486**	-0.0070	0.9454***
	(0.0741)	*(0.0612)*	*(0.0730)*

***, **,* denote rejection of null hypothesis at the 1%, 5%, 10% significance levels, respectively.
Standard errors in parentheses.

Table 7. Products of AG-DCC GARCH estimates

	Products of AG-DCC GARCH estimates		
	$a_{ii}a_{jj}$	$g_{ii}g_{jj}$	$b_{ii}b_{jj}$
Feeder Cattle (500 – 600 lbs.) – Feeder Cattle (800 – 900 lbs.)	0.0603**	0.1772***	0.5617***
	(0.0273)	*(0.0664)*	*(0.0873)*
Feeder Cattle (500 – 600 lbs.) – Fed Cattle	0.0044	0.0873***	0.8162***
	(0.0072)	*(0.0301)*	*(0.0465)*
Feeder Cattle (500 – 600 lbs.) – Barley	-0.0170	0.1282***	0.7954***
	(0.0120)	*(0.0394)*	*(0.0525)*
Feeder Cattle (500 – 600 lbs.) – Corn	-0.0255*	0.0403	0.7796***
	(0.0143)	*(0.0346)*	*(0.0746)*
Feeder Cattle (800 – 900 lbs.) – Fed Cattle	0.0091	0.0467**	0.6742***
	(0.0148)	*(0.0190)*	*(0.0896)*
Feeder Cattle (800 – 900 lbs.) – Barley	-0.0348*	0.0686***	0.6570***
	(0.0209)	*(0.0244)*	*(0.0896)*
Feeder Cattle (800 – 900 lbs.) – Corn	-0.0523**	0.0215	0.6440***
	(0.0233)	*(0.0188)*	*(0.1014)*
Fed Cattle – Barley	-0.0026	0.0338**	0.9547***
	(0.0045)	*(0.0144)*	*(0.0346)*
Fed Cattle – Corn	-0.0038	0.0106	0.9357***
	(0.0066)	*(0.0094)*	*(0.0726)*
Barley – Corn	0.0147	0.0156	0.9119***
	(0.0105)	*(0.0143)*	*(0.0575)*

***, **,* denote rejection of null hypothesis at the 1%, 5%, 10% significance levels, respectively.
Statistical inferences are made based on the delta method.
Standard errors in parentheses.

Table 8. Summary statistics of dynamic conditional correlations

	Summary statistics of $\rho_{t,ij}$			
	Mean	Std. Dev.	Maximum	Minimum
Feeder Cattle (500 – 600 lbs.) – Feeder Cattle (800 – 900 lbs.)	0.4531	0.1197	0.7979 (2003:12:31)[1]	0.0153 (2011:08:31)
Feeder Cattle (500 – 600 lbs.) – Fed Cattle	0.1880	0.0673	0.4399 (2005:03:16)	0.0207 (2003:06:04)
Feeder Cattle (500 – 600 lbs.) – Barley	-0.0346	0.0933	0.4466 (2004:09:01)	-0.2102 (2013:06:05)
Feeder Cattle (500 – 600 lbs.) – Corn	-0.0388	0.0408	0.1542 (2012:01:25)	-0.1542 (2000:01:26)
Feeder Cattle (800 – 900 lbs.) – Fed Cattle	0.2216	0.0417	0.4121 (2005:03:23)	0.0549 (2003:06:04)
Feeder Cattle (800 – 900 lbs.) – Barley	-0.0396	0.0401	0.1334 (2005:01:12)	-0.2143 (2001:06:06)
Feeder Cattle (800 – 900 lbs.) – Corn	-0.0483	0.0562	0.2459 (2013:04:10)	-0.2372 (2008:06:18)
Fed Cattle – Barley	0.0073	0.0527	0.1805 (2000:02:23)	-0.1117 (2013:06:05)
Fed Cattle – Corn	0.0211	0.0123	0.0767 (2007:07:04)	-0.0153 (2011:02:16)
Barley – Corn	0.0928	0.0553	0.2759 (2009:09:16)	-0.0381 (2007:10:10)

Note: [1] dates in parentheses denote time of occurrences of the extremes.

Table 9. Nonlinear combinations of estimated BEKK parameters

$h_{11,t}$	$h_{12,t}$	$h_{22,t}$
$\gamma_{11}(non\ bse) = c_{11}^{\ 2}$	$\gamma_{12}(non\ bse) = c_{11}c_{12}$	$\gamma_{22}(non\ bse) = c_{12}^{\ 2} + c_{22}^{\ 2}$
$\gamma_{11}(with\ bse) = (c_{11} + \omega_{11}bse)^2$	$\gamma_{12}(with\ bse) = (c_{21} + \omega_{21}bse)^2 + (c_{22} + \omega_{22}bse)^2$	$\gamma_{22}(with\ bse) = (c_{21} + \omega_{21}bse)^2 + (c_{22} + \omega_{22}bse)^2$
$\alpha_{11} = a_{11}^{\ 2}$	$\alpha_{12} = \alpha_{11}\alpha_{12}$	$\alpha_{22} = a_{22}^{\ 2}$
$\alpha_{11}^{'} = a_{21}^{\ 2}$	$\alpha_{12}^{'} = \alpha_{21}\alpha_{22}$	$\alpha_{22}^{'} = a_{12}^{\ 2}$
$\alpha_{11}^{''} = 2a_{11}a_{21}$	$\alpha_{12}^{''} = \alpha_{11}\alpha_{22} + \alpha_{12}\alpha_{21}$	$\alpha_{22}^{''} = 2a_{12}a_{22}$
$\beta_{11} = b_{11}^{\ 2}$	$\beta_{12} = \beta_{11}\beta_{12}$	$\beta_{22} = b_{22}^{\ 2}$
$\beta_{11}^{'} = b_{21}^{\ 2}$	$\beta_{12}^{'} = \beta_{21}\beta_{22}$	$\beta_{22}^{'} = b_{12}^{\ 2}$
$\beta_{11}^{''} = 2b_{11}b_{21}$	$\beta_{12}^{''} = \beta_{11}\beta_{22} + \beta_{12}\beta_{21}$	$\beta_{22}^{''} = 2b_{12}b_{22}$
$\varphi_{11} = d_{11}^2$	$\varphi_{12} = \varphi_{11}\varphi_{12}$	$\varphi_{22} = d_{22}^2$
$\varphi_{11}^{'} = d_{21}^2$	$\varphi_{12}^{'} = \varphi_{21}\varphi_{22}$	$\varphi_{22}^{'} = d_{12}^2$
$\varphi_{11}^{''} = 2d_{11}d_{21}$	$\varphi_{12}^{''} = \varphi_{11}\varphi_{22} + \varphi_{12}\varphi_{21}$	$\varphi_{22}^{''} = 2d_{12}d_{22}$

Table 10. Summary statistics for logged weekly prices and price changes (n=969)

Summary statistics for logged weekly prices (i.e., $100 \times \log(p_t)$)	Feeder Cattle (500 – 600 lbs.)	Feeder Cattle (800 – 900 lbs.)	Fed Cattle	Barley	Corn
Statistic					
Mean	481.605	464.217	450.162	502.091	499.474
Minimum	426.704	411.643	355.706	446.935	433.730
Maximum	521.428	496.459	480.974	569.541	580.329
Std. Dev.	19.154	15.662	15.217	26.895	34.125
ADF tests[1] for stationarity					
Test stats (lag = 0)	-1.763	-	-	-	-1.618
Test stats (lag = 1)	-	-2.296	-	-	-
Test stats (lag = 3)	-	-	-	-1.227	-
Test stats (lag = 11)	-	-	-3.554**	-	-
Summary statistics for weekly price changes (i.e., $100 \times \log(p_t / p_{t-1})$)					
Statistic					
Mean	0.025	0.032	0.031	0.087	0.079
Median	0.043	0.107	0.024	0.000	0.156
Minimum	-15.301	-14.60	-35.650	-15.778	-15.059
Maximum	12.258	9.389	51.128	17.984	16.299
Std. Dev.	2.366	2.119	3.333	2.544	4.238
Skewness	-0.411	-0.624	2.007	-0.150	-0.060
Kurtosis (excess)	6.094	5.423	75.914	9.223	1.550
Testing for autocorrelations in price changes					
Ljung-Box Q-stats (6)	15.22**	56.54***	126.11***	32.61***	5.72
	(0.019)[2]	*(0.000)*	*(0.000)*	*(0.000)*	*(0.455)*
Ljung-Box Q-stats (12)	23.37**	96.61***	265.41***	37.67***	21.28**
	(0.025)	*(0.000)*	*(0.000)*	*(0.000)*	*(0.045)*
Testing for ARCH effects in price changes					
Ljung-Box Q-stats (6)	108.80***	343.30***	37.29***	186.88***	62.52***
	(0.000)	*(0.000)*	*(0.000)*	*(0.000)*	*(0.000)*
Ljung-Box Q-stats (12)	245.92***	532.61***	238.20***	188.62***	105.90***
	(0.000)	*(0.000)*	*(0.000)*	*(0.000)*	*(0.000)*
ADF tests for stationarity					
Test stats (lag = 0)	-29.668***	-25.437***			-31.660***
Test stats (lag = 2)	-	-		-15.096***	-
Test stats (lag = 10)	-	-	-12.373***	-	-

***,**,* denote rejection of null hypothesis at the 1%, 5% and 10% significance levels, respectively.
[1]The critical values of the ADF test at 1%, 5% and 10% are -2.865, -2.569 and -3.440, respectively.
[2]p-values in parentheses.
Lags in ADF tests are based on Bayesian Information Criterion (BIC).
These summary statistics are based on natural logarithmically transformed prices multiplied by 100.

Table 11. Johansen trace tests for cointegration

Market pairs	H_0	H_a	λ_{trace}	5% critical value
Barley – Corn	$r=0$	$r>0$	16.2371	15.41
	$r\leq 1$	$r>1$	1.6097	3.76
Barley – Feeder Cattle (800 – 900 lbs.)	$r=0$	$r>0$	8.9476	15.41
	$r\leq 1$	$r>1$	0.3667	3.76
Corn – Feeder Cattle (800 – 900 lbs.)	$r=0$	$r>0$	8.8601	15.41
	$r\leq 1$	$r>1$	2.0391	3.76
Feeder Cattle (500 – 600 lbs.) – Feeder Cattle (800 – 900 lbs.)	$r=0$	$r>0$	32.0813	15.41
	$r\leq 1$	$r>1$	3.6734	3.76
Barley – Feeder Cattle (500 – 600 lbs.)	$r=0$	$r>0$	9.6328	15.41
	$r\leq 1$	$r>1$	1.8427	3.76
Corn – Feeder Cattle (500 – 600 lbs.)	$r=0$	$r>0$	8.8601	15.41
	$r\leq 1$	$r>1$	2.0391	3.76

Cointegrating relationships

$$p_{1t} = -55.497 + 1.157\,p_{2,t}$$
$$\quad (5.920) \quad (0.013)$$

$$p_{4,t} = 156.89 + 0.691\,p_{5,t}$$
$$\quad (6.09) \quad (0.01)$$

Note: $p_{1,t}$, $p_{2,t}$, $p_{4,t}$ and $p_{5,t}$ are logarithmically transformed prices of feeder cattle (500 – 600 lbs.), feeder cattle (800 – 900 lbs.), barley and U.S. corn, each multiplied by 100, respectively.
Standard errors in parentheses.

Table 12. Conditional mean estimations between price changes of feeder cattle (500 – 600 lbs.) and feeder cattle (800 – 900 lbs.)

	Feeder Cattle (500 – 600 lbs.)	Feeder Cattle (800 – 900 lbs.)
	(i = 1)	(i = 2)
$AR(1)_{1i}$	-0.0665** (0.0290)	0.0912** (0.0219)
$AR(3)_{1i}$	-	-0.0636*** (0.0202)
$AR(6)_{1i}$	0.0466* (0.0241)	-
$AR(8)_{1i}$	-	-0.0587*** (0.0202)
$AR(10)_{1i}$	0.0512** (0.0254)	-
$AR(1)_{2i}$	0.2096*** (0.0263)	0.0620** (0.0291)
$AR(6)_{2i}$	-	0.1244*** (0.0239)
$AR(10)_{2i}$	-0.0942*** (0.0276)	-0.0545** (0.0227)
$FeederECT$	0.0409*** (0.0084)	-0.0200*** (0.0073)
BSE	-2.3541** (1.1350)	-1.9643* (1.0191)

***,**,* denote rejection of null hypothesis at the 1%, 5% and 10% significance levels, respectively. Standard errors in parentheses

Note: $FeederECT$ is the error correction term these two cointegrated price changes. BSE is a dummy variable that takes on the value of one from May 28, 2003 to August 28, 2003 (first three months of the BSE crisis), and zero otherwise.

Table 13. Conditional mean estimations between price changes of feeder cattle (500 – 600 lbs.) and fed cattle

	Feeder Cattle (500 – 600 lbs.)	Fed Cattle
	(i = 1)	(i = 2)
$AR(1)_{1i}$	-	-0.0758** (0.0322)
$AR(2)_{1i}$	0.0991*** (0.0294)	-
$AR(1)_{2i}$	0.2074*** (0.0246)	0.2292*** (0.0303)
$AR(2)_{2i}$	-	-0.1313*** (0.0294)
BSE	-0.9263 (1.8448)	-9.9739*** (3.0118)

***,**,* denote rejection of null hypothesis at the 1%, 5% and 10% significance levels, respectively. Standard errors in parentheses.
Note: BSE is a dummy variable that takes on the value of one from May 28, 2003 to August 20, 2003 (first three months of the BSE crisis), and zero otherwise.

Table 14. Conditional mean estimations between price changes of feeder cattle (800 – 900 lbs.) and fed cattle

	Feeder Cattle (800 – 900 lbs.)	Fed Cattle
	(i = 1)	(i = 2)
$AR(1)_{1i}$	-	-0.1606*** (0.0355)
$AR(2)_{1i}$	0.0641** (0.0278)	-
$AR(3)_{1i}$	0.0710** (0.0281)	-
$AR(4)_{1i}$	0.0913*** (0.0288)	-
$AR(5)_{1i}$	-	0.0749** (0.0338)
$AR(6)_{1i}$	0.0730*** (0.0280)	-
$AR(8)_{1i}$	-0.0537* (0.0283)	-
$AR(10)_{1i}$	-0.0720*** (0.0266)	-
$AR(17)_{1i}$	-0.0667** (0.0264)	-
$AR(1)_{2i}$	0.2200*** (0.0211)	0.2120*** (0.0289)
$AR(2)_{2i}$	-	-0.0968*** (0.0293)
$AR(4)_{2i}$	-0.0642*** (0.0224)	-
$AR(12)_{2i}$	-	-0.0574** (0.0266)
BSE	-0.5315 (1.004)	-7.2305* (3.8653)

***,**,* denote rejection of null hypothesis at the 1%, 5% and 10% significance levels, respectively.
Note: BSE is a dummy variable that takes on the value of one from May 28, 2003 to August 28, 2003 (first three months of the BSE crisis), and zero otherwise.

Table 15. Nonlinear combination of coefficients from Asymmetric t-BEKK GARCH model between the price changes of feeder cattle (500 – 600 lbs.) and feeder cattle (800 – 900 lbs.)

	$h_{11,t}$		$h_{12,t}$		$h_{22,t}$	
	Coefficient	Standard error	Coefficient	Standard error	Coefficient	Standard error
$\gamma(non\,bse)$	0.7479***	0.2731	-0.1133	0.1130	0.2906***	0.1216
$\gamma(with\,bse)$	12.1102*	7.6624	0.1770	2.9808	4.3335	3.5806
α	0.0845**	0.0408	-0.0343**	0.0145	0.0907**	0.0390
α'	0.0284	0.0237	-0.0508**	0.0183	0.0139	0.0126
α''	-0.0980*	0.0543	0.1075***	0.0276	-0.0711*	0.0411
β	0.6267***	0.1263	0.0938*	0.0490	0.6729***	0.0964
β'	0.0088	0.0134	0.0770	0.0595	0.0140	0.0139
β''	0.1486	0.1009	0.6605***	0.0690	0.1944**	0.0850
φ	0.0444	0.0418	0.0337	0.0210	0.0287	0.0328
φ'	0.0292	0.0356	0.0289	0.0247	0.0255	0.0231
φ''	0.0720**	0.0362	0.0630***	0.0241	0.0542	0.0282

***,**,* denote rejection of null hypothesis at the 1%, 5% and 10% significance levels, respectively. Standard errors are calculated based on the delta method.
The shaded cells indicate the measurements of volatility spillovers.

Table 16. Nonlinear combination of coefficients from Asymmetric t-BEKK GARCH model between the price changes of feeder cattle (500 – 600 lbs.) and fed cattle

	$h_{11,t}$		$h_{12,t}$		$h_{22,t}$	
	Coefficient	Standard error	Coefficient	Standard error	Coefficient	Standard error
$\gamma(non\,bse)$	0.5037***	0.1543	-0.4319***	0.1246	0.6668***	0.2033
$\gamma(with\,bse)$	21.9131*	12.9271	-30.9734*	15.8751	51.2688*	29.1183
α	0.0857**	0.0209	-0.0157	0.0132	0.0307*	0.0181
α'	0.0000	0.0005	-0.0011	0.0068	0.0029	0.0048
α''	0.0036	0.0224	-0.0516***	0.0156	0.0188	0.0167
β	0.6718***	0.0657	0.0625	0.0413	0.7784***	0.0607
β'	0.0072	0.0050	0.0750***	0.0260	0.0057	0.0077
β''	0.1405***	0.0445	0.7349***	0.0447	0.1335	0.0862
φ	0.0469	0.0389	0.0098	0.0133	0.0277	0.0227
φ'	0.0435*	0.0245	0.0347**	0.0157	0.0021	0.0057
φ''	0.0903***	0.0302	0.0455**	0.0193	0.0151	0.0207

***,**,* denote rejection of null hypothesis at the 1%, 5% and 10% significance levels, respectively. Standard errors are calculated based on the delta method.
The shaded cells indicate the measurements of volatility spillovers.

Table 17. Nonlinear combination of coefficients from Asymmetric t-BEKK GARCH model between the price changes of feeder cattle (800 – 900 lbs.) and fed cattle

	$h_{11,t}$		$h_{12,t}$		$h_{22,t}$	
	Coefficient	Standard error	Coefficient	Standard error	Coefficient	Standard error
$\gamma(non\,bse)$	0.1915***	0.0488	0.1066**	0.0537	0.5370***	0.1350
$\gamma(with\,bse)$	4.6245*	2.8065	2.0455	6.0066	59.0434**	25.5468
α	0.0165	0.0122	0.0286**	0.0143	0.0313	0.0223
α'	0.0013	0.0036	0.0034	0.0093	0.0497**	0.0238
α''	-0.0092	0.0137	-0.0307*	0.0184	-0.0789**	0.0360
β	0.8514***	0.0237	-0.0664***	0.0031	0.7886***	0.0457
β'	0.0002	0.0003	-0.0130	0.0079	0.0052***	0.0005
β''	-0.0270	0.0172	0.8205***	0.0244	-0.1279***	0.0091
φ	0.1102***	0.0344	0.0907***	0.0260	0.0490**	0.0217
φ'	0.0047	0.0061	0.0152	0.0110	0.0747**	0.0302
φ''	0.0455*	0.0261	0.0922***	0.0198	0.1210***	0.0287

***,**,* denote rejection of null hypothesis at the 1%, 5% and 10% significance levels, respectively. Standard errors are calculated based on the delta method.
The shaded cells indicate the measurements of volatility spillovers.

Table 18a. Conditional mean estimations between price changes of feeder cattle (500 – 600 lbs.) and barley (asymmetric effects defined as price decreases in both markets)

	Feeder Cattle (500 – 600 lbs.)	Barley
	(i = 1)	(i = 2)
$AR(2)_{1i}$	0.0816*** (0.0290)	-
$AR(1)_{2i}$	-0.0704*** (0.0224)	-
$AR(2)_{2i}$	-	0.1593*** (0.0295)
$AR(3)_{2i}$	-	0.0930*** (0.0256)
$AR(4)_{2i}$	-	0.0469** (0.0229)
BSE	-2.4971* (1.3000)	-

***,**,* denote rejection of null hypothesis at the 1%, 5% and 10% significance levels, respectively. Standard errors in parentheses.
Note: BSE is a dummy variable that takes on the value of one from May 28, 2003 to August 28, 2003 (first three months of the BSE crisis), and zero otherwise.

Table 18b. Conditional mean estimations between price changes of feeder cattle (500 – 600 lbs.) and barley (asymmetric effects defined as price decrease in feeder cattle market and price increase in barley market)

	Feeder Cattle (500 – 600 lbs.)	Barley
	(i = 1)	(i = 2)
$AR(2)_{1i}$	0.0853*** (0.0302)	-
$AR(1)_{2i}$	-0.0612** (0.0268)	-
$AR(2)_{2i}$	-	0.1640*** (0.0310)
$AR(3)_{2i}$	-	0.0847*** (0.0271)
$AR(4)_{2i}$	-	0.0482* (0.0235)
BSE	-2.1892* (1.3882)	-

***,**,* denote rejection of null hypothesis at the 1%, 5% and 10% significance levels, respectively.
Note: BSE is a dummy variable that takes on the value of one from May 28, 2003 to August 28, 2003 (first three months of the BSE crisis), and zero otherwise

Table 19a. Conditional mean estimations between price changes of feeder cattle (800 – 900 lbs.) and barley (asymmetric effects defined as price decreases in both markets)

	Feeder Cattle (800 – 900 lbs.)	Barley
	(i = 1)	(i = 2)
$AR(1)_{1i}$	0.1268*** (0.0309)	-
$AR(4)_{1i}$	0.0709** (0.0322)	-
$AR(6)_{1i}$	0.0724** (0.0314)	-
$AR(10)_{1i}$	-0.0715** (0.0286)	-
$AR(1)_{2i}$	-0.0529** (0.0214)	-
$AR(2)_{2i}$	-	0.1627*** (0.0331)
$AR(3)_{2i}$	-	0.0972*** (0.0291)
$AR(4)_{2i}$	-	0.0608** (0.0255)
BSE	-2.4023** (1.1898)	-

***,**,* denote rejection of null hypothesis at the 1%, 5% and 10% significance levels, respectively. Standard errors in parentheses.
Note: BSE is a dummy variable that takes on the value of one from May 28, 2003 to August 28, 2003 (first three months of the BSE crisis), and zero otherwise.

Table 19b. Conditional mean estimations between price changes of feeder cattle (800 – 900 lbs.) and barley (asymmetric effects defined as price decrease in feeder cattle market and price increase in barley market)

	Feeder Cattle (800 – 900 lbs.)	Barley
	(i = 1)	(i = 2)
$AR(1)_{1i}$	0.1273*** (0.0297)	-
$AR(4)_{1i}$	0.0635* (0.0310)	-
$AR(6)_{1i}$	0.0728** (0.0303)	-
$AR(10)_{1i}$	-0.0740*** (0.0281)	-
$AR(1)_{2i}$	-0.0518*** (0.0225)	-
$AR(2)_{2i}$	-	0.1637*** (0.0335)
$AR(3)_{2i}$	-	0.0931*** (0.0307)
$AR(4)_{2i}$	-	0.0601** (0.0267)
BSE	-2.5916** (1.0726)	-

***,**,* denote rejection of null hypothesis at the 1%, 5% and 10% significance levels, respectively. Standard errors in parentheses.

Note: BSE is a dummy variable that takes on the value of one from May 28, 2003 to August 28, 2003 (first three months of the BSE crisis), and zero otherwise.

Table 20a. Conditional mean estimations between price changes of fed cattle and barley (asymmetric effects defined as price decreases in both markets)

	Fed Cattle	Barley
	$(i = 1)$	$(i = 2)$
$AR(1)_{1i}$	0.2431*** (0.0282)	-
$AR(2)_{1i}$	-0.1415*** (0.0282)	-
$AR(2)_{2i}$	-	0.1756*** (0.0314)
$AR(3)_{2i}$	-	0.0831*** (0.0288)
$AR(4)_{2i}$	-	0.0434* (0.0251)
$AR(30)_{2i}$	-0.0708*** (-0.0708)	-
BSE	-6.1946* (3.5651)	-

***,**,* denote rejection of null hypothesis at the 1%, 5% and 10% significance levels, respectively. Note: BSE is a dummy variable that takes on the value of one from May 28, 2003 to August 28, 2003 (first three months of the BSE crisis), and zero otherwise.

Table 20b. Conditional mean estimations between price changes of fed cattle and barley (asymmetric effects defined as price decrease in fed cattle market and price increase in barley market)

	Fed Cattle ($i = 1$)	Barley ($i = 2$)
$AR(1)_{1i}$	0.2410*** (0.0299)	-
$AR(2)_{1i}$	-0.1417*** (0.0295)	-
$AR(2)_{2i}$	-	0.1813*** (0.0344)
$AR(3)_{2i}$	-	0.0872*** (0.0872)
$AR(4)_{2i}$	-	0.0421 (0.0267)
$AR(30)_{2i}$	-0.0715*** (0.0244)	-
BSE	-6.2443* (3.5959)	-

***,**,* denote rejection of null hypothesis at the 1%, 5% and 10% significance levels, respectively. Note: BSE is a dummy variable that takes on the value of one from May 28, 2003 to August 28, 2003 (first three months of the BSE crisis), and zero otherwise.

Table 21. Nonlinear combination of coefficients from Asymmetric t-BEKK GARCH model between price changes of feeder cattle (500 – 600 lbs.) and barley (asymmetric effects defined as price decreases in both markets)

	$h_{11,t}$		$h_{12,t}$		$h_{22,t}$	
	Coefficient	Standard error	Coefficient	Standard error	Coefficient	Standard error
$\gamma(non\,bse)$	0.5019***	0.1609	-0.3516***	0.1354	1.4920***	0.3050
$\gamma(with\,bse)$	7.6729	6.3378	2.7618	3.5370	7.5047	4.6965
α	0.0159	0.0181	-0.0182	0.0122	0.3941***	0.0937
α'	0.0000	0.0004	-0.0031	0.0280	0.0208	0.0143
α''	0.0012	0.0114	-0.0799	0.0454	0.1810***	0.0692
β	0.7829***	0.0475	0.0192	0.0274	0.3141***	0.0771
β'	0.0138	0.0092	0.0660***	0.0208	0.0005	0.0014
β''	0.2082***	0.0669	0.4989***	0.0605	0.0244	0.0350
φ	0.2439***	0.0749	-0.0673	0.0412	0.2260	0.1390
φ'	0.0081	0.0140	-0.0423	0.0389	0.0186	0.0207
φ''	-0.0888	0.0831	0.2471***	0.0818	-0.1296	0.0854

***,**,* denote rejection of null hypothesis at the 1%, 5% and 10% significance levels, respectively. Standard errors are calculated based on the delta method.
The shaded cells indicate the measurements of volatility spillovers.

Table 22. Nonlinear combination of coefficients from Asymmetric t-BEKK GARCH model between price changes of feeder cattle (500 – 600 lbs.) and barley (asymmetric effects defined as price decrease in both feeder cattle market and price increase in barley market)

	$h_{11,t}$		$h_{12,t}$		$h_{22,t}$	
	Coefficient	Standard error	Coefficient	Standard error	Coefficient	Standard error
$\gamma(non\, bse)$	0.4185***	0.1500	-0.2209	0.1522	1.2687***	0.2917
$\gamma(with\, bse)$	7.0571	5.8269	3.4569	3.9977	6.8680	4.7788
α	0.0001	0.0014	0.0011	0.0128	0.4863***	0.0907
α'	0.0000	0.0004	-0.0037	0.0275	0.0207	0.0154
α''	-0.0001	0.0012	0.0048	0.0315	0.2006**	0.0801
β	0.8092***	0.0450	0.0041	0.0315	0.3607***	0.0807
β'	0.0064	0.0064	0.0481**	0.0227	0.0001	0.0003
β''	0.1440**	0.0700	0.5406***	0.0622	0.0055	0.0419
φ	0.1944**	0.0607	-0.0450	0.0363	0.0022	0.0138
φ'	0.0378	0.0405	-0.0061	0.0199	0.0104	0.0160
φ''	0.1883*	0.1089	0.0339	0.0650	-0.0096	0.0295

***,**,* denote rejection of null hypothesis at the 1%, 5% and 10% significance levels, respectively. Standard errors are calculated based on the delta method.
The shaded cells indicate the measurements of volatility spillovers.

Table 23. Nonlinear combination of coefficients from Asymmetric t-BEKK GARCH model between price changes of feeder cattle (800 – 900 lbs.) and barley (asymmetric effects defined as price decreases in both markets)

	$h_{11,t}$		$h_{12,t}$		$h_{22,t}$	
	Coefficient	Standard error	Coefficient	Standard error	Coefficient	Standard error
$\gamma(non\,bse)$	0.2757***	0.0935	-0.1499	0.1489	1.5196***	0.2161
$\gamma(with\,bse)$	6.0513	3.8467	-1.4751	3.8746	8.6470	7.5178
α	0.0128	0.0170	-0.0004	0.0065	0.3527***	0.0694
α'	0.0002	0.0013	-0.0087	0.0260	0.0000	0.0004
α''	0.0033	0.0103	-0.0670	0.0446	-0.0046	0.0688
β	0.8296***	0.0387	-0.0118	0.0425	0.3019***	0.0522
β'	0.0045	0.0051	0.0370*	0.0211	0.0002	0.0012
β''	0.1226*	0.0685	0.4996	0.0440	-0.0143	0.0514
φ	0.1692***	0.0512	-0.0174	0.0435	0.2471**	0.1255
φ'	0.0001	0.0013	-0.0049	0.0336	0.0018	0.0089
φ''	-0.0082	0.0555	0.2049***	0.0613	-0.0420	0.1085

***,**,* denote rejection of null hypothesis at the 1%, 5% and 10% significance levels, respectively. Standard errors are calculated based on the delta method.
The shaded cells indicate the measurements of volatility spillovers.

Table 24. Nonlinear combination of coefficients from Asymmetric t-BEKK GARCH model between price changes of feeder cattle (800 – 900 lbs.) and barley (asymmetric effects defined as price decrease in feeder cattle market and price increase in barley market)

	$h_{11,t}$		$h_{12,t}$		$h_{22,t}$	
	Coefficient	Standard error	Coefficient	Standard error	Coefficient	Standard error
$\gamma(non\,bse)$	0.2495***	0.0857	-0.0695	0.1272	1.2616***	0.3055
$\gamma(with\,bse)$	5.7039**	2.4131	-0.9623	3.1295	6.5193*	3.6935
α	0.0004	0.0040	0.0026	0.0148	0.4357***	0.1078
α'	0.0000	0.0000	-0.0002	0.0113	0.0183	0.0252
α''	0.0000	0.0000	0.0126	0.0688	0.1787	0.1281
β	0.8455***	0.0407	-0.0148	0.0281	0.3627**	0.1740
β'	0.0015	0.0343	0.0232	0.0219	0.0003	0.0010
β''	0.0710	0.0816	0.5531***	0.1344	-0.0193	0.0381
φ	0.1943***	0.0570	-0.0022	0.0191	0.0002	0.0024
φ'	0.0156	0.0135	-0.0017	0.0115	0.0000	0.0004
φ''	0.1100**	0.0539	-0.0066	0.0408	0.0001	0.0016

***,**,* denote rejection of null hypothesis at the 1%, 5% and 10% significance levels, respectively. Standard errors are calculated based on the delta method.
The shaded cells indicate the measurements of volatility spillovers.

Table 25. Nonlinear combination of coefficients from Asymmetric t-BEKK GARCH model between price changes of fed cattle and barley (asymmetric effects defined as price decreases in both markets)

	$h_{11,t}$		$h_{12,t}$		$h_{22,t}$	
	Coefficient	Standard error	Coefficient	Standard error	Coefficient	Standard error
$\gamma(non\, bse)$	0.6355***	0.2252	0.0949	0.1855	1.2918***	0.3268
$\gamma(with\, bse)$	51.2974	31.7530	6.1972	9.5014	7.0300	5.3615
α	0.0002	0.0044	-0.0009	0.0087	0.3406***	0.0886
α'	0.0022	0.0041	-0.0276	0.0253	0.0036	0.0064
α''	0.0015	0.0129	-0.0120	0.0818	0.0702	0.0615
β	0.8316***	0.0500	-0.0120	0.0222	0.3551***	0.1098
β'	0.0002	0.00013	0.0085	0.0273	0.0002	0.0006
β''	0.0260	0.0835	0.5432***	0.0840	-0.0157	0.0289
φ	0.0942*	0.0564	0.0247	0.0546	0.1683	0.1175
φ'	0.0019	0.0056	0.0177	0.0256	0.0065	0.0308
φ''	0.0264	0.0383	0.1293**	0.0553	0.0659	0.1555

***,**,* denote rejection of null hypothesis at the 1%, 5% and 10% significance levels, respectively. Standard errors are calculated based on the delta method.
The shaded cells indicate the measurements of volatility spillovers.

Table 26. Nonlinear combination of coefficients from Asymmetric t-BEKK GARCH model between price changes of fed cattle and barley (asymmetric effects defined as price decrease in fed cattle market and price increase in barley market)

	$h_{11,t}$		$h_{12,t}$		$h_{22,t}$	
	Coefficient	Standard error	Coefficient	Standard error	Coefficient	Standard error
$\gamma(non\,bse)$	0.6476***	0.2408	0.1338	0.1992	1.2135***	0.2830
$\gamma(with\,bse)$	53.1365	32.4631	6.4674	8.9504	6.6726	4.7862
α	0.0000	0.0001	0.0000	0.0048	0.4299***	0.0801
α'	0.0000	0.0000	-0.0001	0.0238	0.0033	0.0054
α''	0.0000	0.0000	0.0005	0.0545	0.0750	0.0626
β	0.8268***	0.0515	-0.0118	0.0188	0.3745***	0.0987
β'	0.0000	0.0002	0.0014	0.0275	0.0002	0.0005
β''	0.0042	0.0816	0.5563***	0.0739	0.0037	0.0323
φ	0.0962**	0.0442	0.0189	0.0804	0.0026	0.0185
φ'	0.0064	0.0084	-0.0040	0.0147	0.0037	0.0323
φ''	-0.0496	0.0336	0.0109	0.0496	0.0062	0.0423

***,**,* denote rejection of null hypothesis at the 1%, 5% and 10% significance levels, respectively. Standard errors are calculated based on the delta method.

The shaded cells indicate the measurements of volatility spillovers.

Table 27. Conditional mean estimations between price changes of barley and corn (asymmetric effects defined as price decreases in both markets)

	Barley (i = 1)	Corn (i = 2)
$AR(2)_{1i}$	0.2143*** (0.0321)	-
$AR(3)_{1i}$	0.0989*** (0.0297)	-
$AR(1)_{2i}$	0.0786*** (0.0153)	-
$AR(2)_{2i}$	0.0591*** (0.0138)	-
$AR(5)_{2i}$	-	0.0765** (0.0316)
$AR(8)_{2i}$	-	0.0581** (0.0298)
$GrainECT$	-0.0119*** (0.0042)	0.0149 (0.0100)

***,**,* denote rejection of null hypothesis at the 1%, 5% and 10% significance levels, respectively.
Note: $GrainECT$ is the error correction term for these two cointegrated price changes.

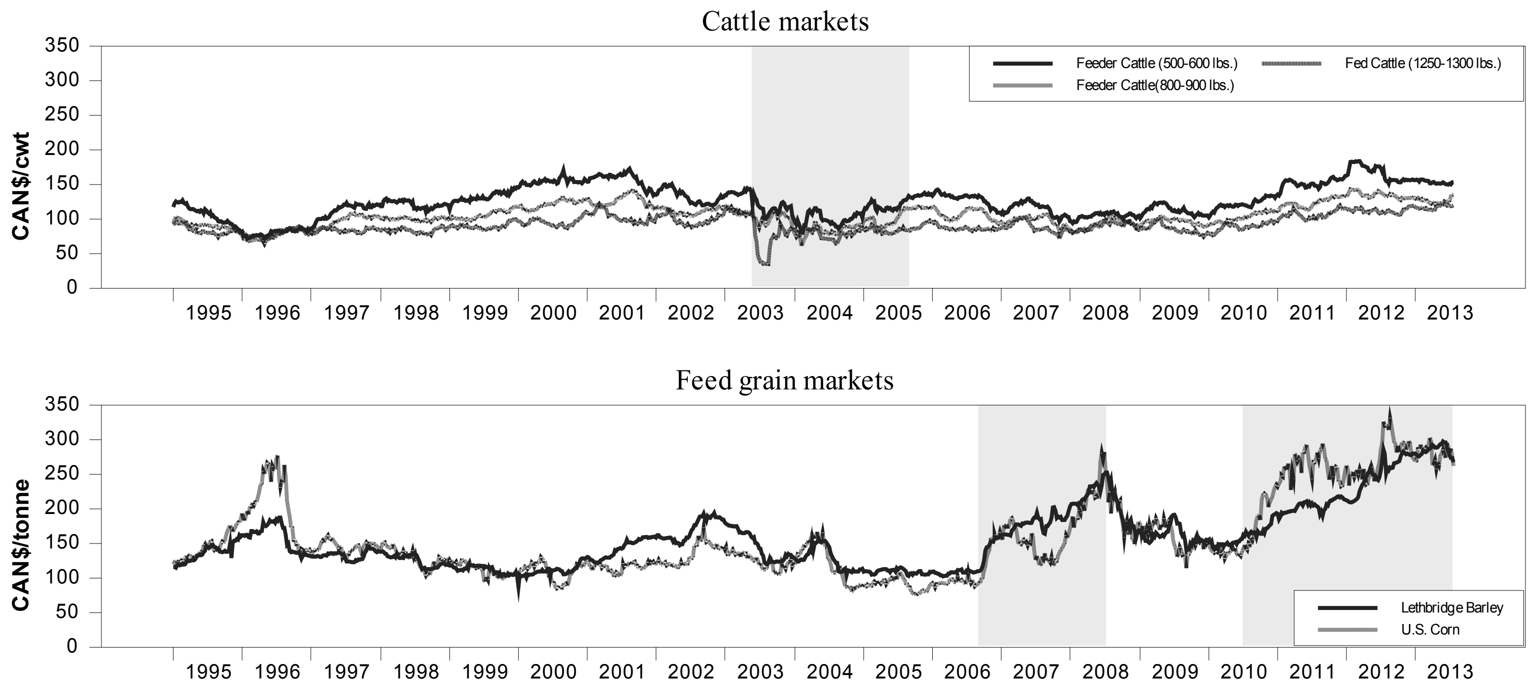
Table 28. Nonlinear combination of coefficients from Asymmetric t-BEKK GARCH model between price changes of barley and corn (asymmetric effects defined as price decreases in both markets)

	$h_{11,t}$		$h_{12,t}$		$h_{22,t}$	
	Coefficient	Standard error	Coefficient	Standard error	Coefficient	Standard error
$\gamma(non\,bse)$	1.1619***	0.2096	1.5609***	0.2306	2.0969***	0.5015
α	0.2910***	0.0794	0.0149	0.0328	0.0794**	0.0312
α'	0.0058	0.0078	0.0214	0.0174	0.0008	0.0033
α''	0.0820	0.0500	0.1541***	0.0226	0.0156	0.0317
β	0.3585***	0.0478	-0.0100	0.0311	0.7855***	0.0315
β'	0.0149***	0.0047	-0.1082***	0.0160	0.0003	0.0017
β''	-0.1462***	0.0224	0.5327***	0.0373	-0.0295	0.0903
φ	0.2545*	0.1405	0.0089	0.0257	0.0431	0.0395
φ'	0.0379*	0.0379	0.0404**	0.0168	0.0003	0.0178
φ''	-0.1963**	0.0918	-0.1081**	0.0483	-0.0073	0.0221

***,**,* denote rejection of null hypothesis at the 1%, 5% and 10% significance levels, respectively. Standard errors are calculated based on the delta method.
The shaded cells indicate the measurements of volatility spillovers.

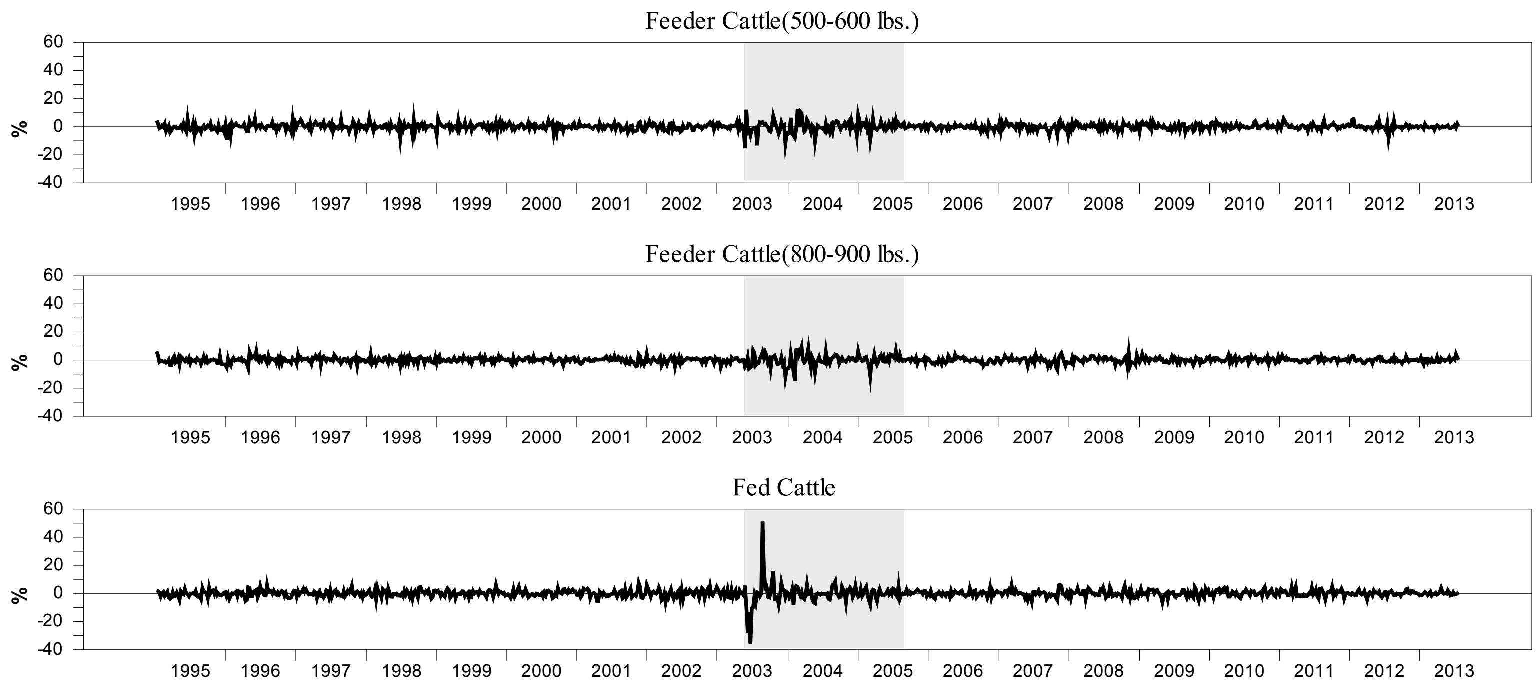
Figures

Figure 1. Price movements (1995-2013)



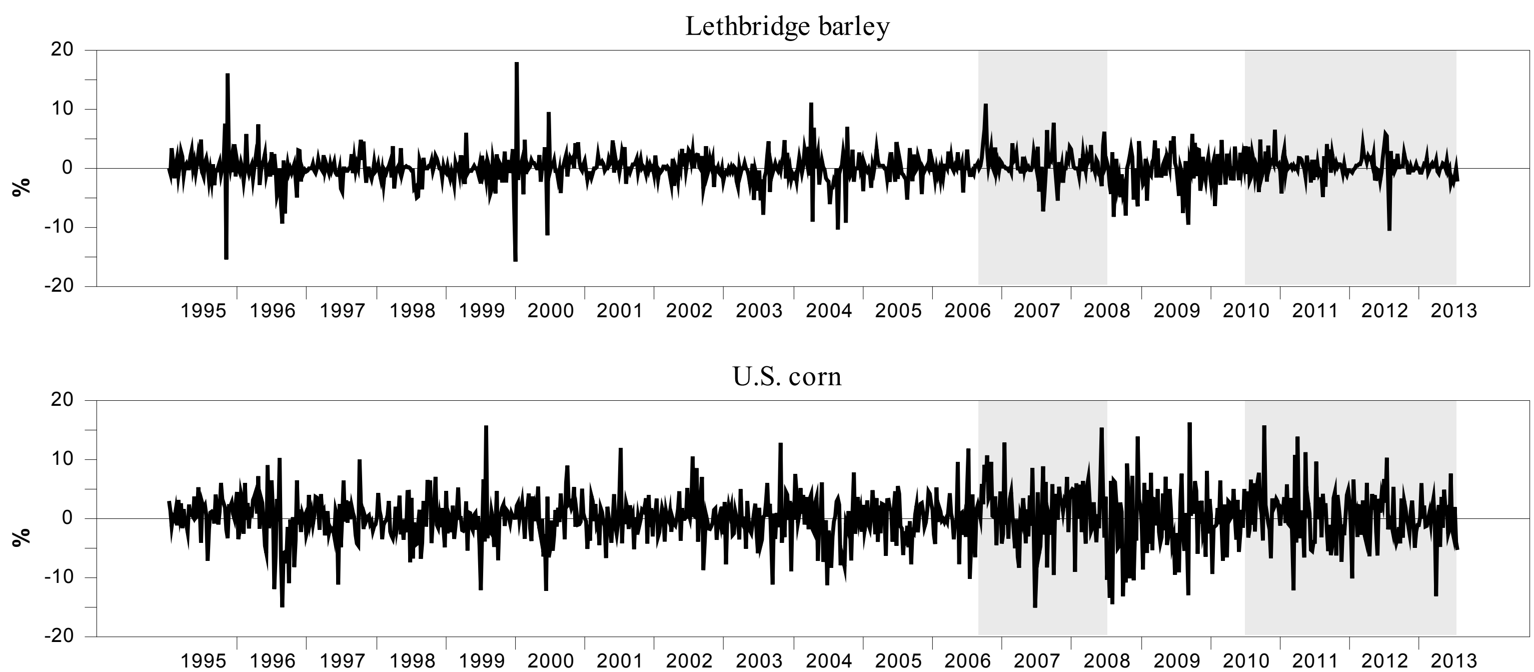
Notes: shaded areas indicate major events occurred in the studied markets

Figure 2a. Cattle price changes



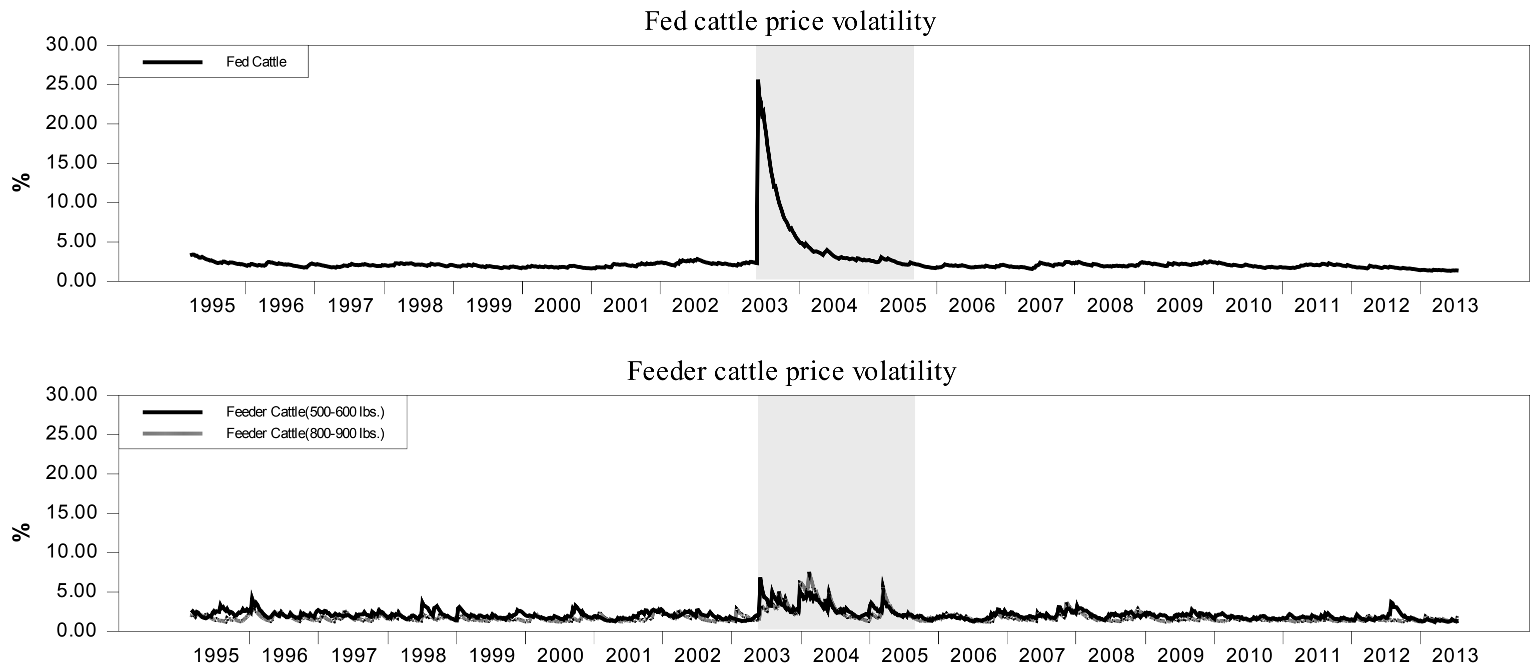
Notes: shaded areas indicate the 2003 Canadian BSE crisis.

Figure 2b. Feed grain price changes



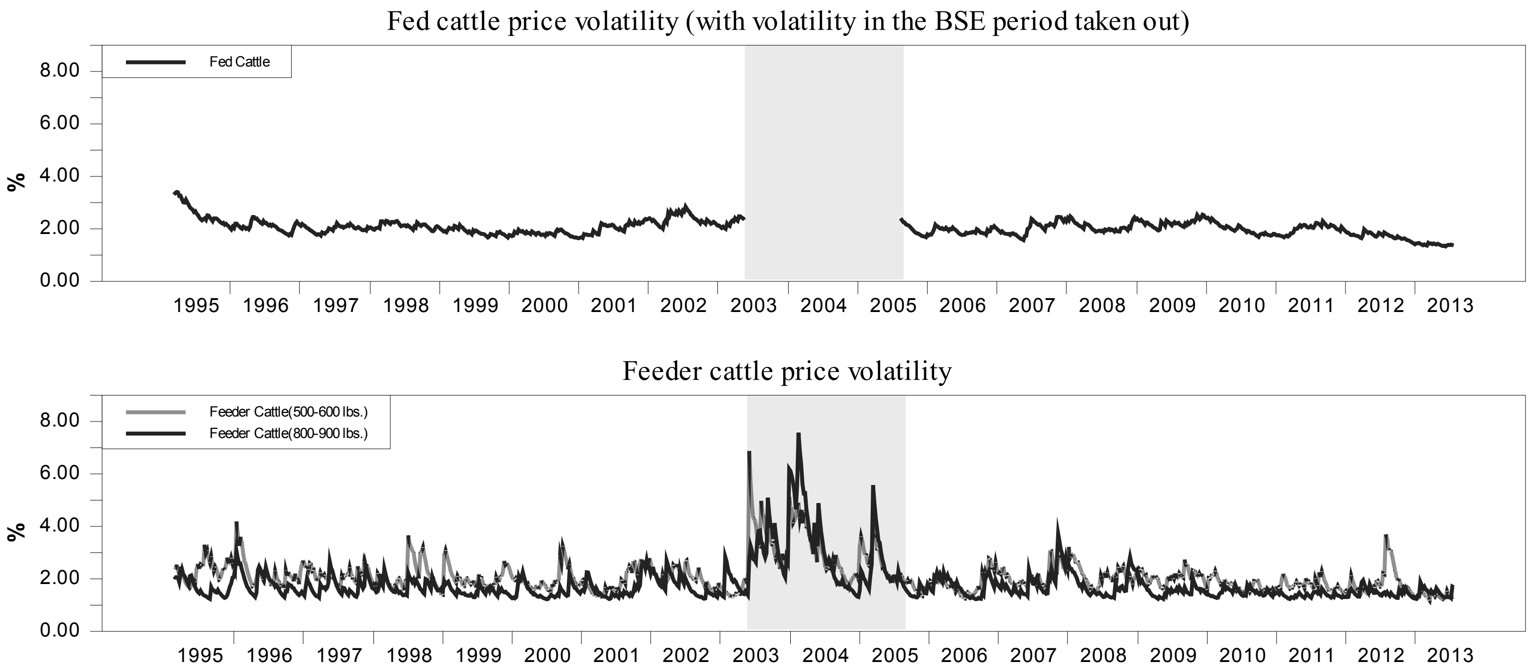
Notes: shaded areas indicate the 2003 Canadian BSE crisis.

Figure 3a. Conditional volatility in cattle markets



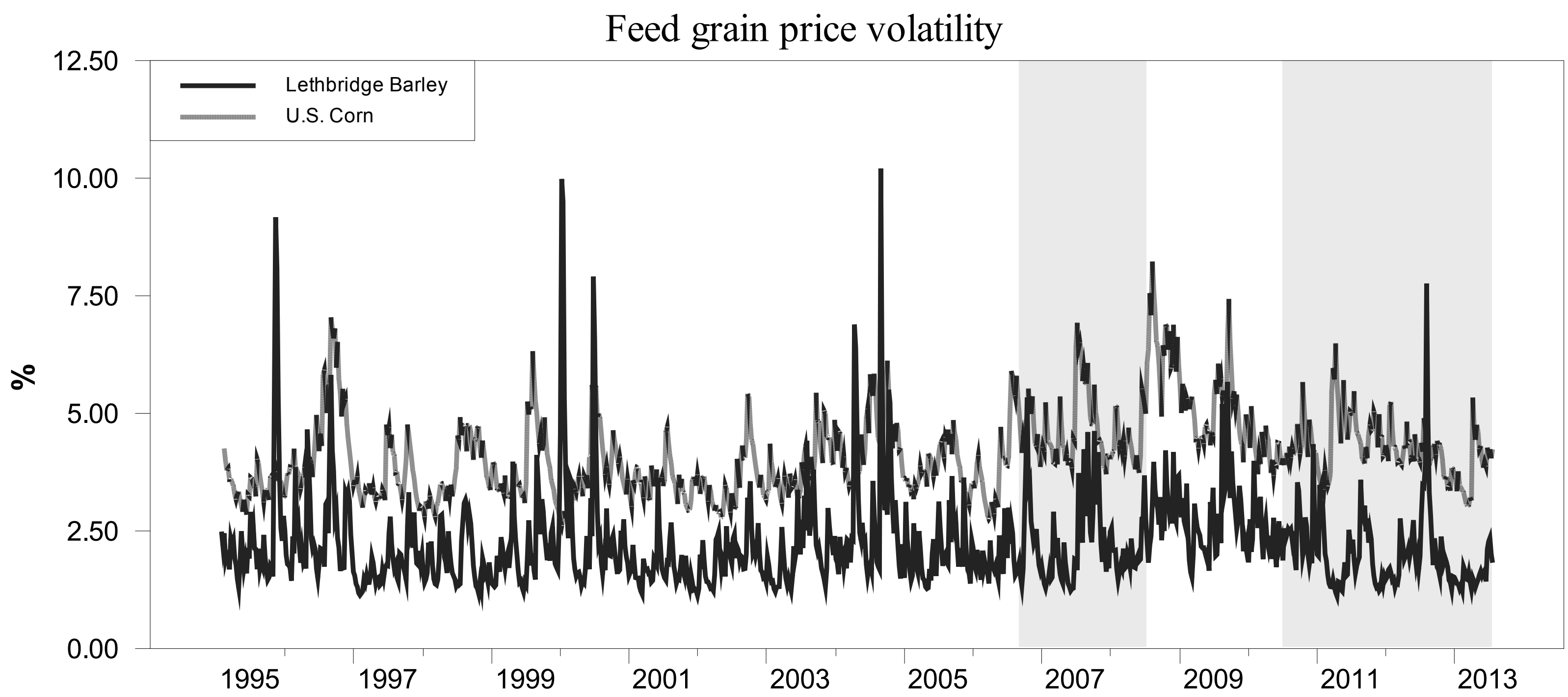
Notes: shaded areas indicate the 2003 Canadian BSE crisis.

Figure 3b. Conditional volatility in cattle markets



Notes: due to scale reasons, fed cattle price volatility in the BSE period is omitted from this figure.

Figure 4. Conditional volatility in feed grain markets



Notes: shaded areas indicate periods of feed price surges.

Figure 5. Dynamic conditional correlations between cattle price changes

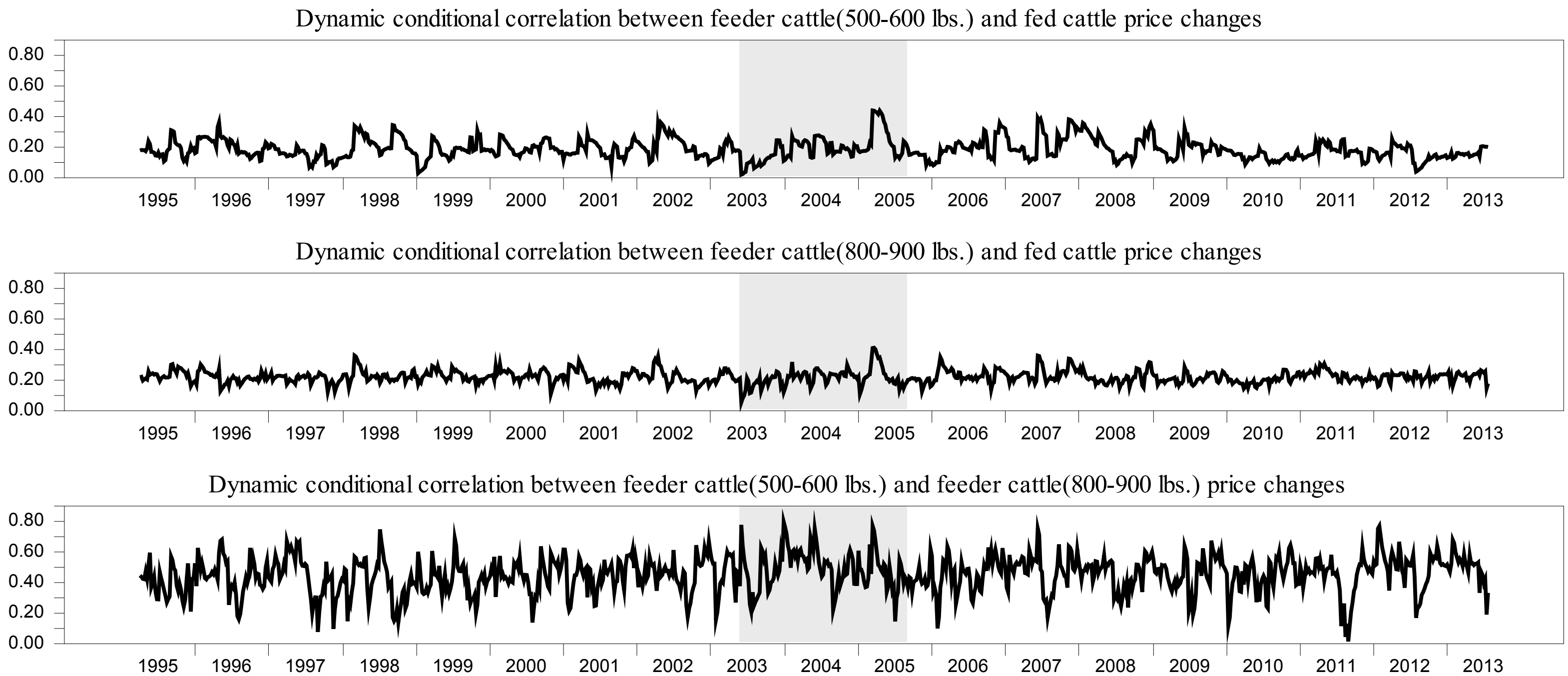
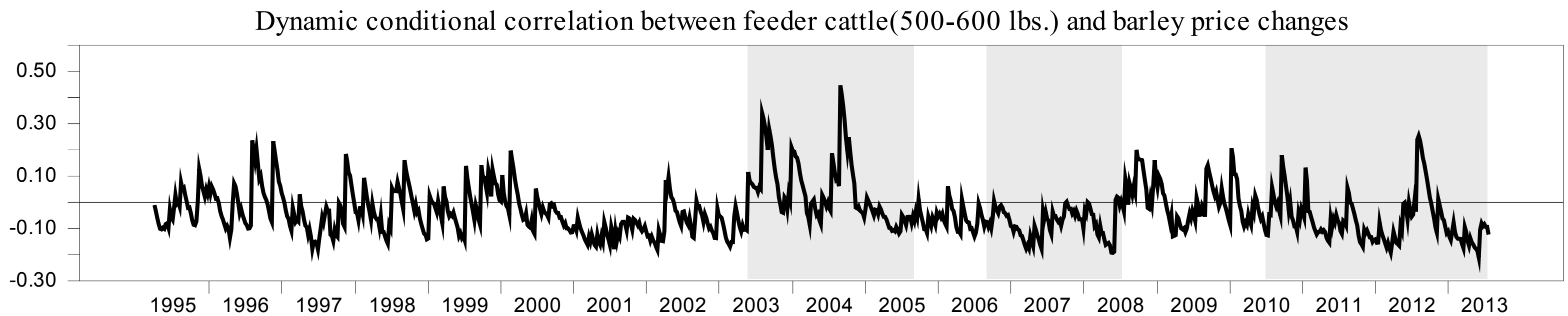


Figure 6. Dynamic conditional correlations between feeder cattle and barley price changes



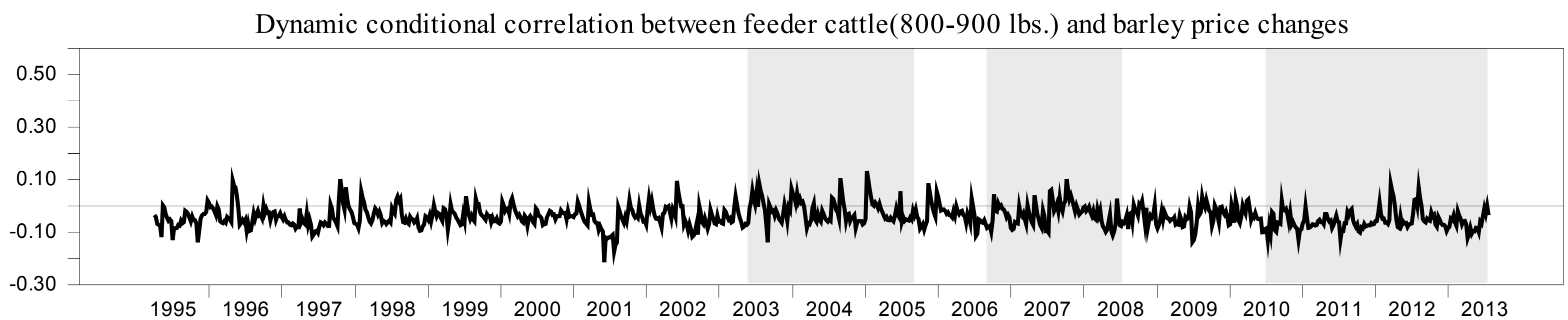
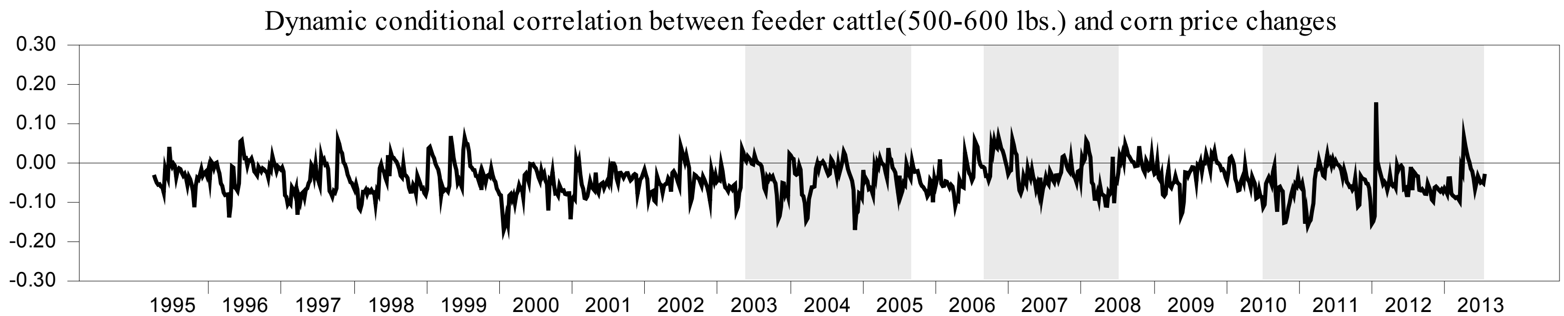


Figure 7. Dynamic conditional correlations between feeder cattle and corn price changes



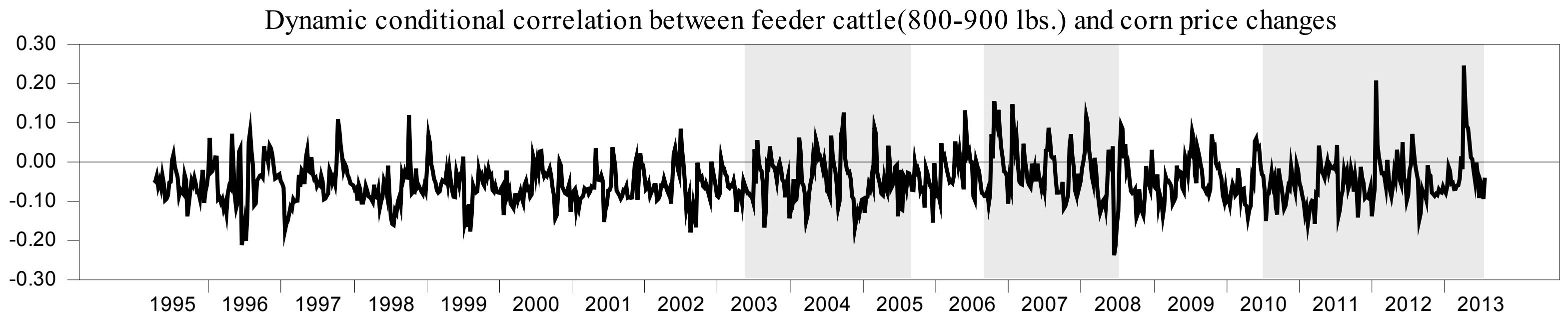


Figure 8. Dynamic conditional correlations between fed cattle and feed grain price changes

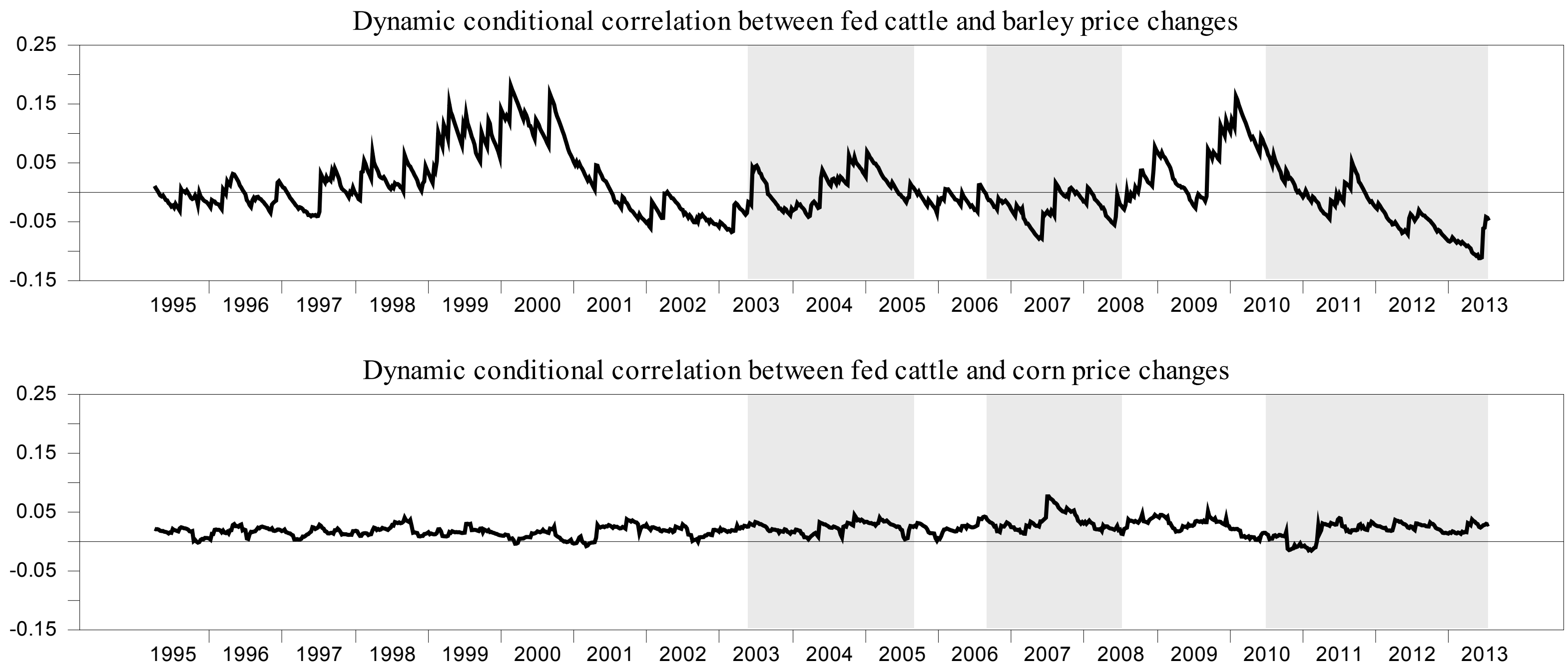


Figure 9. Dynamic conditional correlation between barley and corn price changes

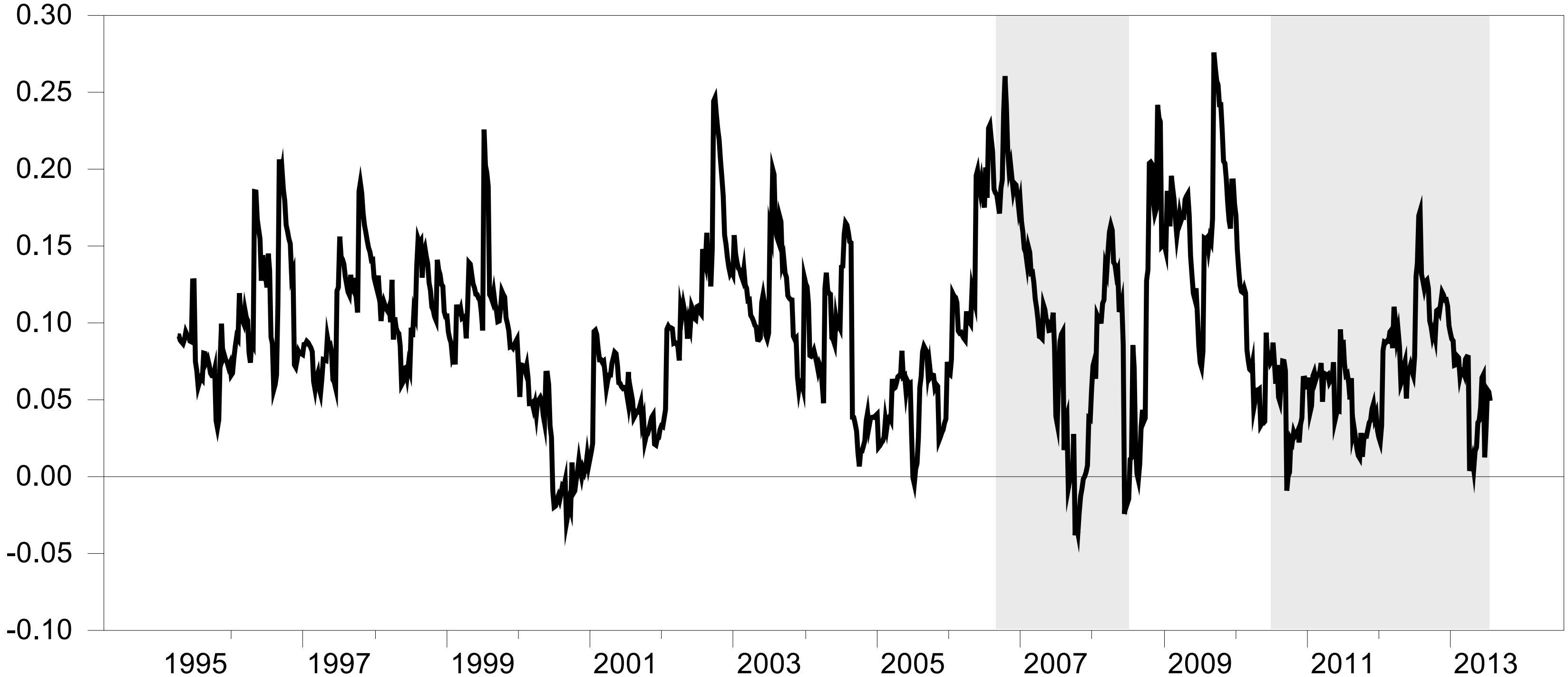
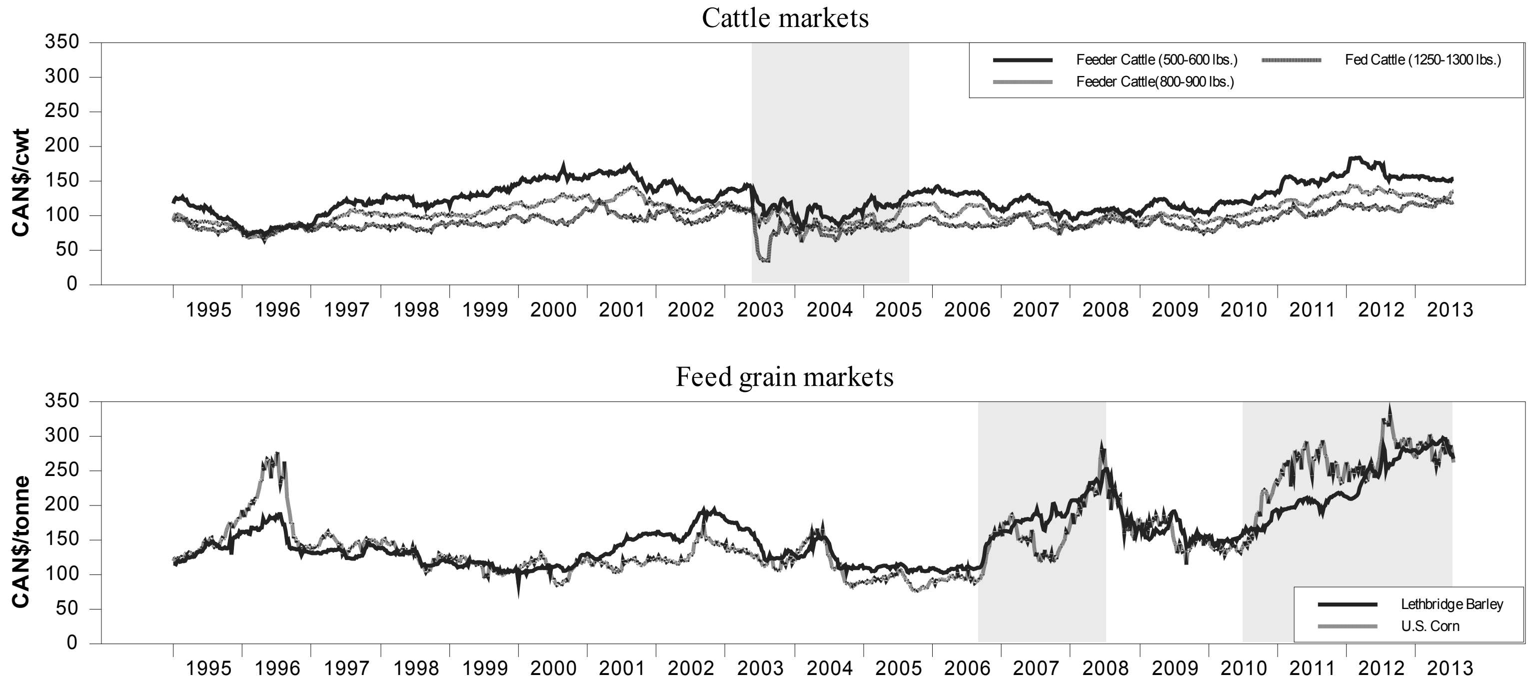
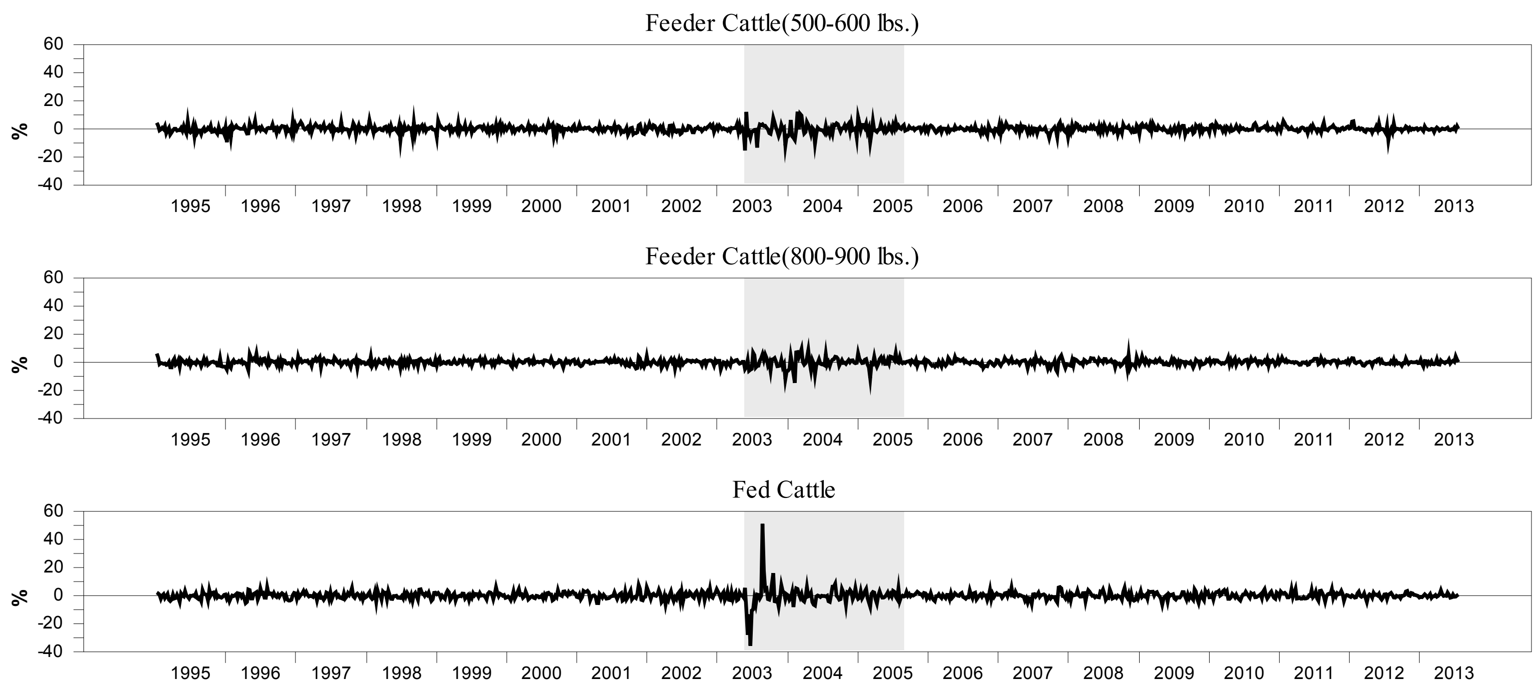


Figure 10. Price movements (1995-2013)



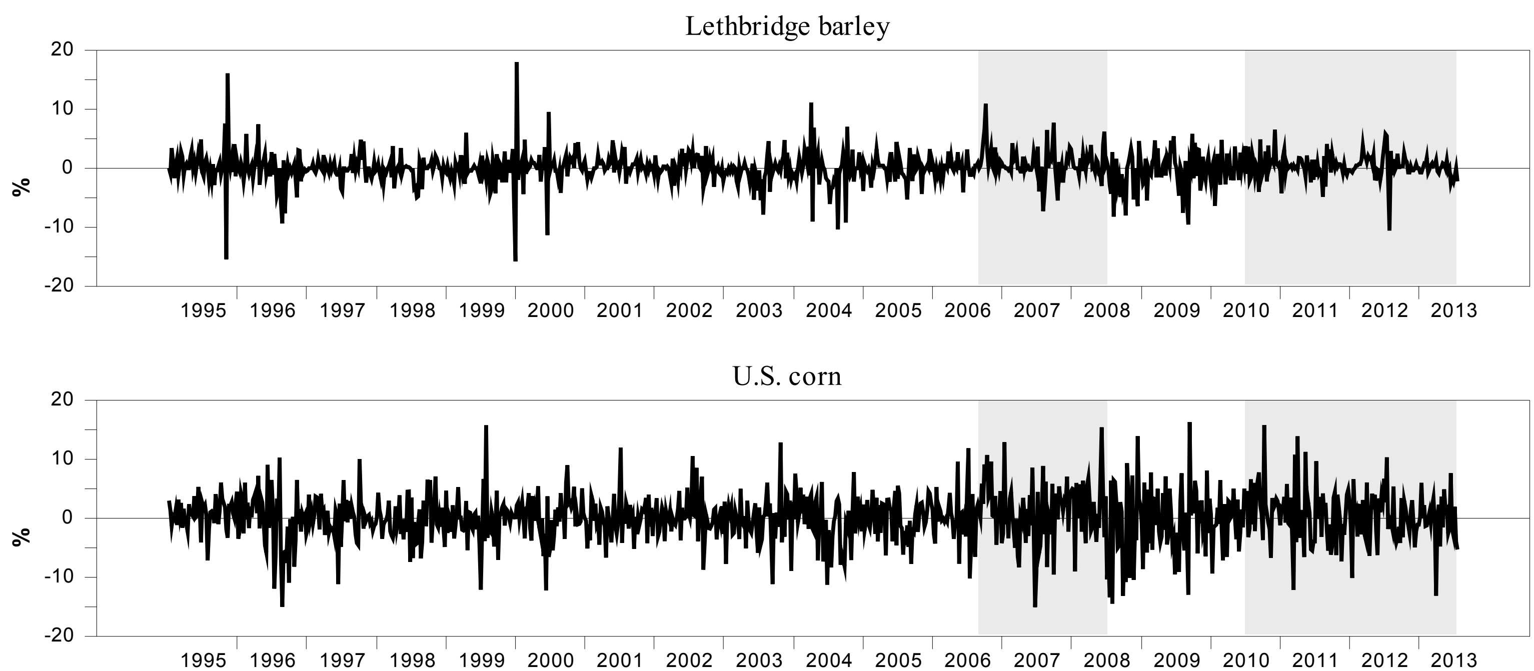
Notes: shaded areas indicate major events occurred in the studied markets

Figure 11a. Cattle price changes



Notes: shaded areas indicate the 2003 Canadian BSE crisis.

Figure 11b. Feed grain price changes



Notes: shaded areas indicate the 2003 Canadian BSE crisis.

Figure 12. Conditional volatility in Alberta cattle markets (generated from BEKK GARCH model)

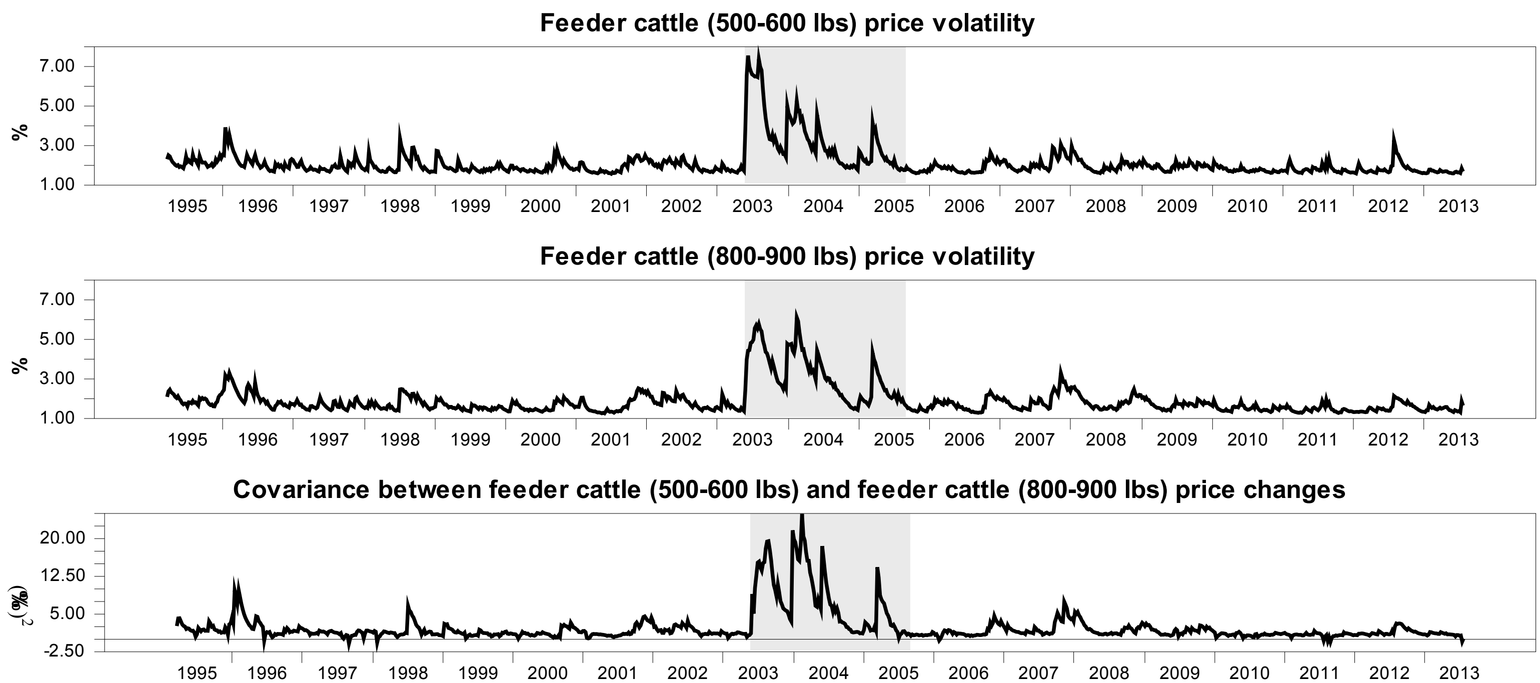


Figure 13. Conditional volatility and covariance in feeder cattle (500-600 lbs.) and fed cattle markets

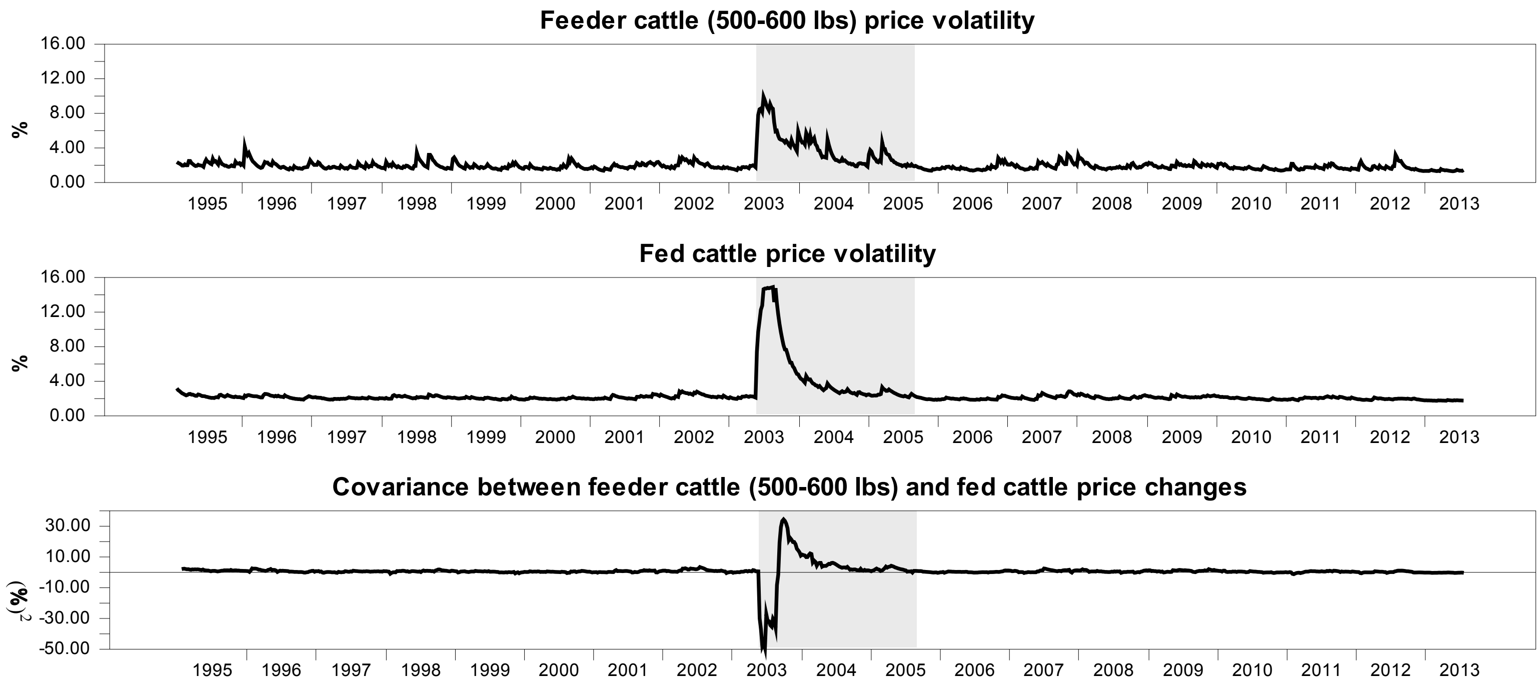


Figure 14. Conditional volatility and covariance in feeder cattle (800-900 lbs.) and fed cattle markets

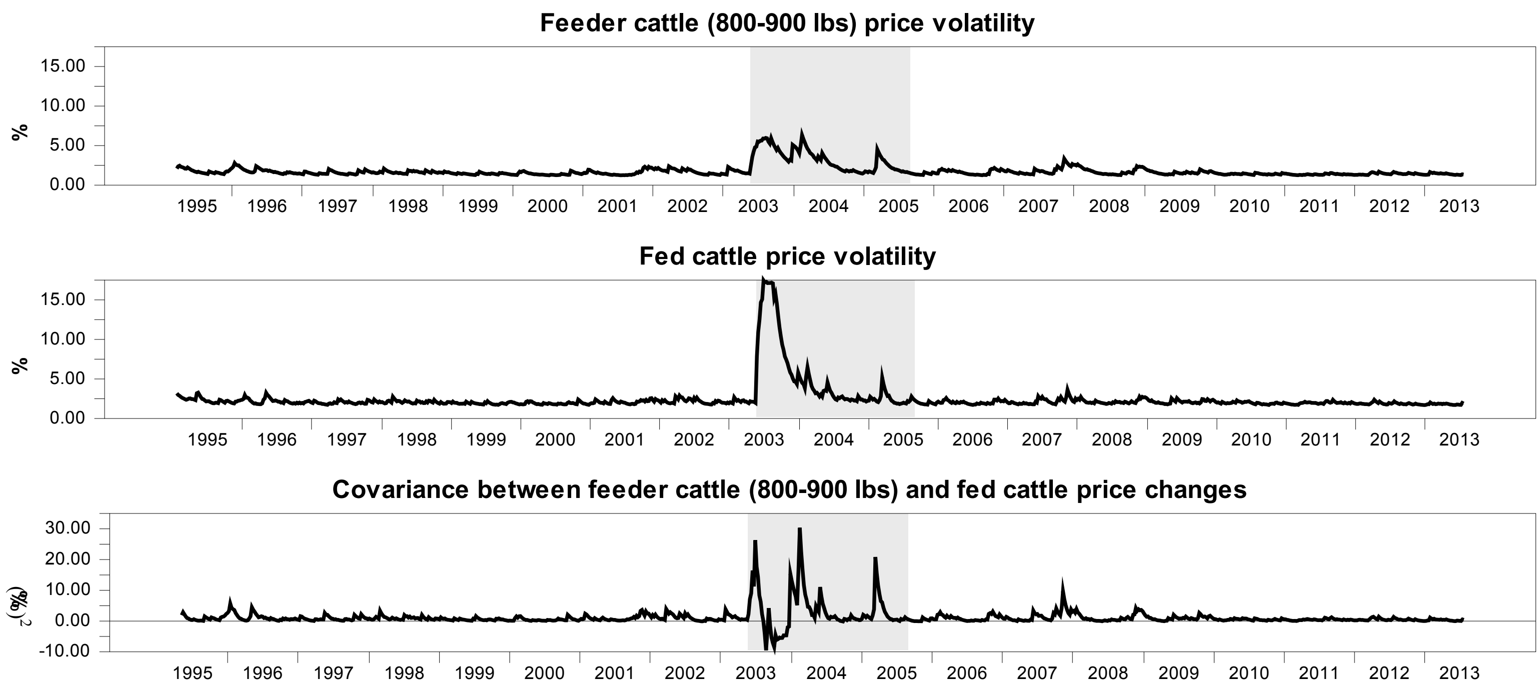


Figure 15a. Conditional volatility and covarance in feeder cattle (500-600 lbs.) and barley markets (asymmetric effects defined as price decreases in both markets)

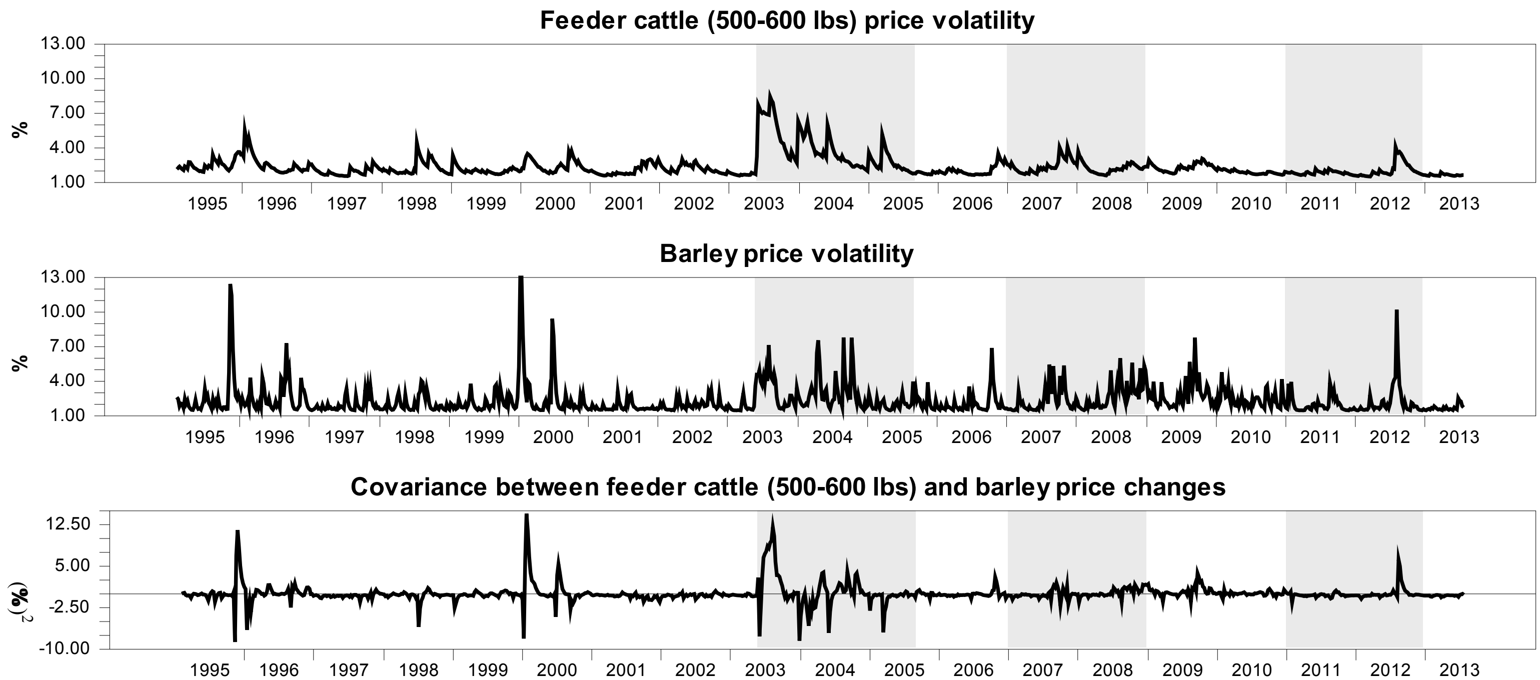


Figure 15b. Conditional volatility and covarance in feeder cattle (500-600 lbs.) and barley markets (asymmetric effects defined as price decrease in cattle market and price increase in barley market)

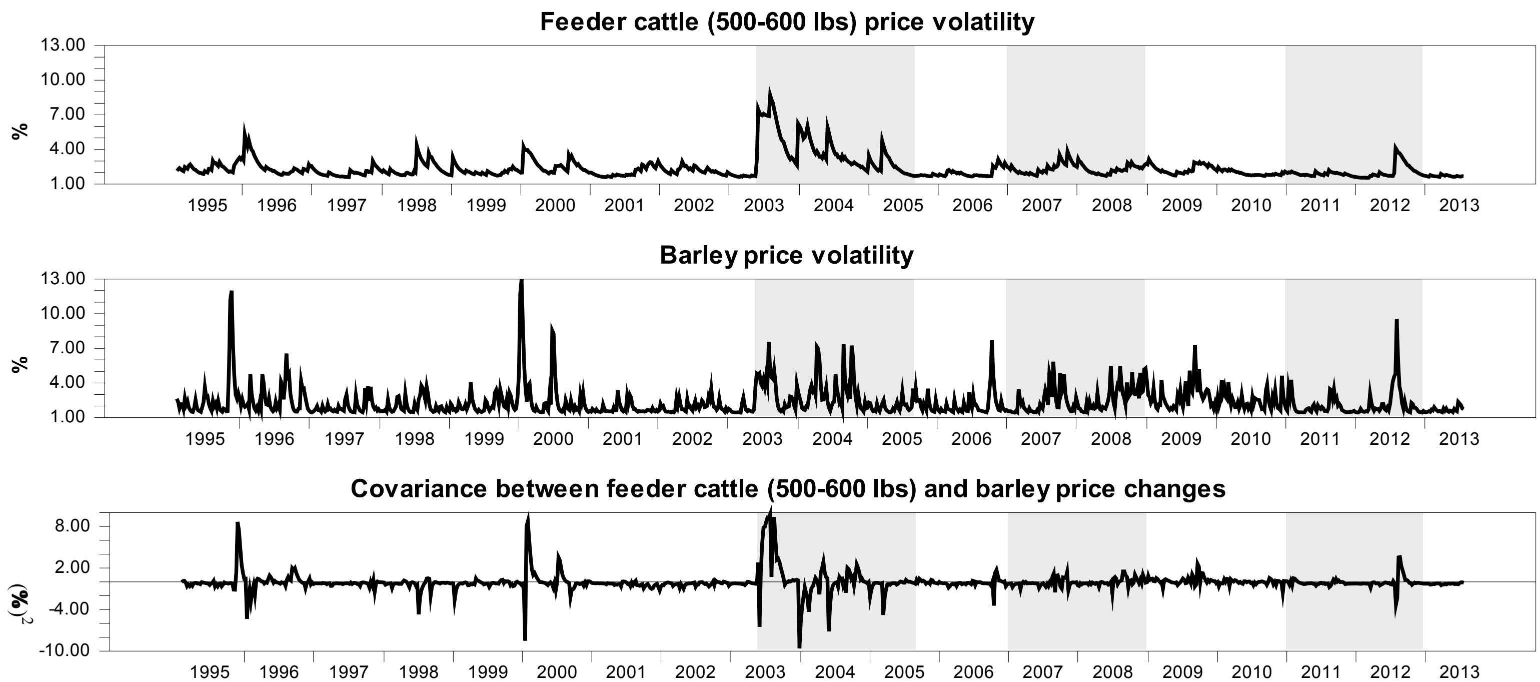


Figure 16a. Conditional volatility and covariance in feeder cattle (800-900 lbs.) and barley markets (asymmetric effects defined as price decreases in both markets)

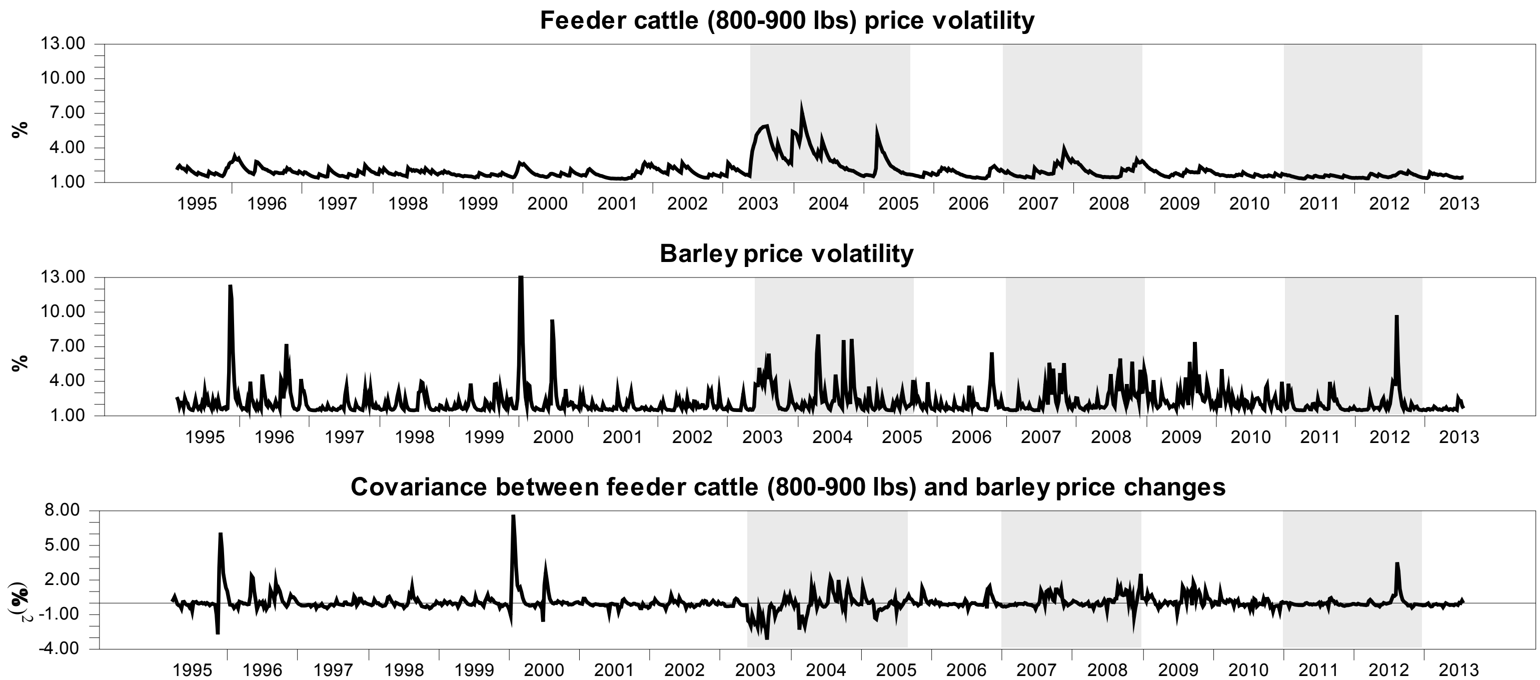


Figure 16b. Conditional volatility and covariance in feeder cattle (800-900 lbs.) and barley markets (asymmetric effects defined as price decrease in cattle market and price increase in barley market)

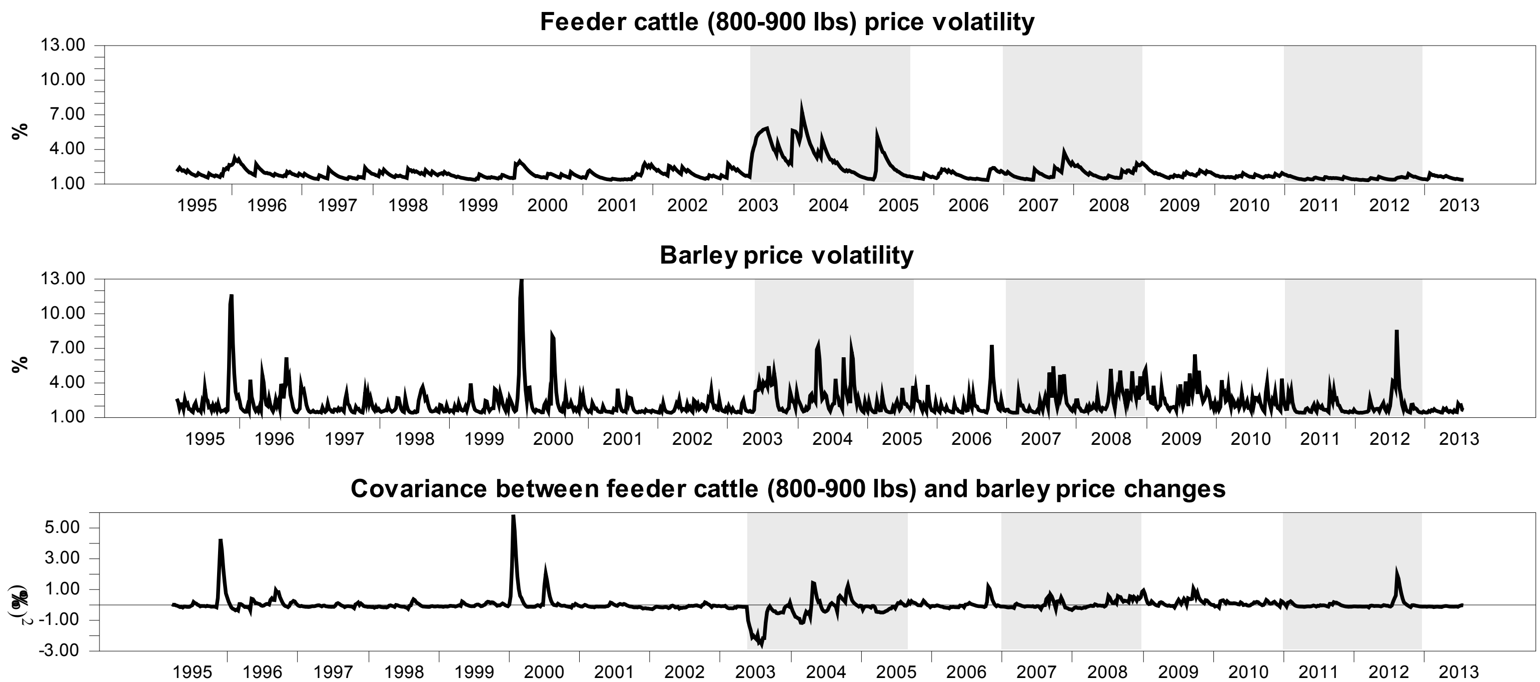


Figure 17a. Conditional volatility and covariance in fed cattle and barley markets (asymmetric effects defined as price decreases in both markets)

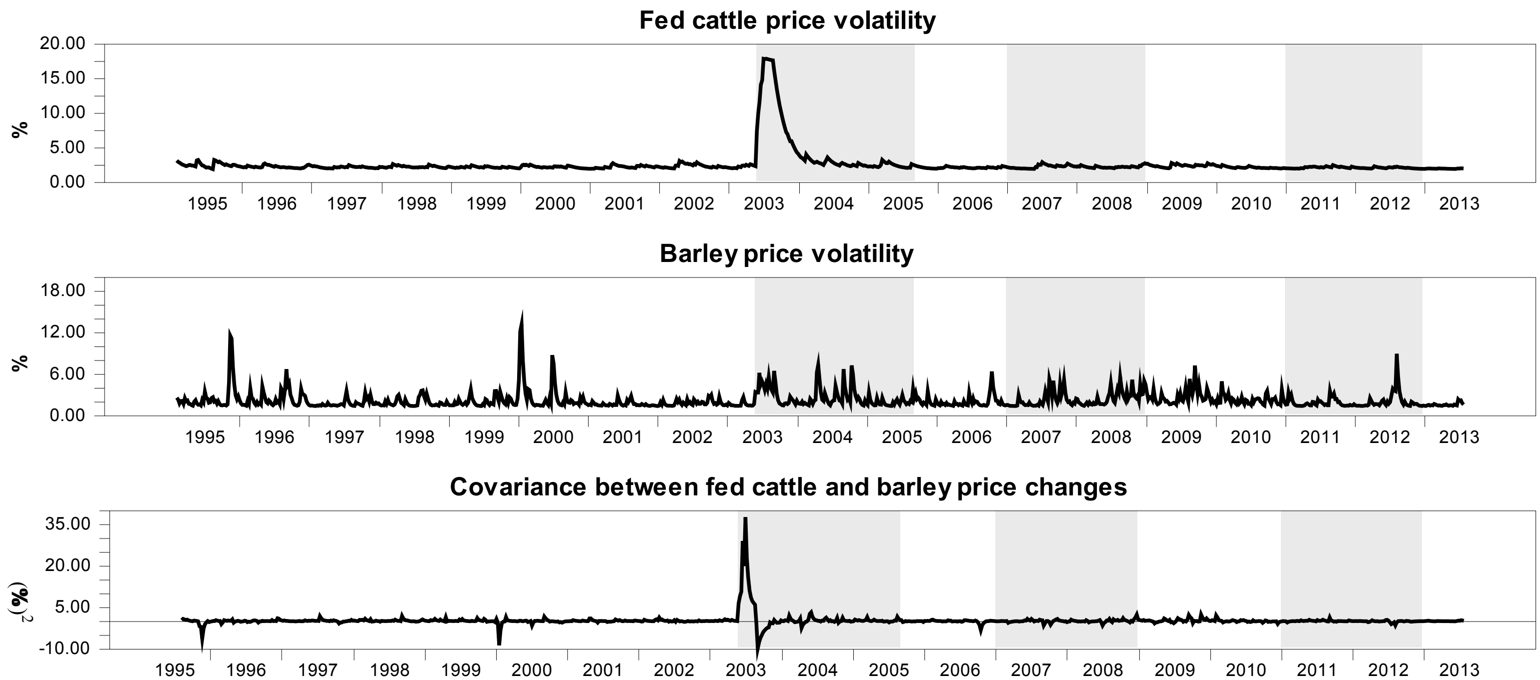


Figure 17b. Conditional volatility and covariance in fed cattle and barley markets (asymmetric effects defined as price decrease in cattle market and price increase in barley market)

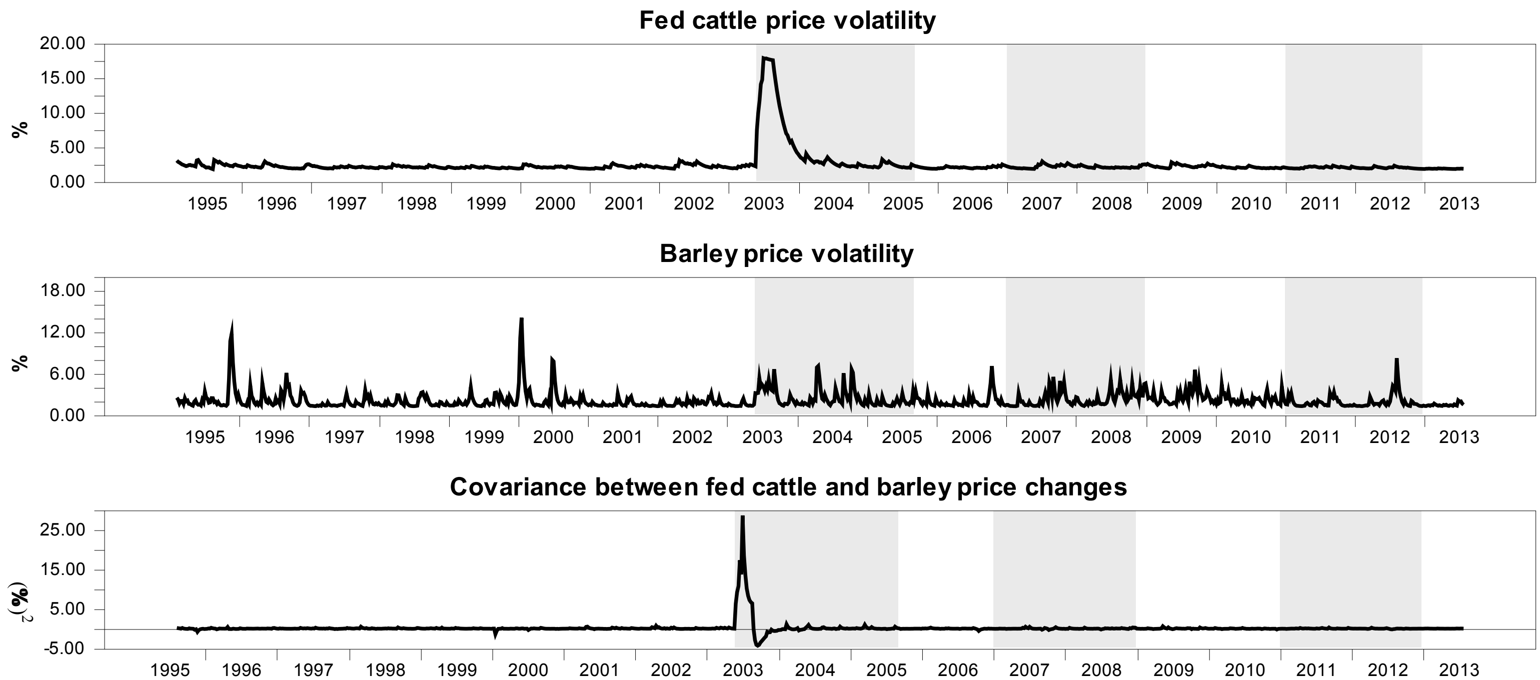


Figure 18. Conditional volatility in barley and corn markets

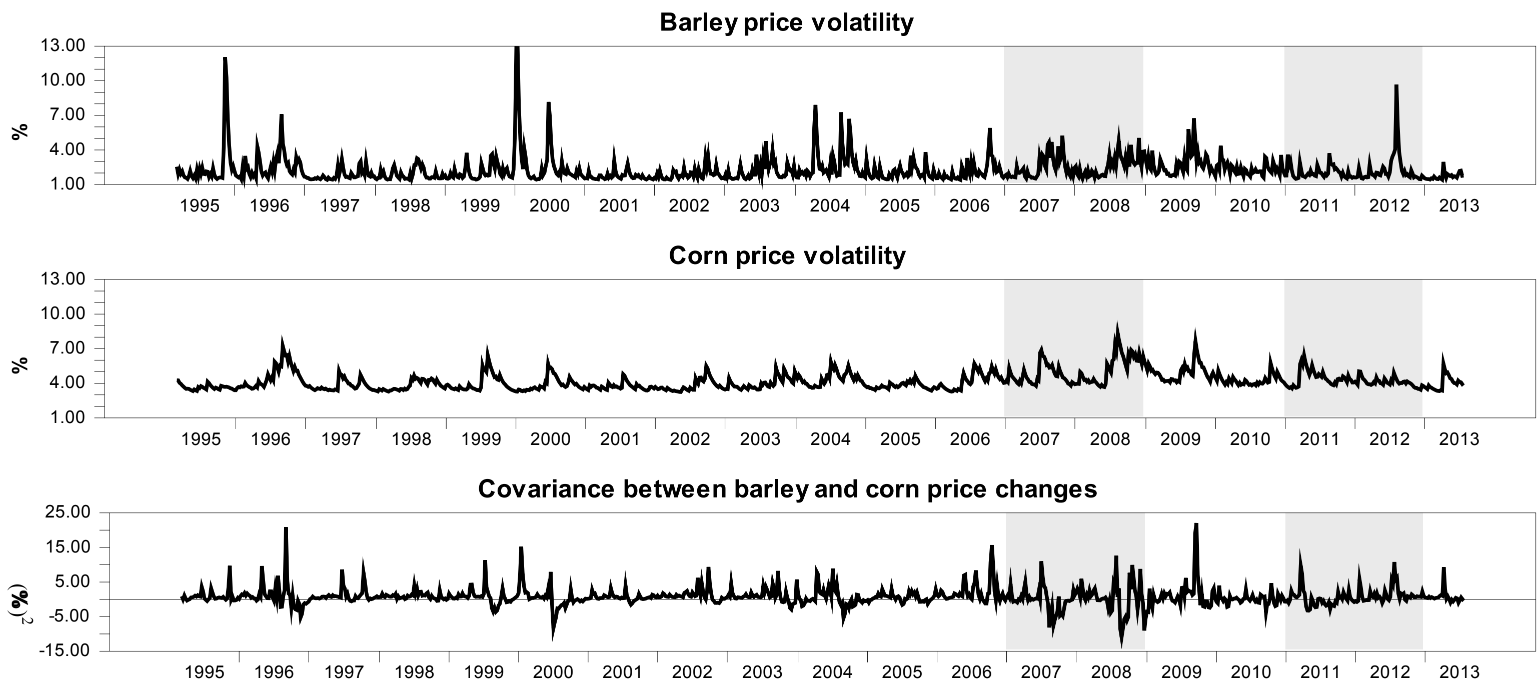
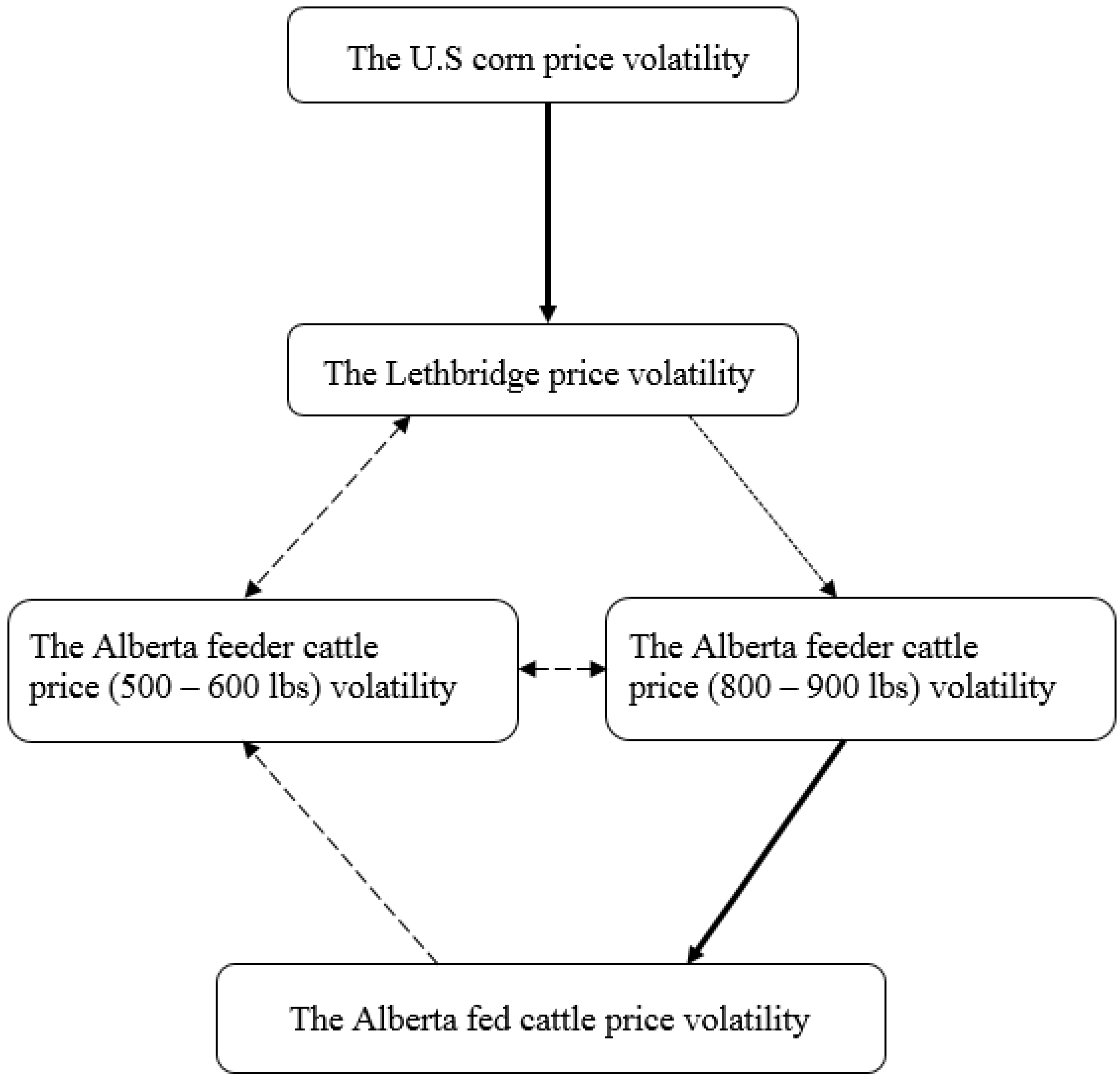


Figure 19. Flow chart of volatility spillovers



Note: arrows indicate the direction of price volatility spillovers and double arrows denote bidirectional price volatility spillovers. The bond straight lines, long dash lines and the dot dash line (between barley and 800 to 900 lbs feeder cattle markets) represent strong, intermediate and weak volatility spillovers, respectively.

Appendix A.

The conditional mean equations and conditional variance equations are shown below (subscripts 1 = feeder cattle (500-600 lbs.), 2 = feeder cattle (800-900 lbs.), 3 = fed cattle, 4 = barley and 5 = corn):

$$\begin{cases} \Delta\log(p_{1,t}) = A_{13}\Delta\log(p_{1,t-3}) + A_{15}\Delta\log(p_{1,t-5}) + A_{21}\Delta\log(p_{2,t-1}) \\ +A_{31}\Delta\log(p_{3,t-1}) + A_{36}\Delta\log(p_{3,t-6}) + A_{37}\Delta\log(p_{3,t-7}) + \varphi_1 \cdot feederECT_{t-1} \\ +\omega \cdot BSEcrash + e_{1,t} \\ e_{1,t} = z_t\sqrt{h_{11,t}}, z_t \sim \text{i.i.d.}(0,1) \\ \log(h_{11,t}) = \alpha_0 + \alpha_1\left|\frac{e_{1,t-1}}{\sqrt{h_{11,t-1}}}\right| + \beta_1\log(h_{11,t-1}) + d_1 e_{1,t-1}/\sqrt{h_{11,t-1}} \end{cases} \tag{32}$$

$$\begin{cases} \Delta\log(p_{2,t}) = A_{22}\Delta\log(p_{2,t-2}) + A_{24}\Delta\log(p_{2,t-4}) + A_{31}\Delta\log(p_{3,t-1}) \\ +A_{41}\Delta\log(p_{4,t-1}) + \varphi_2 \cdot feederECT_{t-1} + e_{2,t} \\ e_{2,t} = z_t\sqrt{h_{22,t}}, z_t \sim \text{i.i.d.}(0,1) \\ h_{22,t} = \alpha_0 + \alpha_2 e_{2,t-1}^2 + \gamma_2 G e_{2,t-1}^2 + \beta_2 h_{22,t-1} \\ where \begin{cases} G = 1\ if\ e_t < 0 \\ G = 0\ if\ e_t \geq 0 \end{cases} \end{cases} \tag{33}$$

$$\begin{cases} \Delta\log(p_{3,t}) = A_{14}\Delta\log(p_{1,t-4}) + A_{21}\Delta\log(p_{2,t-1}) + A_{31}\Delta\log(p_{3,t-1}) \\ +A_{32}\Delta\log(p_{3,t-2}) + A_{39}\Delta\log(p_{3,t-9}) + \omega \cdot BSEcrash + e_{3,t} \\ e_{3,t} = z_t\sqrt{h_{33,t}}, z_t \sim \text{i.i.d.}(0,1) \\ \log(h_{33,t}) = \alpha_0 + \alpha_3\left|\frac{e_{3,t-1}}{\sqrt{h_{33,t-1}}}\right| + \beta_3\log(h_{33,t-1}) + d_3 e_{3,t-1}/\sqrt{h_{33,t-1}} + \tau BSEcrash \end{cases} \tag{34}$$

$$\begin{cases} \Delta\log(p_{4,t}) = A_{42}\Delta\log(p_{4,t-2}) + A_{43}\Delta\log(p_{4,t-3}) + A_{51}\Delta\log(p_{5,t-1}) \\ +A_{52}\Delta\log(p_{5,t-2}) + A_{53}\Delta\log(p_{5,t-3}) + \varphi_4 \cdot grainECT_{t-1} + e_{4,t} \\ e_{4,t} = z_t\sqrt{h_{44,t}}, z_t \sim \text{i.i.d.}(0,1) \\ \log(h_{44,t}) = \alpha_0 + \alpha_4\left|\frac{e_{4,t-1}}{\sqrt{h_{44,t-1}}}\right| + \beta_4\log(h_{44,t-1}) + d_4 e_{4,t-1}/\sqrt{h_{44,t-1}} \end{cases} \tag{35}$$

$$\begin{cases} \Delta \log(p_{5,t}) = A_{55}\Delta \log(p_{5,t-5}) + \varphi_5 \cdot grainECT_{t-1} + e_{5,t} \\ e_{5,t} = z_t\sqrt{h_{5,t}}, z_t \sim \text{i.i.d.}(0,1) \\ \log(h_{55,t}) = \alpha_0 + \alpha_5 \left| \dfrac{e_{5,t-1}}{\sqrt{h_{55,t-1}}} \right| + \beta_5 \log(h_{55,t-1}) + d_5 e_{5,t-1} / \sqrt{h_{55,t-1}} \end{cases} \quad (36)$$

Where $\Delta \log(p_{i,t}) = \log\left(\dfrac{p_{i,t}}{p_{i,t-1}}\right) \times 100$, $e_{i,t} \forall i = 1, \ldots, 5$ are residuals in the VAR - GARCH model, $feederECT_{t-1}$ and $grainECT_{t-1}$ are error correction terms based on results from the Johansen trace test. To account for a potential outlier caused by BSE in the fed cattle price, a dummy variable (i.e., $BSEcrash$) was added to the conditional mean equation of the feeder cattle (500-600 lbs.) and fed cattle price changes.[13] This variable takes the value of 1 on the day of June 4, 2003 and 0 otherwise.

[13] The BSE dummy was originally added to the conditional mean equation of the feeder cattle (800-900 lbs.) price changes; however it was taken out in the final estimation because the estimated coefficient on this variable appeared to statistically insignificant at the 10% level.

Appendix B.

The Delta Method

The parameters in Eq. (6) do not have direct interpretations because they enter the diagonal AG-DCC GARCH model as product forms (as shown in Eq. (11)). Therefore, the delta method was employed to derive the asymptotic variances and the standard errors for the products of the parameters (e.g., $a_{ii}a_{jj}$ in Eq. (11)). The basic concept of the delta method is shown below (Davison 2003). Suppose $\{\hat{x}_n\}$ is a sequence of $K \times 1$ random vectors that have the following property:

$$\sqrt{n}(\hat{x}_n - x_0) \xrightarrow{d} N(0, V) \tag{37}$$

where x_0 is a $K \times 1$ vector that contains the asymptotical means of $\{\hat{x}_n\}$, $N(0,V)$ is a multivariate normal distribution with zero mean, V is the variance co-variance matrix and $\xrightarrow{d}$ denotes convergence in the distribution. The delta method can be utilized to derive the asymptotic variance of a non-linear function of the $K \times 1$ random vectors (i.e., $\{\hat{x}_n\}$) based on the assumptions that the function is continuous and differentiable with respect to $\{\hat{x}_n\}$. Let $f(\hat{x}_n)$ be a function that satisfies these assumptions; the asymptotic variance of $f(\hat{x}_n)$ can be derived as follows:

$$\sqrt{n}(f(\hat{x}_n) - f(x_0)) \xrightarrow{d} N(0, J_f(x_0)VJ_f(x_0)') \tag{38}$$

Eq. (21) can be further transformed into

$$(f(\hat{x}_n) - f(x_0)) \xrightarrow{d} N(0, n^{-1}J_f(x_0)VJ_f(x_0)') \tag{39}$$

where J_f is the Jacobian matrix of $f(\hat{x}_n)$, which is the matrix that contains all of the first-order partial derivatives of $f(\hat{x}_n)$.

Appendix C.

Figure 20a. Conditional volatility and covariance in feeder cattle (500-600 lbs.) and corn markets (asymmetric effects defined as price decreases in both markets)

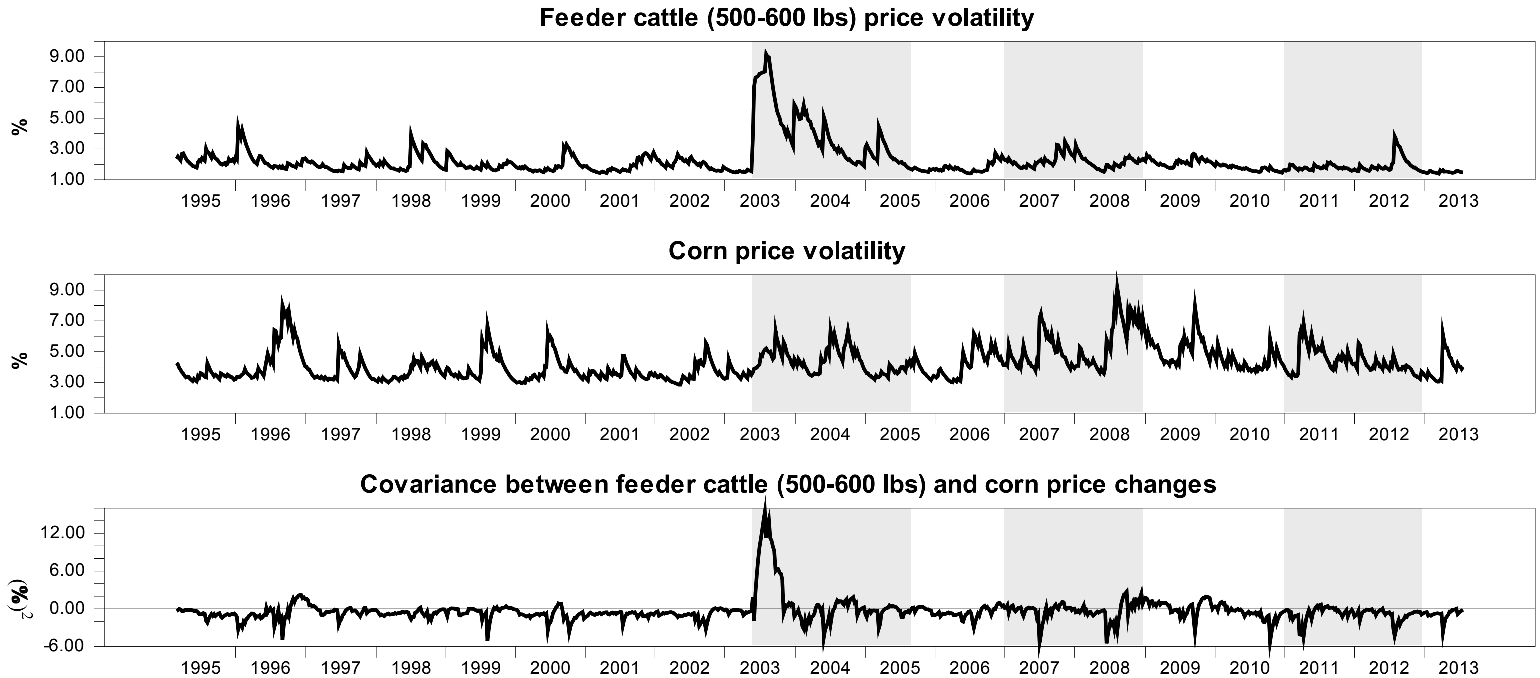


Figure 20b. Conditional volatility and covariance in feeder cattle (500-600 lbs.) and corn markets (asymmetric effects defined as price decrease in cattle market and price increase in barley market)

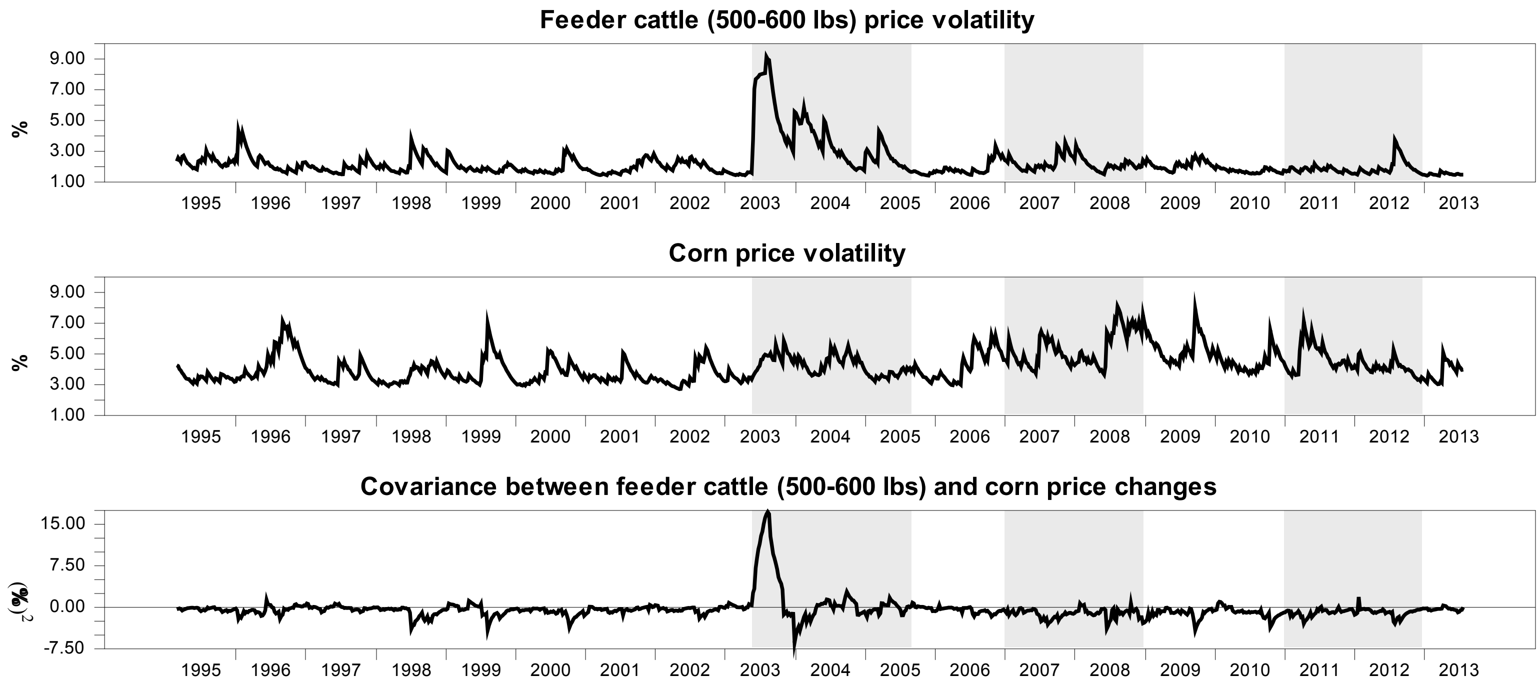


Figure 21a. Conditional volatility and covariance in feeder cattle (800-900 lbs.) and corn markets (asymmetric effects defined as price decreases in both markets)

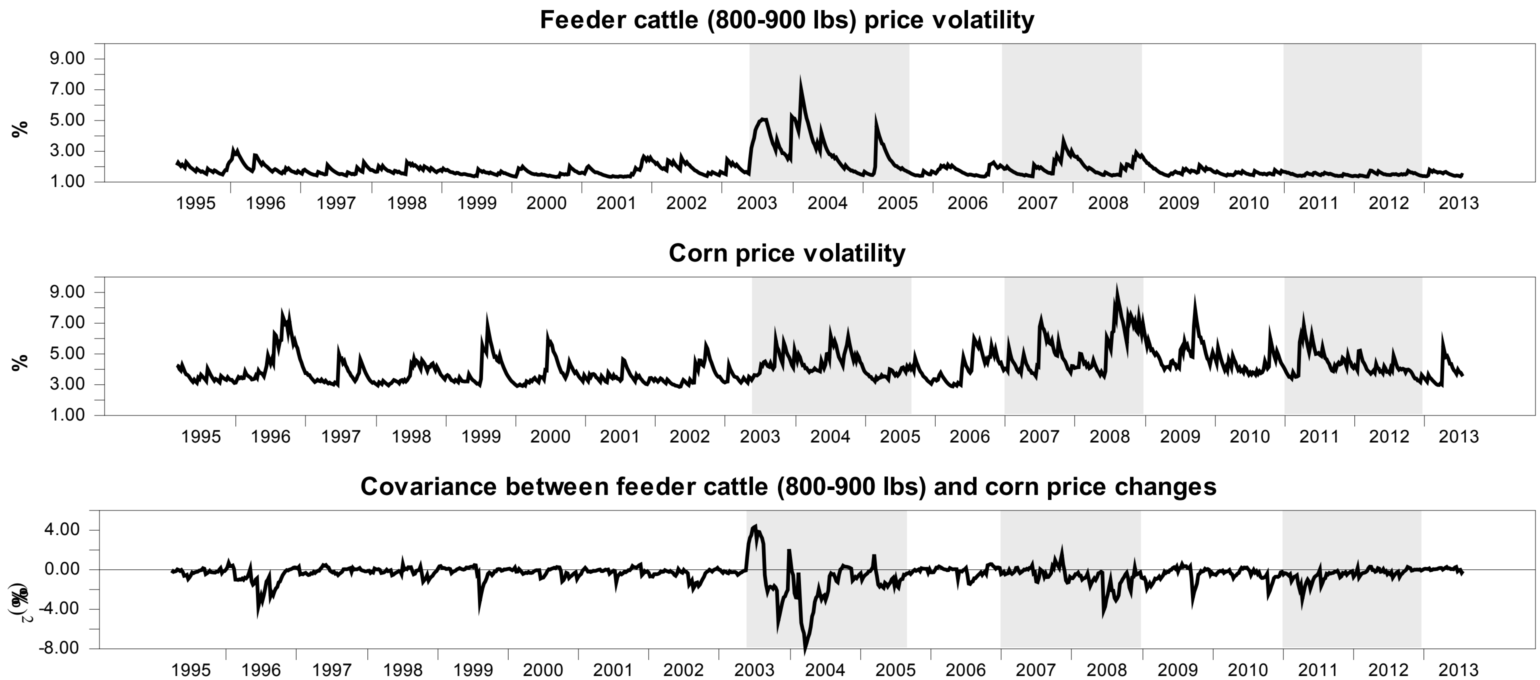


Figure 21b. Conditional volatility and covariance in feeder cattle (800-900 lbs.) and corn markets (asymmetric effects defined as price decrease in cattle market and price increase in corn market)

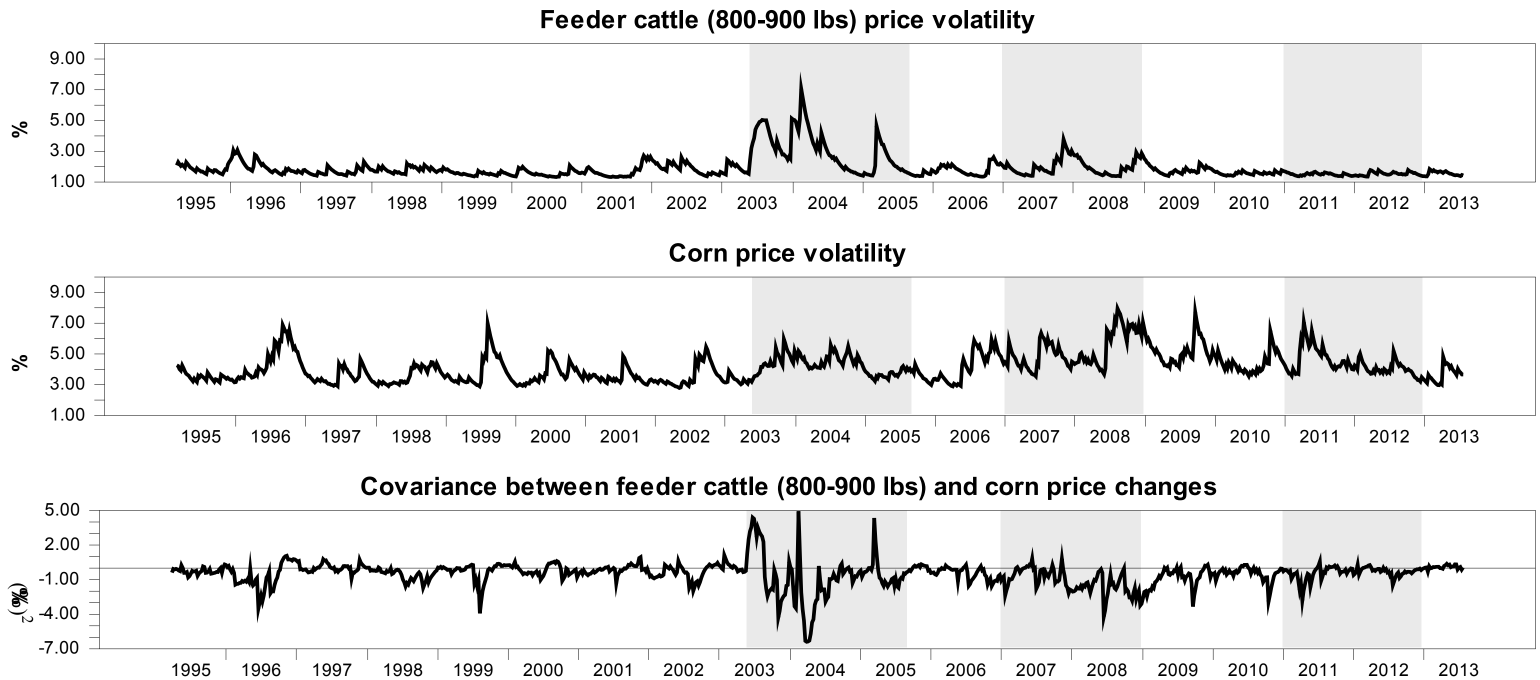


Figure 22a. Conditional volatility and covariance in fed cattle and corn markets (asymmetric effects defined as price decreases in both markets)

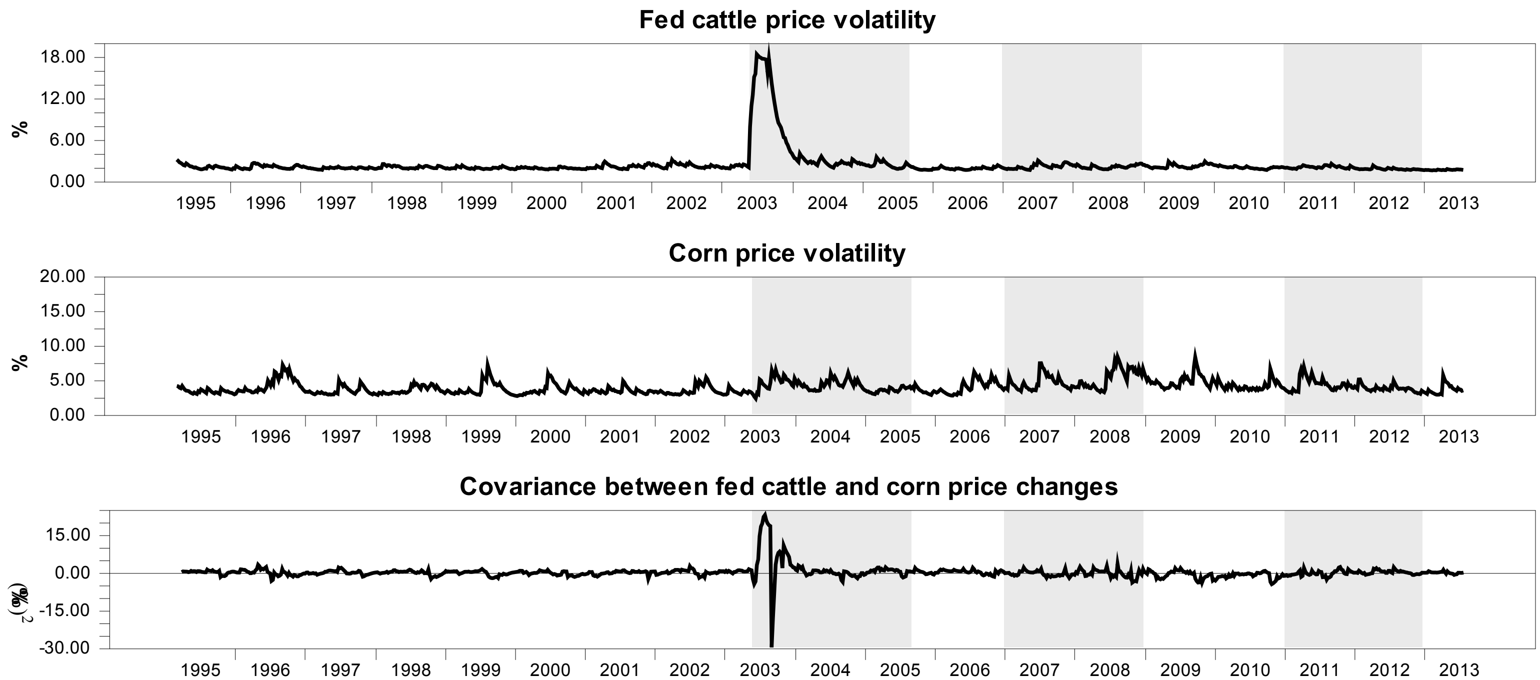
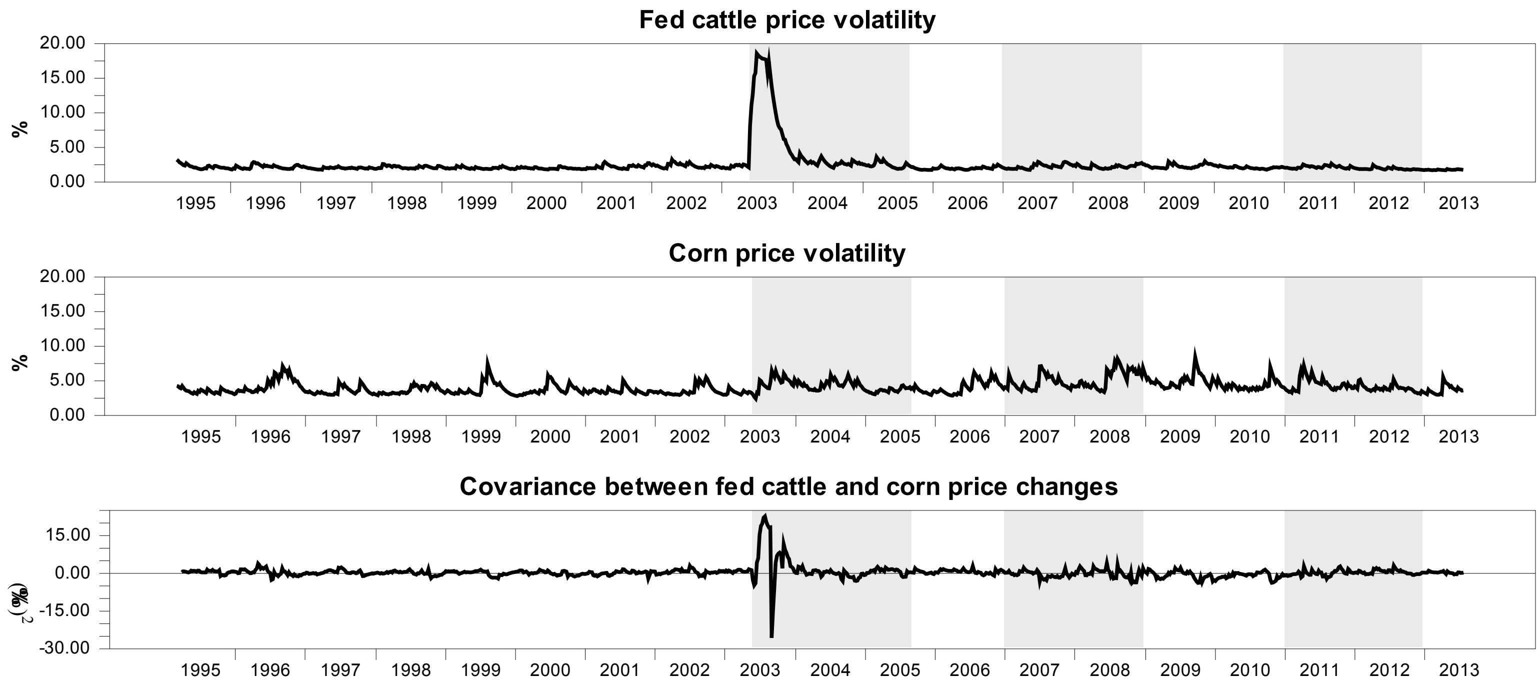


Figure 22b. Conditional volatility and covariance in fed cattle and corn markets (asymmetric effects defined as price decrease in cattle market and price increase in corn market)



Appendix D.

Table 29. Asymmetric t-BEKK GARCH model between the price changes of feeder cattle (500 – 600 lbs.) and feeder cattle (800 – 900 lbs.)

Conditional variance-covariance model:

$$H_t = \left(C + \Omega BSE\right)\left(C + \Omega BSE\right)' + A'\varepsilon_{t-1}\varepsilon_{t-1}^{'}A + B'H_{t-1}B + \mathrm{D}'\epsilon_{t-1}\epsilon_{t-1}^{'}\mathrm{D}$$

$$C = \begin{bmatrix} \underset{(0.1579)}{0.8648} & 0 \\ \underset{(0.1339)}{-0.1310} & \underset{(0.1156)}{0.5229} \end{bmatrix} \qquad A = \begin{bmatrix} \underset{(0.0701)}{0.2907} & \underset{(0.0535)}{-0.1180} \\ \underset{(0.0703)}{-0.1685} & \underset{(0.06478)}{0.3012} \end{bmatrix}$$

$$B = \begin{bmatrix} \underset{(0.0798)}{0.7916} & \underset{(0.0587)}{0.1185} \\ \underset{(0.0715)}{0.0939} & \underset{(0.0588)}{0.8203} \end{bmatrix} \qquad D = \begin{bmatrix} \underset{(0.0992)}{0.2108} & \underset{(0.0723)}{0.1598} \\ \underset{(0.1042)}{0.1707} & \underset{(0.0966)}{0.1695} \end{bmatrix}$$

$$\Omega = \begin{bmatrix} \underset{(1.0497)}{2.6152} & 0 \\ \underset{(0.8321)}{0.1819} & \underset{(0.8404)}{1.5582} \end{bmatrix}$$

Estimated shape parameter for student t distribution	
υ	7.6425***
Multivariate Q test for autocorrelation in standardized residuals	
Multivariate Q (6)	29.2896
Multivariate Q (12)	50.1838
Multivariate Q test for ARCH effects in squared standardized residuals	
Multivariate Q (6)	10.7946
Multivariate Q (12)	36.3119
Bayesian Information Crierion (BIC)	8.1244

***,**,* denote rejection of null hypothesis at the 1%, 5% and 10% significance levels, respectively. Standard errors in parentheses.

Table 30. Asymmetric t-BEKK GARCH model between the price changes of feeder cattle (500 – 600 lbs.) and fed cattle

Conditional variance-covariance model:

$$H_t = (C + \Omega BSE)(C + \Omega BSE)' + A'\varepsilon_{t-1}\varepsilon_{t-1}^{'}A + B'H_{t-1}B + D'\epsilon_{t-1}\epsilon_{t-1}^{'}D$$

$$C = \begin{bmatrix} \underset{(0.1087)}{0.7097} & 0 \\ \underset{(0.1443)}{-0.6085} & \underset{(0.1606)}{0.5445} \end{bmatrix} \qquad A = \begin{bmatrix} \underset{(0.0634)}{-0.2927} & \underset{(0.0448)}{0.0537} \\ \underset{(0.0383)}{-0.0062} & \underset{(0.0517)}{0.1752} \end{bmatrix}$$

$$B = \begin{bmatrix} \underset{(0.0398)}{0.8257} & \underset{(0.0511)}{0.0757} \\ \underset{(0.0291)}{0.0851} & \underset{(0.0344)}{0.8822} \end{bmatrix} \qquad D = \begin{bmatrix} \underset{(0.0898)}{0.2166} & \underset{(0.0634)}{0.0453} \\ \underset{(0.0587)}{0.2086} & \underset{(0.0683)}{0.1664} \end{bmatrix}$$

$$\Omega = \begin{bmatrix} \underset{(1.3527)}{3.9715} & 0 \\ \underset{(1.9109)}{-6.0081} & \underset{(3.0586)}{2.1921} \end{bmatrix}$$

Estimated shape parameter for student t distribution	
υ	9.8296***
Multivariate Q test for autocorrelation in standardized residuals	
Multivariate Q (6)	30.9511
Multivariate Q (12)	55.8698
Multivariate Q test for ARCH effects in squared standardized residuals	
Multivariate Q (6)	14.7117
Multivariate Q (12)	41.1724
Bayesian Information Criterion (BIC)	8.7687

***,**,* denote rejection of null hypothesis at the 1%, 5% and 10% significance levels, respectively. Standard errors in parentheses.

Table 31. Asymmetric t-BEKK GARCH model between the price changes of feeder cattle (500 – 600 lbs.) and fed cattle

Conditional variance-covariance model:

$$H_t = (C + \Omega BSE)(C + \Omega BSE)' + A'\varepsilon_{t-1}\varepsilon_{t-1}' A + B'H_{t-1}B + D'\epsilon_{t-1}\epsilon_{t-1}' D$$

$$C = \begin{bmatrix} \underset{(0.0558)}{0.4376} & 0 \\ \underset{(0.1081)}{0.2436} & \underset{(0.0708)}{0.6911} \end{bmatrix} \qquad A = \begin{bmatrix} \underset{(0.0474)}{-0.1283} & \underset{(0.0534)}{-0.2229} \\ \underset{(0.0503)}{-0.0360} & \underset{(0.0630)}{0.1769} \end{bmatrix}$$

$$B = \begin{bmatrix} \underset{(0.0128)}{0.9227} & \underset{(0.0036)}{-0.0720} \\ \underset{(0.0093)}{-0.0146} & \underset{(0.0257)}{0.8880} \end{bmatrix} \qquad D = \begin{bmatrix} \underset{(0.0518)}{0.3320} & \underset{(0.0552)}{0.2732} \\ \underset{(0.0445)}{0.0685} & \underset{(0.0490)}{0.2214} \end{bmatrix}$$

$$\Omega = \begin{bmatrix} \underset{(0.6366)}{1.7128} & 0 \\ \underset{(2.6214)}{0.7075} & \underset{(1.5086)}{6.9338} \end{bmatrix}$$

Estimated shape parameter for student t distribution	
υ	15.6424***
Multivariate Q test for autocorrelation in standardized residuals	
Multivariate Q (6)	9.9909
Multivariate Q (12)	25.5833
Multivariate Q test for ARCH effects in squared standardized residuals	
Multivariate Q (6)	32.4692
Multivariate Q (12)	53.5062
Bayesian Information Criterion (BIC)	8.4626

***,**,* denote rejection of null hypothesis at the 1%, 5% and 10% significance levels, respectively. Standard errors in parentheses.

Table 32. Asymmetric t-BEKK GARCH model between price changes of feeder cattle (500 – 600 lbs.) and barley (asymmetric effects defined as price decreases in both markets)

Conditional variance-covariance model:

$$H_t = (C + \Omega BSE)(C + \Omega BSE)' + A'\varepsilon_{t-1}\varepsilon_{t-1}^{'}A + B'H_{t-1}B + D'\epsilon_{t-1}\epsilon_{t-1}^{'}D$$

$$C = \begin{bmatrix} \underset{(0.1136)}{0.7084} & 0 \\ \underset{(0.1643)}{-0.4964} & \underset{(0.1388)}{1.1161} \end{bmatrix} \qquad A = \begin{bmatrix} \underset{(0.0718)}{-0.1262} & \underset{(0.0496)}{0.1442} \\ \underset{(0.0446)}{-0.0049} & \underset{(0.0746)}{0.6278} \end{bmatrix}$$

$$B = \begin{bmatrix} \underset{(0.0268)}{0.8848} & \underset{(0.0311)}{0.0217} \\ \underset{(0.0390)}{0.1176} & \underset{(0.0687)}{0.5609} \end{bmatrix} \qquad D = \begin{bmatrix} \underset{(0.0758)}{0.4939} & \underset{(0.0760)}{-0.1363} \\ \underset{(0.0781)}{-0.0899} & \underset{(0.1461)}{0.4754} \end{bmatrix}$$

$$\Omega = \begin{bmatrix} \underset{(1.1219)}{2.0616} & 0 \\ \underset{(1.2750)}{1.4934} & \underset{(0.9533)}{1.4355} \end{bmatrix}$$

Estimated shape parameter for student t distribution	
υ	4.3211***
Multivariate Q test for autocorrelation in standardized residuals	
Multivariate Q (6)	33.9111*
Multivariate Q (12)	53.0669
Multivariate Q test for ARCH effects in squared standardized residuals	
Multivariate Q (6)	16.9442
Multivariate Q (12)	35.7398
Bayesian Information Criterion (BIC)	8.6767

***,**,* denote rejection of null hypothesis at the 1%, 5% and 10% significance levels, respectively.
Standard errors in parentheses.

Table 33. Asymmetric t-BEKK GARCH model between price changes of feeder cattle (500 – 600 lbs.) and barley (asymmetric effects defined as price decrease in feeder cattle market and price increase in barley market)

Conditional variance-covariance model:

$$H_t = (C + \Omega BSE)(C + \Omega BSE)' + A'\varepsilon_{t-1}\varepsilon_{t-1}' A + B' H_{t-1} B + D'\epsilon_{t-1}\epsilon_{t-1}' D$$

$$C = \begin{bmatrix} \underset{(0.1159)}{0.6469} & 0 \\ \underset{(0.2135)}{-0.3415} & \underset{(0.1301)}{1.0734} \end{bmatrix} \qquad A = \begin{bmatrix} \underset{(0.0902)}{-0.0080} & \underset{(0.0535)}{0.1438} \\ \underset{(0.0394)}{-0.0053} & \underset{(0.0650)}{0.6973} \end{bmatrix}$$

$$B = \begin{bmatrix} \underset{(0.0250)}{0.8996} & \underset{(0.0350)}{0.0046} \\ \underset{(0.0397)}{0.0800} & \underset{(0.0672)}{0.6006} \end{bmatrix} \qquad D = \begin{bmatrix} \underset{(0.0689)}{0.4409} & \underset{(0.0782)}{-0.1022} \\ \underset{(0.0577)}{0.1301} & \underset{(0.1474)}{-0.0468} \end{bmatrix}$$

$$\Omega = \begin{bmatrix} \underset{(1.0824)}{2.0096} & 0 \\ \underset{(1.4951)}{1.6428} & \underset{(1.1355)}{1.2014} \end{bmatrix}$$

Estimated shape parameter for student t distribution	
υ	4.3183***
Multivariate Q test for autocorrelation in standardized residuals	
Multivariate Q (6)	35.4952*
Multivariate Q (12)	55.6510
Multivariate Q test for ARCH effects in squared standardized residuals	
Multivariate Q (6)	18.4614
Multivariate Q (12)	37.3152
Bayesian Information Criterion (BIC)	8.6797

***,**,* denote rejection of null hypothesis at the 1%, 5% and 10% significance levels, respectively. Standard errors in parentheses.

Table 34. Asymmetric t-BEKK GARCH model between price changes of feeder cattle (800 – 900 lbs.) and barley (asymmetric effects defined as price decreases in both markets)

Conditional variance-covariance model:

$$H_t = (C + \Omega BSE)(C + \Omega BSE)' + A'\varepsilon_{t-1}\varepsilon_{t-1}^{'}A + B'H_{t-1}B + D'\epsilon_{t-1}\epsilon_{t-1}^{'}D$$

$$C = \begin{bmatrix} \underset{(0.0890)}{0.5251} & 0 \\ \underset{(0.2684)}{-0.2855} & \underset{(0.1038)}{1.1992} \end{bmatrix} \quad A = \begin{bmatrix} \underset{(0.0752)}{-0.1129} & \underset{(0.0579)}{-0.0039} \\ \underset{(0.0437)}{-0.0146} & \underset{(0.0585)}{0.5939} \end{bmatrix}$$

$$B = \begin{bmatrix} \underset{(0.0212)}{0.9108} & \underset{(0.0466)}{-0.0130} \\ \underset{(0.0377)}{0.0673} & \underset{(0.0475)}{0.5494} \end{bmatrix} \quad D = \begin{bmatrix} \underset{(0.0622)}{0.4113} & \underset{(0.1054)}{-0.0423} \\ \underset{(0.0672)}{-0.0100} & \underset{(0.1262)}{0.4971} \end{bmatrix}$$

$$\Omega = \begin{bmatrix} \underset{(0.7538)}{1.9349} & 0 \\ \underset{(1.4737)}{-0.3142} & \underset{(1.3442)}{1.6796} \end{bmatrix}$$

Estimated shape parameter for student t distribution	
υ	5.4518***
Multivariate Q test for autocorrelation in standardized residuals	
Multivariate Q (6)	13.6707
Multivariate Q (12)	38.2612
Multivariate Q test for ARCH effects in squared standardized residuals	
Multivariate Q (6)	18.8067
Multivariate Q (12)	31.5581
Bayesian Information Criterion (BIC)	8.4572

***,**,* denote rejection of null hypothesis at the 1%, 5% and 10% significance levels, respectively. Standard errors in parentheses.

Table 35. Asymmetric t-BEKK GARCH model between price changes of feeder cattle (800 – 900 lbs.) and barley (asymmetric effects defined as price decrease in feeder cattle market and price increase in barley market)

Conditional variance-covariance model:

$$H_t = (C + \Omega BSE)(C + \Omega BSE)' + A'\varepsilon_{t-1}\varepsilon_{t-1}^{'}A + B'H_{t-1}B + D'\epsilon_{t-1}\epsilon_{t-1}^{'}D$$

$$C = \begin{bmatrix} \underset{(0.0858)}{0.4995} & 0 \\ \underset{(0.2587)}{-0.1391} & \underset{(0.2361)}{1.1146} \end{bmatrix} \qquad A = \begin{bmatrix} \underset{(0.1038)}{0.0191} & \underset{(0.0932)}{0.1354} \\ \underset{(0.0171)}{-0.0003} & \underset{(0.0816)}{0.6601} \end{bmatrix}$$

$$B = \begin{bmatrix} \underset{(0.0222)}{0.9195} & \underset{(0.0307)}{-0.0161} \\ \underset{(0.0445)}{0.0386} & \underset{(0.1445)}{0.6022} \end{bmatrix} \qquad D = \begin{bmatrix} \underset{(0.0647)}{0.4408} & \underset{(0.0432)}{-0.0051} \\ \underset{(0.0542)}{0.1248} & \underset{(0.0890)}{-0.0135} \end{bmatrix}$$

$$\Omega = \begin{bmatrix} \underset{(0.5823)}{1.8888} & 0 \\ \underset{(1.2806)}{-0.2638} & \underset{(0.7996)}{1.4067} \end{bmatrix}$$

Estimated shape parameter for student t distribution	
υ	5.4738***
Multivariate Q test for autocorrelation in standardized residuals	
Multivariate Q (6)	14.7477
Multivariate Q (12)	39.8316
Multivariate Q test for ARCH effects in squared standardized residuals	
Multivariate Q (6)	16.3057
Multivariate Q (12)	30.4074
Bayesian Information Criterion (BIC)	8.4604

***,**,* denote rejection of null hypothesis at the 1%, 5% and 10% significance levels, respectively. Standard errors in parentheses.

Table 36. Asymmetric t-BEKK GARCH model between price changes of fed cattle and barley (asymmetric effects defined as price decreases in both markets)

Conditional variance-covariance model:

$$H_t = (C + \Omega BSE)(C + \Omega BSE)' + A'\varepsilon_{t-1}\varepsilon_{t-1}^{'}A + B'H_{t-1}B + D'\epsilon_{t-1}\epsilon_{t-1}^{'}D$$

$$C = \begin{bmatrix} \underset{(0.1412)}{0.7972} & 0 \\ \underset{(0.2322)}{0.0601} & \underset{(0.1466)}{1.1303} \end{bmatrix} \quad A = \begin{bmatrix} \underset{(0.1416)}{-0.0157} & \underset{(0.0530)}{0.0601} \\ \underset{(0.0436)}{-0.0474} & \underset{(0.0759)}{0.5836} \end{bmatrix}$$

$$B = \begin{bmatrix} \underset{(0.0274)}{0.9119} & \underset{(0.0243)}{-0.0132} \\ \underset{(0.0458)}{0.0143} & \underset{(0.0921)}{0.5959} \end{bmatrix} \quad D = \begin{bmatrix} \underset{(0.0918)}{0.3069} & \underset{(0.1917)}{0.0804} \\ \underset{(0.0648)}{0.0431} & \underset{(0.1432)}{0.4102} \end{bmatrix}$$

$$\Omega = \begin{bmatrix} \underset{(2.1157)}{6.3650} & 0 \\ \underset{(1.1701)}{0.7462} & \underset{(1.0120)}{1.3759} \end{bmatrix}$$

Estimated shape parameter for student t distribution	
υ	5.5978***
Multivariate Q test for autocorrelation in standardized residuals	
Multivariate Q (6)	7.6734
Multivariate Q (12)	23.9530
Multivariate Q test for ARCH effects in squared standardized residuals	
Multivariate Q (6)	27.7346
Multivariate Q (12)	49.3028
Bayesian Information Criterion (BIC)	8.9120

***,**,* denote rejection of null hypothesis at the 1%, 5% and 10% significance levels, respectively.
Standard errors in parentheses.

Table 37. Asymmetric t-BEKK GARCH model between price changes of fed cattle and barley (asymmetric effects defined as price decrease in fed cattle market and price increase in barley market)

Conditional variance-covariance model:

$$H_t = (C + \Omega BSE)(C + \Omega BSE)' + A'\varepsilon_{t-1}\varepsilon_{t-1}' A + B' H_{t-1} B + D'\epsilon_{t-1}\epsilon_{t-1}' D$$

$$C = \begin{bmatrix} \underset{(0.1496)}{0.8047} & 0 \\ \underset{(0.2489)}{0.1663} & \underset{(0.1401)}{1.0890} \end{bmatrix} \qquad A = \begin{bmatrix} \underset{(0.0838)}{0.0008} & \underset{(0.0469)}{0.0572} \\ \underset{(0.0363)}{-0.0002} & \underset{(0.0611)}{0.6557} \end{bmatrix}$$

$$B = \begin{bmatrix} \underset{(0.0283)}{0.9093} & \underset{(0.0206)}{-0.0130} \\ \underset{(0.0449)}{0.0023} & \underset{(0.0806)}{0.6119} \end{bmatrix} \qquad D = \begin{bmatrix} \underset{(0.0713)}{0.3101} & \underset{(0.2651)}{0.0608} \\ \underset{(0.0528)}{-0.0799} & \underset{(0.1817)}{0.0508} \end{bmatrix}$$

$$\Omega = \begin{bmatrix} \underset{(2.1079)}{6.4847} & 0 \\ \underset{(1.0970)}{0.7209} & \underset{(0.8683)}{1.3370} \end{bmatrix}$$

Estimated shape parameter for student t distribution	
υ	5.7071***
Multivariate Q test for autocorrelation in standardized residuals	
Multivariate Q (6)	8.5693
Multivariate Q (12)	25.0233
Multivariate Q test for ARCH effects in squared standardized residuals	
Multivariate Q (6)	30.7307
Multivariate Q (12)	52.7480
Bayesian Information Criterion (BIC)	8.9159

***,**,* denote rejection of null hypothesis at the 1%, 5% and 10% significance levels, respectively. Standard errors in parentheses.

Table 38a. Conditional mean estimations between price changes of feeder cattle (500 – 600 lbs.) and corn (asymmetric effects defined as price decreases in both markets)

	Feeder Cattle (500 – 600 lbs.)	Corn
	(i = 1)	(i = 2)
$AR(2)_{1i}$	0.0935*** (0.0315)	-
$AR(5)_{2i}$	-	0.0708** (0.0298)
$AR(7)_{2i}$	-0.0377*** (0.0144)	-
BSE	-2.8670* (1.7010)	-

***,**,* denote rejection of null hypothesis at the 1%, 5% and 10% significance levels, respectively.
Note: BSE is a dummy variable that takes on the value of one from May 28, 2003 to August 28, 2003 (first three months of the BSE crisis), and zero otherwise.

Table 38b. Asymmetric t-BEKK GARCH model between price changes of feeder cattle (500 – 600 lbs.) and corn (asymmetric effects defined as price decreases in both market)

Conditional variance-covariance model:

$$H_t = (C + \Omega BSE)(C + \Omega BSE)' + A'\varepsilon_{t-1}\varepsilon_{t-1}^{'}A + B'H_{t-1}B + D'\epsilon_{t-1}\epsilon_{t-1}^{'}D$$

$$C = \begin{bmatrix} \underset{(0.0985)}{0.5535} & 0 \\ \underset{(0.3943)}{-0.7294} & \underset{(0.2167)}{0.9166} \end{bmatrix} \qquad A = \begin{bmatrix} \underset{(0.0628)}{0.1682} & \underset{(0.0641)}{0.0182} \\ \underset{(0.0217)}{0.0560} & \underset{(0.0466)}{-0.2876} \end{bmatrix}$$

$$B = \begin{bmatrix} \underset{(0.0231)}{0.9097} & \underset{(0.0266)}{0.0210} \\ \underset{(0.0173)}{0.0304} & \underset{(0.0215)}{0.9021} \end{bmatrix} \qquad D = \begin{bmatrix} \underset{(0.0597)}{0.3871} & \underset{(0.0769)}{-0.1372} \\ \underset{(0.0329)}{-0.0214} & \underset{(0.0718)}{0.2829} \end{bmatrix}$$

$$\Omega = \begin{bmatrix} \underset{(1.0176)}{2.7202} & 0 \\ \underset{(0.8400)}{1.2846} & \underset{(0.6606)}{0.7196} \end{bmatrix}$$

Estimated shape parameter for student t distribution	
υ	6.6973***
Multivariate Q test for autocorrelation in standardized residuals	
Multivariate Q (6)	7.4900
Multivariate Q (12)	34.0630
Multivariate Q test for ARCH effects in squared standardized residuals	
Multivariate Q (6)	19.2495
Multivariate Q (12)	42.3346
Bayesian Information Criterion (BIC)	10.0336

***,**,* denote rejection of null hypothesis at the 1%, 5% and 10% significance levels, respectively. Standard errors in parentheses.

Table 38c. Nonlinear combination of coefficients from Asymmetric t-BEKK GARCH model between price changes of feeder cattle (500 – 600 lbs.) and corn (asymmetric effects defined as price decreases in both markets)

	$h_{11,t}$		$h_{12,t}$		$h_{22,t}$	
	Coefficient	Standard error	Coefficient	Standard error	Coefficient	Standard error
$\gamma(non\,bse)$	0.3064***	0.1091	-0.4037*	0.2142	1.3721***	0.4696
$\gamma(with\,bse)$	10.7171	6.8407	1.8176	2.8097	2.9853	2.1526
α	0.0283	0.0211	0.0031	0.0107	0.0827***	0.0268
α'	0.0031	0.0024	-0.0161**	0.0071	0.0003	0.0023
α''	0.0188*	0.0097	-0.0474**	0.0187	-0.0105	0.0369
β	0.8275***	0.0420	0.0191	0.0241	0.8138***	0.0389
β'	0.0001	0.0011	0.0275*	0.0152	0.0004	0.0011
β''	0.0554*	0.0316	0.8212	0.0274	0.0379	0.0477
φ	0.1499***	0.0462	-0.0531*	0.0312	0.0800**	0.0407
φ'	0.0005	0.0014	-0.0060	0.0101	0.0188	0.0211
φ''	-0.0165	0.0262	0.1124***	0.0339	-0.0776	0.0525

***,**,* denote rejection of null hypothesis at the 1%, 5% and 10% significance levels, respectively. Standard errors are calculated based on the delta method.
The shaded cells indicate the measurements of volatility spillovers.

Table 39a. Conditional mean estimations between price changes of feeder cattle (500 – 600 lbs.) and corn (asymmetric effects defined as price decrease in fed cattle market and price increase in corn market)

	Feeder Cattle (500 – 600 lbs.)	Corn
	(i = 1)	(i = 2)
$AR(2)_{1i}$	0.0981*** (0.0319)	-
$AR(5)_{2i}$	-	0.0673** (0.0311)
$AR(7)_{2i}$	-0.0390*** (0.0134)	-
BSE	-2.6894** (1.2822)	-

***,**,* denote rejection of null hypothesis at the 1%, 5% and 10% significance levels, respectively.
Note: BSE is a dummy variable that takes on the value of one from May 28, 2003 to August 28, 2003 (first three months of the BSE crisis), and zero otherwise.

Table 39b. Asymmetric t-BEKK GARCH model between price changes of feeder cattle (500 – 600 lbs.) and corn (asymmetric effects defined as price decrease in fed cattle market and price increase in corn market)

Conditional variance-covariance model:

$$H_t = (C + \Omega BSE)(C + \Omega BSE)' + A'\varepsilon_{t-1}\varepsilon_{t-1}^{'}A + B'H_{t-1}B + D'\epsilon_{t-1}\epsilon_{t-1}^{'}D$$

$$C = \begin{bmatrix} \underset{(0.0875)}{0.5317} & 0 \\ \underset{(0.4520)}{-0.0562} & \underset{(0.1881)}{0.9433} \end{bmatrix} \qquad A = \begin{bmatrix} \underset{(0.0577)}{-0.1727} & \underset{(0.0571)}{-0.0269} \\ \underset{(0.0266)}{-0.0060} & \underset{(0.0433)}{-0.3090} \end{bmatrix}$$

$$B = \begin{bmatrix} \underset{(0.0204)}{0.9087} & \underset{(0.0296)}{0.0093} \\ \underset{(0.0214)}{0.0004} & \underset{(0.0203)}{0.9340} \end{bmatrix} \qquad D = \begin{bmatrix} \underset{(0.0537)}{0.3657} & \underset{(0.0734)}{-0.0089} \\ \underset{(0.0253)}{-0.0554} & \underset{(0.0639)}{0.1200} \end{bmatrix}$$

$$\Omega = \begin{bmatrix} \underset{(1.0356)}{2.8584} & 0 \\ \underset{(0.8846)}{0.7929} & \underset{(0.6130)}{0.5412} \end{bmatrix}$$

Estimated shape parameter for student t distribution	
υ	6.7465***
Multivariate Q test for autocorrelation in standardized residuals	
Multivariate Q (6)	7.7479
Multivariate Q (12)	35.8027
Multivariate Q test for ARCH effects in squared standardized residuals	
Multivariate Q (6)	19.5941
Multivariate Q (12)	45.1951
Bayesian Information Criterion (BIC)	10.0355

***,**,* denote rejection of null hypothesis at the 1%, 5% and 10% significance levels, respectively. Standard errors in parentheses.

Table 39c. Nonlinear combination of coefficients from Asymmetric t-BEKK GARCH model between price changes of feeder cattle (500 – 600 lbs.) and corn (asymmetric effects defined as price decrease in fed cattle market and price increase in corn market)

	$h_{11,t}$		$h_{12,t}$		$h_{22,t}$	
	Coefficient	Standard error	Coefficient	Standard error	Coefficient	Standard error
$\gamma(non\,bse)$	0.2828***	0.0931	-0.0299	0.240	0.8931**	0.3495
$\gamma(with\,bse)$	11.4928	7.1898	2.4974	3.0303	2.7464	2.1590
α	0.0298	0.0199	0.0046	0.0099	0.0955***	0.0268
α'	0.0000	0.0003	-0.0018	0.0083	0.0007	0.0031
α''	0.0021	0.0091	-0.0532***	0.0179	-0.0166	0.0355
β	0.8257***	0.0371	0.0084	0.0269	0.8537***	0.0375
β'	0.0000	0.0000	0.0004	0.0198	0.0001	0.0005
β''	0.0007	0.0390	0.8396***	0.0260	0.0171	0.0547
φ	0.1338***	0.0393	-0.0032	0.0269	0.0144	0.0153
φ'	0.0031	0.0028	-0.0066	0.0050	0.0000	0.0013
φ''	-0.0405**	0.0177	0.0444*	0.0236	-0.0021	0.0173

***,**,* denote rejection of null hypothesis at the 1%, 5% and 10% significance levels, respectively. Standard errors are calculated based on the delta method.
The shaded cells indicate the measurements of volatility spillovers.

Table 40a. Conditional mean estimations between price changes of feeder cattle (800 – 900 lbs.) and corn (asymmetric effects defined as price decreases in both markets)

	Feeder Cattle (800 – 900 lbs.)	Corn
	(i = 1)	(i = 2)
$AR(1)_{1i}$	0.1268*** (0.0360)	-
$AR(10)_{1i}$	-0.0726* (0.0315)	-
$AR(5)_{2i}$	-	0.0840** (0.0349)
$AR(11)_{2i}$	-	-0.0840** (0.0353)
BSE	-1.8702* (0.9895)	-

***,**,* denote rejection of null hypothesis at the 1%, 5% and 10% significance levels, respectively.
Note: BSE is a dummy variable that takes on the value of one from May 28, 2003 to August 28, 2003 (first three months of the BSE crisis), and zero otherwise.

Table 40b. Asymmetric t-BEKK GARCH model between price changes of feeder cattle (800 – 900 lbs.) and corn (asymmetric effects defined as price decreases in both markets)

Conditional variance-covariance model:

$$H_t = (C + \Omega BSE)(C + \Omega BSE)' + A'\varepsilon_{t-1}\varepsilon_{t-1}^{'} A + B' H_{t-1} B + D'\epsilon_{t-1}\epsilon_{t-1}^{'} D$$

$$C = \begin{bmatrix} \underset{(0.0853)}{0.4971} & 0 \\ \underset{(0.3194)}{0.2383} & \underset{(0.2265)}{1.0926} \end{bmatrix} \qquad A = \begin{bmatrix} \underset{(0.0586)}{0.1280} & \underset{(0.1033)}{-0.0213} \\ \underset{(0.0197)}{0.0304} & \underset{(0.0458)}{-0.3005} \end{bmatrix}$$

$$B = \begin{bmatrix} \underset{(0.0220)}{0.9152} & \underset{(0.0296)}{-0.0527} \\ \underset{(0.0137)}{0.0022} & \underset{(0.0259)}{0.9033} \end{bmatrix} \qquad D = \begin{bmatrix} \underset{(0.0565)}{0.3673} & \underset{(0.0959)}{0.0149} \\ \underset{(0.0210)}{0.0091} & \underset{(0.0829)}{0.2179} \end{bmatrix}$$

$$\Omega = \begin{bmatrix} \underset{(0.4906)}{1.4930} & 0 \\ \underset{(0.7250)}{0.5217} & \underset{(0.7026)}{0.3033} \end{bmatrix}$$

Estimated shape parameter for student t distribution	
υ	7.9953***
Multivariate Q test for autocorrelation in standardized residuals	
Multivariate Q (6)	34.9127*
Multivariate Q (12)	60.2461
Multivariate Q test for ARCH effects in squared standardized residuals	
Multivariate Q (6)	11.8417
Multivariate Q (12)	42.9705
Bayesian Information Criterion (BIC)	9.7683

***,**,* denote rejection of null hypothesis at the 1%, 5% and 10% significance levels, respectively. Standard errors in parentheses.

Table 40c. Nonlinear combination of coefficients from Asymmetric t-BEKK GARCH model between price changes of feeder cattle (800 – 900 lbs.) and corn (asymmetric effects defined as price decreases in both markets)

	$h_{11,t}$		$h_{12,t}$		$h_{22,t}$	
	Coefficient	Standard error	Coefficient	Standard error	Coefficient	Standard error
$\gamma(non\,bse)$	0.2471***	0.0848	0.1184	0.1636	1.2506**	0.4888
$\gamma(with\,bse)$	3.9607*	2.0468	1.5124	1.5559	2.5262	2.0820
α	0.0164	0.0150	-0.0027	0.0133	0.0903***	0.0275
α'	0.0009	0.0012	-0.0091	0.0061	0.0005	0.0044
α''	0.0078	0.0055	-0.0391**	0.0187	0.0128	0.0623
β	0.8376***	0.0403	-0.0482	0.0360	0.8160***	0.0469
β'	0.0000	0.0000	0.0020	0.0124	0.0028	0.0042
β''	0.0041	0.0251	0.8266***	0.0305	-0.0952	0.0712
φ	0.1349***	0.0415	0.0055	0.0353	0.0475	0.0361
φ'	0.0001	0.0004	0.0020	0.0044	0.0002	0.0029
φ''	0.0067	0.0152	0.0802***	0.0310	0.0065	0.0416

***,**,* denote rejection of null hypothesis at the 1%, 5% and 10% significance levels, respectively. Standard errors are calculated based on the delta method.
The shaded cells indicate the measurements of volatility spillovers.

Table 41a. Conditional mean estimations between price changes of feeder cattle (800 – 900 lbs.) and corn (asymmetric effects defined as price decrease in feeder cattle market and price increase in corn market)

	Feeder Cattle (800 – 900 lbs.)	Corn
	(i = 1)	(i = 2)
$AR(1)_{1i}$	0.1283*** (0.0320)	-
$AR(10)_{1i}$	-0.0697** (0.300)	-
$AR(5)_{2i}$	-	0.0755** (0.0332)
$AR(11)_{2i}$	-	-0.0879** (0.0353)
BSE	-1.8463* (1.000)	-

***,**,* denote rejection of null hypothesis at the 1%, 5% and 10% significance levels, respectively.
Note: BSE is a dummy variable that takes on the value of one from May 28, 2003 to August 28, 2003 (first three months of the BSE crisis), and zero otherwise.

Table 41b. Asymmetric t-BEKK GARCH model between price changes of feeder cattle (800 – 900 lbs.) and corn (asymmetric effects defined as price decrease in feeder cattle market and price increase in corn market)

Conditional variance-covariance model:

$$H_t = (C + \Omega BSE)(C + \Omega BSE)' + A'\varepsilon_{t-1}\varepsilon_{t-1}^{'}A + B'H_{t-1}B + D'\epsilon_{t-1}\epsilon_{t-1}^{'}D$$

$$C = \begin{bmatrix} \underset{(0.0792)}{0.5063} & 0 \\ \underset{(0.2786)}{0.1703} & \underset{(0.1984)}{0.9609} \end{bmatrix} \qquad A = \begin{bmatrix} \underset{(0.0637)}{-0.1154} & \underset{(0.0904)}{0.0129} \\ \underset{(0.0182)}{-0.0198} & \underset{(0.0464)}{0.3051} \end{bmatrix}$$

$$B = \begin{bmatrix} \underset{(0.0218)}{0.9129} & \underset{(0.0387)}{-0.0614} \\ \underset{(0.0116)}{0.0088} & \underset{(0.0217)}{0.9183} \end{bmatrix} \qquad D = \begin{bmatrix} \underset{(0.0502)}{0.3699} & \underset{(0.0930)}{0.1214} \\ \underset{(0.0332)}{-0.0299} & \underset{(0.0783)}{0.1337} \end{bmatrix}$$

$$\Omega = \begin{bmatrix} \underset{(0.4793)}{1.4929} & 0 \\ \underset{(0.6849)}{0.6121} & \underset{(0.0628)}{0.3781} \end{bmatrix}$$

Estimated shape parameter for student t distribution	
υ	8.0617
Multivariate Q test for autocorrelation in standardized residuals	
Multivariate Q (6)	34.1537*
Multivariate Q (12)	59.5967
Multivariate Q test for ARCH effects in squared standardized residuals	
Multivariate Q (6)	11.7087
Multivariate Q (12)	42.2078
Bayesian Information Criterion (BIC)	9.7699

***,**,* denote rejection of null hypothesis at the 1%, 5% and 10% significance levels, respectively. Standard errors in parentheses.

Table 41c. Nonlinear combination of coefficients from Asymmetric t-BEKK GARCH model between price changes of feeder cattle (800 – 900 lbs.) and corn (asymmetric effects defined as price decrease in feeder cattle market and price increase in corn market)

	$h_{11,t}$		$h_{12,t}$		$h_{22,t}$	
	Coefficient	Standard error	Coefficient	Standard error	Coefficient	Standard error
$\gamma(non\ bse)$	0.2563***	0.0802	0.0862	0.1455	0.9524**	0.3754
$\gamma(with\ bse)$	3.9968**	2.0100	1.5642	1.5165	2.4051	1.8025
α	0.1331	0.1471	-0.0015	0.0105	0.0931***	0.0283
α'	0.0004	0.0007	-0.0061	0.0057	0.0002	0.0023
α''	0.0046	0.0045	-0.0355*	0.0198	0.0078	0.0552
β	0.8334***	0.0398	-0.0561	0.0350	0.8433***	0.0399
β'	0.0001	0.0002	0.0081	0.0107	0.0038	0.0048
β''	0.0160	0.0214	0.8378***	0.0284	-0.1128	0.0708
φ	0.1368***	0.0371	0.0449	0.0353	0.0179	0.0209
φ'	0.0009	0.0020	-0.0040	0.0054	0.0147	0.0226
φ''	-0.0221	0.0241	0.04584*	0.0272	0.0325	0.0362

***,**,* denote rejection of null hypothesis at the 1%, 5% and 10% significance levels, respectively. Standard errors are calculated based on the delta method.
The shaded cells indicate the measurements of volatility spillovers.

Table 42a. Conditional mean estimations between price changes of fed cattle and corn (asymmetric effects defined as price decreases in both markets)

	Fed Cattle	Corn
	$(i = 1)$	$(i = 2)$
$AR(1)_{1i}$	0.2039*** (0.0325)	-
$AR(1)_{2i}$	0.0280* (0.0159)	-
$AR(5)_{2i}$	-	0.0858*** (0.0303)
$AR(11)_{2i}$	-	-0.0754** (0.0293)
BSE	-7.5811** (3.2205)	-

***,**,* denote rejection of null hypothesis at the 1%, 5% and 10% significance levels, respectively.
Note: BSE is a dummy variable that takes on the value of one from May 28, 2003 to August 28, 2003 (first three months of the BSE crisis), and zero otherwise.

Table 42b. Asymmetric t-BEKK GARCH model between price changes of fed cattle and corn (asymmetric effects defined as price decreases in both markets)

Conditional variance-covariance model:

$$H_t = (C + \Omega BSE)(C + \Omega BSE)' + A'\varepsilon_{t-1}\varepsilon_{t-1}^{'}A + B'H_{t-1}B + D'\epsilon_{t-1}\epsilon_{t-1}^{'}D$$

$$C = \begin{bmatrix} \underset{(0.1532)}{0.7218} & 0 \\ \underset{(0.2883)}{0.3956} & \underset{(0.2092)}{1.2147} \end{bmatrix} \quad A = \begin{bmatrix} \underset{(0.0559)}{-0.2101} & \underset{(0.0423)}{0.0880} \\ \underset{(0.0277)}{-0.0083} & \underset{(0.0469)}{0.3456} \end{bmatrix}$$

$$B = \begin{bmatrix} \underset{(0.0343)}{0.8946} & \underset{(0.0194)}{0.0303} \\ \underset{(0.0194)}{-0.0318} & \underset{(0.0317)}{0.8744} \end{bmatrix} \quad D = \begin{bmatrix} \underset{(0.0731)}{0.2959} & \underset{(0.0793)}{0.1058} \\ \underset{(0.0370)}{0.0210} & \underset{(0.1146)}{0.1708} \end{bmatrix}$$

$$\Omega = \begin{bmatrix} \underset{(1.9708)}{7.0375} & 0 \\ \underset{(0.7163)}{-0.7892} & \underset{(0.9838)}{-1.2147} \end{bmatrix}$$

Estimated shape parameter for student t distribution	
υ	12.1212***
Multivariate Q test for autocorrelation in standardized residuals	
Multivariate Q (6)	33.4970*
Multivariate Q (12)	57.6437
Multivariate Q test for ARCH effects in squared standardized residuals	
Multivariate Q (6)	15.9741
Multivariate Q (12)	42.3160
Bayesian Information Criterion (BIC)	10.2314

***,**,* denote rejection of null hypothesis at the 1%, 5% and 10% significance levels, respectively. Standard errors in parentheses.

Table 42c. Nonlinear combination of coefficients from Asymmetric t-BEKK GARCH model between price changes of fed cattle and corn (asymmetric effects defined as price decreases in both markets)

	$h_{11,t}$		$h_{12,t}$		$h_{22,t}$	
	Coefficient	Standard error	Coefficient	Standard error	Coefficient	Standard error
$\gamma(non\ bse)$	0.5210**	0.2211	0.2855	0.2038	1.6320***	0.5659
$\gamma(with\ bse)$	60.2073*	32.0866	-3.0540	5.6532	0.1549	0.5633
α	0.0441*	0.0235	-0.0185**	0.0088	0.1194***	0.0324
α'	0.0001	0.0005	0.0029	0.0097	0.0077	0.0074
α''	-0.0035	0.0117	-0.0719***	0.0183	0.0608*	0.0325
β	0.8003***	0.0614	0.0271	0.0173	0.7646***	0.0554
β'	0.0010	0.0012	-0.0278*	0.0165	0.0009	0.0012
β''	-0.0569*	0.0344	0.7812***	0.0379	0.0530	0.0337
φ	0.0876**	0.0432	0.0313	0.0249	0.0292	0.0391
φ'	0.0004	0.0015	0.0036	0.0072	0.0112	0.0168
φ''	0.0124	0.0214	0.0528	0.0341	0.0361	0.0342

***,**,* denote rejection of null hypothesis at the 1%, 5% and 10% significance levels, respectively. Standard errors are calculated based on the delta method.
The shaded cells indicate the measurements of volatility spillovers.

Table 43a. Conditional mean estimations between price changes of fed cattle and corn (asymmetric effects defined as price decrease in fed cattle market and price increase in corn market)

	Fed Cattle	Corn
	(i = 1)	(i = 2)
$AR(1)_{1i}$	0.2025*** (0.0348)	-
$AR(1)_{2i}$	0.0261 (0.0163)	-
$AR(5)_{2i}$	-	0.0858** (0.0351)
$AR(11)_{2i}$	-	-0.0751** (0.0318)
BSE	-7.6769** (3.4263)	-

***,**,* denote rejection of null hypothesis at the 1%, 5% and 10% significance levels, respectively.
Note: BSE is a dummy variable that takes on the value of one from May 28, 2003 to August 28, 2003 (first three months of the BSE crisis), and zero otherwise.

Table 43b. Asymmetric t-BEKK GARCH model between price changes of fed cattle and corn (asymmetric effects defined as price decrease in fed cattle market and price increase in corn market)

Conditional variance-covariance model:

$$H_t = (C + \Omega BSE)(C + \Omega BSE)' + A'\varepsilon_{t-1}\varepsilon_{t-1}^{'}A + B'H_{t-1}B + D'\epsilon_{t-1}\epsilon_{t-1}^{'}D$$

$$C = \begin{bmatrix} \underset{(0.1644)}{0.7455} & 0 \\ \underset{(0.2804)}{0.3933} & \underset{(0.2144)}{1.1543} \end{bmatrix} \qquad A = \begin{bmatrix} \underset{(0.0597)}{-0.1997} & \underset{(0.0437)}{0.0844} \\ \underset{(0.0278)}{0.0187} & \underset{(0.0503)}{0.3622} \end{bmatrix}$$

$$B = \begin{bmatrix} \underset{(0.0404)}{0.8911} & \underset{(0.0182)}{0.0302} \\ \underset{(0.0213)}{-0.0312} & \underset{(0.0317)}{0.8821} \end{bmatrix} \qquad D = \begin{bmatrix} \underset{(0.0794)}{0.3098} & \underset{(0.0811)}{0.1149} \\ \underset{(0.0531)}{-0.0171} & \underset{(0.1177)}{0.0072} \end{bmatrix}$$

$$\Omega = \begin{bmatrix} \underset{(2.1908)}{7.1265} & 0 \\ \underset{(0.7235)}{-0.8298} & \underset{(1.0641)}{-1.1543} \end{bmatrix}$$

Estimated shape parameter for student t distribution	
υ	11.9379***
Multivariate Q test for autocorrelation in standardized residuals	
Multivariate Q (6)	33.2572*
Multivariate Q (12)	57.0828
Multivariate Q test for ARCH effects in squared standardized residuals	
Multivariate Q (6)	15.8796
Multivariate Q (12)	41.5605
Bayesian Information Criterion (BIC)	10.2327

***,**,* denote rejection of null hypothesis at the 1%, 5% and 10% significance levels, respectively. Standard errors in parentheses.

Table 43c. Nonlinear combination of coefficients from Asymmetric t-BEKK GARCH model between price changes of fed cattle and corn (asymmetric effects defined as price decrease in fed cattle market and price increase in corn market)

	$h_{11,t}$		$h_{12,t}$		$h_{22,t}$	
	Coefficient	Standard error	Coefficient	Standard error	Coefficient	Standard error
$\gamma(non\ bse)$	0.5558**	0.2451	0.2932	0.2051	1.4872***	0.5596
$\gamma(with\ bse)$	61.9684*	36.1939	-3.4354	5.7141	0.1905	0.6180
α	0.0399	0.0238	-0.0168*	0.0089	0.1312***	0.0364
α'	0.0003	0.0010	0.0068	0.0103	0.0071	0.0074
α''	-0.0075	0.0111	-0.0708***	0.0210	0.0611*	0.0348
β	0.7940***	0.0720	0.0268*	0.0162	0.7780***	0.0559
β'	0.0010	0.0013	-0.0275	0.0183	0.0009	0.0011
β''	-0.0556	0.0379	0.7850***	0.0394	0.0532*	0.0319
φ	0.0960*	0.0492	0.0356	0.0267	0.0001	0.0017
φ'	0.0003	0.0018	-0.0001	0.0020	0.0132	0.0186
φ''	-0.0106	0.0325	0.0003	0.0371	0.0017	0.0273

***,**,* denote rejection of null hypothesis at the 1%, 5% and 10% significance levels, respectively. Standard errors are calculated based on the delta method.
The shaded cells indicate the measurements of volatility spillovers.

Table 44. Asymmetric t-BEKK GARCH model between price changes of barley and corn (asymmetric effects defined as price decreases in both markets)

Conditional variance-covariance model:

$$H_t = CC' + A'\varepsilon_{t-1}\varepsilon_{t-1}^{'}A + B'H_{t-1}B + D'\epsilon_{t-1}\epsilon_{t-1}^{'}D$$

$$C = \begin{bmatrix} \underset{(0.0972)}{1.0779} & 0 \\ \underset{(0.1732)}{1.4481} & \underset{(0.1145)}{-0.0001} \end{bmatrix} \qquad A = \begin{bmatrix} \underset{(0.0736)}{0.5395} & \underset{(0.0595)}{0.0277} \\ \underset{(0.0515)}{0.0760} & \underset{(0.0554)}{0.2818} \end{bmatrix}$$

$$B = \begin{bmatrix} \underset{(0.0399)}{0.5988} & \underset{(0.0511)}{-0.0167} \\ \underset{(0.0194)}{-0.1221} & \underset{(0.0178)}{0.8863} \end{bmatrix} \qquad D = \begin{bmatrix} \underset{(0.1393)}{-0.5044} & \underset{(0.0508)}{-0.0176} \\ \underset{(0.524)}{0.1947} & \underset{(0.0951)}{0.2076} \end{bmatrix}$$

Multivariate Q test for autocorrelation in standardized residuals	
Multivariate Q (6)	30.6890
Multivariate Q (12)	66.2307**
Multivariate Q test for ARCH effects in squared standardized residuals	
Multivariate Q (6)	25.9409
Multivariate Q (12)	55.3990
Bayesian Information Criterion (BIC)	10.1346

***,**,* denote rejection of null hypothesis at the 1%, 5% and 10% significance levels, respectively. Standard errors in parentheses.