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An Asymmetric Price Transmission Analysis in the U.S. Pork Market Using Threshold Co-integration Analysis*

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Keywords

structural change, price transmission mechanism, (M) TAR model, vertically asymmetric price transmission, market inefficiency

Abstract

The objective of this study is to examine asymmetric price transmission in the U.S. pork market. The motivation of this study needs to be found in the structural changes in the U.S. pork market characterized by more extensive and intensive operation of pork production, consolidation of the small and medium scale producers, many mergers and acquisitions of meat packers and retailers. For this purpose, threshold co-integration analysis is applied to allow for an asymmetric pattern of price adjustment towards a long-run equilibrium in the price relationship among farm, wholesale, and retail levels. The empirical findings suggest that there is asymmetric price adjustment in the U.S. pork market while its pattern appears to be different across marketing channels. That is, wholesalers tend to respond more quickly to an increase in producer price (i.e., margin squeezing) than to a decrease in producer price (i.e., margin stretching), while wholesale price responds more quickly to a decrease in retail price. These may be generally understood in the presence of non-competitive pricing behavior of agents at a certain chain beyond farm gate. Such findings imply that the recent structural changes in the U.S. pork market may hinder an efficient price transmission mechanism across the marketing channels.

* This paper is based on a part of the author's dissertation study.

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1. Introduction

Over the last two decades, the U.S. pork industry has been marked by numerous structural changes which have significantly improved efficiency for pork production (USDA, 2006). The structure of the pork industry has become more concentrated with more intensive operations for meat production using low priced inputs (e.g., feed, labor and equipment etc.) to provide low-priced products to consumers. Consolidation of small and medium scale farms has led to a small number of large scale farms in producing hogs. In 2012, only 12 percent of large operations with more than 2,000 hogs and pigs¹ bred 90 percent of hogs and pigs (USDA/NASS, 2014). Furthermore, the meat packing industry also has been dominated by a few major firms through many mergers and acquisitions, resulting in industry concentration. Specifically, the degree of concentration in the food market is measured by the four-firm concentration ratio (CR4)².

According to USDA (2006) and the National Farmers Union (2014), the recent CR4 for pork packers was about 63 percent in 2013, compared to 46 percent in 1995. By definition of the CR4, the U.S. pork market could be considered as a market exhibiting characteristics of an imperfectly competitive market. This assumption implies that a small number of large-scale pork packers may have significant market share and exercise market power. The presence of market power in the processing or retail sectors is most commonly cited as a factor leading to asymmetric price transmission (Meyer and von Cramon-Taubadel, 2004). Under imperfect competition in processing and retail levels, sticky or slow response of price in one stage of the market channel to changes in another stage of the market channel might

¹ By definition, a hog usually refers to an older and bigger domesticated pig weighing more than 54 kilograms or 120 lbs. A pig is part of the *Sus* genus under the *Suidae* family. The word pig describes ten currently known living species, including domesticated pigs (*Sus scrofa domesticus*), forest hogs, babirusas, warhogs, red river boars and bushpigs.

² CR4 is defined as the concentration ratio (relative to 100%) of the top four firms in a specific food industry, which implies that if the value is lower, the market might be close to be perfect competition. The top four firms of meat packers include Smithfield, Tyson, Swift, and Cargill.

be a common concern. Especially in the agricultural sector, many studies suggest that an increase in input prices leading to margin squeezing is likely to be more quickly transferred to the output prices than the case of margin stretching created by a decrease in input prices (von Cramon-Taubadel, 1998; Boyd and Brorsen, 1988; Miller and Hayenga, 2001; Abdulai, 2002). Given the facts which described the U.S. pork industry, it can be hypothesized that price transmission across the marketing channels in the U.S. pork market is likely to be asymmetric.

The objective of this study is to test for asymmetric price transmission from the farm to the wholesale, and to the retail levels of the U.S. pork market. For this purpose, threshold co-integration analysis proposed by Enders and Granger (1998) is applied in the context of a potential consistency of the assumption of asymmetric adjustment for co-integration analysis. In this regard, Enders and Granger (1998) and Enders and Siklos (2001) argue that the standard co-integrating tests from Engle-Granger and Johansen approaches are misspecified if adjustment to the long run equilibrium is asymmetric. Accordingly, specification of the error correction model (ECM) should be based on the results of the threshold co-integration test.

Knowledge of the vertical price transmission among the various marketing levels is important to understand the overall operation of the market. There are some studies of empirical application of co-integration analysis to test for vertically asymmetric price transmission of the pork market. The study by von Cramon-Taubadel (1998) examines the asymmetric price transmission between producer and wholesale pork prices in northern Germany based on 200 weekly observations over the period from January 1990 to October 1993. His results suggested that there is asymmetric price transmission between producer and wholesale pork price in northern Germany by showing quicker response to margin squeezing than to margin stretching.

Another study by Goodwin and Harper (2000) investigated linkages among farm, wholesale, and retail levels in the U.S. pork market by using the threshold error correction

model proposed by Balke and Fomby (1997) allowing for asymmetric adjustment to positive and negative price shocks. Main findings of this study showed that asymmetries exist, but observed asymmetries are minor. Furthermore, price adjustment reveals asymmetry and its pattern is unidirectional from farm, to wholesale, to retail markets.

The study by Abdulai (2002) aimed to analyze asymmetric adjustment to long-run equilibrium between producer and retail pork prices in Switzerland. The analysis comes to the conclusion that price transmission between farm and retail levels in the Swiss pork market is asymmetric, in the sense that a decrease in the marketing margin more quickly passes through to retail prices than an increase in the marketing margin.

In consideration of the various stages of the market linked primarily by price mechanisms, the degree and the speed of adjustment to which prices are transmitted in the marketing chain might be a crucial indicator in presenting the behaviors of market participants at alternative levels and may have important implications for welfare distribution associated with spreading marketing margins and mark-up pricing practices in a normative fashion (Goodwin and Holt, 1999). Asymmetric price adjustment in a vertical context is widely accepted as evidence of the potential inefficiencies across the marketing channels (Meyer and von Cramon-Taubadel, 2004) that should be corrected. For policy purposes, the findings in this study will have greater implications on how the pork market pursues better resource allocation and improves market efficiency across the marketing channels.

This study is structured as follows. Section 2 highlights the econometric methods. Section 3 introduces data to be analyzed in this study. Section 4 presents the empirical results and section 5 concludes this study with a consideration of implications for further study.

2. Econometric methodology

Generally, in the study of vertical asymmetry price transmission, upstream prices are thought of as input prices for processing and manufacturing or prices quoted on higher market levels. Downstream prices are considered as output prices for processing and manufacturing or prices quoted on lower market levels. Further, Miller and Hayenga (2001) present that the asymmetric price response is measured by the relative response in downstream prices to increases and decreases in prices in upstream stages. Based on this concept, in the relationship between farm and wholesale level, producer prices are regarded as the input price to wholesalers, and wholesale prices represent the output prices. Accordingly, in the case of the relationship between wholesale and retail levels, wholesale prices stand for the input prices while retail prices are considered as the output prices.

In this sense, this study follows the definition of asymmetric price transmission in a vertical context presented in Meyer and von Cramon-Taubadel (2004): 1) positive asymmetry proposes that the price movement that squeezes the margin (i.e. an increase in input price or a decrease in output price) is transmitted more rapidly and/or completely (to output price or input price, respectively) than the equivalent movement that stretches the margin; and 2) negative asymmetry means that price movements that stretch the margin (i.e. a decrease in input price or an increase in output price) are transmitted more rapidly, and/or completely, than movements that squeeze it.

To conduct tests for the co-integration relationship between a pair of price series in pork marketing channels, it is necessary to confirm the presence of a unit root in the time series. By doing so, three methods such as the Augmented Dickey-Fuller (ADF), Phillips-Perron (PP), and Kwiatkowski, Phillips, Schmidt, and Shin (KPSS) are applied. The KPSS has certain advantages over the ADF and PP tests in that it assumes stationarity of the time series, as opposed to the null assumed by the ADF and PP. Due to the assumption of the

null of the ADF and PP, if there is no strong evidence for stationarity of time series, the ADF and PP might have a low power to reject the null, which might result in a Type II error. Consequently, testing a unit root of the time series throughout these three approaches would be a good strategy in terms of a robustness check of the characteristic of the time series. The length of lag can be determined in selecting the minimum Bayesian Information Criterion (BIC).

In this paper, co-integration tests allowing for the assumption of the null hypothesis of symmetric price transmission are conducted. For this purpose, the Engle-Granger two step procedure is applied. Alternatively, the threshold co-integration test introduced by Enders and Granger (1998) allowing for the assumption of asymmetric price adjustment is also used to correct the potential inconsistency which might result from the mis-specification if price transmission is asymmetric.

The Engle and Granger (1987) approach is composed of two steps. Initially, the long-run supply response is estimated using variables shown by the example of the relationship between producer and wholesale prices in Equation (1) below:

$$(1) \quad WP_t = \alpha_0 + \alpha_1 PP_t + \epsilon_t$$

where WP_t and PP_t are the pork wholesale price and the hog producer price, respectively. These two variables are expressed in logged terms. ϵ_t is the error term assuming a white noise process. Second, by using the residuals obtained from Equation (1), ADF tests for stationarity of residuals are used to estimate γ_0 in the following equation:

$$(2) \quad \Delta \hat{\epsilon}_t = \gamma_0 \hat{\epsilon}_{t-1} + \rho_0 \Delta \hat{\epsilon}_{t-1} + \omega_t$$

where ω_t is a white noise process. If the null hypothesis of $H_0 : \gamma_0 = 0$ is rejected, the residuals in Equation (1) are stationary with zero mean. This implies that two variables are

co-integrated with each other in the sense that there is a long-run equilibrium relationship between two variables.

On the other hand, Enders and Granger (1998) argue that the tests for co-integration could lead to inconsistent results if adjustment is asymmetric. Therefore, they proposed an alternative specification allowing for asymmetric adjustment, which is known as the threshold autoregressive (TAR) and the momentum threshold autoregressive (M-TAR) model, and it can be written in the form of (3) ~ (5):

$$(3) \quad \Delta \hat{\epsilon}_t = I_t \gamma_1 \hat{\epsilon}_{t-1} + (1 - I_t) \gamma_2 \hat{\epsilon}_{t-1} + \phi_t$$

where $\Delta \hat{\epsilon}_t$ is the first difference of the error term from Equation (1), γ_1 and γ_2 are the adjustment rates, I_t is the Heaviside indicator function such that:

$$(4) \quad I_t = \begin{cases} 1 & \text{if } \hat{\epsilon}_{t-1} \geq \tau \\ 0 & \text{if } \hat{\epsilon}_{t-1} < \tau \end{cases}$$

$$(5) \quad I_t = \begin{cases} 1 & \text{if } \Delta \hat{\epsilon}_{t-1} \geq \tau \\ 0 & \text{if } \Delta \hat{\epsilon}_{t-1} < \tau \end{cases}$$

τ represents the threshold value proposed by Chan (1993).

According to Tong (1983), if adjustment is asymmetric, the sample mean of the residuals is a biased estimate of the long-run equilibrium value. For this reason, Chan (1993) suggests that “it is necessary to find the possible long-run equilibrium values to minimize the sum of squared errors from the fitted model as a super-consistent estimate of threshold”. For example, the estimation procedures of the threshold proposed by Chan (1993) have the following steps: first, the estimated residual series ($\Delta \hat{\epsilon}_t$) are arranged in ascending order; second, 15% of the smallest observations and 15% of the largest observations are excluded,

and then the remaining 70% of the values are used as a possible threshold; and finally, for each possible threshold parameter, the threshold value that minimizes the residual sum of squares from the fitted model is chosen. This can be considered as the consistent TAR or M-TAR model.

The combination of Equations (3) and (4) is referred to as the TAR model and the combination of Equations (3) and (5) is said to be the M-TAR model. According to Enders and Granger (1998), the TAR model captures “deep” movements in the series, while the possibility of asymmetrically “sharp” movements in the series can be detected by the M-TAR model³. In the M-TAR model, the threshold depends on the change in ϵ_{t-1} in the previous period. To interpret the adjustment rate of γ_1 and γ_2 , if, for example, $-1 < \gamma_1 < \gamma_2 < 0$, the TAR model represents that the positive discrepancies of the $\hat{\epsilon}_t$ series will tend to revert rapidly back to the long-run equilibrium relative to the negative discrepancies of the $\hat{\epsilon}_t$ series. Furthermore, if, for example, $|\gamma_1| < |\gamma_2|$, the M-TAR model suggests that the negative $\Delta \hat{\epsilon}_{t-1}$ is substantially in decay, while the positive $\Delta \hat{\epsilon}_{t-1}$ is little adjusted to the long-run equilibrium.

For both TAR and M-TAR models, the first step is to check that the analyzed series are co-integrated. To do so, the null hypothesis of $H_0 : \gamma_1 = \gamma_2 = 0$ of no co-integration is tested. Since the F -statistics for the above null hypothesis have a non-standard distribution, the Φ -statistic is used. If the null hypothesis of $H_0 : \gamma_1 = \gamma_2 = 0$ is rejected, the result concludes that the series are co-integrated and to proceed with the test for the asymmetric adjustment. Therefore, the null hypothesis of symmetric adjustment ($H_0 : \gamma_1 = \gamma_2$) is tested. In this case, standard F -statistics can be used. If the null hypothesis cannot be rejected, it supports the evidence of symmetric price adjustment. Rejecting the null hypothesis would suggest that price responds differently to whether the departure from the long-run equilibrium is increasing or decreasing. Diagnostic checking for a white noise process for

³ With the definition of the two terms as to “deep” and “sharp” described by Ghoshray (2002), “deepness indicates the asymmetry in the magnitude of peaks and troughs and steepness represents the asymmetry in the form of differing speeds at which peaks and troughs are approached”.

the residuals ϕ_t is performed by using the Breusch–Godfrey test⁴, the Ljung-Box test⁵, and Durbin Watson test. If the residuals are serially correlated, Equation (3) should be re-estimated by adding the additional lags of $\Delta \hat{\epsilon}_t$ in the following form:

$$(6) \quad \Delta \hat{\epsilon}_t = I_t \gamma_1 \hat{\epsilon}_{t-1} + (1 - I_t) \gamma_2 \hat{\epsilon}_{t-1} + \sum_{t=1}^p \theta_t \Delta \hat{\epsilon}_{t-1} + \phi_t$$

If a pair of price series are co-integrated and adjustment is symmetric, an error correction model (ECM) in the following form is the example in the relationship between farm and wholesale level:

$$(7) \quad \Delta WP_t = \beta_0 + \lambda_1 \hat{\epsilon}_{t-1} + \sum_{i=1}^p \delta_i \Delta WP_{t-i} + \sum_{j=1}^q \theta_j \Delta PP_{t-j} + \mu_t$$

where ΔWP_t and ΔPP_t are vectors of the first differences of log prices for wholesale and farm level, respectively, $\hat{\epsilon}_{t-1}$ is the lagged residual from Equation (1), μ_t is the error term, and λ_t represents the short-run adjustment speed of the dependent variable to the long-run equilibrium and its sign should be negative. The selection of the correct lag length is conducted by minimizing the Schwarz criterion (SBC), and test for autocorrelation of the residuals, μ_t is conducted by using the Ljung-Box Q test, the Breusch-Godfrey LM test, and Durbin-Watson test.

If either one of the TAR and the M-TAR models or both models assure that the null

⁴ The procedures of the Breusch–Godfrey test are as follows: 1) run OLS regression to compute an estimate of the model, $Y = \alpha_0 + \alpha_1 X_1 + \dots + \alpha_k X_k + \epsilon$ and find the residuals e_1, e_2, \dots, e_n , 2) using e_1, e_2, \dots, e_n , run an OLS regression for the model $e_t = \beta_0 + \beta_1 x_{i1} + \dots + \beta_k x_{ik} + \rho_1 e_{i-1} + \dots + \rho_j e_{i-j} + \omega_t$, 3) test the null hypothesis of $H_0 : \rho_1 = \rho_2 = \dots = \rho_p = 0$ with the test statistic $LM = (n - p)R^2 \sim \chi^2_{(p)}$ where n is sample size and R^2 is the value calculated in step 2. If p-value is less than significant level of α , the null is rejected, which means that at least one of the ρ_j is significantly different from zero.

⁵ The Ljung-Box test is designed to test for the null hypothesis of H_0 : the residuals are uncorrelated with its test statistic of $Q = n(n+2) \sum_{k=1}^m \hat{\rho}_k^2 / (n-k)$ where n is the sample size, $\hat{\rho}_k$ is the sample autocorrelation at lag k , and h is the number of lags being tested. Under H_0 , the statistic Q follows a $\chi^2_{(h)}$. If Q -statistic is greater than $\chi^2_{(h)}$, the null is rejected.

hypothesis of symmetric price adjustment ($H_0 : \gamma_1 = \gamma_2$) is rejected, the asymmetric error correction model can be specified as follows:

$$(8) \quad \Delta WP_t = \beta_0 + \lambda_2 \hat{\epsilon}_{t-1}^+ + \lambda_3 \hat{\epsilon}_{t-1}^- + \sum_{i=1}^p \delta_i \Delta WP_{t-i} + \sum_{j=1}^q \theta_j \Delta PP_{t-j} + \psi_t$$

where $\hat{\epsilon}_{t-1}^+$ and $\hat{\epsilon}_{t-1}^-$ represent error correction terms (ECT) meaning the positive and negative deviations to the long-run equilibrium created by a change in ΔPP_t , respectively and ψ_t is error terms.

The number of months (n) it takes the WP_t series to adjust back to the equilibrium after the change in PP_t can be estimated by using the formula in the study by Ghoshray (2002):

$$(9) \quad n = \frac{\log(1-p)}{\log(1-\lambda_i)}$$

where p is a given proportion of the disequilibrium to be corrected and λ_i ($i = 1, 2, 3$) is the coefficients of short-run adjustment rate from Equations (7) and (8).

3. Data

Empirical investigation in this study is conducted by using the 132 monthly observations of producer, wholesale, and retail prices for pork in the United States over the time period from January 2005 to December 2015. The producer prices (PP, USD per cwt) and the wholesale prices (WP, USD per cwt) represent barrow and gilt price and price of Central U.S. pork cutout composite sourced from USDA/ERS, respectively. The retail prices (RP,

USD per cwt) stand for retail pork value of retail weight equivalent obtained from USDA/ERS. All series are expressed in logarithm in the regression. Descriptive statistics and characteristic of each data series are found in Table 1.

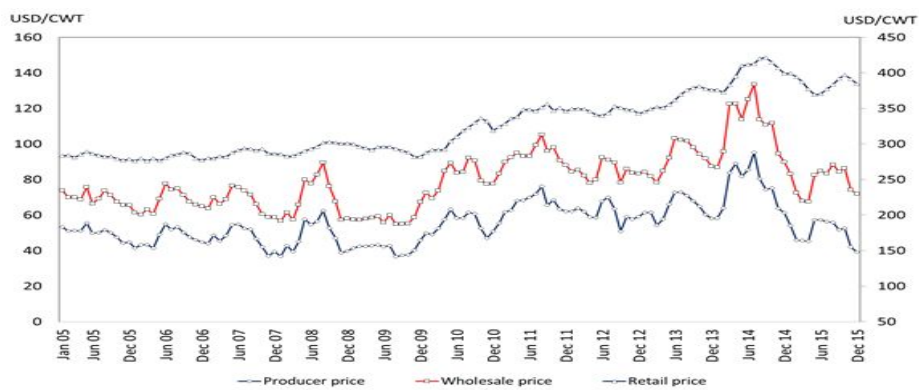
TABLE 1. Basic statistical measures of the price series in levels

Variable	Obs	Min	Max	Mean	SD	Variance	Skewness	Kurtosis
PP	132	36.56	95.17	55.09	11.77	138.53	0.79	0.64
WP	132	54.94	133.58	79.33	16.28	264.91	0.78	0.63
RP	132	276.29	421.55	326.27	43.20	1866.48	0.53	-1.05

Source: USDA/ERS.

The visualized plots of each price series in this study are presented in Figure 1. As shown in the graphs, producer prices and wholesale prices appear to move together over time. However, all price series obviously appear to have an increasing trend over time and variation of price series is generally intensified at the end of the sample period in the sense that all price series might be non-stationary.

FIGURE 1. The plot of hog and pork price series



Source: USDA/ERS.

4. Empirical results

4.1. Testing for a unit root

The test for a unit root is conducted by using the ADF, PP and KPSS tests. The approach to find the appropriate length of lags is based on the lowest BIC. According to Table 2, the ADF and PP test results of the null hypothesis of non-stationarity of the series assure that all price series in log levels are non-stationary by retaining the null hypothesis. The results of the KPSS assuming the null hypothesis of stationarity of series also indicate that all series in log levels have a unit root by rejecting the null hypothesis. This implies that all price series need to be differenced to make them stationary.

According to the results of Table 3, on the other hand, the null hypothesis that price series in the first difference has a unit root is rejected from the ADF and the PP test, and the fact that all price series in the first difference are stationary is confirmed by the KPSS test. These results indicate that all price series analyzed are I(1).

TABLE 2. Results of stationary tests in logged prices

	No. of lags	ADF		PP		KPSS	
		Drift	Drift & trend	Drift	Drift & trend	Drift	Trend
PP	1	-2.73*	-2.94	-2.51	-2.68	2.52**	0.32**
WP	2	-2.49	-3.13	-2.41	-3.01	2.27**	0.21**
RP	2	-0.79	-2.91	-0.54	-2.56	4.41**	0.45**

Notes: * and ** are for 10% and 5% significance level, respectively. The critical values of ADF and PP tests at 5% and 10% significance level are obtained from the R. Davidson and J.G. Mackinnon (1993), *Estimation and Inference in Econometrics*. The critical values of test with a drift and with a drift and a trend (n=100) at 5% significance are -2.89 and -3.45, respectively and at 10% significance are -2.58 and -3.15, respectively. For the KPSS tests, the critical values with a drift and with a trend at 5% significance are 0.463 and 0.146, respectively and at 10% significance are 0.347 and 0.119, respectively.

TABLE 3. Results of stationary tests in the logged first difference

	No. of lags	ADF		PP		KPSS	
		Drift	Drift & trend	Drift	Drift & trend	Drift	Trend
PP	1	-7.41**	-7.40**	-10.05**	-10.04**	0.08	0.06
WP	1	-7.73**	-7.71**	-9.83**	-9.80**	0.05	0.05
RP	1	-6.23**	-6.19**	-7.90**	-7.87**	0.10	0.08

Notes: ** are for 10% and 5% significance level, respectively. The critical values of ADF and PP tests at 5% and 10% significance level are obtained from the R. Davidson and J.G. Mackinnon (1993), Estimation and Inference in Econometrics. The critical values of test with a drift and with a drift and a trend (n=100) at 5% significance are -2.89 and -3.45, respectively and at 10% significance are -2.58 and -3.15, respectively. For the KPSS tests, the critical values with a drift and with a trend at 5% significance are 0.463 and 0.146, respectively and at 10% significance are 0.347 and 0.119, respectively.

4.2. Threshold co-integration tests

For the co-integrating test that assumes that price transmission is symmetric, the Engle-Granger two step procedure is conducted by initially estimating Equation (1) by OLS, and then by testing that the residuals estimated in the fitted model have a unit root. If the null hypothesis of $H_0 : \gamma_0 = 0$ is rejected, this suggests that residuals are stationary with zero mean, which implies that two price series are co-integrated with each other.

TABLE 4. Engle-Granger co-integration tests

	Co-integrating regression		ADF test				
	α_0	α_1	No. of lag	γ_0	$Q(6)$	LM_{test}	DW
WP - PP	0.64 [7.62]**	0.93 [44.06]**	1	-1.92*	9.60 (0.15)	0.52 (0.47)	1.99
RP - WP	3.62 [22.49]**	0.50 [13.41]**	1	-2.42**	3.95 (0.68)	1.52 (0.22)	1.97

Notes: * and ** stand for 10% and 5% significance level, respectively. The t-statistic is stated in square brackets. α_0 and α_1 are parameters in equation 1. The ADF test is conducted by using residuals of equation 2. The critical values of the ADF test with zero mean (n=100) are -1.95 at 5% significance and -1.61 at 10% significance. The p-values are stated in parenthesis for the Ljung-Box Q-statistic and Breusch-Godfrey statistic for autocorrelation of residuals.

Table 4 presents the results of the Engle-Granger co-integration test. The parameters α_0 and α_1 stand for the constant absolute margin and the price transmission elasticity, respectively. These parameter values are significantly different from zero at the 5% significance level in both price relationships. To interpret each parameter value, there is a constant absolute margin of 0.64 dollars per cwt between the producer and wholesale marketing levels. A one percent increase in producer price results in a 0.93 percent increase in wholesale price. Furthermore, wholesale and retail prices are linked by a constant absolute margin of 3.62 dollars per cwt, and retail price is increased by 0.50 percent given a one percent increase in wholesale price.

For the results of the Engle-Granger test, the estimated values of γ_0 are -1.92 and -2.42 for the case of producer and wholesale prices and the case of wholesale and retail prices, respectively. The null hypothesis in the case of the producer and wholesale prices is rejected at the 10% significance level, and for the case of wholesale and retail price, the null hypothesis is also rejected at the 5% level of significance as compared to the critical values. This suggests that there is a long-run equilibrium relationship in between producer and wholesale prices and between wholesale and retail prices in the U.S. pork market. Meanwhile, the Ljung-Box Q-statistic, Breusch-Godfrey and Durbin-Watson statistic assure that the residuals (ω_t) of Equation (2) are uncorrelated.

TABLE 5. The results of TAR model across the pork marketing channels

	PP – WP		WP – RP	
	TAR	Consistent TAR	TAR	Consistent TAR
Lag length	0	0	1	1
γ_1	-0.08 [-1.03]	-0.18 [-0.96]	-0.06 [-1.08]	-0.05 [-1.00]
γ_2	-0.25 [-2.82]**	-0.25 [-2.89]**	-0.16 [-2.55]**	-0.17 [-2.65]**
$H_0 : \gamma_1 = \gamma_2 = 0 (\Phi)$	4.52*	4.65**	3.72	3.92*
$H_0 : \gamma_1 = \gamma_2 (F)$	2.01 (0.16)	2.24 (0.14)	1.54 (0.22)	1.93 (0.17)
τ	0	0.0192	0	-0.0247
$Q(6)$	9.99 (0.13)	10.40 (0.11)	3.92 (0.69)	3.95 (0.68)
LM_{test}	2.39 (0.12)	2.45 (0.12)	2.50 (0.15)	2.06 (0.15)
DW	2.19	2.19	1.97	1.97
F_{test}	4.52 (0.01)	4.64 (0.01)	2.55 (0.06)	2.69 (0.05)
SBC	-531.25	-531.48	-470.27	-470.67

Notes: * and ** stand for 10% and 5% significance level, respectively. γ_1 and γ_2 stand for the coefficients of adjustment and t-statistics is in brackets for the null hypothesis $\gamma_1 = 0$ and $\gamma_2 = 0$, respectively. Values of Φ -statistic for the TAR model with n=100 for the null hypothesis $\gamma_1 = \gamma_2 = 0$ at 5% and 10% significance levels are 4.64 and 3.79, respectively. Critical values for Φ -statistic are computed by Enders and Granger (1998). P-values are stated in the parenthesis for the Ljung-Box Q-statistic, Breusch-Godfrey statistic, and F-statistic.

Next, in order to conduct a threshold co-integration test allowing for the assumption of asymmetric price transmission in this study, the TAR and the M-TAR models are estimated by using two threshold values with zero and consistent threshold estimates with the Heaviside Indicator function as an attractor. The results of the TAR model are presented in Table 5. Based on the SBC, the consistent TAR model is preferable to the TAR model with the zero attractor in both cases of price relationships. For the consistent TAR model in each price relationship, adjustment rates of γ_1 (positive deviation showing a decrease in producer or wholesale price) are insignificant, while adjustment rates of γ_2 (negative deviation meaning an increase in producer or wholesale price) are significant at the 5% significance level. Focusing on the adjustment rate of a γ_2 in the case of producer and wholesale price relationship, the point estimate of (-0.25) suggests that approximately 25

percent of a negative deviation from a long-run equilibrium is corrected within a month. The point estimate of γ_2 (-0.17) for the case of wholesale and retail price relationship indicates that approximately 17 percent of a negative deviation from a long-run equilibrium is eliminated within a month. When it comes to the hypotheses tests, Φ -statistics for the case of producer and wholesale price and the case of wholesale and retail price in the consistent TAR model are 4.65 and 3.92, respectively. Since these values are larger than the critical value of 4.64 at the 5% significance level and 3.79 at the 10% significance level respectively, the null hypothesis of $H_0 : \gamma_1 = \gamma_2 = 0$ is rejected, meaning that the price series are co-integrated. F -statistics recorded to test for asymmetric price transmission for the case of producer and wholesale price relationship and the case of wholesale and retail price relationship in the consistent TAR model are 2.24 and 1.93, respectively. Retaining the null hypothesis of $H_0 : \gamma_1 = \gamma_2$ in both cases of the price relationships is allowed due to lower values of each F-statistic than the critical value, indicating that price flow from producer to wholesale, and wholesale to retail is symmetrically transmitted. A diagnostic check for the serial correlation of residuals suggests that residuals of the consistent TAR model for both cases are significantly uncorrelated with each other.

The results of the M-TAR model are found in Table 6. According to Table 6, the consistent M-TAR model can be regarded as a more appropriate model due to the lower value of the SBC in both cases of price relationship. In both cases, adjustment rates of γ_1 are insignificant, while adjustment rates of γ_2 are significant at the 5% significance level. From these results, the point estimate of γ_2 (-0.44) for the case of producer and wholesale prices represents that approximately 44 percent of a negative deviation from a long-run equilibrium is eliminated within a month. Similarly, in the case of the relationship between wholesale and retail price, the point estimate of γ_2 (-0.25) shows that approximately 25 percent of a negative deviation from a long-run equilibrium is eliminated within a month.

From the results of the threshold co-integration test with the null hypothesis of $H_0 : \gamma_1 = \gamma_2 = 0$, for both price relationships in the case of producer and wholesale price

relationship and wholesale and retail price relationship, the consistent M-TAR model supports that there is a long-run equilibrium relationship in each price combination by rejecting the null at the 5% significance level. Furthermore, by contrast with the results of the consistent TAR model, F -statistics of both cases to test for the null hypothesis of $H_0 : \gamma_1 = \gamma_2$ of the consistent M-TAR model are greater than the critical value at the 5% level of significance. These results suggest that price transmission from producer price to wholesale price, and wholesale price to retail price is asymmetrically adjusted. In addition, the residuals of the consistent M-TAR model in both cases are significantly uncorrelated based on the results of diagnostic checking from the Ljung-Box, Breusch-Godfrey and Durbin-Watson test.

TABLE 6. The results of M-TAR model across the pork marketing channels

	PP – WP		WP – RP	
	M-TAR	Consistent M-TAR	M-TAR	Consistent M-TAR
Lag length	0	0	0	0
γ_1	-0.14 [-1.25]	-0.09 [-1.36]	0.04 [0.35]	-0.03 [-0.55]
γ_2	-0.26 [-1.90]*	-0.44 [-3.38]**	0.04 [0.29]	-0.25 [-3.35]**
$H_0 : \gamma_1 = \gamma_2 = 0 (\Phi)$	2.59	6.63**	0.10	5.74**
$H_0 : \gamma_1 = \gamma_2 (F)$	0.45 (0.50)	5.81 (0.02)	0.00 (0.97)	6.47 (0.01)
τ	0	-0.0241	0	-0.0209
$Q(6)$	14.20 (0.03)	9.52 (0.15)	8.70 (0.19)	9.62 (0.14)
LM_{test}	1.69 (0.19)	3.13 (0.08)	1.11 (0.29)	2.41 (0.12)
DW	2.03	2.22	1.98	1.76
F_{test}	2.59 (0.08)	6.63 (0.00)	0.10 (0.90)	5.74 (0.00)
SBC	-522.74	-530.40	-467.74	-478.71

Notes: * and ** stand for 10% and 5% significance level, respectively. γ_1 and γ_2 stand for the coefficients of adjustment and t-statistics is in brackets for the null hypothesis $\gamma_1 = 0$ and $\gamma_2 = 0$, respectively. Values of Φ -statistic for the TAR model with n=100 for the null hypothesis $\gamma_1 = \gamma_2 = 0$ at 5% and 10% significance levels are 5.02 and 4.11, respectively. Critical values for Φ -statistic are computed by Enders and Granger (1998). P-values are stated in the parenthesis for the Ljung-Box Q-statistic, Breusch-Godfrey statistic, and F-statistic.

In short, given the results from the four different models, the consistent model would be preferable to the model with zero mean threshold based on the value of the SBC. Specifically, a consistent M-TAR model can be considered as an appropriate model to explain asymmetric price adjustment in the U.S. pork market. In this context, based on the studies of Goychuk & Meyers (2014) and Abudlai (2000, 2002), if either the TAR model or the M-TAR model can support the null hypothesis of asymmetric price transmission, an ECM should be specified to allow for asymmetric price transmission in this study.

4.3. Estimation of asymmetric error correction model

As mentioned above, given the finding that the consistent M-TAR model supports the evidence of asymmetric price transmission, asymmetric ECM should be specified to estimate the price adjustment to positive and negative ECT and the short-run dynamic in this study.

Table 7 represents estimation results of asymmetric ECM. First, estimates of asymmetric ECM for the case of producer and wholesale price are reported in the first and second column. In the first column, wholesale price responds significantly and quickly to $\hat{\epsilon}_{t-1}^-$ meaning negative deviation created by increase in producer price, while it tends to be more persistent to $\hat{\epsilon}_{t-1}^+$ implying positive deviation created by a decrease in producer price. Specifically, wholesale price adjusts to correct approximately 23 percent of negative deviation from the long-run equilibrium created by an increase in producer price within a month. On the other hand, wholesale price adjusts to correct only 6 percent, approximately, of positive deviation from the long equilibrium created by a decrease in producer price within a month. For the long-run adjustment of wholesale price to positive and negative error correction term by using Equation (9), it will take about 8.8 months to adjust toward the long-run equilibrium to negative deviation created by an increase in producer price, while, for positive deviation created by a decrease in producer price, it will take

approximately 39.8 months. This suggests that adjustment of wholesale price toward a long-run equilibrium is faster as producer price increases than as producer price decreases. On the other hand, in the second column, producer price responds insignificantly to positive or negative deviation created by a decrease or an increase in wholesale price.

Meanwhile, while the lagged change in the producer price does not affect the wholesale price, the response of wholesale price is significantly derived by only a contemporaneous change in the producer price at 5% level of significance. On the other hand, in the case for producer price as a dependent variable, the null hypothesis that lagged changes in wholesale price do not affect producer price should be retained. In short, in the case of the relationship between producer and wholesale prices, there is unidirectional price adjustment from producer to wholesale price. The possible explanation of this result is that it might be difficult for producers to adjust production to a transitory change in the wholesale price in the short-run due to the biological constraints of hog production. In contrast, wholesalers are able to relatively quickly adjust prices to a change in producer prices. This is consistent with the possible behavior of wholesalers described in the previous study that wholesalers respond more quickly to margin squeezing (an increase in producer price) than margin stretching (a decrease in producer price). As aforementioned, this may not be unrelated with imperfect competition in the pork processing level, exerting market power by a small number of meat packers.

Next, for the results of the price relationship between wholesale price and retail price, in the third column, the adjustment rates of retail price to positive and negative ECT are the same, while the retail price only responds significantly to positive ECT ($\hat{\epsilon}_{t-1}^+$) created by a decrease in wholesale price. Specifically, the retail price adjusts to correct approximately only 4 percent toward a long-run equilibrium to positive deviation (decrease in wholesale price) within a month. On the other hand, in the fourth column, wholesale price responds significantly and strongly to positive ECT ($\hat{\epsilon}_{t-1}^+$) created by a decrease in retail price. With the point estimate of positive error correction term, wholesale price

adjusts to correct approximately 35 percent of positive deviation from the long-run equilibrium created by a decrease in retail price within a month. In terms of the long-run correction adjustment given a 90 percent probability with regard to retail price, 55.8 months will be required to adjust toward the long-run equilibrium to the positive deviation (decrease in wholesale price). However, for the wholesale price, it will take only about 5.3 months to adjust to the long-run equilibrium.

TABLE 7. Estimates of the asymmetric ECM across the pork marketing channels

Independent variable	Dependent variable			
	Between producer and wholesale price relationship		Between wholesale and retail price relationship	
	ΔWP_t	ΔPP_t	ΔRP_t	ΔWP_t
Constant	-0.001 [-0.33]	0.003 [0.25]	0.002 [0.97]	0.002 [1.54]
ΔPP_t	0.79 [28.22]**	-	-	-
ΔPP_{t-1}	0.07 [0.82]	-0.28 [-1.08]	-	-
ΔWP_t	-	-	0.02 [1.37]	-
ΔWP_{t-1}	-0.10 [-1.08]	0.52 [1.76]	0.07 [4.73]**	0.06 [0.12]
ΔRP_{t-1}	-	-	0.23 [3.11]**	0.29 [2.97]**
$\hat{\epsilon}_{t-1}^+$	-0.06 [-0.60]	-0.30 [-0.88]	-0.040 [-1.73]*	-0.35 [-2.71]**
$\hat{\epsilon}_{t-1}^-$	-0.23 [-2.09]**	-0.003 [-0.01]	-0.038 [-1.26]	-0.02 [-0.22]
$Q(6)$	14.39 (0.03)	8.95 (0.18)	4.41 (0.62)	6.42 (0.38)
LM_{test}	2.28 (0.13)	0.95 (0.33)	12.89 (0.00)	0.45 (0.50)
DW	2.03	1.96	2.28	2.03
F_{test}	165.26 (0.00)	1.88 (0.12)	14.95 (0.00)	3.38 (0.01)

Notes: * and ** stand for 10% and 5% significance level, respectively. t -values are stated in square brackets. $\hat{\epsilon}_{t-1}^+$ and $\hat{\epsilon}_{t-1}^-$ stand for error correction terms representing adjustment rate with respect to increasing and decreasing deviations from the long-run equilibrium, respectively. p -values are stated in a parenthesis for the Ljung-Box Q-statistic, Breusch-Godfrey statistic, and F -statistic.

The null hypothesis that contemporaneous changes in wholesale price do not affect retail price is not rejected since its estimated coefficient is not statistically different from zero at

the 5% level of significance, while the response of retail price is significantly derived by only a lagged change in wholesale price. The null hypothesis that lagged changes in retail price do not affect wholesale price is rejected at 5% level of significance. Overall, this finding suggests that there is bidirectional price adjustment in the price relationship between wholesale and retail level.

In focusing on the point estimate of positive ECT ($\hat{\epsilon}_{t-1}^+$) in the price relationship between wholesale and retail, the wholesale price adjusts quickly toward a long-run equilibrium in response to a decrease in retail price, while the retail price tends to adjust very slowly towards a long-run equilibrium to a decrease in wholesale prices. In this context, the possible explanation on the slow response of retailers to a change in the wholesale price is that retailers are less likely to frequently adjust their prices to a transitory price change due to adjustment costs (e.g., menu costs) accompanied by repricing or relabeling products. Since adjustment costs at the retail stage could lead to rigidity and less frequent repricing of retail price, wholesale price movements may induce a very sluggish response in retail prices. Meanwhile, more swift adjustment of the wholesale price to a decrease in the retail price as compared to that of an increase in the retail price may attribute to the fact that the demand at the wholesale level is relatively more inelastic than consumer demand. This implicitly means that the imbalance between a decrease in input demand by retailers at the wholesale level due to declining retail price by weakening consumer demand and an increase in input supply at the wholesale stage could lead to further declines in the wholesale price. Another plausible explanation is that retailers may exercise oligopsony power to enable them to make up for margin reduction due to a decrease in output price by quickly being passed through to wholesalers with a low rate⁶.

The conclusion of wholesalers' behavior in adjusting more quickly to the price signal for squeezing margins than stretching margins in the unidirectional price flow from producer

⁶ When it comes to this view, the findings on the positive relationship between firms' concentration and wholesale-retail margin reported by Schroeter, Azzam, and Zhang (2000) indicate that there is little evidence of oligopoly power by meat packers but some evidence of oligopsony power by retailers in the U.S. pork market.

to wholesale level found in this study is consistent with the results analyzed in the price transmission studies by Hahn (1990), Miller and Hayenga (2001), and Abdulai (2002) for the pork market. The results in this study, on the other hand, are in contradiction to the results of the previous studies for the U.S. pork market by Boyd and Brorsen (1988) and Goodwin and Harper (2000) in terms of an asymmetric pattern of price adjustment. In particular, the findings in the study by Goodwin and Harper (2000) show that there exists the unidirectional price transmission from wholesale to retail markets but not vice versa, which is distinctly different from results in this study that there is bidirectional price transmission in the price flow from wholesale to retail levels.

5. Conclusion

This study aims to examine asymmetric price transmission of pork prices from the farm to the wholesale, and the wholesale to the retail levels in the U.S. pork market by using threshold co-integration analysis proposed by Enders and Granger (1998) as an alternative method when evaluating monthly producer, wholesale, and retail prices over the period from January 2005 to December 2015. Specifically, the application of the threshold co-integration approach to ensure the consistent ECM model allows for the possible asymmetric pattern of price adjustment presented in the previous studies in such a way that adjustment of the margin is relatively faster to squeezing margins as compared to stretching margins due to the existence of market power across marketing chain. For this purpose, both threshold autoregressive (TAR) model and momentum threshold autoregressive (M-TAR) model are used to test for asymmetric price transmission. Therefore, the findings can provide information for policy implications in accessing the benefits of the recent structural changes in the U.S. pork market in terms of market efficiency.

Focusing on the main results, the consistent M-TAR model supports the evidence of asymmetric price transmission in both the case of the producer price to the wholesale price and the wholesale price to the retail price. This is consistent with the notion of an asymmetric pattern of price transmission across the marketing chains from farm to wholesale, and from the wholesale to the retail level described in previous studies.

The estimates from the asymmetric ECM estimation provide the characteristic of price flow, the short-run dynamic and the long-run price adjustment in each price relationship. In the case of the producer price to the wholesale price, the producer price is significantly transmitted to the wholesale price but not vice versa and the wholesale price more quickly adjusts towards the long-run equilibrium to an increase in the producer price than to a decrease in the producer price. In the case of the wholesale price to the retail price, there is the presence of bidirectional price flow for only positive ECT in its relationship, but a decrease in retail price induces a quicker and stronger response of wholesale price than the response of retail price to a decrease in wholesale price in opposite direction.

The literature has proposed various factors such as imperfect competition (market power), adjustment costs, input availability at different marketing channels, and price policies to explain the presence of asymmetric price transmission across the marketing chain. The findings in this study, which are not largely different from other research, suggest that there is evidence of asymmetric price adjustment in the U.S. pork market. This implies that the recent structural change in the U.S. pork industry does not improve market efficiency by undermining the price transmission mechanism across the marketing channel. Therefore, in the context of policy implications, it implies that the recent structural changes in the U.S. pork market increase asymmetric price adjustment which then implies that there is the presence of the potential market inefficiencies in the U.S. pork market. However, it is beyond the scope of this study to examine the direct impact of these factors on price transmission. Thus, it is necessary to examine the direct impact of these factors across marketing stages on price transmission in future research.

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