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Animal disease outbreaks and food market price dynamics: Evidence from regime-dependent modelling and connected scatterplots*

Alejandro Acosta, Carlos Barrantes and Rico Ihle[†]

The economic impacts of animal disease outbreaks have been widely discussed in the literature. Most authors have centred their attention on estimating the direct costs. Recent studies have shown that the indirect economic effects might lead to equal or even higher welfare losses. This study aims to contribute to this field of research by assessing the effect of an animal disease outbreak on food market price dynamics in Mexico, accounting for the potential effect of an antitrust intervention. We employ a regime-dependent vector error correction model and a connected scatterplot analysis. The results show that both the outbreak and the antitrust intervention caused structural breaks in food market price dynamics between producers and consumers, reflected in an increase in the absolute component of the marketing margin, with serious food security implications.

Key words: antitrust intervention, highly pathogenic avian influenza, market integration, price transmission.

1. Introduction

In June 2012, the Servicio Nacional de Sanidad, Inocuidad y Calidad Agroalimentaria (SENASICA) of Mexico notified the World Animal Health Organization (OIE) of three outbreaks of the highly pathogenic avian influenza (HPAI) virus in the state of Jalisco. The epidemiological investigation found that the HPAI outbreak corresponded to the virus subtype H7N3. As a preventive measure to avoid the spread of the virus, more than 20 million birds were slaughtered and disposed of (OIE 2012). As a result of the

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[†]Alejandro Acosta (email: alejandro.acosta@fao.org) is Economist Policy Officer at Animal Production and Health Division, Food and Agriculture Organization of the United Nations, Rome, Italy. Carlos Barrantes is Doctoral Researcher at Department of Agricultural Economics and Rural Development, Georg-August-Universität Göttingen, Göttingen, Germany. Rico Ihle is Assistant Professor at Agricultural Economics and Rural Policy Group, Wageningen University, Wageningen, The Netherlands.

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subsequent shortage of eggs, prices rose 82 per cent between May and August 2012.

The efforts made by Mexican authorities to control the disease threat helped to restore egg production fully by 2013 (Hernandez and Hernandez 2016). Nevertheless, real egg prices remained high, rising from 17 pesos/kg on average before the outbreak to 25 pesos thereafter. In March 2015, following several notifications of potential market concentration in the egg market, the Federal Commission of Economic Competition (COFECE) announced the opening of an investigation concerning anti-competitive practices in the egg market (COFECE 2015a 2015b). A subsequent drop in real egg prices was observed from an average price of 25 pesos since the outbreak to 19 pesos after the antitrust intervention.

In Mexico, the spatial concentration of egg production is very high, as only two of the 31 states in Mexico – Jalisco and Puebla – accounted for 71 per cent of total egg production by 2014 (COFECE 2018). COFECE (2018) also reports that the Mexican egg industry consists of nine large firms (with more than 3.5 million laying hens) which account for 47 per cent of production share in Mexico, whereas 35 middle-sized firms (with a laying population between 800,000 and 3.49 million laying hens) and 121 small-scale firms (less than 799,000 laying hens) account for 37 per cent and 16 per cent of production share, respectively. With regard to the distribution channels, COFECE (2018) indicates that 82 per cent of the Mexican egg production is sold *a granel* or in bulk, in packages containing 360 eggs. Once bought from producers, the eggs are sold in wholesale markets to retailers. A smaller proportion – 14 per cent – is sold as *empaque cerrado* or enclosed packages in supermarkets and convenient stores, and the remaining 4 per cent is intended for industrial use. Whereas the large firms are vertically integrated (Hernandez and Parrish 2017; Kuypers and Lara 2019), most farms with small-scale operations have limited access to distribution channels (COFECE 2015a).

Economic analysis of animal disease outbreaks has been traditionally focused on assessing the direct costs associated with health risks, veterinary service expenditures, disease control reactions, production and trade losses (e.g. Bennett 2003; Caskie *et al*., 1999; Fadiga and Katjiuongua 2014; Knight-Jones and Rushton 2013; Pendell *et al*. 2007; Traill and Koenig, 2010). However, recent studies have shown that animal disease outbreaks can alter food price dynamics along the associated supply chains, affecting consumers and producers' welfare differently (James and Anderson 1998; Tozer and Marsh 2012). Although several countries have been reconsidering the role of the public sector in the delivery of animal health services, the implementation of private solutions alone for the externalities associated with the control of infectious diseases might not be socially optimal (Bicknell *et al*. 1999). Discussions about who should pay for control and prevention services should be based on economic welfare analysis.

The objective of this study is to assess the effect of the HPAI outbreak on price transmission and marketing margins along the egg supply chain, capturing the potential effects of the above-mentioned antitrust intervention of COFECE. For that aim, we employ a regime-dependent vector error correction model (RVECM), complemented by a visual connected scatterplot analysis based on Haroz *et al.* (2016) and a large dataset with 596 weekly observations. The results show that both the HPAI outbreak and the COFECE intervention caused structural breaks in the Mexican egg market's price dynamics, affecting wholesalers and retailers differently.

In Mexico, the contribution of the egg sector to the general economy accounts for nearly 49 billion pesos and 450,000 jobs (SAGARPA 2016; UNA 2016). With a per capita consumption of 23 kilograms in 2018, the country ranks as the largest consumer of eggs worldwide (Kuypers and Lara 2019). During the same year, production reached 3 million tons, making the country one of the top five producers in the world (Parrish 2018). As the most affordable source of animal protein, consumed by 63 per cent of households (INEGI 2018), eggs comprise 17 per cent of the total animal protein intake (Kuypers and Lara 2019). Considering that 49 per cent of the population is below the poverty line and 20 per cent are food insecure (CONEVAL 2019), an external shock in the Mexican egg market may not only have serious economic implications but may also increase the burden of malnutrition.

This analysis extends the existing literature in several directions. First, we use three regimes for the estimation of the RVECM, while previous studies using the model employed – to the best of our knowledge – only two regimes. Furthermore, we suggest the use of connected scatterplots for visually characterising the regime-dependent price–margin trajectories. The length and frequency of the time series analysed allow us to capture the impacts of the disease outbreak as well as the effects of the antitrust intervention subsequently implemented by the Mexican government.

2. Literature review

Using a Food Publicity Index (FPI) as an exogenous variable in a three-equation vector autoregressive (VAR) model, Lloyd *et al.* (2001) authored one of the first studies on the impact of food scares on prices at various stages of the marketing chain. They analysed the impact of the Bovine Spongiform Encephalography (BSE) outbreak on producer, wholesale and retail prices for beef in the UK. Their work demonstrated that beef prices were responsive to the publicity of BSE with variations occurring along different stages of the supply chain. This caused wholesale–producer and retail–wholesale marketing margins to expand. Sanjuan and Dawson (2003) extended the analysis of Lloyd *et al.* (2001) by allowing for structural breaks in the cointegrating relationship. They found that the BSE crisis caused a structural break in the beef price relationship between producers and retailers, which was reflected in a significant change in the intercept.

Livanis and Moss (2005) assessed the impact of BSE on the US beef market using a food safety index (FSI) as an endogenous variable in a vector error correction model allowing for structural breaks. They report that shocks in the FSI produce greater reductions in wholesale and producer prices than in retail prices and hence an increase in the retail margin. Park *et al.* (2008) considered the impact of animal disease outbreaks originating in different countries on Korean beef, pork and poultry prices. Using a VECM and historical decomposition, they found that the foot and mouth disease and avian influenza (AI) outbreaks in Korea, as well as the BSE outbreak in the US, impacted the prices of the three commodities. They report that retailers benefitted by increasing their marketing margins.

Saghaian *et al.* (2008) analysed the implications of the AI outbreak in the Turkish poultry market using a VECM. They reported that the AI crisis initially caused a larger decrease in retail prices than in farm prices, but a faster recovery of the former led to an expansion of retail margins. Hassouneh *et al.* (2010) used a regime-switching vector error correction model (RSVECM) with an FSI as a threshold variable to analyse the impact of the BSE outbreak on beef prices in Spain. They showed that only producer prices corrected disequilibria caused by the food scare, meaning that producer margins were squeezed, whereas retail margins remained unaffected.

Hassouneh *et al.* (2012) considered the impact of food scares on prices in developing countries. Using a smooth transition vector error correction model and an FSI as the transition variable, they reported that the AI crisis in Egypt affected prices along the poultry supply chain differently. Whereas wholesale prices were found to correct disequilibria during the crisis, consumer prices moved in the opposite direction, resulting in increased retailers' marketing margins. Ihle *et al.* (2012) analysed the structural change experienced by EU calf markets caused by the bluetongue disease outbreaks in combination with decoupling of support payments in the EU in 2007. They assessed the influence of both of these major market disturbances on the long-run price equilibria between Dutch, German, French and Spanish calf prices by including both variables into the cointegration relationship. The disease outbreak is shown to suppress calf prices in various EU member states and to affect long-run price equilibria between them in a heterogeneous way.

Cacchiarelli and Sorrentino (2015) analysed the effect of an antitrust sentence in the Italian pasta markets to investigate whether price adjustment in food markets changed due to the intervention. They showed that the antitrust intervention had a substantial effect on getting food markets back to intense competition. Using a VAR model and historical decomposition, Seok *et al.* (2018) authored the first analysis on the effects of the HPAI outbreak on price transmission along the egg supply chain in Korea. Their results showed that the effect of the HPAI shock on egg prices was distributed unevenly, allowing processors and wholesalers to increase their margins, thus forcing farmers to receive lower prices and consumers to pay higher prices compared to those in a competitive market.

This large and growing body of literature has either assessed the impacts of animal disease outbreaks or of government interventions on food price dynamics. Using a RVECM with three regimes distinguishing the periods before, during and after the HPAI crisis, this study complements this field of research by assessing the effects of the highly pathogenic avian influenza as well as of the subsequent antitrust intervention. Moreover, Acosta *et al.* (2019) argue that the sole application of econometric methods is not sufficient for generating concrete insights to support evidence-based policymaking. Therefore, we complement the econometric analysis by using connected scatterplots, as suggested by Haroz *et al.* (2016), for visually characterising the regime-dependent price–margin trajectories.

3. Methodology

This study uses a time-series method to assess the effects of the HPAI outbreak on egg price dynamics in Mexico. We employ a large dataset with 596 weekly observations of real wholesale prices (WP) and retail prices (RP) per kilogram of white eggs from 3 January 2007 to 30 May 2018. This information is collected at the Mexico D.F Main Central Market and published by the National System of Information and Integration of Markets (SNIIM, 2019) of the Mexican Secretariat of Economy. Both series were deflated by using the Consumer Price Index reported by the National Institute of Statistics and Geography (INEGI 2019).

Following the work of Ihle (2010) and Schüttel *et al.* (2011), which provide evidence for the existence of nonlinearities and of structural changes in price transmission, we conduct a visual analysis of the time series by plotting WP, RP and the marketing margin (MM = RP – WP) which is calculated as the difference between RP and WP. This plot allows us to examine the effects of the disease outbreak and the subsequent policy response on price levels and dynamics, splitting the data into three regimes (see Figure 1).

We suggest the use of connected scatterplots (Haroz *et al.* 2016) as a means for visually inspecting differences and similarities in price and margin levels across these regimes. Haroz *et al.* (2016) have explored this technique, finding that connected scatterplots are an effective technique for visualising and communicating complex relationships between time series. They emphasise the power of this graphical illustration in providing an intuitive graphical summary of the temporal trajectory of the relationship between two variables. As 596 data points would render this graph unintelligible, we aggregate the data plotted to a quarterly frequency.

Before conducting the econometric analysis, we test for the stationarity of the price series using the ADF and KPSS tests. Having confirmed the presence of a unit root in the series, we test for cointegration using the test developed by Johansen (1988). However, the potential presence of one or more structural breaks in the time series might affect the reliability of the standard unit root and cointegration tests. Therefore, we apply the breakpoint and the Chow forecast tests to detect potential structural changes

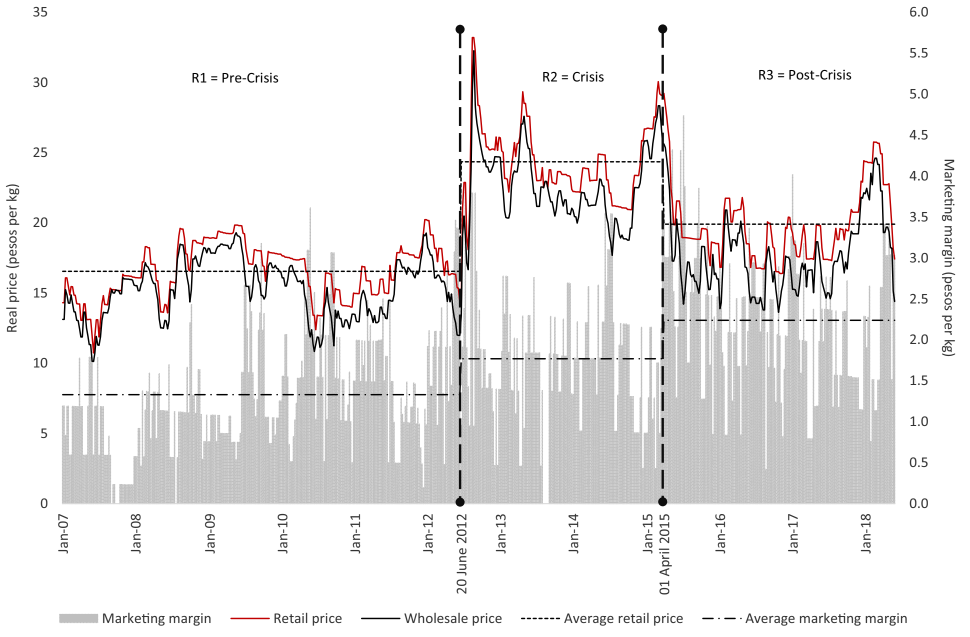

Figure 1 Egg weekly prices at wholesale and retail levels in Mexico. *Source*: Authors, based on SNIIM (2019). [Colour figure can be viewed at wileyonlinelibrary.com]

caused by the HPAI outbreak and the notification of the COFECE investigation.

Accounting for these structural breaks, we employ a RVECM to analyse the effects of the HPAI outbreak on the egg market's price dynamics. The RVECM allows us not only to identify potential nonlinearities in the price adjustment process but also to provide more information on the short-run price dynamics (Hassouneh *et al*. 2010). The main benefit of the RVECM lies in the fact that the regimes are exogenously determined either by certain market characteristics or other relevant indicator variables (Ihle, 2010).

For example, Hassouneh *et al*. (2010) use a self-constructed media-based food scare information index which defines the two regimes of food scares of high and low intensity that form the basis of the estimation. Ihle *et al*. (2010) use a variable measuring observed trade flows for defining two regimes in the context of the tomato trade in Ghana. Ihle and Rubin (2013) use an institutional variable in the context of violent political conflict which defines the two regimes considered, depending on whether the security measure is enforced.

In contrast to these publications, the context of our analysis suggests three regimes m={R1,R2,R3} which are indicated by the structural break tests as in equation (2). The first regime (R1) corresponds to the 'pre-crisis' period before the notification of the outbreak at time t_1, ranging from 3 January 2007 to 13 June 2012 (see equation (2)). The second regime (R2) corresponds to the 'crisis' period between the outbreak (t_1) and the antitrust investigation in week t_2 during the period 20 June 2012 to 25 March 2015. The third regime (R3) marks the 'post-crisis' period after the antitrust investigation (t_2) from 1 April 2015 until 30 May 2018. Hence, our version of the RVECM is specified as in equation (1):

$$\Delta P_t = \alpha^m ECT_{t-1}^m + \sum_{j=1}^{J^m} \Gamma_j^m \Delta P_{t-j} + \varepsilon_t^m \quad (1)$$

The regimes m are defined as:

$$m = \begin{cases} R1 & if \;\; t < t_1 \\ R2 & if \;\; t_1 \leq t < t_2 \\ R3 & if \;\; t_2 \leq t. \end{cases} \quad (2)$$

The term $P_t = (RP \;\; WP)'$ is a two-dimensional vector containing wholesale prices and retail prices, and Δ represents the first difference operator. The error correction term for each regime m is defined as $ECT_t^m = RP_t - \beta_0^m - \beta_1^m WP_t$. It contains the deviations from the regime-specific long-run equilibrium relationship between both prices. When transforming the price series into a logarithmic scale, the β_1^m parameter reveals the magnitude of price transmission elasticity, while β_0^m denotes the intercept of this bivariate relationship. The $\alpha^m = (\alpha_1 \;\; \alpha_2)'$ is a two-dimensional vector containing the speed at which retail and wholesale prices correct long-run disequilibria, respectively. Lastly, Γ_j^m are (2×2) parameter matrices containing the impacts of price changes from j periods ago on current price changes.

4. Results

By plotting RP, WP and MM, we obtain a visual impression of the extent of the co-movement between wholesale and retail price series, as well as changes in the average marketing margin. This visual analysis of the time series (Figure 1) signals that both WP and RP move together, implying a potentially existing cointegrating relationship. Furthermore, two potential structural breaks are observed on about 20 June 2012 and 1 April 2015. Both dates coincide with the notification of the HPAI outbreak and the opening of the COFECE investigation for presumably monopolistic practices in the Mexican egg market.

In order to depict potential changes in the price dynamics before the outbreak in regime (R1), between the outbreak and the COFECE investigation in regime (R2) and after the COFECE investigation in regime (R3), the average RP and the average MM are also displayed in Figure 1. The average RP increases from 16.5 pesos/kg in regime (R1) to 24.3 pesos/kg in

R2. The average marketing margin expands from 1.3 to 1.8 pesos. Although the domestic supply of white eggs recovered within one year, the increase in real prices was sustained for nearly three years.

This situation alerted the COFECE about the potential for abuse of monopolistic practices, which were suspected to be the reason why egg price levels were sustained after the outbreak in June 2012 above pre-outbreak levels. Following the announcement of the opening of an investigation by COFECE on 1 April 2015 for assessing the presumable use of monopolistic practices, the average RP dropped from 24.3 to 19.9 pesos/kg (R3). However, the MM increased from 1.8 to 2.2 pesos due to a larger drop in wholesale prices in comparison with retail prices, allowing retailers to enduringly capture a larger margin.

Figure 1 suggests that the levels of WP and RP, as well as the wholesale–retail marketing margin MM = RP – WP, show distinctive trajectories in each phase. Using the connected scatterplots in Figure 2, we provide a nuanced insight into how the relationship between price levels and the size of the margin developed over time during each of the regimes. Figure 2 plots the average WP price on the abscissa and the average MM on the ordinate for each quarter throughout the observed period. The observations of subsequent quarters are connected by a line. Thus, Figure 2 indicates the temporal development of the bivariate relationship between the WP and the MM, which emphasises the differences in margins as well as wholesale price levels in each of the regimes R1 to R3 and complements the univariate insights of the development of the separate variables shown in Figure 1.

The three regimes show markedly different ranges of wholesale prices and marketing margins. R1 shows the lowest levels of WP-MM combinations located in the bottom left corner of Figure 1. The HPAI outbreak marks a disruptive increase in WP as depicted in the first observation in crisis regime R2. In this crisis regime, the lowest WP exceeds the highest WP in R1 by about half a peso/kg. Wholesale prices reach the highest levels while marketing margins roughly resemble the range they displayed during the pre-crisis regime R1.

As the blue rectangle and the red rectangle are of similar horizontal width, the range of prices within each regime is of about the same magnitude. The margin MM appears to be more stable during R2 than during R1, as it varies in R2 between 1.1 and 2.4 pesos/kg, whereas in R1 it ranges from 0.2 to 2.3 pesos/kg. The post-crisis regime R3 markedly differs from the previous two regimes as the grey rectangle only partly overlaps the other two vertically, reaching the highest margin levels at its beginning and its end of up to 3 pesos/kg.

The length and the direction of the lines between any two adjacent points visualise the stability of WP-MM combinations during subsequent quarters. Connecting lines which are nearly vertical (horizontal) indicate that average WP (MM) stayed virtually constant while the change in MM (WP) between

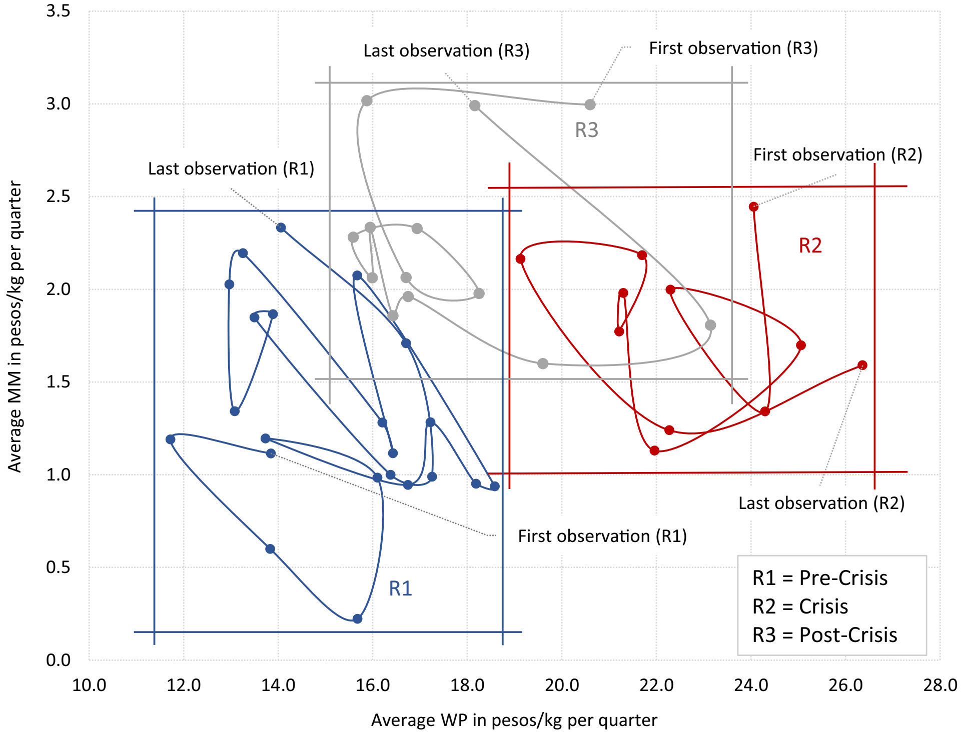

Figure 2 Wholesale prices and marketing margins before (R1), during (R2) and after (R3) the HPAI outbreak. *Source*: Authors. Note: Two points connected with a line denote subsequent combinations of observed quarterly average wholesale price and margin levels. The horizontal and vertical straight dashed lines delimit the range of the price–margin trajectory in each regime, denoting the minimum and the maximum observations of each of the two variables in each of the regimes. [Colour figure can be viewed at wileyonlinelibrary.com]

subsequent quarters is higher the longer the distance between points. The three regimes show very differing characteristics in this respect. The pre-crisis regime R1 shows substantial instability in WP-MM combinations for the first five points (quarters), followed by many points located very close to each other, indicating a phase of pronounced stability. Towards the end of this regime, instability rises again. The crisis regime R2 shows barely closely adjacent points. In contrast to the two preceding regimes, the post-crisis regime R3 exhibits the largest instabilities in price–margin combinations, as shown by the longest distances between adjacent points, especially during its first three and the last four quarters.

This graphical analysis confirms that the price levels and margins indeed develop along very distinctive trajectories in three regimes. That is, the structural breaks are not only statistically significant; they also imply markedly different bivariate trajectories of the combinations of the price levels and margins. Thus, considering these structural breaks caused both by the outbreak and the COFECE investigation, we estimate first the model using the full sample, and we subsequently use the Chow tests proposed by Candelon and Lütkepohl (2001) to test whether these events affected the parameter stability of the model. The test statistics and associated chi-squared and bootstrapped *p*-values indicate that the null hypothesis of parameter constancy can be rejected at the 1 per cent and 10 per cent levels of significance, respectively, confirming the presence of these two structural breaks in the time series (Table 1).

These results suggest the need to specify a RVECM with three different regimes. The first regime corresponds to the pre-crisis (R1) period, comprised of the observations before the notification of the outbreak (3 January 2007 to 13 June 2012); the second regime (R2) corresponds to the 'crisis' period between the outbreak and the COFECE investigation (20 June 2012 to 25 March 2015); and the third regime (R3) corresponds to the 'post-crisis' period, after the antitrust investigation (1 April 2015 to 30 May 2018). The outputs of both the unit root test (Table 2) and the Johansen test (Table 3) suggest that the time series are integrated in order, that is, I (1), and share a long-term equilibrium relationship in each of the three regimes.

The RVECM estimates in Table 4 quantify the distinct price–margin dynamics in the relationship between wholesaler and retailer prices during the pre-crisis (R1), crisis (R2) and post-crisis (R3) regimes, which were suggested by the graphical analysis of Figures 1 and 2 above. The long-run price equilibrium quantified by β_0 and β_1 is found to be stable across all three regimes. The estimates of the long-run elasticity β_1 indicate that after the outbreak, the magnitude of price transmission from wholesalers towards retailers decreased slightly from 0.89 to 0.84.

Retail prices significantly responded in the short run to disequilibria in all three regimes. Their estimates of the speed of adjustment are fairly similar in the pre- and post-crisis periods, correcting about 25 per cent of the deviations from the long-run equilibria. However, this speed increased to 53 per cent per week during the crisis regime, signalling more uncertainty in the market during this period, as random equilibrium deviations are corrected for at a higher intensity, resulting in a less smooth development of the retail price during this time.

Table 1 Chow tests for structural breaks.

Break date	Test	Test statistic	Asymptotic Chi2 *P*-value	Bootstrapped *P*-value
20 June 2012	Breakpoint Chow test	46.39	0.01	0.08
	Forecast Chow test	1.35	0.00	0.04
1 April 2015	Breakpoint Chow test	48.57	0.00	0.06
	Forecast Chow test	1.32	0.00	0.07

Note: Bootstrap *p*-values based on 2000 replications; sample period from 14 February 2007 to 30 May 2018.

Table 2 Unit root tests.

Regime	Test type	Levels (lag)		First difference (lag)	
		RP	WP	RP	WP
Pre-Crisis (R1)					
ADF	Without constant	−0.13 (1)	−0.26 (1)	−14.93 (0)***	−10.35 (2)***
	With constant	−2.68 (6)*	−3.10 (1)**	−14.90 (0)***	−10.33 (2)***
	With constant and trend	−2.63 (6)	−3.04 (1)	−6.94 (5)***	−10.34 (2)***
KPSS	Level	0.62 (5)**	0.37 (5)*	0.08 (5)	0.08 (5)
	Trend	0.45 (5)***	0.38 (5)***	0.03 (5)	0.03 (5)
Crisis (R2)					
ADF	Without constant	0.92 (0)	−0.10 (1)	−7.35 (3)***	−7.11 (0)***
	With constant	−2.48 (3)	−3.36 (1)**	−7.38 (3)***	−7.10 (0)***
	With constant and trend	−2.54 (3)	−3.22 (1)*	−4.13 (12)***	−7.10 (0)***
KPSS	Level	0.24 (4)	0.24 (4)	0.18 (4)	0.21 (4)
	Trend	0.18 (4)**	0.20 (4)***	0.14 (4)*	0.14 (4)*
Post−Crisis (R3)					
ADF	Without constant	−0.82 (1)	−0.78 (3)	−9.35 (0)***	−8.62 (2)***
	With constant	−3.71 (1)***	−3.26 (3)**	−9.40 (0)***	−9.75 (0)***
	With constant and trend	−3.89 (1)**	−3.61 (3)**	−9.40 (0)***	−9.73 (0)***
KPSS	Level	0.51 (4)**	0.55 (4)**	0.14 (4)	0.10 (4)
	Trend	0.44 (4)***	0.36 (4)***	0.09 (4)	0.08 (4)

Note: The optimal lag length for the ADF test is determined by the Akaike information criterion. In the case of the KPSS test, the lag length is determined by the truncation lag parameter $4*(T/100)^{1/4}$, where T is the sample size. *, ** and *** indicate statistical significance at the 10%, 5% and 1% levels, respectively.

Table 3 Johansen λ_{trace} test for cointegration.

Regime	Ho	Ha	λ_{trace}	5% critical value
Pre-crisis [R1] (2)	$r = 0$	$r > 0$	57.28	25.73
	$r \leq 1$	$r > 1$	11.63	12.45
Crisis [R2] (2)	$r = 0$	$r > 0$	42.84	25.73
	$r \leq 1$	$r > 1$	11.58	12.45
Post-crisis [R3] (1)	$r = 0$	$r > 0$	84.12	25.73
	$r \leq 1$	$r > 1$	11.53	12.45

Note: r is the cointegration rank. The lag length in parenthesis is determined by the Schwarz Criterion.

On the other hand, wholesale prices appear to be weakly exogenous before and during the crisis. This rigidity of wholesale prices with respect to deviations from the long-run disequilibria implies that only retail prices change to correct disequilibria; that is, the persistency of wholesale prices will contribute to maintaining both retail and wholesale prices at high levels. Such rigidity of prices at the wholesale level might be caused by the highly vertically integrated egg supply chain in Mexico. After the crisis, however,

Table 4 RVECM parameter estimates.

Parameters	Pre-crisis (m = R1)		Crisis (m = R2)		Post-crisis (m = R3)	
	PE	(SD)	PE	(SD)	PE	(SD)
Retail price equation						
ΔRP_{t-1}	-0.15*	(0.08)	0.15	(0.11)	0.03	(0.09)
ΔWP_{t-1}	0.35***	(0.07)	0.26**	(0.11)	0.20***	(0.07)
ΔRP_{t-2}	-0.22***	(0.07)				
ΔWP_{t-2}	0.03	(0.06)				
α_1^m	−0.23***	(0.05)	−0.53***	(0.11)	-0.27***	(0.08)
Wholesale price equation						
ΔRP_{t-1}	0.12	(0.10)	0.21*	(0.11)	0.12	(0.14)
ΔWP_{t-1}	0.17**	(0.09)	0.22*	(0.12)	0.31***	(0.12)
ΔRP_{t-2}	-0.25***	(0.09)				
ΔWP_{t-2}	0.05	(0.08)				
α_2^m	0.01	(0.07)	0.11	(0.12)	0.26**	(0.13)
Error correction term						
β_1^m	0.89***	(0.05)	0.84***	(0.04)	0.87***	(0.03)
β_0^m	0.38***	(0.13)	0.56***	(0.12)	0.48***	(0.09)

Note: PE is the parameter estimate, and SD is the standard deviation. The optimal lag lengths J^{R1}, J^{R2} and J^{R3} are determined by the Akaike information criterion. *, ** and *** indicate statistical significance at the 10%, 5% and 1% levels, respectively.

wholesale prices respond to correct long-run disequilibria at about the same speed as retail prices do.

The announcement of the COFECE investigation for the presumed abuse of monopolistic practices allows us to obtain some evidence on the effects of this antitrust intervention on prices. The comparison of the coefficients of interest between the crisis and post-crisis regimes reveals a change in egg price dynamics following the COFECE notification on 1 April 2015. The adjustment coefficient of retail prices α_1 suggests a decrease in the speed of adjustment from 53 per cent per week during the crisis to 27 per cent after the crisis. The speed of adjustment of wholesale prices α_2 increases strongly from being non-responsive during the crisis to becoming significant during the post-crisis regime, correcting 26 per cent of the deviations per week. The speed at which retail and wholesale prices jointly correct disequilibria in the post-crisis regime (27 per cent by RP and 26 per cent by WP) appears to be of about the same magnitude as the speed of retail prices alone during the crisis regime. The estimate of β_0 suggests a slight difference in the additive component of the mark-up between the crisis (0.56) and post-crisis (0.48) regimes[1]. Although the antitrust intervention was associated with price decreases, prices did not go back to the levels before the outbreak, confirming

[1] Note that the long-run equilibrium $ECT_t^m = RP_t - \beta_0^m - \beta_1^m WP_t$ consists of the multiplicative term β_1^m as well as the additive term β_0^m. Thus, although Figure 1 indicates that the difference $RP_t - WP_t$ tends to be larger in R3 than in R2, this difference is decomposed into an additive part β_0^m as well as a multiplicative part β_1^m. The finding that the additive part shrinks therefore does not contradict the grey bars in Figure 1.

the identified structural break in the price dynamics between wholesalers and retailers.

5. Food security implications

Contrary to other animal source foods (ASF), which are usually the most expensive calories in the food basket (Bouis *et al.* 2011) and are thereby classified as superior goods in the human diet (Green *et al.* 2013), eggs are rather inexpensive. Indeed, eggs are a relevant source of essential micronutrients (Miranda *et al.* 2015) which are commonly deficient among poor populations (Bouis *et al.* 2011). In Mexico, eggs are the most affordable and accessed animal protein, consumed by 63 per cent of Mexican households in 2016 (INEGI 2018). Considering that 61 million people in Mexico are poor and nearly 25 million people are food insecure (CONEVAL 2019), abrupt increases in egg prices may represent a serious food security threat.

There are a number of problems with food security as a result of the outbreak which need to be empirically tested, but the main implications can be explored here. The first problem is related to access to food. As shown, real prices for eggs reached 30 pesos/kg during the crisis period, 40 per cent higher than the pre-crisis period. This price shock might have led to a reduction in household levels of access to this important source of animal protein. The second problem is related to a decrease in real income. In Mexico, eggs are a staple food and a price-inelastic product; thus, a rise in egg prices might have led to an increase in household monthly expenditures on eggs and therefore a reduction in real income. The third effect is related to the structural break in the egg market's long-term price dynamics. As shown, egg prices dropped after the antitrust intervention, but they nevertheless remained above the pre-crisis average prices, with a potential long-term effect on household food access and income levels.

Low consumption of ASF is a major risk factor for micronutrient malnutrition (Black *et al.* 2008), which is among the main nutritional problems in the world (Allen 2003). The irreversible effects of micronutrient deficiencies in the population are worrisome, as they can foster persistent poverty, reinforcing the consequences of food insecurity (Barrett 2010). Currently, the prevalence of micronutrient deficiencies is imprecisely known, but it is estimated to affect nearly two billion people worldwide (Thompson and Amoroso 2011), with an unacceptably high economic and social cost to all countries estimated at 2–3 per cent of the global GDP (FAO 2013).

6. Conclusions

Using an RVECM, this study assessed the indirect effect of the highly pathogenic avian influenza (HPAI) outbreak on the egg market's price dynamics in Mexico. Based on the results of the statistical tests, three different regimes were specified. The first regime (R1) corresponds to the pre-crisis period; the second regime (R2) corresponds to the crisis period and the third regime (R3) to the post-crisis period. The descriptive analysis of the time series shows that after the outbreak, retailer prices increased from 16 to 24 pesos/kg. Although supply was restored within one year, prices remained high for nearly three years until prices dropped to 19 pesos/kg after the antitrust intervention.

The loading coefficient α_1 reveals that the speed of adjustment in retail prices increased from 0.23 per week in R1 to 0.53 in R2, eventually decreasing to 0.27 in R3; however, the loading coefficient α_2 indicates that wholesale prices did not react equally quickly to correct for disequilibrium during R1 and R2, but only in R3. The long-run parameter β_1 indicates that the magnitude of price transmission decreased from 0.89 in R1 to 0. 84 in R2, increasing again to 0.87 in R3. Finally, the intercept β_0 shows an increase in the marketing margin from 0.38 in R1 to 0.56 in R2, followed by a slight decrease to 0.48 after the COFECE antitrust intervention in R3 (but without returning to the marketing margin level observed in R1). These results suggest a structural break in the price dynamics between wholesalers and retailers.

In Mexico, eggs are one of the most affordable sources of animal protein, consumed by 62.9 per cent of households (INEGI 2018) and comprising 17 per cent of the total animal protein intake (Kuypers and Lara 2019). Considering that 49 per cent of the population is below the poverty line and 20 per cent are food insecure (CONEVAL 2019), an HPAI outbreak may have had serious food security implications at the household level, reflected in a reduction in access to this important source of animal protein and a decrease in real income, thus affecting the ability of a large proportion of the population to afford a diet with an adequate micronutrient intake. The irreversible effects of micronutrient deficiencies in the population are worrisome as they can foster persistent poverty, reinforcing the consequences of food insecurity.

This analysis contributes to the existing literature from different angles. First, we use three regimes for the estimation of the RVECM while, to the best of our knowledge, previous studies employing the model used only two regimes. Furthermore, we suggest the use of connected scatterplots as a technique to better visualise the regime-dependent price-margin trajectories. The length and frequency of the time series considered allow us to capture the impacts of the disease outbreak, as well as the effects of the antitrust intervention subsequently implemented by the Mexican government.

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