Cycles in cattle and hog prices in South America

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Prices of agricultural products often vary in relatively stable patterns around their long-run trends. These variations translate into fluctuations of selling prices as well as farm revenues. We provide an overview of the current literature on agricultural price cycles. Using a transparent and reproducible model selection process and the Kalman filter, we select optimal models and estimate the cyclic patterns of hog and cattle prices for Brazil, Chile and Uruguay. Durations of those cycles are found to be about three years and seven years, respectively. These durations are in line with the literature and the biological characteristics of livestock production. Our results can inform producers forecasts on price developments in the short and medium run. They are useful for guiding policy makers on the timing of policy interventions for influencing the duration or the amplitudes of cycles.

Key words: cattle cycle, Kalman filter, pork cycle, price fluctuations, state-space models.

1. Introduction

Agricultural and food markets are characterised by regular fluctuations of inventories and prices of varying degrees. The importance of such price fluctuations for food supply and policy intervention is widely acknowledged by international institutions dealing with the subject. For example, the World Bank has established 'Food Price Watch' in order to inter alia outline the policy implications of food price fluctuations (World Bank Group 2018). FAO has authored a number of policy documents that assess the amount of food price fluctuations and recommend ways for dealing with them (Barker *et al*. 2009). One essential component of these fluctuations is regular and permanent patterns referred to as cycles. A good understanding of these cycles is important for livestock producers, the meat processing industry and policy makers due to the implications they have for the timing of farm investments and policy interventions.[1]

Price fluctuations are a normal attribute as well as a necessary prerequisite for functioning competitive markets (FAO 2010). They may be regular or irregular, have various durations and can potentially overlap so that they may enforce or neutralise each other. Substantial fluctuations have been

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[1] We thank an anonymous reviewer for pointing this out.

reported to be caused by weather, technology or other supply-caused shocks; the more inelastic demand is – as is the case for most food products – the more pronounced they will be. The pork cycle is one example of such regular fluctuations. This phenomenon is a regular pattern observed in pork prices first noticed by Hanau (1928) estimated of having a duration of three to four years. Similar regular cyclical patterns have been observed in cattle slaughter prices. For example, Mundlak and Huang (1996) found that such regular patterns in cattle prices re-appear every six to ten years.

Monitoring and understanding cycles in agricultural prices allow informative insights into the current status of medium-run price dynamics. Our contribution is to expand the literature by providing comprehensive up-to-date evidence on the extent of cycles in the context of South America during past 30 years as it is a major meat production region worldwide. The main purpose of this research consists in isolating and statistically characterising cycles in cattle and hog prices. Livestock production is a major agricultural activity in Latin America as 85 per cent of the total agricultural area of being connected with the livestock sector (ECLAC FAO and IICA 2017).

We take a pronounced farm-gate perspective in our analysis by focusing on agricultural producer prices as our goal is to create insights into cyclical patterns of the prices which farmers actually receive. Therefore, our analysis analyses prices of life cattle and life hogs as sold at the farm gate.[2] The choice of countries considered is based on the size of domestic meat production as well as data availability; thus, we selected Brazil, Chile and Uruguay representing major meat production and trading countries among members and associated members of Mercosur (USDA 2020).[3]

Section 2 presents the key characteristics of agricultural price cycles, followed by a discussion of their major determinants in Section 3. Section 4 gives an overview of the current literature[4]. Section 5 includes a brief descriptive analysis of the data. The methodology used is outlined in Section 6. The empirical results of are presented in Section 7. Section 8 summarises the main results, relates them to the existing literature and concludes the paper.

2. Characteristics of agricultural price cycles

A cycle of agricultural prices is usually understood as a periodic price fluctuation lasting more than one year (Koester 2010). Hanau (1928) and Coase and Fowler (1935) published seminal academic papers on this

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[2] As an anonymous reviewer pointed out, it would be also very insightful to detect cyclical patterns in inventories which tend to be longer than cycles in prices and move into the opposite direction. However, inventory data are less likely to be publicly accessible which was also the case for the countries included in our analysis.

[3] Price or inventory data of Argentina as another big cattle producer in South America were not available.

[4] Details are provided in the online appendix.

phenomenon – called pork cycle or cobweb theorem – analysing the pork markets in Germany and Great Britain, respectively. More recent literature indicates the existence of cycles also in cattle prices in the USA, Argentina and Uruguay (Mundlak and Huang 1996), and in pork prices in China (Fengying *et al.* 2009) and the USA and Europe (Holst and von Cramon-Taubadel 2012).

The traditional theoretical explanation of such a regular price patterns is the delayed reaction by producers to generate agricultural supplies due to biological production constrains. For livestock producers, such delays can be substantial and are determined by the time from insemination to slaughter (gestation, nursery and fattening), which effects producers' ability to respond with changing supply quantities to price changes.

Figure 1 displays typical production cycles of hog and cattle. This figure based on Goodwin (1994) and PIC (2012) includes the gestation, birth and growth of female piglets, followed by the sexual maturity and insemination of the sows, and then adding the time required by the farrow to achieve the slaughter weight. On average, from the point when the producer decides to increase her cattle herd, it takes about 4.5 years until increased beef supplies show up on the market due to the overall production process. Twenty-four months after birth, a heifer can be inseminated; after 10 additional months, the calf is born which needs to be fattened 1.5–2 years until ready for slaughter. For pigs, the production process consists of the same steps but has with 1.5 years a substantially shorter duration (right panel of Figure 1). Goodwin (1994, p. 104) mentions a rule of thumb for the length of a livestock reproduction cycle: 'The minimum length of a cycle (from peak (trough) to peak (trough)) is about quadruple the time required from birth to first reproduction'.

Anderson *et al.* (1996) argue that since the middle of the 1980s, cattle business has exhibited cyclical fluctuations, for example, as cow–calf producers expand inventories in response to profits incurred and, ultimately, contract herd sizes in response to losses. Calf producers respond to profitable prices by holding back more replacement heifers and slaughtering less cows in order to produce more calves for the coming year. However, additional heifers held back for entry into the herd do not increase beef production for at least 2.5 years (see Figure S1), as they first need to reach sexual maturity. Eventually, the increase in cattle inventory, and subsequent beef supplies, leads to a lower price (P_2 in Figure S1). Ultimately, prices decline below many cow–calf producers' break-even level, which leads to higher costs and firms starting to liquidate their herds. Herd liquidation continues until prices return to profitable levels. The time it takes production to respond to higher (lower) prices creates a lag between price peaks such as P_1 (troughs) and subsequent inventory peaks (troughs). Producers expand and reduce their herds according to the expected profit, and supply cannot be immediately adapted to the demand, resulting in price cycles.
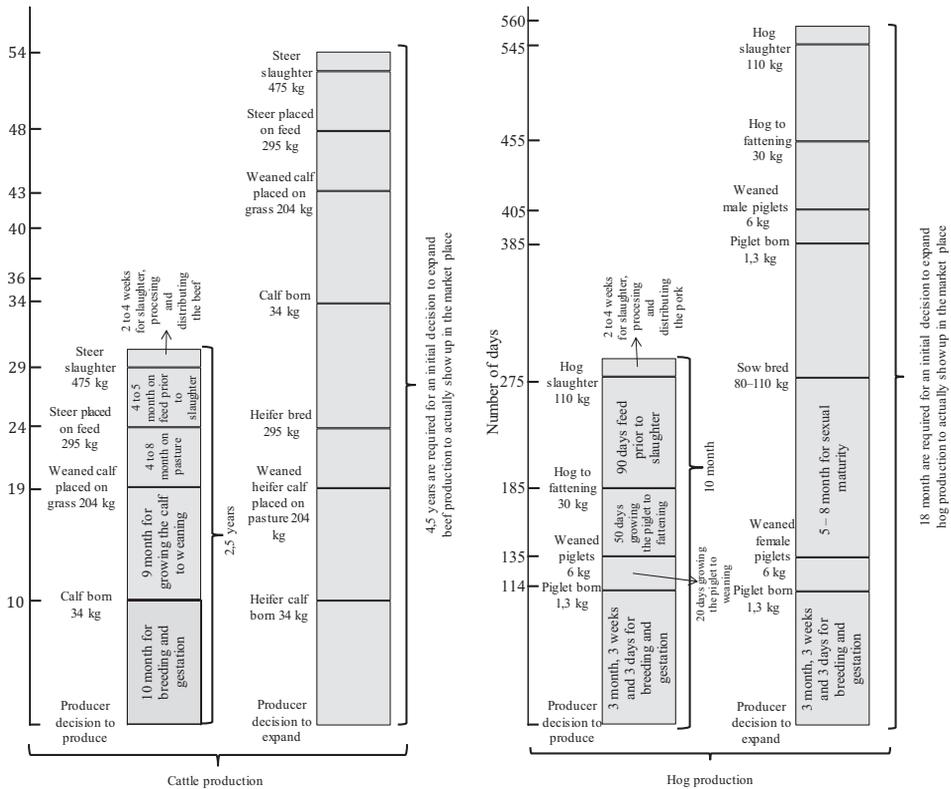
Figure 1 Stages of hog and cattle production cycles.
Source: Authors based on Goodwin (1994, p. 107) and PIC (2015, p. 35)

3. Determinants of agricultural price cycles

Cycles may arise due to regular changes in supply and demand. Ezekiel (1938) stressed the temporal delay necessary for the adaptation of quantities supplied by farmers as a key determinant. Not all agricultural products display price cycles. Cycles are more likely to be observed for livestock, livestock products and tree crops, which all require relatively long time periods for supply quantities adapting to changed market prices (Tomek and Kaiser 2014). A delay in the adaptation in quantities supplied is a consequence of this inability to change production quantities instantaneously. Such supply delay refers to the amount of years required to adjust production, the time to achieve the optimal slaughter weight or the time until fruits can be harvested. It does not only depend on farmers' decisions, but also on the nature of the production process of the commodity (hogs, cattle or perennial tree crops). Section S1 of the appendix provides a detailed account of the classical underlying model.

Koester (2010) mentions the role of another exogenous factor, the so-called *echo effect,* which disturbs economic equilibrium causing price cycles due to

production alterations. This *echo effect* arises, for example, due to political destabilisation or natural disaster and causes simultaneous replacement of production inputs, for example, in the form of the large-scale destruction or establishment of new infrastructure or herd regeneration both of which may result in a synchronised production cycle.

Country-specific business cycles are another exogenous factor for price cycle formation that influences the investment and the consumption patterns in a country (Koester 2010). Increases in disposable income due to an economic boom and low unemployment, for instance, are likely to influence meat consumption patterns. Consumers having low income prefer cheaper protein sources; with temporarily increasing incomes, however, consumption preferences are likely to change, so that these households purchase more meat (ODEPA 2007; Bifaretti *et al.* 2014).

Hanau's pork cycle and Ezekiel's cobweb theorem are based on naive producer price expectations, which is in the current literature mostly considered as not being an adequate description of reality. Naive expectations refer to the belief that current prices are going to remain constant in the next future (see Gouel 2012, for a comprehensive reflection). Such an assumption, however, does not consider the ability of producers to learn from past experiences. Nerlove (1958) introduced adaptive price expectations, in each new period the individual revises the own expectation of future price in view of the current expectation error, that is, the discrepancy between the expectation of the current price and the actual current price.

Muth (1961) introduced rational expectations extending the principle of individual rationality from resource allocation to the formation of expectations. The individual is supposed to use all of the available information when formulating her forecast of prices. Rosen *et al.* (1994) used a rational expectations model with rational, profit-maximising farmers. They suggest that the cattle cycle is the result of producers' responses to exogenous shocks in their environment, coupled with lengthy biological and maturation lags. Aadland (2004) used a combination of adaptive and rational expectations and obtained a cycle length of about 10 years. Gouel (2012) in detail reviews and discusses the literature relating to the two dominant competing theoretical explanations for price dynamics in agriculture being, first, cobweb model whose dynamics are driven by forecast errors created by naïve expectations of farmers and, second, rational expectations of agents. He adds a comprehensive consideration of model versions driven by non-linear and endogenous dynamics as well as competitive storage. Gouel (2012) asserts that most of empirical evidence tends to be more in line with the latter framework.

Lastly, regular fluctuations in consumption patterns and meat demand as well as supply chain instabilities such as the so-called bullwhip effect are also likely to contribute causing price cycles.

In the Brazilian and Uruguayan cattle sector, price discovery occurs in the regions of commercialisation. Cattle are sold directly to slaughterhouses and

later on to refrigerating storage house (frigorificos). Only a minor part is traded through intermediaries or agents. In Brazil, marketing is done by farmers in concentrated regional marketplaces. In Uruguay, the commercialisation of replacement cattle is done in the farm via television avoiding the cattle transport to regional markets. Cattle in slaughter weight is sold via consignees taking care of further arrangements with slaughterhouses and refrigerating storage houses. Commercialisation is also done directly between producers and slaughterhouses (ODEPA 2005). In Chile, livestock auctions are the main price discovery mechanism, even though only 30 per cent of total quantity are commercialised through this channel. The remaining cattle commercialisation is directly carried out between producers and slaughterhouses. Farías *et al.* (2016) report significant price transmission from international to domestic Chilean prices adding variability to domestic Chilean farm-gate selling prices.

Hog production patterns in Brazil follow a pronounced regional pattern. In the south, many small producers specialised in specific production phases (breeding and gestation, growing phase, fattening, etc.). In the southeast, producers mostly cover the whole production process (Fava *et al.* 2016). In general, a system of quasi-integration dominates: small and medium farms produce for meat processing firms or cooperatives on a contractual basis receiving genetics, feed, medication, supervision and technical support (Lima 2015). In 2015, cooperatives and the five biggest pork firms slaughtered 56 per cent of domestic production. In Uruguay, the hog sector has been experiencing production concentration and intensification led by big production firms. Bell *et al.* (2014) report domestic prices to be substantially influenced by international ones. Acuña and Pizarro (2019) characterise hog production in Chile as input- and technology-intensive, mostly vertically integrated and highly concentrated on few actors.

4. Current empirical evidence

Price cycles have been assessed for a number of agricultural markets. Table S1 in the online appendix contains a list of publications on price cycles found in pork and cattle production between 1928 and 2016. The table highlights the methodologies used and the estimated cycle durations. Seven of these studies look at pork price cycles in the USA, Germany, Australia, Great Britain, Canada and China. Cattle price cycles have been studied several times for the USA (four studies) and Canadian markets (three studies), but only once, more than 20 years ago, for Argentina and Uruguay (Mundlak and Huang 1996).

As shown in Table S1, 36–48 months are the most frequent estimate of the length of the pork price cycle in the considered publications. The cattle price cycle has most frequently been found to stretch over a period of approximately 120 months (Table S1). Mundlak and Huang (1996) found a length of only 72 months for Argentina and Uruguay. The longest and shortest price

cycle durations reported in the literature are 84 and 33 months for pork and 132 and 76 months for cattle, respectively. Harmonic analysis and the Hodrick–Prescott filter are the most frequently used methodologies applied for analysing pork price cycles. Spectral decomposition is the most often used approach implemented for analysing cattle price cycles. We follow Harding and Pagan (2002) who recommend using the Kalman filter to extract cycles.

The empirically estimated cycle lengths of about 36 months (Table S1) correspond to two pork production periods of about 18 months according to average production periods (Figure 1). The cattle price cycles of 120 months of Table S1 are fairly close to the 108 months (two times 4.5 years) of the typical cattle production cycle. Empirically estimated cattle cycle lengths of less than 120 months do not agree with Goodwin's (1994) rule of thumb regarding cycle length, according to which four times the time needed from birth to the first reproduction (4 times 34 months) presents one cycle. The same holds for pork cycles shorter than 48 months (four times 12 months).

The most recent contributions to the analysis of pork and cattle price cycles have been authored by Berg and Huffaker (2015) and Twine *et al.* (2016), respectively. Berg and Huffaker (2015) identify two important causal factors of price cycles using a diagnostic modelling approach based on non-linear time series analysis. The first factor is the irreversibility of investments due to sunk costs caused by the high specificity of the production technology, which impedes a switch from hog production to other commodities without losing the capital invested. The second factor is the liquidity-driven investment behaviour of farmers in Germany, who have been found to have strong preferences for financial consolidation after having made a large investment before they decide to make another one. Twine *et al.* (2016) found a ten-year price cycle of slaughtered steers using a spectral decomposition.

5. Data

We analyse deflated monthly farm-gate prices of hogs and cattle in Brazil, Chile and Uruguay. Table S2 in the online appendix gives an overview of the data sources, exact descriptions of the types of prices used and their respective currencies. Analysed prices are based on nominal, monthly farm-gate selling prices of live animals. The raw data are transformed into real prices in national currency using domestic CPIs with January 2001 as base.[5] The total numbers of observations T of the hog price series are as follows: 324, 492 and 300 for Brazil, Chile and Uruguay, respectively. For the cattle series, we have 324, 492 and 396 observations available for Brazil, Chile and Uruguay, respectively.

Table S3 in the online appendix summarises the descriptive statistics of the data. For each series, mean and median almost equal each other pointing to fairly symmetric price distributions. The coefficient of variation (CV) is 0.3 of

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[5] As an anonymous reviewer pointed out, it would have been better to use producer price indices for deflating. However, those are only available for Chile for 14 instead of 40 years.

hog producer prices in Brazil and Chile, and 0.4 for Uruguay. The CV of cattle prices of all three countries is 0.2 indicating a similar degree of relative dispersion.

6. Methodology

6.1 Detection of price cycles in general

In order to be explicit about the statistical characteristics of price cycles, we first define their crucial features. The duration of one full cycle is referred to as length or period (Figure 2). The vertical distance between the long-run trend, determining the direction of the movement of the cycle in the long run, to a peak or trough is the amplitude. For simplicity, the long-run trend is assumed to be linear in Figure 2, but can also take any other smooth functional form.

The only element in this graph that can be empirically observed is the price series y_t. This series is traditionally being decomposed into single components as shown in the figure according to the following additive time series model:

$$y_t = \mu_t + c_t + \gamma_t + \varepsilon_t \quad t = 1, \ldots T \tag{1}$$

The variable y_t measures the observed price in a given country in each period t. The component μ_t measures the smooth long-run potentially time-
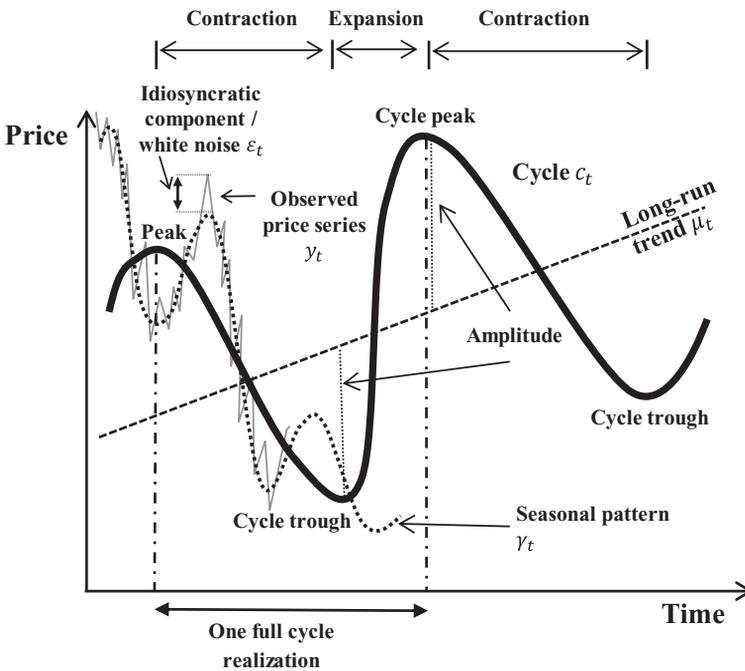

Figure 2 Characteristics of price cycles.
Source: Authors based on Goodwin (1994, p.158).

dependent trend, c_t denotes the cycle component, y_t the seasonal component, and ε_t the unexplained white noise component.

Burns and Mitchell (1946) have authored the classical textbook of cycle analysis. A formal methodology how to detect and describe cycles has been developed by Harding and Pagan (2002). They define three steps to detect cycles: the detection of potential set of turning points, that is the sequences of peaks and troughs in a series; a procedure for ensuring that peaks and troughs alternate; and a minimum duration of a phase lasting at least half a year as well as a complete cycle having a minimum duration of 15 months.

6.2 Empirical approach taken in this analysis

Following Harding and Pagan (2002), we employ the filter developed by Kalman (1960), which takes full advantage of the information available in time series. Structural time series models are formulated in terms of unobserved components that have a direct interpretation. The statistical treatment of such models is based on the state-space form (Carvalho and Harvey 2005). The Kalman filter decomposes times series into a smoothed long-run trend, a cycle and a seasonal and an irregular component as formulated in Equation (1). Estimation of the trend, the cycle and seasonal components is based on a state-space model with time-varying parameters that results in smooth non-parametric, typically non-constant estimates. For the analysis, the additive model (1) is used in which we account for automatically selected level and slope breaks which are not explicitly mentioned in Equation (1). The automatic break detection is based on the auxiliary residuals and consists of a two-step procedure. First, the selected model is estimated, and the diagnostics are investigated. Then, a first (larger) set of potential level and sloped trend breaks are selected from the auxiliary residuals. After re-estimating the model, only those interventions that survive are considered to be significant. The trend component is the smooth growth or decline in the long term modelled as:

$$\mu_t = \mu_{t-1} + \beta \tag{2}$$

where β is the deterministic slope of the trend. The stochastic cyclical component c_t, which measures the deviations of the observed price series from the long-run trend μ_t cleaned from the seasonal component γ_t and the error term ε_t, is estimated as:

$$\begin{bmatrix} c_t \\ c_t^* \end{bmatrix} = \rho \begin{bmatrix} \cos \lambda_c + \sin \lambda_c \\ -\sin \lambda_c + \cos \lambda_c \end{bmatrix} \begin{bmatrix} c_{t-1} \\ c_{t-1}^* \end{bmatrix} + \begin{bmatrix} \phi_t \\ \phi_t^* \end{bmatrix} \tag{3}$$

with λ_c being the cycle frequency. It serves for calculating the period of the cycle as $2\pi/\lambda_c$. The parameters ϕ_t and ϕ_t^* are normally distributed and mutually independent white noise disturbances with identical variances, that

is, $\phi_t \sim N(0; \sigma_\phi^2)$ and $\phi_t^* \sim N(0; \sigma_{\phi^*}^2)$. The parameter $0 < \rho < 1$ is the dampening factor of a stationary process. A damping factor of less than 1 indicates a stationary stochastic process, if $\rho = 1$ a non-stationary one.

Seasonality is a regularly repeating price pattern within individual years. The seasonal component is modelled using a seasonal dummy model. This concept and the possibility of letting the seasonal pattern change over time results in the formulation:

$$\gamma_{t+1} = -\sum\nolimits_{j=1}^{s-1} \gamma_{t+1-j} + \omega_t \quad \omega_t \sim N\big(0; \sigma_\omega^2\big) \tag{4}$$

where γ_{t+1} is the seasonal component, s is the number of periods per year ($s = 12$ if monthly data are considered), and ω_t is a normally distributed disturbance term.

Once the model has been specified, the Kalman filter yields estimates of the unknown variances σ_ϕ^2, σ_ω^2 and σ_ε^2, the unobserved amplitude, period, ρ and λ_c. These estimates are obtained from one-step-ahead prediction error estimations using maximum likelihood. A smoothing algorithm produces the final estimates of the components for all observations so that the key outputs of the procedure are graphs.

We consider three potential specifications for each country and product as basis for selecting the most adequate specification. All eighteen models include a deterministic level and a stochastic cycle, and the differences between the models consist in the inclusion of a deterministic slope and/or stochastic seasonality; the first version of each model (M1) includes a deterministic level with a stochastic cycle (Equation (3)), but without slope and seasonality. The second model (M2) includes a deterministic level and a slope component (Equation (2)) as well as a stochastic cycle (Equation (3)), but no seasonal component. The third model (M3) contains a deterministic level and a slope component (Equation (2)) as well as a stochastic cycle (Equation (3)) and a stochastic seasonal component (Equation (4)).

We follow a transparent model selection approach by selecting the most adequate specifications of each univariate model for each commodity and country based on objective and reproducible residual testing and model selection criteria. The challenge is to obtain an interpretable and applicable model with as desirable as possible residual characteristics. The criteria employed are normal distribution, autocorrelation, heteroscedasticity and having the smallest model selection criterion. In the ideal case, both model selection strategies yield consistent results: the models having optimal residual characteristics also show minimum selection criteria and are straightforwardly interpretable. However, in empirical analysis, this appears to be rarely the case. Only focusing on statistical characteristics can lead to complex and uninterpretable models. Therefore, the foundation of our model selection process is obtaining a sensible interpretability of the estimation

results with the underlying model having as optimal as possible statistical characteristics.

First, we test each of the eighteen estimated models for residual normality, homoscedasticity and autocorrelation. Considering three possible specifications for each country and product, we select the most adequate model with the best residual properties and, if more than one best model is obtained, then choose the model with the smallest selection criterion. The residual testing checks whether there is evidence against that the model is capable to extract the most relevant signals from the data, that is, whether residuals are normally distributed (using the test of Bowman and Shenton (1975)), whether they are homoscedastic (tested with a non-parametric test) and not autocorrelated (using the test of Durbin and Watson (1950) as well as the Ljung and Box (1978) statistic). The model selection criterion employed is Akaike's information criterion (AIC, Akaike 1974).

7. Results

Table 1 presents the finally selected model specifications for each of the six country–commodity combinations[6]. The most appropriate model for hog in Chile and for hog and cattle in Brazil contain a deterministic linear trend with fixed drift[7] including a stochastic cycle, seasonality and structural breaks. The best fitting model for Uruguayan hog and cattle as well as for Chilean cattle includes a deterministic linear trend with fixed drift including a stochastic cycle and structural breaks, but no seasonal component.

Table 2 shows the amplitude of the estimated cycles[8]. The cycles of the Brazilian hog and cattle prices have an amplitude of 0.004 R$/kg and 0.012 R$/kg corresponding to only 6.7 and 4.2 per cent of the average the respective prices.[9] The cycles of the Uruguayan hog and cattle prices have an amplitude of 1.1 Ur$/kg and 0.98 Ur$/kg corresponding to 6.9 and 7.8 per cent of the price averages, respectively. The Chilean hog and cattle price cycles are estimated to have an amplitude of 535 Ch$/kg and 961 Ch$/kg corresponding to 4.2 and 5.1 per cent of the respective price averages. Hence, Uruguay has

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[6] As indicated in Table S4 in the online appendix, the finally chosen models have homoscedastic and mostly normally distributed residuals, which, however, show autocorrelation to a low extent. We decided not to integrate autocorrelation corrections in order to avoid complex and uninterpretable models. The structural breaks included in the corresponding models are shown in Table S5 in the appendix.

[7] Drift means the inclusion of a slope term in the long-run trend.

[8] For the sake of simplicity, we only present the results regarding the price cycles, as this is the focus of our analysis. Further results may be obtained from the authors upon request.

[9] The coefficient of variation of the cycle amplitude gives an indication of the magnitude of the relative deviation from the cycle mean, with other words; it provides some inside on the width of the cycle relative to its mean value.

Table 1 Selected models and equations by country and product

Model	Model equation
Brazil hog (M3) Chile hog (M3) Brazil cattle(M3)	$y_t = \mu_t + c_t + \gamma_t + \varepsilon_t$ $\mu_t = \mu_{t-1} + \beta$ $\begin{bmatrix} c_t \\ c_t^* \end{bmatrix} = \rho \begin{bmatrix} \cos \lambda_c + \sin \lambda_c \\ -\sin \lambda_c + \cos \lambda_c \end{bmatrix} \begin{bmatrix} c_{t-1} \\ c_{t-1}^* \end{bmatrix} + \begin{bmatrix} \phi_t \\ \phi_t^* \end{bmatrix}$ $\gamma_{t+1} = -\sum_{j=1}^{s-1} \gamma_{t+1-j} + \omega_t$
Uruguay hog (M2) Chile cattle (M2) Uruguay cattle (M2)	$y_t = \mu_t + c_t + \gamma_t + \varepsilon_t$ $\mu_t = \mu_{t-1} + \beta$ $\begin{bmatrix} c_t \\ c_t^* \end{bmatrix} = \rho \begin{bmatrix} \cos \lambda_c + \sin \lambda_c \\ -\sin \lambda_c + \cos \lambda_c \end{bmatrix} \begin{bmatrix} c_{t-1} \\ c_{t-1}^* \end{bmatrix} + \begin{bmatrix} \phi_t \\ \phi_t^* \end{bmatrix}$

Source: Authors.

Table 2 Estimated price cycle parameters for hog and cattle prices by country

	Hog			Cattle		
	Brazil	Chile	Uruguay	Brazil	Chile	Uruguay
Parameters						
Average amplitude	0.004 R $/kg	534.8 Ch $/kg	1.1 Ur $/kg	0.012 R $/kg	961.2 Ch $/kg	0.98 Ur $/kg
Coefficient of variation of the cycle	6.7%	4.2%	6.9%	4.2%	5.1%	7.8%
Period $2\pi/\lambda_c$ (years)	3.8	3.3	2.4	6.4	1.3	2.6
Frequency λ_c	0.1	0.2	0.2	0.1	0.4	0.2
Damping factor ρ	0.9	0.8	0.9	0.9	0.8	0.9

Source: Authors.

the highest relative cycle amplitudes for hog and cattle prices as also visible in Figures 3 and 4.

Table 2 shows that the period of the hog cycle has been estimated to amount to 2.4, 3.3 and 3.8 years in Uruguay, Chile and Brazil, respectively. These cycle periods coincide with two complete hog production cycles of 18 months as depicted in Figure 1. The cattle cycles are found to have a period of 1.3, 2.6 and 6.4 years for Chile, Uruguay and Brazil, respectively. This means, for example, that in the case of the Uruguayan cattle cycle, the amount of cattle supplied by the producers leads to a peak or a trough every 2.6 years as illustrated in Figure 4. This result is in line with the time elapsed between producers' decisions to increase production and slaughter weight indicated in Figure 1. Brazil and Uruguay exhibit the largest damping factors in the hog sector, followed by Chile with a smoother cycle having a damping factor of 0.8.
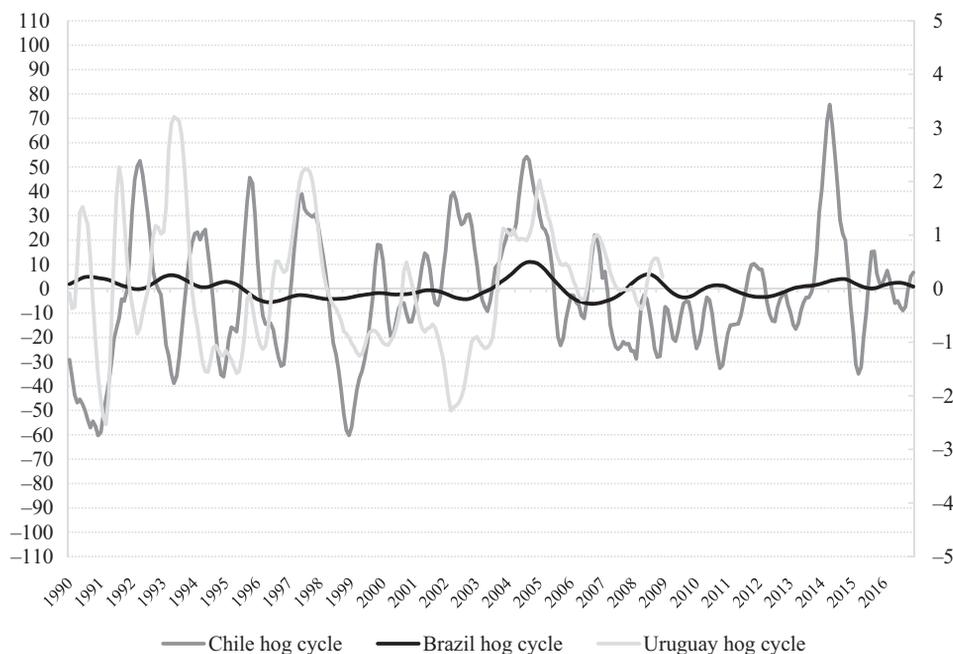
Figure 3 Estimated cycles of hog prices by country, 1990-2016.Note: The scale for Brazil and Uruguay is at the right-hand side of the graph and for Chile at the left-hand side. *Source:* Authors.

Figure 3 shows the estimated cycles of hog prices. The Uruguayan and Chilean cycles coincide for their ascending and descending phases from 1997 to 1998, 2003 to 2005 and 2006 to 2007. The Brazilian cycle is smoother and has an ascending and descending phase from, for example, 2003 to 2005. Since 1993, the developments of Uruguay's and Chile's cattle price cycles largely coincide showing peaks and troughs often during similar periods (Figure 4).

8. Conclusions

The concept of price cycles in the context of agriculture refers to periodic price fluctuations around the long-run trend lasting more than 1 year. Such cycles may arise, among others, due to naïve expectations based on changes in demand or temporal delays necessary for the adaptation of supply quantities produced by farmers or, more likely, due to rational expectations. Biological characteristics of production are crucially influencing cycle duration resulting in an average time required for cattle and hog supply to respond to price changes by herd size expansion or shrinking of typically about 4.5 and 1.5 years, respectively.

Our analysis contributes to the literature by isolating price cycles in the South American context and providing up-to-date measurements of their
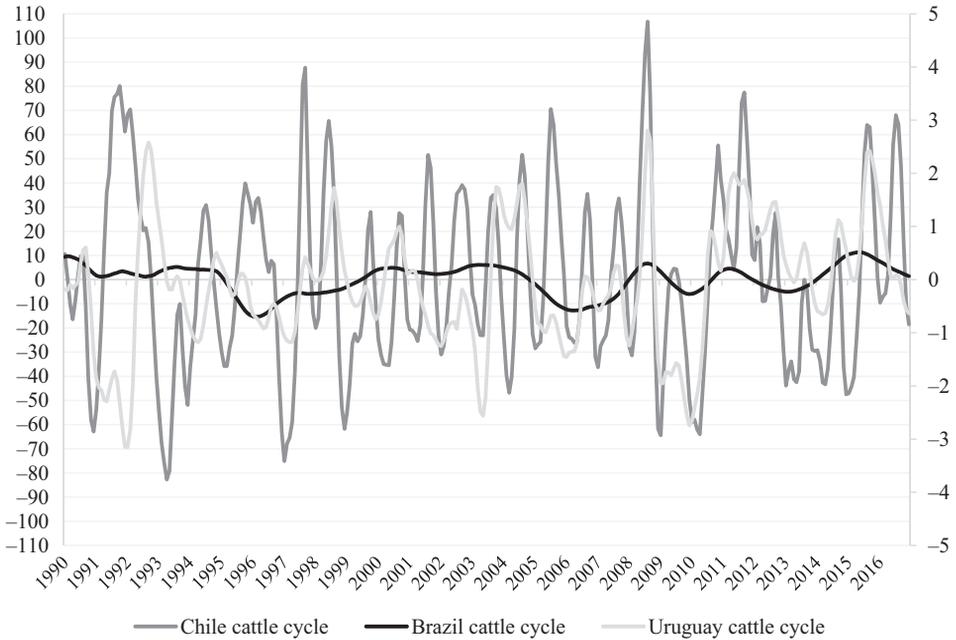
Figure 4 Estimated cycles of cattle prices by country, 1990-2016. Note: The scale for Brazil and Uruguay is at the right-hand side of the graph and for Chile at the left-hand side. *Source:* Authors.

statistical characteristics. Our literature review provides an inventory listing all countries for which the presence of price cycles has been studied so far. Although South America has a prominent role in global meat production, there has been little attention given to cycles in meat prices in this region. The Kalman filter is used to estimate univariate state-space models, which are selected based on a transparent and reproducible model selection process seeking to identify meaningful and interpretable model specifications that exhibit ideal residual characteristics and are optimal regarding the chosen model selection criterion.

The hog price cycles of all three countries are estimated to have lengths varying between three and four years being in line with the results reported in the literature. This duration coincides with about two complete agronomic hog production cycles of 18 months. The cattle cycle lengths of Brazil, Chile and Uruguay are estimated to have durations of 1.3–6.4 years being shorter than the 10-year cycles often found in the literature, but being roughly in line with the biological reproduction cycles of cattle production taking 3–4 years. Price cycles are found to be least pronounced in terms of duration and amplitude in Brazil. Absolute and relative amplitudes in Uruguay appear to be considerably higher and durations much shorter.

The analysis of agricultural price cycles, as presented in this paper, sheds light on crucial aspects of price dynamics. Identifying such cycles or

predicting them for the immediate future can greatly support producers in their production decisions. This knowledge also provides insight to policy makers into the width and the speed of the regular price fluctuations around the long-run trend. It helps indicating whether and when there currently is and when there will be a need for support policies – whatever forms such support might take – during the troughs of the cycles. Based on such knowledge, policy makers are enabled to set up policies for the purpose of extending price cycle durations or attenuating cycle amplitudes.

This research can be extended by identifying relevant determinants[10] and quantifying their partial effects on cycle patterns. This might, for example, mean to clarify to what extent supply quantities or inventories of meat have been changing periodically and what price effects resulted from that. A relevant extension could assess to what extent combinations of further factors – some of them mentioned above – are impacting cycle characteristics. Future research might also tackle the analysis to price cycles in Argentina given that it is a large global beef producer if sufficient data become available. Also assessing cycle spillovers and cycle synchronisation between the neighbouring countries, substitutable types of meat and prices at various processing levels of meat products might yield interesting and policy-relevant insights. We thank an anonymous reviewer for pointing out that future research might also tackle the question of quantifying implications of cycles in livestock or meat price series in major exporting countries of South America for regional or global trade in beef and pork.

Data Availability Statement

The data that support the findings of this study are available from the corresponding author upon reasonable request.

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[10] Labys & Cohen (2006) also recommend identifying the determinants of changes in wine cycles. This includes demand-side variables such as prices, as well as the causes of variations in production. Wang (2009) defines the price cycles demand drivers for the station level gasoline.

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Supporting Information

Additional Supporting Information may be found in the online version of this article:

Appendix S1. Theoretical background.

Figure S1. Convergent price cycle amplitude.

Figure S2. Constant price cycle amplitude.

Figure S3. Explosive price cycle amplitude.

Appendix S2. Empirical evidence.

Table S1. Price cycle lengths and used methodology by commodity, country and period.

Appendix S3. Data.

Table S2. Data sources.

Table S3. Descriptive statistics of analyzed producer prices for hog and cattle by country.

Figure S4. Annual minima and maxima of indexed hog price by country, 1976–2016.

Figure S5. Annual minima and maxima of indexed cattle prices by country, 1976–2016.