Journal of Agriculture and Food Research 18 (2024) 101511

Contents lists available at ScienceDirect

Journal of Agriculture and Food Research

journal homepage: www.sciencedirect.com/journal/journal-of-agriculture-and-food-research

Wheat price dynamics in Hungary: Resilience to shocks

Tibor Bareith [a], Imre Fertő [a,b,c], Szilárd Podruzsik [a,*]

[a] HUN-REN Centre for Economic and Regional Studies, Institute of Economics, Budapest, Hungary
[b] Corvinus University of Budapest, Budapest, Hungary
[c] Czech University of Life Sciences, Prague, Czech Republic

ARTICLE INFO

Keywords:
Supply chain
Market
Producer price
Consumer price
NARDL model

ABSTRACT

This study investigates the impact of recent global disruptions, focusing on the Covid-19 pandemic and the ongoing Ukraine-Russia war, on Hungary's wheat-flour supply chain, with a focus on price transmission and market integration. While much research has explored food supply chain disruptions and rising prices globally, there has been limited analysis of their effects on Central and Eastern European agricultural markets, particularly Hungary. This study fills that gap by using linear and non-linear cointegration approaches to examine price relationships along the wheat supply chain. Causality tests indicate a strong bidirectional relationship between producer and consumer prices, demonstrating a tightly integrated market. Cointegration analysis reveals a long-term equilibrium between these prices, with no significant structural breaks during either the pandemic or the Ukraine war. Despite short-term price asymmetries, the study finds that producer-level price changes are ultimately transmitted to consumer prices in the long run, offering insights into Hungary's unique agricultural market dynamics.

1. Introduction

Wheat plays a critical role in Hungary's food security, economic stability, and geopolitical strategy, especially during crises such as the COVID-19 pandemic and the Ukraine war. As a staple crop, wheat supports the national diet and generates export revenue, bolstered by Hungary's self-sufficiency in production. The ongoing war in Ukraine has further emphasized Hungary's potential as a key wheat supplier amid global supply chain disruptions. Wheat production also fosters rural employment and stability, benefiting from Hungary's favorable climate and robust agricultural infrastructure.

Hungary's wheat supply chain is highly organized, starting from cultivation in the Great Hungarian Plain to the processing and distribution phases. Wheat is harvested, stored, and graded before being transported via road, rail, and river, positioning Hungary as a central hub in Europe's wheat trade. The processed wheat products are distributed domestically and exported to international markets, with quality control regulated by the government.

Price transmission in the wheat markets has been a focus of extensive research, primarily due to its significant implications for market efficiency, producer income stability, and consumer welfare [1,12,18,19,24].Various studies have investigated the dynamics of price adjustments across different stages of the wheat supply chain, revealing key insights related to asymmetric price transmission, market structure influences, and the effects of international price shocks [29]. Recent research has consistently demonstrated that price transmission in the wheat market exhibits asymmetry, indicating that price changes are not transmitted through the wheat supply chain with equal intensity or speed for both increases and decreases [11,17].

The Covid-19 outbreak in December 2019 has had profound and far-reaching consequences, severely disrupting global market processes and supply-demand dynamics [24]. The stringent control measures implemented by governments worldwide have created substantial barriers to the free movement of people and goods, leading to significant negative impacts on both societal and economic fronts [14,24]. Despite the extensive research on agricultural markets and price transmission [11,21,29], there remains a notable gap in the literature regarding the impact of the Covid-19 pandemic on the price transmission on food chain especially on wheat an floor chain.

This study aims to provide an in-depth analysis of price transmission in the Hungarian wheat-flour supply chain in response to external shocks, particularly the Covid-19 pandemic and the Ukraine war. As the eighth-largest wheat producer in the European Union, Hungary holds a significant, though not leading, position in wheat production among

* Corresponding author.
E-mail address: podruzsik.szilard@krtk.hu (S. Podruzsik).

https://doi.org/10.1016/j.jafr.2024.101511
Received 6 August 2024; Received in revised form 8 November 2024; Accepted 9 November 2024
Available online 12 November 2024

Central and Eastern European countries. While countries like Poland and Romania are larger producers, Hungary remains an essential contributor to the region's wheat supply, known for its high-quality output and strategic role in the market, making it highly sensitive to global supply disruptions. The outbreak of the Ukrainian-Russian war has introduced an additional shock to the international food market, further amplifying the impact of geopolitical tensions on Hungarian wheat prices due to Hungary's proximity to these major wheat suppliers [19,20]. These factors, combined with Hungary's unique agricultural policies and market conditions, present a compelling case for studying how prices are transmitted along the wheat-flour supply chain in Hungary. Such insights are valuable for policymakers at both the national and EU levels, especially in times of crisis.

This research contributes to the literature in several ways. First, it broadens the geographical scope of price transmission studies by focusing on Central and Eastern European country, particularly Hungary. Second, it provides an in-depth analysis of the Hungarian wheat and flour supply chain during global disruptions. Third, by utilizing various econometric models such as linear and non-linear cointegration tests, this study offers a robust framework for analyzing market responses to shocks. Finally, the findings aim to inform policymakers about stabilizing agricultural markets and ensuring food security in the face of external disruptions. The second section covers Hungary's wheat production and its role in food security and economic stability. The third section outlines the data and methodology, focusing on price adjustments in response to market shocks. Empirical findings from econometric models are presented in the fourth section, followed by a robustness analysis in the fifth section. The final section concludes with policy recommendations for stabilizing agricultural markets and ensuring food security amid external disruptions.

2. Hungarian wheat sector

The European Union (EU) remains one of the world's leading wheat producers, alongside other key global players such as Russia and the United States. Within the EU, France and Germany dominate production, contributing substantially to the total output. According to the U.S. Department of Agriculture [28], the EU produced approximately 134.9 million tonnes of wheat in 2023, underscoring its significant role in global wheat markets. Hungary, as the EU's eighth-largest wheat producer, plays a notable part in supporting this output, reinforcing the region's overall position in the international wheat supply chain.

Hungary's wheat production has experienced fluctuations over recent years due to factors such as environmental conditions, market dynamics, and agricultural policies [15]. After reaching 5.378 million tonnes in 2019, production declined to 5.121 million tonnes in 2020 and further to 4.355 million tonnes in 2022, representing a significant decrease of approximately 17.7 % from 2021. However, in 2023, production rebounded sharply to 5.900 million tonnes, the highest within the seven-year period, indicating a strong recovery.

As illustrated in Fig. 1, both wheat yield and production in Hungary dropped significantly in 2022 compared to 2017 levels, with yield at 75.04 % and production at 82.33 % of the 2017 figures. This decline could be attributed to adverse weather conditions or other challenges affecting agricultural output. The recovery in 2023, with both yield and production returning to 100 % of the 2017 levels, signals the sector's resilience.

In terms of domestic consumption and trade, a significant portion of Hungary's wheat is utilized by the milling industry, while smaller shares are allocated for animal feed and export. Industrial processing uses only a very small percentage, and imports remain minimal. Annual losses are estimated between 50,000 and 100,000 tonnes [15].

These production fluctuations have directly impacted flour prices in Hungary. Fig. 2 illustrates the increase in flour prices from 2017 to 2023. Fine flour prices rose from 137 HUF/kg in 2017 to 213 HUF/kg in 2023, marking a 55 % increase over this period. Meadow flour experienced an even more significant surge, with prices rising from 178 HUF/kg to 426 HUF/kg, representing a 139 % increase. The most notable price hikes occurred after 2021, particularly for meadow flour, which jumped from 233 HUF/kg in 2021 to 393 HUF/kg in 2022—a 68.7 % increase in just one year. These sharp increases align with the ongoing effects of the COVID-19 pandemic and the onset of the Ukraine-Russia conflict in 2022, reflecting heightened volatility and disruptions in the global wheat-flour supply chain.

Understanding the wheat value chain—from farmers through milling to bakers and retailers—is critical for analyzing price transmission within the supply chain. This analysis provides insights into the dynamics of wheat supply and enables a comprehensive examination of price fluctuations at different stages of the chain, which is essential for improving market efficiency and informing policy interventions.

3. Data description and methodology

Data used for the analysis are from the Institute of Agricultural Economics supervised by the Ministry of Agriculture (AKI).[1] The weekly resolution of the wheat producer (P_{pt}) and wheat flour consumer (P_{ct}) price per kilogram data is from the 14th week of 2017 to the 21st week of 2024. The database, containing 374 weekly observations, was analyzed after transformation to the natural logarithm.

Table 1 provides descriptive statistics for both consumer and producer prices in the Hungarian wheat market over 374 weekly observations. The mean value of consumer price is 0.62, with a standard deviation of 0.087, indicating relatively moderate variation in consumer prices during the observed period. The minimum and maximum values for consumer price range from 0.46 to 0.93, reflecting fluctuations in consumer prices, though these variations appear to be contained within a relatively narrow band.

In comparison, the mean producer price is lower, at 0.312, with a higher standard deviation of 0.093. This suggests that producer prices were not only lower on average than consumer prices but also exhibited greater volatility. The range of producer prices is broader, with a minimum of 0.22 and a maximum of 0.55. This wider range implies that producer prices were more sensitive to external shocks and market fluctuations, which could be attributed to factors such as input cost variability, production risks, and market dynamics, as seen in agricultural sectors.

The observed disparity between the mean values of consumer and producer prices, as well as the differences in volatility, reveals the possibility of asymmetry in the price transmission process, where changes at the producer level may not be fully or immediately passed on to consumer prices.

Fig. 3 shows the natural logarithm of producer and consumer prices at the two levels of the Hungarian wheat supply chain. The producer and consumer price series show an upward trend until the second half of 2023, after which both prices fall and stabilize at lower levels. After the outbreak of Covid-19, consumer prices have remained stable, while producer prices have risen. Both producer and consumer prices fell after Ukraine increased its wheat imports to Hungary. The Hungarian government imposed an import ban on Ukrainian grain in April 2023 to prevent a further decline in domestic producer prices.

In the first half of 2023, wheat prices experienced a marked decline, particularly at the producer level. This downturn was influenced by several factors. Positive developments in major wheat-producing countries played a key role, with Australia reporting an exceptional harvest in the first quarter and optimistic forecasts for Russia, India, and Brazil. The USDA (U.S. Department of Agriculture) also revised its global crop projections upwards, contributing to a more favorable supply outlook.

[1] The data are available at Ministry of Agriculture (AKI) Market Price Information System: https://www.aki.gov.hu/en/market-price-information-system-mpis/.

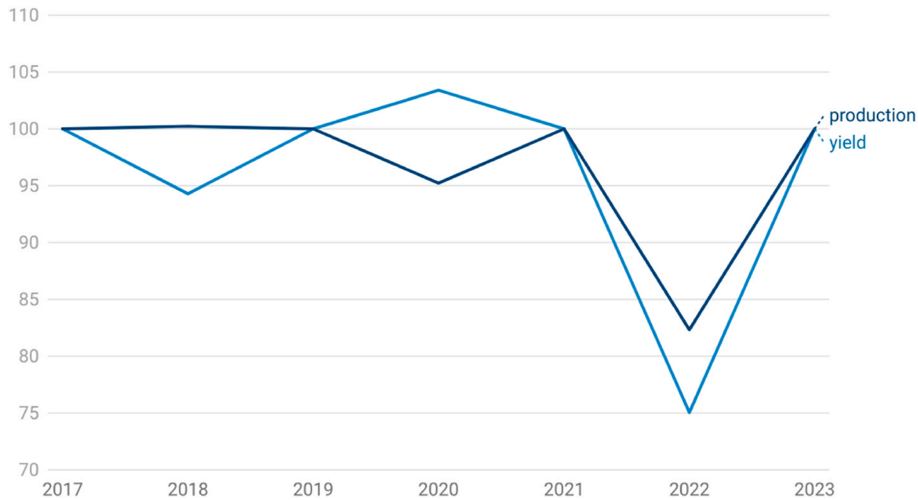

Fig. 1. Change in % in Hungarian wheat production and yield (2017 = 100) [15].

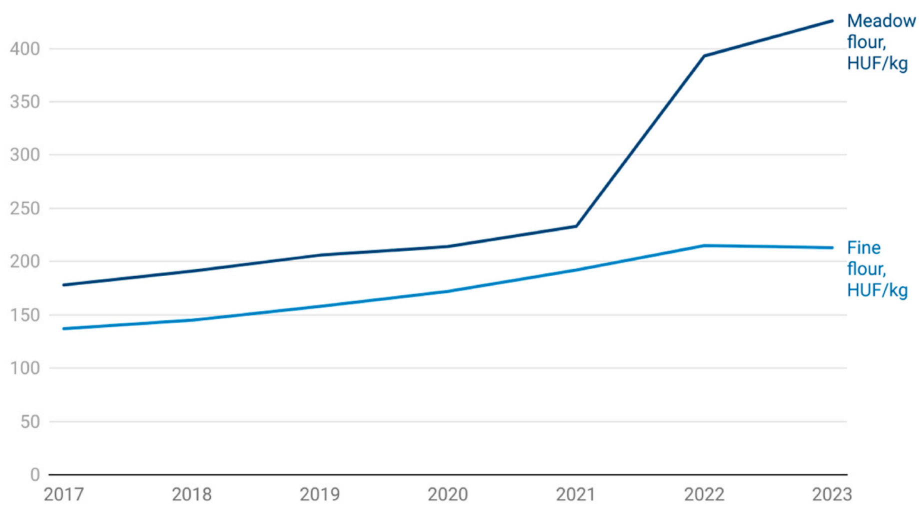

Fig. 2. Hungarian flour prices [16].

Table 1
Descriptive statistics of variables.

Variable	Obs	Mean	Std. dev.	Min	Max
producer price	374	0.312	0.093	0.220	0.550
consumer price	374	0.620	0.087	0.460	0.930

In Europe, especially in South-East Europe, favorable weather conditions further bolstered production expectations. While prolonged drought in Spain caused concern, it was largely offset by beneficial rains in countries like France. Global export demand remained weak, leading to significant price drops in major markets such as Germany, as high stock levels contributed to the overall price reduction. Additionally, the renewal of grain exports from Russia and Ukraine, facilitated by the Black Sea Grain Agreement in May and June 2023, further supported the decline in wheat prices as the market anticipated increased supply.

To capture the complexity of price transmission across the Hungarian wheat supply chain, we employed a multi-layered econometric approach. This approach integrates both linear and nonlinear techniques, ensuring that the analysis captures both the short-term price dynamics and the long-term equilibrium relationships. Special attention is paid to the effects of external shocks, such as the COVID-19 pandemic and the Ukraine war, which may disrupt the market.

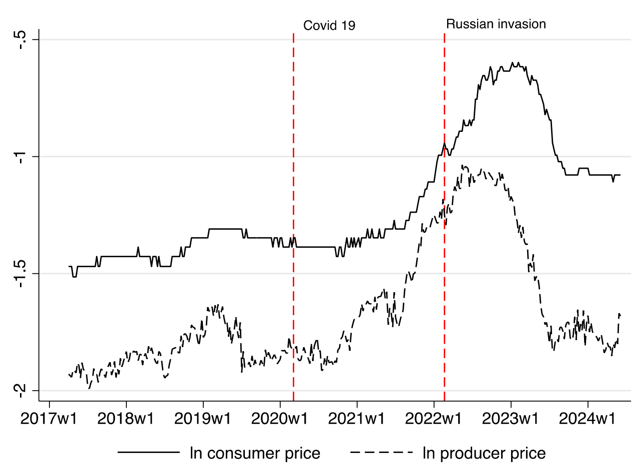

Fig. 3. The natural logarithm of producer and consumer prices.

The first step in our analysis involved testing for stationarity, a crucial preliminary step in time series analysis. To this end, we applied the Phillips-Perron [23] and Elliott-Rothenberg-Stock [7] unit root tests.

Both tests were employed to assess whether the producer and consumer price series were stationary in levels or needed to be differenced to achieve stationarity. Establishing whether the time series are non-stationary in levels but stationary in first differences is critical for valid cointegration analysis, as the presence of unit roots in levels but not in first differences is a necessary condition for cointegration. This step ensures that any long-term relationships detected between producer and consumer prices are not spurious but reflect actual underlying economic linkages.

Following the stationarity tests, we employed several cointegration tests to identify the presence of long-run equilibrium relationships between wheat producer and consumer prices. The first of these tests is the Johansen [13] cointegration test, which is widely recognized for its ability to detect multiple cointegrating relationships in a multivariate context. Additionally, we applied the Engle-Granger [6] two-step procedure, which provides a simpler, bivariate approach to testing for cointegration. To complement these approaches, we also applied the Banerjee et al. [2] and Boswijk [4] cointegration tests, which are single-equation error correction-based methods. These tests are particularly useful for validating cointegration in systems where the variables might exhibit non-linear adjustments or where the cointegration vector is not constant over time. By using multiple cointegration tests, we aimed to ensure robustness in detecting long-term price relationships, as each method offers a different perspective on the possible existence of such relationships. Given the potential for structural breaks in the cointegration relationship due to significant external events like the COVID-19 pandemic and the Ukraine war, the Gregory-Hansen [9] test was employed to capture structural breaks in the cointegration process.

To further examine the relationship between producer and consumer prices, we conducted causality tests. We utilized both both the Granger Causality Test [8] and the Toda-Yamamoto [27]. The Granger test allows us to determine whether past values of producer prices can predict current consumer prices and vice versa. This causality is critical for understanding the flow of information in the market and has significant policy implications. For instance, if producer prices are found to Granger-cause consumer prices, this would indicate that shocks to production costs or supply are likely to be passed along to consumers. Conversely, if consumer prices Granger-cause producer prices, it could suggest that demand-side factors are driving the price adjustments in the supply chain.

To further explore the dynamic causal relationship between producer and consumer prices over time, we employed the Time-Varying Lag-Augmented Vector Autoregressive (LA-VAR) Granger test, developed by Shi et al. [25]. This test extends traditional Granger causality analysis by allowing the relationship between variables to change over time, capturing shifts in the causal structure that may arise due to external shocks or policy interventions. By testing the causality over different time periods, we can assess whether the strength or direction of causality between producer and consumer prices varies in response to events like the COVID-19 pandemic or the Ukraine war. The LA-VAR Granger test also accounts for possible lagged effects in a time-varying context, which is particularly important for capturing short-run dynamics and adjusting for evolving market conditions.

In addition to causality analysis, we tested for nonlinearity in the data using the Broock-Dechert-Scheinkman (BDS) test [5]. The BDS test examines whether the residuals of the linear models exhibit independent and identical distribution (i.i.d.). Detecting nonlinearity is an important step in confirming that simple linear models may not be sufficient to fully capture the complexities of price transmission in the wheat market.

While linear cointegration models provide valuable insights into long-run price relationships, agricultural markets frequently exhibit nonlinear dynamics, especially in the transmission of price changes. For this reason, we applied the Nonlinear Autoregressive Distributed Lag (NARDL) model, developed by Shin, Yu, and Greenwood-Nimmo [26]. The NARDL model is particularly useful in distinguishing between the effects of positive and negative shocks, which is crucial in agricultural markets where price increases are often transmitted more quickly through the supply chain than price decreases. By allowing for asymmetric responses to price changes, the NARDL model provides a more nuanced understanding of how producer price shocks affect consumer prices. This is particularly relevant in the wheat market, where factors such as production costs, storage capabilities, and market power can lead to differential impacts of price increases versus decreases.

The definition of the asymmetric long-run equilibrium is as follows:

$$y_t = \beta^+ x_t^+ + \beta^- x_t^- + \varepsilon_t \tag{1}$$

where y_t is the dependent variable (consumer price), x_t^+ and x_t^- are the partial cumulative sum processes of positive and negative changes in the dependent variables (producer price, x_t), β^+ and β^- represent the asymmetric long-run parameter for positive and negative price changes, ε_t is the random error term.

Equation (1) establishes the framework for modeling asymmetric responses in price transmission, distinguishing between positive x_t^+ and negative x_t^- shocks. This is important for capturing the different effects of rising versus falling producer prices on consumer prices.

To model the dynamics of the relationship between these variables, we combine Equation (1) with the unconstrained linear ARDL (*p, q*) specification to formulate the NARDL model. The general form of the NARDL model is expressed as:

$$\Delta y_t = \alpha_0 + r y_{t-1} + \theta^+ x_{t-1}^+ + \theta^- x_{t-1}^- + \sum_{j=1}^{p-1} \tau_j \Delta y_{t-j} + \sum_{j=0}^{q-1} \left(\pi_j^+ \Delta x_{t-j}^+ + \pi_j^- \Delta x_{t-j}^- \right) + \varepsilon_t \tag{2}$$

In this model, Δyt represents the first difference of the dependent variable, consumer price. The terms y_{t-1} and x_{t-1}^+ and x_{t-1}^- denote the lagged values of the dependent and independent variables, respectively, capturing past values that influence current outcomes. The long-run effects of positive and negative price changes are described by the coefficients θ^+ and θ^-, while τj accounts for the short-run dynamics of the dependent variable. Similarly, the terms π_j^+ and π_j^- represent the short-run coefficients for positive and negative changes in the independent variable. Lastly, α_0 is the intercept, and ε_t denotes the error term.

The NARDL model thus enables the analysis of both short-run and long-run asymmetries in the relationship between wheat producer and consumer prices. In particular, $\sum_{j=0}^{q-1} \pi_j^+$ and $\sum_{j=0}^{q-1} \pi_j^-$ represent he short-run impacts of positive and negative shocks, respectively, while the long-run asymmetries are parameterized as follows:

$$\beta^+ = -\frac{\theta^+}{r} \; and \; \beta^- = -\frac{\theta^-}{r} \tag{3}$$

Here, r is the adjustment speed coefficient, then θ^+ and θ^- represent the long-run asymmetric responses to positive and negative changes in producer prices.

To account for potential structural breaks during external shocks such as the COVID-19 pandemic and the Ukraine war, we extended the NARDL model by incorporating break points in both the short- and long-run dynamics. The procedure for including breaks involves applying the Gregory-Hansen [9] test for cointegration with structural breaks to identify the timing of possible break points. Once identified, these break points were included in the NARDL frameworks by modifying the lag structure and allowing for regime shifts in both the intercept and slope coefficients.

By incorporating breaks into the model, we ensured that both the long-term equilibrium relationship and short-term adjustments between producer and consumer prices reflect the structural changes brought about by these external shocks. The use of the Pesaran, Shin, and Smith [22] bounds testing approach further validated the presence of cointegration in the presence of these breaks.

The optimal lag structure for the ARDL and NARDL models, including the break points, was selected based on the Akaike Information Criterion (AIC). This criterion ensures that the model captures the underlying dynamics of the wheat price transmission process while minimizing overfitting. The analyses were carried out using STATA MP 18.

4. Results

Table 2 shows that the results of the Elliot-Rothenberg-Stock (ERS) and the Phillips and Person (PP) unit root tests for both level and first differences. The results of the two unit root tests are contradictory. ERS shows that wheat producer prices (P_{pt}) are not stationary, even after the first difference. In the Phillips-Perron case, the first difference is significant, i.e. no unit root is present in the time series. The dynamics are different for consumer prices (P_{ct}), where the two tests are partially identical, with the Elliot-Rothenberg-Stock test being significant at 10 % after the first difference and the Phillips-Perron at 1 %.

Table 3 presents the unit root test of Zivot and Andrews [30] with structural break. The results show that for (logarithmic) producer prices, the null hypothesis of a unit root cannot be rejected. The Zivot-Andrews unit root test confirms the Philips-Perron results, so it can be said that the first differences can be considered stationary.

4.1. BDS tests

After testing for unit root tests, we estimated the linear model and employed BDS independence test. The results confirm that of the series is not identically and independently distributed which confirms the presence of asymmetries. Therefore, it is necessary to the employ dynamic asymmetric framework for the analysis of the nonlinear relationship between consumer prices and producer prices in Hungary. The results of the BDS test are reported in Table 4.

Next, we applied linear and nonlinear causality tests. Among linear the causality tests [8,27] in Table 5. Both the Granger causality tests and the Toda-Yamamoto causality tests provide strong evidence of bidirectional causality between producer and consumer prices. The bidirectional relationships are in line with earlier result by Han & Ahn [10].

Table 6 presents the results of time-varying LA-VAR (Lag-Augmented Vector Autoregressive) Granger tests developed by Shi et al. [25]. Each hypothesis is tested against critical values at the 1 %, 5 %, and 10 % significance levels. For all models (FE, RO, RE), the test statistics are greater than the critical values at the 1 %, 5 %, and 10 % significance levels. This indicates strong evidence that $\ln P_{ct}$ causes $\ln P_{pt}$.

For the FE model, the test statistic is less than the critical values at all significance levels, indicating no evidence that $\ln P_{pt}$ causes $\ln P_{ct}$. For the RO and RE models, the test statistics are greater than the critical values at the 5 % and 10 % significance levels but less than the 1 % level. This suggests weak evidence that $\ln P_{pt}$ might cause $\ln P_{ct}$ under these models. In summary, the results provide strong evidence that $\ln P_{ct}$ causes $\ln P_{pt}$ across all models. There is weak evidence that $\ln P_{pt}$ might cause $\ln P_{ct}$ under the random effects and random errors models, but not under the fixed effects model.

Table 2
Elliot-Rothenberg-Stock test and Philips-Perron unit root tests.

	Elliot-Rothenberg-Stock		Phillips-Perron	
variable	intercept	intercept, trend	intercept	intercept, trend
$\mathbf{lnP_{pt}}$	−0.868	−2.123	−1.428	−0.532
$\mathbf{lnP_{ct}}$	−0.822	−3.042***	−0.828	−0.745
$\mathbf{\Delta lnP_{pt}}$	−0.884	−1.421	−27.855***	−27.998***
$\mathbf{\Delta lnP_{ct}}$	−1.623*	−2.306*	−19.208***	−19.203***

Note: Δ is the first difference operator. The optimal lag structure of the Elliot-Rothenberg-Stock test is chosen based on the Schwarz Information Criterion. The optimal lag structure of the Phillips–Perron test is chosen based on the Newey–West bandwidth with Bartlett weights.
***, ** and * indicate rejection of the null hypothesis of the unit root at 1 %, 5 % and 10 % level.

4.2. Cointegration tests

Table 7 shows that the Johansen, Banerjee, and Boswijk tests [2,4,13] consistently show strong evidence of cointegration, both with and without a trend. The Engle-Granger test, however, does not indicate cointegration in either case. This suggests that while the Engle-Granger test does not find a long-term relationship, the other tests strongly support the existence of a cointegrating relationship between the variables, regardless of the trend component.

We employ Gregory and Hansen cointegration tests, to investigate for cointegration in the presence of potential structural breaks [9]. Table 8 includes the test statistics (Zt) for different models, the break date, and the asymptotic critical values at the 1 %, 5 %, and 10 % significance levels. or all three models (change in level and trend, change in regime, change in regime and trend), the test statistics are less negative (higher) than the critical values at the 1, 5 10 % levels. This indicates that in each case, there is not enough evidence to reject the null hypothesis of no cointegration. The consistent break date (2022w31) across all models suggests that this is the identified point where a potential structural break is considered.

However, the evidence for cointegration around this break date is not significant according to the Gregory and Hansen test statistics. In summary, the Gregory and Hansen tests suggest that there is no significant cointegration relationship detected in the presence of structural breaks for the specified models and break date. These results also imply that we have not been able to identify a structural break in the cointegration relationship during either the Covid or the Ukrainian war period.

The Pesaran, Shin, and Smith [22] bounds test was used to establish the existence of long-term cointegration. The optimal lag selection based on Akaike Information Criterion. Notice that alternative lag selection criteria including Schwarz-Bayesian, Hannan-Quinn Information Criteria yield the same results. Table 9 displays four different model configurations. ARDL model: this represents the standard Autoregressive Distributed Lag model. ARDL with break: this model introduces potential structural break identifying by Gregory and Hansen tests into the ARDL. NARDL model allowing for the detection of asymmetric relationships between positive and negative changes in producer prices and how they transmit to consumer prices. NARDL with the break: combining both non-linearity and regime shifts in the cointegration analysis. Table 10 demonstrates strong evidence of long-term cointegration between wheat producer and consumer prices, but the strength of the relationship diminishes when non-linearities and structural breaks are considered. This suggests that while Hungary's wheat supply chain remains resilient in the long run, external shocks and market asymmetries can introduce complexities that require more flexible modelling approaches, such as NARDL, to fully capture.

Table 10 presents the results of the NARDL model, which investigates the asymmetric effects of producer price changes on consumer prices in Hungary's wheat supply chain. The model distinguishes between positive $\left(P_{pt}^{+}\right)$ and negative $\left(P_{pt}^{-}\right)$ producer price shocks, allowing us to analyze the differing impacts of price increases and decreases on consumer prices (P_{ct}).

The long-run elasticities for both positive (0.050) and negative (0.049) changes in producer prices are similar and statistically significant, indicating a nearly symmetric transmission of price changes from producers to consumers in the long run. This suggests that a 1 % increase or decrease in producer prices leads to approximately a 0.05 % change in consumer prices, regardless of the direction of the shock. However, in the short-run dynamics, a 1 % decrease in producer prices results in a 0.071 % decline in consumer prices, a statistically significant effect, whereas the short-run impact of positive producer price changes is not significant. This suggests that decreases in producer prices are more

Table 3
Zivot-Andrews unit root tests.

	Model A	TB	Model B	TB	Model C	TB
$\mathbf{lnP_{pt}}$	−3.326	2023w4	−2.378	2022w21	−4.088	2021w31
$\mathbf{lnP_{ct}}$	−2.490	2021w34	−1.785	2022w52	−3.374	2022w2
$\mathbf{\Delta lnP_{pt}}$	−30.222***	2022w24	−29.729***	2021w43	−30.616***	2022w48
$\mathbf{\Delta lnP_{ct}}$	−7.729***	2023w3	−6.926***	2022w17	−8.186***	2023w12

Note: Δ is the first difference operator. TB denotes the time of break. Model A allows a break at an unknown point in the intercept; Model B allows a break at an unknown point in the linear trend; and Model C allows a break at an unknown point in both. The optimal lag structure of the Zivot and Andrews [30] test is chosen based on the Akaike Information Criterion and is displayed in parentheses. The critical values were obtained from Zivot and Andrews [30].
***, ** and * indicate rejection of the null hypothesis of the unit root at 1 %, 5 % and 10 % level of significance, respectively.

Table 4
BDS tests.

	BDS statistic at different dinemsions				
	2	3	4	5	6
lnP_{pt}	41.492***	45.032***	49.104***	54.845***	62.579***
lnP_{ct}	46.256***	49.526***	53.494***	59.236***	67.002***

***, ** and * indicate the rejection of null hypothesis that states that residuals are iid at 1 %, 5 % and 10 % level of significance, respectively.

Table 5
Causality tests.

Hypothesis	chi2	Prob > chi2
Granger tests		
lnP_{ct} does not cause lnP_{pt}	103.08	0.000
lnP_{pt} does not cause $lnPc_{t}$	8.389	0.004
Toda-Yamamoto causality test		
lnP_{ct} does not cause lnP_{pt}	63.46	0.000
lnP_{pt} does not cause $lnPc_{t}$	9.44	0.009

***, ** and * indicate the rejection of null hypothesis that states that no causality at 1 %, 5 % and 10 % level of significance, respectively.

Table 6
Time-varying LA-VAR Granger tests.

Hypothesis	Test statistics	1 %	5 %	10 %
lnP_{ct} does not cause lnP_{pt}				
Max Wald FE	18.389	13.425	9.112	7.271
Max Wald RO	24.024	12.820	9.133	7.242
Max Wald RE	31.894	14.315	9.558	7.642
lnP_{pt} does not cause lnP_{ct}				
Max Wald FE	1.689	13.423	8.521	6.619
Max Wald RO	12.081	13.491	8.703	6.923
Max Wald RE	13.686	13.833	9.025	7.180

***, ** and * indicate the rejection of null hypothesis that states that no causality at 1 %, 5 % and 10 % level of significance, respectively.

Table 7
Linear cointegration tests without and with trend.

	Engle-Granger	Johansen	Banerjee	Boswijk
	without trend			
P-Values	0.630	0.000	0.000	0.000
Test Statistics	−1.172	36.008	−5.091	26.203
	with trend			
P-Values	0.914	0.000	0.000	0.000
Test Statistics	−1.532	58.898	−5.289	58.142

***, ** and * indicate the rejection of null hypothesis that states that no cointegration at 1 %, 5 % and 10 % level of significance, respectively.

Table 8
Gregory and Hansen cointegration tests.

			Asymptotic Critical Values		
Model	Zt	Break date	1 %	5 %	10 %
change in level and trend	−3.92	2022w31	−5.13	−4.61	−4.34
change in regime	−3.87	2022w31	−5.47	−4.95	−4.68
change in regime and trend	−4.50	2022w31	−6.02	−5.50	−5.24

***, ** and * indicate the rejection of null hypothesis that states that no cointegration at 1 %, 5 % and 10 % level of significance, respectively.

Table 9
Pesaran, Shin, and Smith [22] bounds test.

Statistics	ARDL	ARDL with break	NARDL	NARDL with break
$\mathbf{t_{BDM}}$	−7.808***	−6.728***	−5.331***	−3.453
$\mathbf{F_{PSS}}$	38.420***	31.340***	18.600***	3.635

***, ** and * indicate the rejection of null hypothesis that states that no cointegration at 1 %, 5 % and 10 % level of significance, respectively.

Table 10
Nonlinear ARDL results.

Variable	coefficients	Std. Errors
lnP_{ct-1}	−0.047***	0.008
lnP^{+}_{pt-1}	0.050***	0.007
lnP^{-}_{pt-1}	0.049***	0.006
ΔlnP_{ct-1}	−0.280***	0.048
ΔlnP^{+}_{pt}	0.046	0.042
ΔlnP^{+}_{pt-1}	0.028	0.044
ΔlnP^{-}_{pt}	0.071*	0.041
ΔlnP^{-}_{pt-1}	−0.040	0.041
constant	0.070***	0.013
R^2	0.195	
N	372	
	statistics	p value
Portmanteau test	48.98	0.1560
Breusch/Pagan test	1.814	0.1780
Ramsey test	1.811	0.144
Jarque-Bera test	62.15	0.000

***, ** and * indicate the significance at 1 %, 5 % and 10 % level.

rapidly passed on to consumers than increases, though these short-run effects are relatively small.

Table 11 summarises the long-term impacts on both the positive and negative side, based on the results of the NARDL model in Table 10. The bottom part of the table shows the asymmetry tests (positive vs. negative side), also for short and long term. For producer prices, both the positive and negative long-run effects are highly significant, indicating a strong bidirectional influence on consumer prices. Consumer prices react more strongly to a 1 % change in prices (1.062 % and −1.039 %). This bidirectional relationship suggests that changes in producer prices directly impact consumer prices and vice versa, reinforcing the tightly integrated

Table 11
Asymmetry statistics.

	Long-run effect [+]			Long-run effect [−]		
Exog. var.	coef.	F-stat	P > F	coef.	F-stat	P > F
lnP_{pt}	1.062	70.07	0.000	−1.039	55.96	0.000
	Long-run asymmetry			Short-run asymmetry		
	F-stat		P > F	F-stat		P > F
lnP_{pt}	1.88		0.171	0.193		0.660

***, ** and * indicate the significance at 1 %, 5 % and 10 % level.

market structure within Hungary's wheat-flour supply chain. The results confirm that there is not statistically significant long-run asymmetry in price transmission, as the F-statistic (1.88) for long-run asymmetry is insignificant ($p = 0.171$). This further supports the interpretation that, in the long run, price changes at the producer level—whether increases or decreases—are transmitted symmetrically to consumer prices. Similarly, the short-run asymmetry test shows no significant differences (F-stat = 0.193, $p = 0.660$), indicating that any short-run deviations from symmetric price transmission are minimal.

In summary, the findings from Tables 11 and 12 suggest that while short-term price fluctuations may exhibit some minor differences, the wheat supply chain in Hungary maintains a largely symmetric price transmission process in both the short and long run. This symmetric response is crucial for maintaining price stability and indicates that producer price shocks are transmitted efficiently across the supply chain.

The CUSUM line (Fig. 4.) stays within these bounds, it suggests model stability over the time period (from 2017 to 2024). In this case, the line remains within the critical bounds, which indicates that the model's parameters have not experienced significant structural changes during this period. The $CUSUM^2$ line appears close to the boundaries at certain points, which may suggest some periods of variability, but it largely stays within the critical range.

Fig. 5 illustrates the cumulative impact of changes in the producer price on the consumer price, with a focus on identifying asymmetries in this relationship. This analysis is necessary to understand whether positive and negative changes in producer prices translate differently into consumer prices over time, thereby highlighting potential differences in market response dynamics. The short- and long-range asymmetry is zero (dark blue line), which is consistent with the asymmetry test results in Table 11.

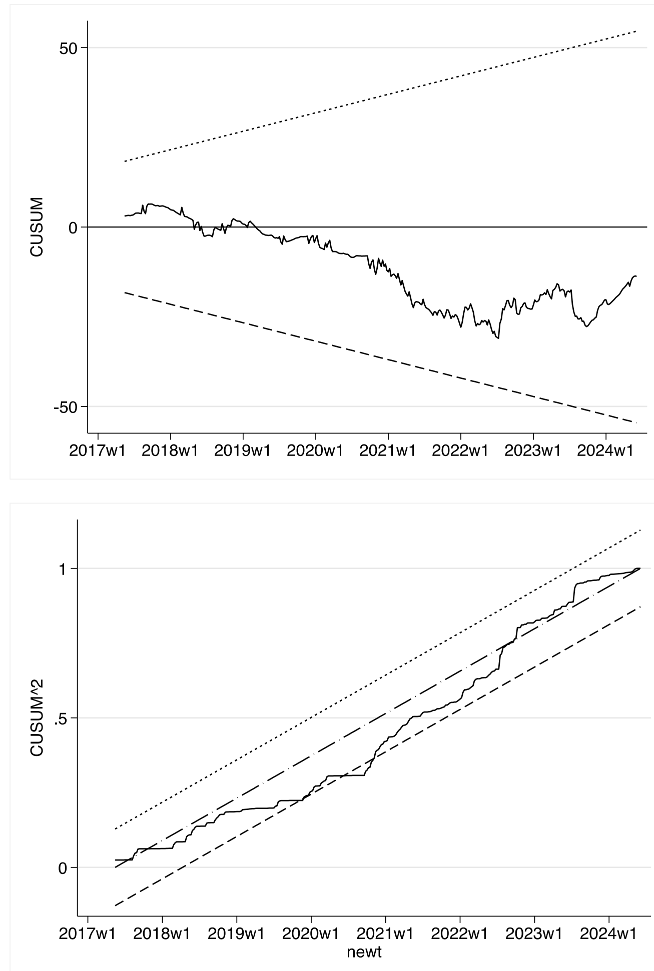

Fig. 4. Cusum tests on NARDL model.

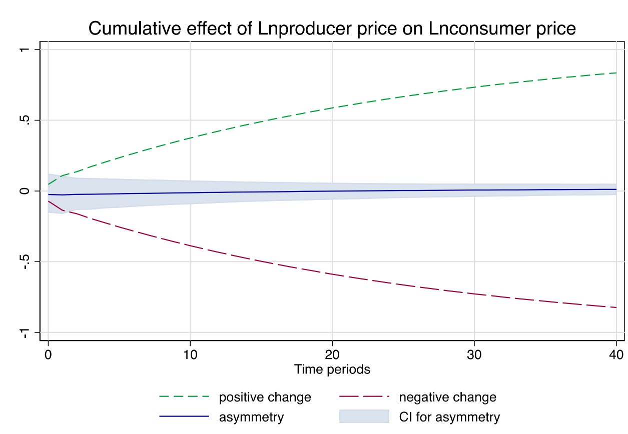

Fig. 5. Cumulative effect of ln producer price on consumer price.

5. The effect of Covid-19 and Ukraine war

Now we focus on understanding how the Covid-19 pandemic and the Ukraine-Russia war have affected wheat price dynamics in Hungary. To capture the influence of these global disruptions, we introduce structural break points corresponding to the onset of the Covid-19 pandemic and the Ukraine war. These break points are integrated into the econometric models to assess their impact on price transmission along the Hungarian wheat supply chain.

The results from Tables 12 and 13 expand on the findings from Tables 9, and Table 11, particularly in light of external shocks like the COVID-19 pandemic and the Ukraine war. The alternative structural break models in Table 12 confirm that the long-term cointegration between producer and consumer prices remains intact even when accounting for these shocks, reinforcing the strong evidence of cointegration seen in Table 9. Although the strength of the long-term relationship diminishes slightly during the COVID-19 period, as reflected by lower t_{BDM} and F_{PSS} values, the overall findings support the resilience of Hungary's wheat supply chain.

The results from Table 13 highlight the long-run and short-run

Table 12
Pesaran-Shin-Smith [22] bounds test for NARDL with alternative breaks points.

Statistics	NARDL with Covid break	NARDL with War break
t_{BDM}	−3.915*	−4.828***
F_{PSS}	4.679**	6.963***

***, ** and * indicate the rejection of null hypothesis that states that no cointegration at 1 %, 5 % and 10 % level of significance, respectively.

Table 13
Asymmetry statistics for alternative models.

NARDL with Covid break						
	Long-run effect [+]			Long-run effect [−]		
Exog. var.	coef.	F-stat	P > F	coef.	F-stat	P > F
lnP_{pt}	0.381	8.975	0.003	−0.787	17.81	0.000
	Long-run asymmetry F-stat		P > F	Short-run asymmetry F-stat		P > F
lnP_{pt}	20.7		0.000	0.232		0.630
NARDL with War break						
	Long-run effect [+]			Long-run effect [−]		
Exog. var.	coef.	F-stat	P > F	coef.	F-stat	P > F
lnP_{pt}	0.985	51.95	0.000	−0.976	44.24	0.000
	Long-run asymmetry F-stat		P > F	Short-run asymmetry F-stat		P > F
lnP_{pt}	0.026		0.871	0.912		0.340

***, ** and * indicate the significance at 1 %, 5 % and 10 % level.

asymmetries in price transmission between producer and consumer prices for the Covid-19 and Ukraine war periods using the NARDL model. During the Covid-19 period, a 1 % increase in producer prices results in a 0.38 % increase in consumer prices, while a 1 % decrease leads to a larger 0.79 % reduction in consumer prices. This shows significant long-run asymmetry, where price decreases have a greater effect than price increases, as confirmed by the asymmetry test. However, short-run asymmetry is not significant, indicating symmetrical price transmission in the short term.

In the case of the Ukraine war break, the long-run effects show near-symmetric transmission of both price increases and decreases. The positive long-run effect of producer prices on consumer prices is 0.985, indicating that nearly the entire price increase at the producer level is passed on to consumers. Similarly, the negative long-run effect is −0.976, meaning that a 1 % decrease in producer prices results in a nearly equivalent decrease in consumer prices. Unlike the Covid-19 period, there is no significant long-run asymmetry during the Ukraine war. Short-run asymmetry is also insignificant, suggesting that price changes at the producer level are transmitted symmetrically to consumer prices both in the short and long run.

In sum, the Covid-19 period shows long-run asymmetry, where producer price decreases have a greater impact than increases, while the Ukraine war period exhibits symmetric transmission in both the short and long run. This highlights distinct transmission dynamics during these two global disruptions.

6. Discussion

The NARDL model results offer critical insights into the price transmission mechanisms between wheat producer and consumer prices in Hungary, especially during the COVID-19 pandemic and the Ukraine war. The NARDL model indicates symmetric price transmission in the long run, with similar elasticities for both positive and negative changes in producer prices. This suggests that fluctuations in producer prices, whether increases or decreases, are proportionally transmitted to consumer prices over time. Asymmetry tests confirm the absence of significant asymmetries in both short and long runs.

The complementary analysis, incorporating structural breaks corresponding to the onset of COVID-19 and the Ukraine war, reaffirms these findings. Despite global disruptions, the Hungarian wheat market maintained efficient and symmetric price transmission mechanisms. This contrasts with observations in other countries where such events led to increased price asymmetries and market inefficiencies [11,17,29].

The resilience of Hungary's wheat supply chain may be attributed to effective domestic policies and strong market structures. Aday and Aday [1] highlighted that disruptions in food supply chains during the pandemic were mitigated in regions with robust infrastructures. Similarly, Hobbs [12] emphasized the importance of supply chain adaptability in maintaining food security during crises.

Global studies have documented significant impacts of COVID-19 and the Ukraine war on food prices and security [3,18,20]. These events have exacerbated price volatility and disrupted supply chains, particularly in countries heavily reliant on imports. Hungary's substantial domestic wheat production likely insulated it from such shocks, reducing vulnerability to global market fluctuations.

In sum, the NARDL model results suggest that Hungary's wheat market exhibited efficient and symmetric price transmission during the COVID-19 pandemic and the Ukraine war. This resilience emphasizes the importance of robust domestic policies and efficient supply chain management. Policymakers should continue to monitor market conditions but can be reassured by the demonstrated stability of the supply chain.

7. Conclusions

Although the research focuses exclusively on Hungary, the findings are relevant for generalizing broader regional patterns across Central and Eastern Europe. Hungary represents a medium-sized wheat producer with characteristics similar to neighboring countries, such as comparable climate conditions, agricultural practices, and market dynamics. Examining Hungary's wheat market enables the research to capture the effects of global events, such as the COVID-19 pandemic and the Ukraine war, on wheat pricing—impacts that are likely mirrored in other countries with similar contexts.

Hungary's wheat market offers insights into how small to mid-sized producers adapt to global disruptions, though factors such as its geopolitical position, agricultural policies, and economic environment are not the focus of this research. These insights provide a foundation for understanding how regional markets respond to external shocks, making the study relevant beyond Hungary. By analyzing Hungary's wheat-flour chain, this study identifies patterns that could be generalized to other wheat-producing nations within Central and Eastern Europe.

The cointegration tests reveal the evidence of a long-term relationship between producer and consumer wheat prices in Hungary, as supported by the Johansen, Banerjee, and Boswijk tests, even with trend adjustments. In contrast, the Engle-Granger test does not detect cointegration, indicating variability in test results. Despite this, the overall findings confirm a stable price transmission mechanism in the wheat supply chain.

The Gregory and Hansen tests, which account for structural breaks, identify a potential breakpoint in 2022 (week 31), yet there is insufficient evidence of significant cointegration disruption during the COVID-19 pandemic or Ukraine war. This suggests the Hungarian wheat market's resilience, with no major structural changes affecting price transmission during these shocks.

The NARDL model further supports long-term cointegration, showing that both positive and negative producer price changes are transmitted symmetrically to consumer prices over time, though short-term deviations are observed, particularly for negative shocks. These results emphasize the wheat supply chain's stability, despite temporary external disruptions.

Overall, the study highlights the resilience of Hungary's wheat market in maintaining long-term price stability, even amidst global crises. Policymakers should focus on reinforcing supply chain transparency and infrastructure to mitigate short-term price volatility while supporting the market's capacity to absorb external shocks.

Despite the insights provided by this study, several limitations must be acknowledged. First, the analysis primarily focuses on the domestic transmission of producer to consumer prices without fully integrating the broader international trade dynamics that may influence Hungary's wheat market. Future research could incorporate global market factors, such as trade flows, international policy changes, and global supply chain disruptions, to provide a more comprehensive view. Additionally, while structural breaks for the COVID-19 pandemic and the Ukraine-Russia war were included, further refinement of these breakpoints, along with the inclusion of other potential shocks, could enhance the robustness of the results. Expanding the model to account for other agricultural products and conducting cross-country comparisons could also offer deeper insights into price transmission patterns across diverse agricultural contexts.

CRediT authorship contribution statement

Tibor Bareith: Validation, Formal analysis, Conceptualization. **Imre Fertő:** Visualization, Methodology, Formal analysis. **Szilárd Podruzsik:** Writing – original draft, Resources.

Funding

This work was supported by the Hungarian Scientific Research Fund (OTKA: otka.hu) grant No. PD146385.

Funding source had no involvement in this research.

Declaration of competing interest

We have nothing to declare.

Data availability

Data will be made available on request.

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