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ORIGINAL ARTICLE

Russia's invasion of Ukraine increased the synchronisation of global commodity prices

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Abstract

The Russian Federation's efforts to expand its regional political influence culminated in launching a full-scale war of aggression on Ukraine on 24 February 2022. As both countries are large exporters of commodities crucial for global food and energy security, the resulting abrupt supply chains disruptions created substantial uncertainty in commodity markets worldwide. This study quantifies to what extent this major shock induced global commodity prices to move more synchronously by gauging their time-varying comovement. Using the concordance index, it analyses the development of 15 key global commodity price indices from January 2010 to July 2022. We find that the supply chains disruptions increased synchronisation of grain, energy and fertiliser prices at the global level in direction and magnitude. Moreover, they resulted in contagion across numerous food and non-food markets, creating a global covariate shock to food and energy security. Notably, the increased synchronisation at broad scale restricts the ability of consumers to mitigate the adverse effects of food and energy price inflation by resorting to inexpensive alternatives. Hence, policymakers must improve the resilience of global food supply chains sustainably such that adverse effects of attaining the Sustainable Development Goals in crises can be minimised.

KEYWORDS
commodity price indices, covariate market shock, food market vulnerability, food system resilience, price comovement, supply chain disruption, war

JEL CLASSIFICATION
F51, H12, H56, Q11, Q31, Q34

1 | INTRODUCTION

Since March 2014, Russia has been challenging the international community by fueling violent unrest in Eastern and Southern Ukraine to expand the boundaries of its political influence on Ukrainian domestic and foreign policy design (Malyarenko & Wolff, 2018). These efforts culminated in launching a full-scale war against Ukraine, starting on 24 February 2022 (UN, 2022), inflicting huge damages on the country (KSE, 2022). The unprecedented escalation of military aggression heavily impacted global commodity markets, producing the 'largest commodity price shock we've experienced since the 1970s' (World Bank, 2022a). The shock magnitude stems from the fact that both countries are major exporters of key food and energy commodities and metals and minerals (World Bank, 2022a). Notably, this escalation disrupted international supply chains by blocking Ukrainian export flows of such commodities, for which the country is a global market player (wheat, barley, corn, sunflower oil and crude iron). Moreover, exports of Russia's key food and nonfood commodities[1] plummeted, either because they were included in the Western sanctions against Russia, Russia limited its exports, or the sanctions substantially impeded payment transactions and, thus, physical commerce (Reuters, 2022). Furthermore, many commodities for which neither Ukraine nor Russia influences global markets have been reported to have experienced similar trajectories (FAO, 2022; World Bank, 2022a).

This abrupt disruption of various international supply chains induced sudden supply shortages in global food markets. Producer and consumer prices of many agricultural and food commodities skyrocketed (World Bank, 2022a). Hence, the international community and national policymakers (European Commission, 2022a; The Guardian, 2022) are concerned about the resulting adverse effects on food security in low- and middle-income countries (IFPRI, 2022; Osendarp et al., 2022). Consequently, approximately 20 countries have limited agricultural exports (Laborde & Mamun, 2022), exacerbating supply chain disruptions (SCDs) and increasing price uncertainty in global food markets (Glauber et al., 2022).

If prices of a broad set of food commodities increase simultaneously around the globe, the ability of vulnerable consumers to cushion the resulting pressure on disposable food expenditures becomes severely restricted as substituting for cheaper alternatives gets less feasible. The larger the magnitude of such a synchronous price development, the larger and the more sudden the shock is challenging household food resilience (Ansah et al., 2020). This study, hence, probes the extent to which the synchronisation between global price indices of 15 core commodity categories has been impacted by the global repercussions of Russia's invasion of Ukraine. We test whether the directions and the magnitudes of global commodity price comovement differ during the invasion from their levels before February 2022.

This study contributes insights into the comovement and synchronisation literature as follows. First, it assesses the effects of the most significant event for commodity markets in recent years (World Bank, 2022b) on structurally changing commodity price trajectories. Second, this

[1] For example, sunflower seeds and oil, barley, wheat, natural gas, palladium, nickel, fertilisers, coal, platinum and crude oil (FAO, 2022; Guénette et al., 2022).

study is—to the best of our knowledge—the first to consider two complementary dimensions of synchronisation, namely direction and magnitude of price changes. Third, it focuses on global impacts by analysing global price indices of the most important commodity categories. Such categories cover commodities for which supply chains have been physically disrupted by Russia's invasion (e.g. wheat and maize) and those for which international supply chains have not been impeded (e.g. raw materials or rice). Fourth, this analysis enriches the method toolkit beyond the frequently applied approaches of vector autoregressive models and correlation by applying the Harding and Pagan (2002, 2006) synchronisation measurement, which has the advantage of providing an objective quantification of the intuitive notions of price comovement. The remainder of this paper proceeds as follows. Section 2 reviews the SCDs and price synchronisation literature. Section 3 describes how the invasion induced disruptions of commodity exports from Ukraine. Section 4 presents the data. Section 5 details the empirical approach for measuring synchronisation. Section 6 reports the results. Section 7 concludes the study and discusses the policy implications.

2 | POTENTIAL ECONOMIC EFFECTS OF SUPPLY CHAIN DISRUPTIONS

Literature on SCDs has been growing, resulting in new strategies for firms, academia and practitioners to address supply chain vulnerabilities, capabilities and risks. Researchers have developed various typologies for analysing the resilience of SCDs and associated risks management strategies (e.g. Katsaliaki et al., 2021; Wicaksana et al., 2022), particularly, in food markets (e.g. Ahmed et al., 2020; Manning et al., 2020).

SCDs are commonly categorised as internal or external to the supply system. While internal SCDs are often defined as uncertainties regarding demand, supply yields, lead times, supply capacity, supply cost or policy decisions about trade flows, external SCDs stem from natural disasters and human-made factors (Kochan & Nowicki, 2018). Many related studies focus on internal SCDs. For example, Svanidze et al. (2021) and Götz et al. (2016) study SCDs in food trade in the Black Sea region and find that they mainly yield increased transaction costs, decreased market integration and hampered overall market development.

Among external SCDs, natural disasters and extreme climatic events have increased partly given human-induced climate change (IPCC, 2021). Moreover, recent examples of man-made disruptions include trade barriers (e.g. tariffs and nontariff barriers), political conflicts (e.g. civil war or terrorism), refugee flows and the COVID-19 pandemic. Unlike natural disasters, man-made events can affect both demand and supply sides, putting extra stress on supply chains (Mishra et al., 2021).

Human disasters, such as war, often create SCDs, which negatively affect food markets (Ali & Lin, 2010; Ihle & Rubin, 2013). Bar-Nahum et al. (2020) examine the effects of economic fragmentation due to the Israeli–Palestinian conflict on food trade and find significant negative effects on food supply and demand. Boungou and Yatie (2022) find that Russia's invasion of Ukraine negatively impacts stock market returns. Moreover, large-scale natural disasters and extreme weather have also been reported to create SCDs, which shocked food markets (Davis et al., 2021) and stock markets (Bourdeau-Brien & Kryzanowski, 2017; Hendricks et al., 2020; Wang & Kutan, 2013; Worthington, 2008). Cavallo et al. (2014) find that the 2010 earthquake in Chile and the 2011 earthquake in Japan led to a significant reduction in product availability, while prices remain relatively stable.

Furthermore, SCDs caused by the COVID-19 pandemic have received considerable attention in the recent literature (Béné, 2020; Savary et al., 2020). Many studies analyse its empirical effects on food markets (Akter, 2020; Hobbs, 2020; Ihle et al., 2020; Wang et al., 2020) and on stock markets (Harjoto et al., 2021; Kusumahadi & Permana, 2021; Liu et al., 2020; Mazur et al., 2021). Mahajan and Tomar (2020) find that COVID-19 caused food SCDs in India, resulting in significant reductions in product availability, with a minimal impact on prices. The mutual occurrence of natural and human disasters is frequent in this century (e.g. COVID-19 and the invasion of Ukraine; droughts and pandemics). Mishra et al. (2021) discuss such occurrences and their compounded effects on food supply chains.

Comovement of commodity prices has gained wide interest in recent times, pioneered by Pindyck and Rotemberg (1990). They find that prices of unrelated raw commodities move together, even after controlling for important macroeconomic indicators. This finding is known as the 'excess co-movement hypothesis', suggesting that the excess comovement may stem from herd behaviour in financial markets. Many studies have reconsidered this hypothesis, stressing the importance of common tendencies in supply and demand factors in explaining price commodity comovement (e.g. Ai et al., 2006; Deb et al., 1996; Lescaroux, 2009). Ai et al. (2006) use inventory and harvest data for wheat, corn, oats, soybean and barley to fit a partial equilibrium model. They explain much of the observed comovement in commodity prices by common movements in supply factors. Natanelov et al. (2011), De Nicola et al. (2016) and Lucotte (2016) assess the comovement between prices of agricultural and energy commodities in the aftermath of the 2007–2008 global food price crisis, which Sumner (2009) puts into historical perspective.

Kose et al. (2003, p. 62) find that there is 'limited support for the conventional wisdom that globalization leads to an increase in the degree of synchronization of business'. Several studies analyse the synchronisation of commodity prices, among which Roberts (2008) finds that the prices of seven industrial and precious metal prices did not move independently in the period between 1947 and 2008. He concludes that a common cycle among these price movements is likely to exist. Rossen (2015) assesses synchronisation, cycles and long-run trends in 20 metal commodities between 1910 and 2011 and finds that synchronous patterns are only common within commodity subgroups destined for common usage, confirming prior findings on super cycles lasting several decades. Fliessbach and Ihle (2022) investigate time-dependent synchronisation in the price cycle components of pig and cattle prices in three Latin American countries. They find moderate levels of unstable and asymmetric comovement. Izzeldin et al. (2022) compare the effects of the global financial crisis, COVID-19, and Russia's invasion on volatility in global financial markets in a window of 180 days around each event. They focus on the realised variance of daily national stock market indices and commodity prices, finding that the volatility of wheat and nickel has been affected most by this military conflict.

Despite the many relevant studies, no study empirically assesses the effects of SCDs on the synchronisation of global commodity price levels. To fill this gap, we test whether the directions and the magnitudes of global price comovement differ before and after the Russian invasion of Ukraine by assessing three hypotheses. First, we hypothesise that global price indices for commodities for which Ukraine has substantial shares in international exports (wheat, maize and barley) were strongly synchronised since the beginning of the invasion than before. Given the substantial economic shock from Russia's invasion (World Bank, 2022b), traders and other world food security stakeholders (World Bank, 2022a) became concerned, and these negative expectations started governing the global economic outlook (Dräger et al., 2022; Ruta, 2022), and dominating commodity price formation, similar to stock market contagions (Barlevy & Veronesi, 2003).

Second, we hypothesise that global energy and fertiliser prices exhibit the same pattern, given that the West has substantially reduced imports of coal, natural gas and crude oil from Russia. The supply and demand fundamentals of the commodities considered in these two hypotheses tend to be correlated, due to the simultaneous physical disruptions of international supply chains originating from both countries. As per Ai et al. (2006) and Lescaroux (2009), a shock with such a similar effect on the supply determinants of several commodities may yield a more synchronous pattern in price development.

Third, we hypothesise that the effects of SCDs caused by substantial limitations or complete abolishment of physical exports from Ukraine and Russia have globally spilled over to commodities for which neither Ukraine nor Russia has substantial shares in global exports (e.g. tea, coffee or dairy products) as stated in earlier qualitative research (FAO, 2022; World Bank, 2022a); that is, we test whether globally traded commodities that did not experience SCDs show increased synchronisation. Hence, the study investigates the excess comovement hypothesis of Pindyck and Rotemberg (1990, p. 1173), who find that 'the prices of raw commodities have a persistent tendency to move together' and assesses to what extent the invasion resulted in a covariate shock to global commodity markets.

3 | TRADE DISRUPTIONS FROM RUSSIA'S INVASION OF UKRAINE

The sudden pressure on international food and other commodity supply chains is due to disruptions of physical trade flows from Ukraine and Russia. This unforeseen shock induced panic and sustained concerns in international commodity markets (Glauber & Laborde, 2022). The military escalation since 24 February 2022 meant that Ukrainian commodity export supply chains, which predominantly use maritime transport, were suddenly disrupted; commodities could no longer leave the country via the Black Sea. Hence, a complex network of international supply chains using wheat, barley, maize and sunflower seeds and oil as input was suddenly halted. The links between Ukraine and countries that process these commodities for satisfying food consumption elsewhere were severed (UkrAgroConsult, 2022).[2] The concerns about global food security were magnified by the SCDs from commodity export complications from Russia[3] due to the comprehensive economic sanctions enforced by Western countries. Figure 1 depicts the average seasonal patterns of Ukrainian export quantities from 2010 to 2021 relative to export quantities in 2022.

As Figure 1 shows, sunflower oil exports are fairly stable throughout the year, oscillating around 400,000 tonnes per month and only dropping in August and September below 300,000 tonnes. On the contrary, wheat and barley exports exhibit pronounced seasonality: they tend to be fairly stable until June, and during and directly after the harvest, they quickly quadruple and quintuple. From October, they show a steady decline towards the January minimum. Maize export quantities exceed those of wheat and show the opposite pattern at approximately 2 million tonnes monthly until May, declining to 150,000 tonnes in September before multiplying 20-fold, reaching 3 million tonnes in December.

UN trade data suggest that grain traders anticipated the Russian invasion, as wheat, barley and maize exports amounted to almost two times the usual quantities in January and February (Table 1). However, as the invasion cut off most trade channels, exports collapsed in March. While maize and sunflower oil exports recovered, reaching approximately half of the average export quantities in May, wheat and barley exports halted. We also compared the change in monthly export patterns given the current military escalation to the trade patterns during the Maidan demonstrations in Kyiv in early 2014 and their aftermath in the entire country. They barely resulted in adverse trade effects for Ukraine. This finding, thus, emphasises the potential dramatic consequences of current events (see Appendix S1).

[2]See the Appendix S1 for a detailed overview of the implications of the war-related events in Ukraine on cutting off international supply chains.

[3]Although food trade has been explicitly exempted, a comprehensive range of trade-related, financial, and business limitations severely impacts Russia's export capabilities. The oil and natural gas price explosion accompanying Russia's invasion induced comprehensive side effects for energy use (and food transport). For details, see, for example, European Commission (2022b) and International Trade Administration (2022).

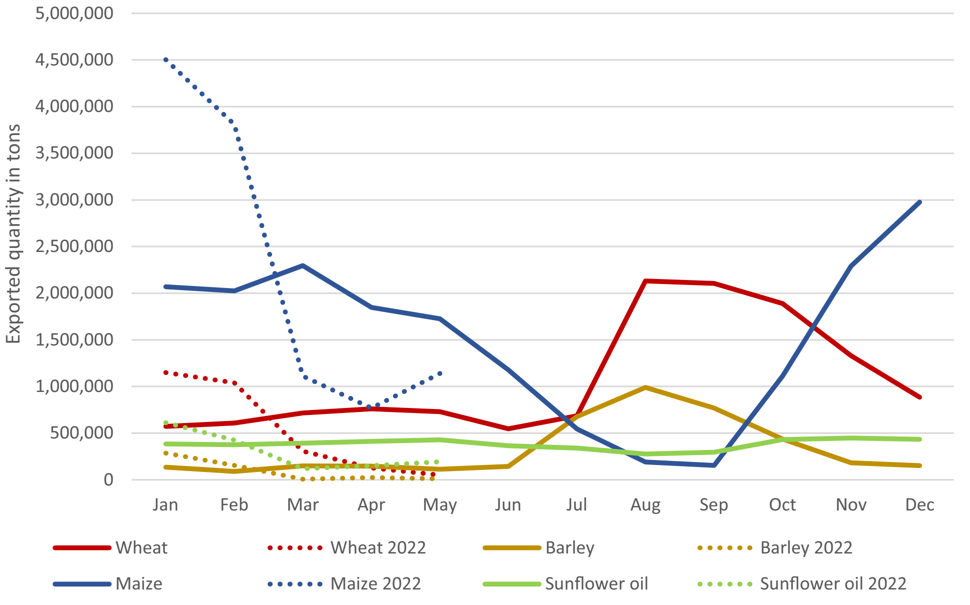

FIGURE 1 Average monthly export quantities from 2010 to 2021 versus 2022. *Note*: For 2022, data were only available until May. *Source*: Authors, based on Comtrade (2022). [Colour figure can be viewed at wileyonlinelibrary.com]

TABLE 1 Ratios between monthly export quantities of 2022 to the averages of 2018 to 2021

Month	Wheat (%)	Barley (%)	Maize (%)	Sunflower oil (%)
January	138	214	150	114
February	122	222	130	81
March	31	4	36	23
April	13	25	26	28
May	5	11	45	40

Note: For a robustness assessment of these numbers, we also calculated the ratios between monthly export quantities of 2022 to the average export quantities of 2018 to 2019, disregarding the 2 years heavily affected by COVID-19. Both sets of ratios are very close, with deviations of only a few percentage points, suggesting that COVID-19 had a minor or even negligible effect on monthly Ukrainian export patterns of the four commodities. The exact numbers can be obtained from the authors upon request.
Source: Authors, based on Comtrade (2022). For 2022, data were only available until May.

The global effects of this supply chain disruption are substantial (World Bank, 2022a). Ten countries, mostly in the Middle East and South and South-East Asia, source at least a quarter of their wheat imports from Ukraine (UkrAgroConsult, 2022). Expecting fierce and sustained price rises, the international community and national policymakers have become concerned about the resulting adverse effects on food security in low- and middle-income countries (Abay et al., 2022; Breisinger et al., 2022; IFPRI, 2022; Kurdi et al., 2022; Osendarp et al., 2022).

4 | DATA

We analyse the development of 15 monthly commodity price indices from January 2010 to July 2022. Six series represent global price developments in grain and oilseeds trade (Figure 2), while

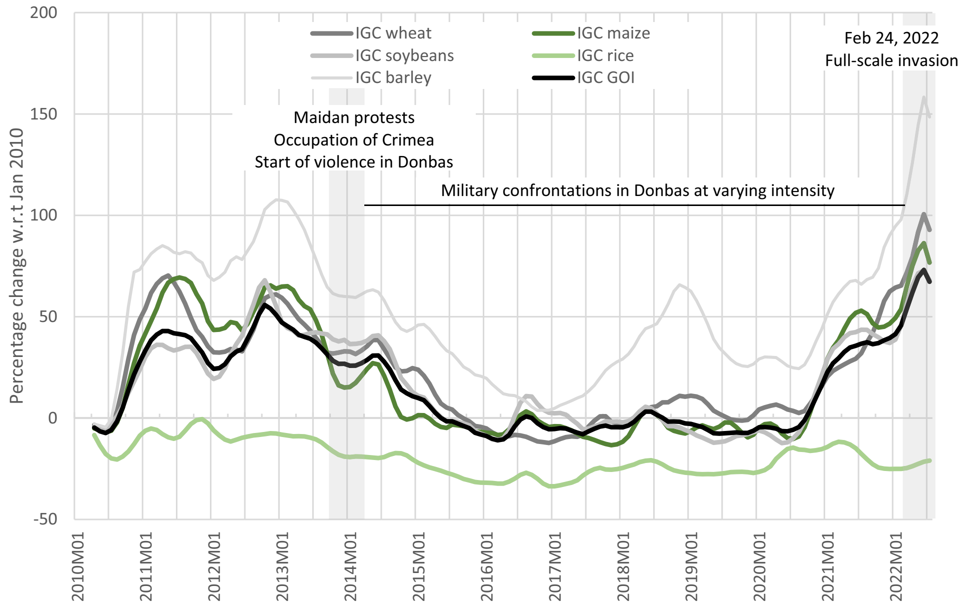

FIGURE 2 Smoothed price indices of the International Grains Council. *Source*: Authors based on IGC (2022). [Colour figure can be viewed at wileyonlinelibrary.com]

nine represent aggregated global price developments for relevant food commodities, fertilisers and energy (Figure 3). The nine composite price indices measure monthly nominal commodity prices in US dollars, representative of global price developments of the respective commodity group. They are computed based on 71 commodity price series by World Bank (2022c). The underlying price series are aggregated with individual weights into price indices of precious metals and energy commodities[4]; all other commodities are grouped as nonenergy commodities (Figure S1). World Bank (2022c) details the choice of individual series, their sources and their weights. For this study, various subindices of the nonenergy commodities index are of interest; we also consider the highest aggregations of the energy and precious metals price indices.[5]

We complement these data with six indices for global grain prices comprising the Grains and Oilseed Index (GOI), and five subindices for specific grains published by the International Grains Council (IGC, 2022). The GOI is designed to represent global grain and oilseed price developments. It comprises 34 price series of the seven most internationally traded grain and oilseed commodities, which ensure global food security. Beyond this main index representing global grain price developments, we also consider the IGC subindices for global wheat, barley, maize, soybeans and rice prices, considering their monthly average values at the same frequency as the indices of World Bank (2022c).

We analyse the period from January 2010 to July 2022 (i.e. 151 months), denoting the 15 indices by i_j^t for $j = 1, \ldots, 15$ and $t = 1, \ldots, 151$. Moreover, we renormalise the data regarding January 2010 as $i_{j,2010}^t$ via the following equation:

$$i_{j,2010}^t = 100\left(\frac{i_j^t}{i_j^1} - 1\right). \tag{1}$$

[4]World Bank (2022c) forms the global energy price index from price indices of coal, crude oil and natural gas, and the precious metal index of gold, silver and platinum prices.

[5]They are iNONFUEL, iENERGY and iPRECIOUSMET, respectively (World Bank, 2022c). See Figure S1 for detailed information on the indices.

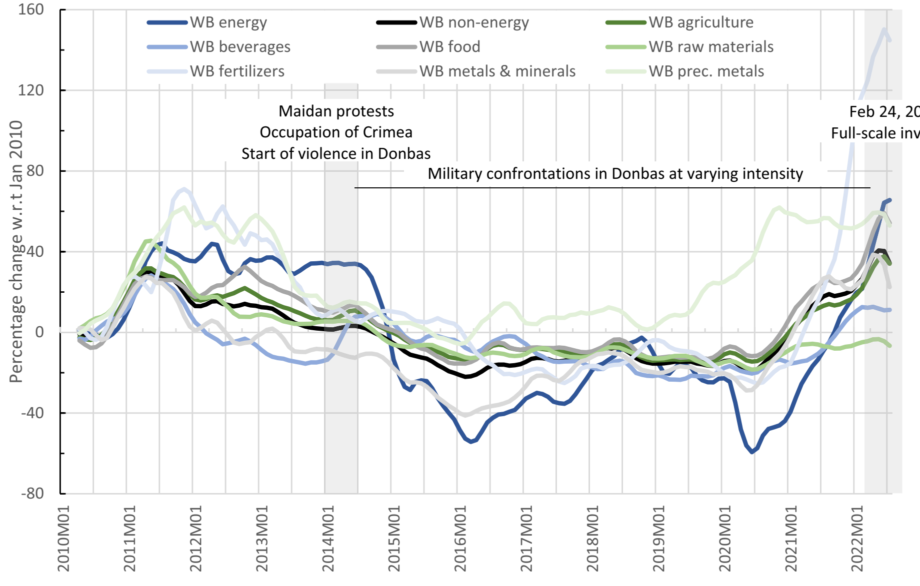

FIGURE 3 Smoothed World Bank commodity price indices. *Source*: Authors, based on World Bank (2022c). [Colour figure can be viewed at wileyonlinelibrary.com]

This approach has several advantages. It ensures that all indices become comparable, as they have an identical starting point of zero as the first observation with a standardised scale. This scale implies that the value of $i^t_{j,2010}$ in period t can be interpreted as the percentage change of the index relative to its first observation in the benchmark month of January 2010. Thus, the percentage change can be directly read from a plot of the transformed indices and compared with trajectories of other indices.

Shiskin (1958) outlines that economic time series can be additively decomposed into a long-run trend, cyclical component, seasonal pattern and unexplained random component. The first three components form the systematic part (i.e. the signal), while the last component denotes the random noise. As we assess whether the systematic parts of the indices are synchronised, we must filter out the unexplained part in each index. Hence, we take the four months moving average[6] denoted by $i^{t*}_{j,2010}$ of each index $i^t_{j,2010}$ as the final series upon which our analysis is based by smoothing out the noise via the arithmetic average:

$$i^{t*}_{j,2010} = \frac{1}{4}\sum_{i=0}^{3} i^{t-i}_{j,2010} \quad \forall \ t = 4, \ \dots, 151. \tag{2}$$

Figures 2 and 3 plot the resulting smoothed indices relative to the major escalations of violence Ukraine experienced since late 2013. Figure 2 illustrates the development of the six IGC indices. Global rice prices, being the most stable index, are unaffected by any potential market turbulences. Its level stayed closest to that of the benchmark month throughout the 12.5 years of interest. Barley prices react with the highest percentage variations among the

[6]The robustness analysis of this choice of the mean showed that the resulting $S_{jt} \forall t, j$ for all three dimensions of synchronisation assessed (synchronised trajectory direction, synchronised trajectory change of more than three and five percentage points, respectively) are fully identical, independent of whether the moving average is based on the arithmetic or geometric mean. Details can be obtained from the authors upon request.

six indices throughout this period. All indices except those for rice show mean-reverting behaviour in the medium run instead of a steady upward or downward trend. Five of the six indices show substantial increases until 2013; global barley prices took the longest to return to 2010's level (6 years), while global wheat, maize and soybeans prices returned a year earlier.

At the end of 2018/early 2019, barley was the only index experiencing a steep price hike of more than 50%. During Russia's invasion of Ukraine in early 2022, it reached 150% of its price levels 12 years ago (Figure 2). Between 2015 and early 2020, global wheat, maize and soybeans prices stayed close to their levels of early 2010. Since late 2020, they have been following the trajectory of barley prices. Contrary to this development, global rice prices sank and were remarkably stable since 2010. Five of the six indices reacted modestly on the Maidan protests and their aftermath in early 2014, showing slight increases between 5 and 10 percentage points.

The global commodity price indices by the World Bank (Figure 3) show considerably less stability manifested by the frequent and large changes in the indices. They show a fairly loose association with each other.[7] Amid the Maidan protests and their aftermath in early 2014, most indices barely changed, whereas many of them grew rapidly since February 2022. Energy prices show pronounced collapses in early 2016 and 2020. Indices of global precious metal and fertiliser prices were at the highest levels relative to the 2010 level, with fertilisers reaching 160% in early 2022.

5 | MEASURING SYNCHRONISATION OF COMMODITY PRICE INDICES

Several approaches have been developed to gauge the synchronisation of economic variables. Bry and Boschan's (1971) approach has been adapted by Candelon et al. (2008, 2009), Harding and Pagan (2006), and Pagan and Sossounov (2003) to analyse stock market prices and commodity prices by Cashin et al. (2002). Roberts (2009) focuses on short-run cycles, while Cuddington and Jerrett (2008) identify super cycles.

We suggest a composite approach. First, we determine sets of global price indices based on the economic and political events (see Table S3). We transform all observations for a given month into one synchronisation measure within each set. We average these measures within a moving window to obtain a local measure of synchronisation that can be plotted to graphically illustrate the time-varying degrees of synchronisation for each set. In the last step, we use the synchronisation measures of all single observations to set up a regression model tailored to test whether the direction and magnitude of global price comovement during Russia's invasion differ from their typical levels before the escalation.

We follow Roberts (2008) and Fliessbach and Ihle (2022) who apply the Harding and Pagan (2002, 2006) approach to measure synchronisation. The basis of this approach is transforming each of the N moving averages of the price indices $i^{t*}_{j,2010}$, $j = 1, \ldots, 15, t = 1, \ldots, T$, each with 148 observations, into a sequence of indicator variables S_{jt}:

$$S_{jt} = \begin{cases} 1 & \text{if } i^{t*}_{j,2010} - i^{t-1*}_{j,2010} > 0 \\ 0 & \text{otherwise} \end{cases}, \tag{3}$$

[7]Table S2 supports that visual impression by highlighting that these series take the maxima and minima during these 12.5 years in a very heterogeneous way.

which forms a stationary and ergodic Markov chain. We follow Harding and Pagan (2006) by operationalizing the synchronisation of at least two time series of equal frequency as the share of periods during which they simultaneously move in the same direction.[8] The major advantage is that it offers a transparent and reproducible representation of the intuitive understanding of the synchronisation of series visually moving in parallel. Harding and Pagan (2006) suggest measuring the degree of synchronisation from multiple series $i^{t*}_{1,2010}, \dots, i^{t*}_{N,2010}$ via the concordance index, which has the form

$$I_N^T = \frac{1}{T}\left[\sum_{t=1}^{T}\left(\prod_{j=1}^{N} S_{jt} + \prod_{j=1}^{N}\left(1-S_{jt}\right)\right)\right] = \frac{1}{T}\sum_{t=1}^{T}\prod_{j=1}^{N} S_{jt} + \frac{1}{T}\sum_{t=1}^{T}\prod_{j=1}^{N}\left(1-S_{jt}\right) = I^T_{N,\mathrm{inc}} + I^T_{N,\mathrm{dec}}, \tag{4}$$

where S_{jt} is the indicator variable sequence resulting from series $i^{t*}_{j,2010}$ from Equation (3). Notice that for the two extrema, for each t, all S_{jt} will simultaneously take the value one (i.e. all series simultaneously increasing) or zero (i.e. all indices simultaneously decreasing during subsequent periods), and the concordance index I_N takes its maximum value of 1. Thus, the series shows strong perfect positive synchronisation (i.e. they move in the same direction in all observed periods). However, if all N series do not move in any period t in the same direction, then I_N takes its minimum value of 0, and the series shows strong perfect negative synchronisation. The concordance index I_N^T can be decomposed into $I^T_{N,\mathrm{inc}} + I^T_{N,\mathrm{dec}}$, denoting the concordance for jointly increasing and decreasing trajectories, respectively.

If T is the total number of observations available per time series, there is a single global estimate of average synchronisation results for the series of interest. If T is set to a (small) subset of the total number of observations, then, for that subperiod, a local estimate of average synchronisation between all indices $i^{t*}_{1,2010}, \dots, i^{t*}_{N_k,2010}$ is obtained. That idea allows for applying a rolling window version of this measure. We follow Fliessbach and Ihle (2022) by applying such time-dependent measurements of synchronisation for equal-sized rolling windows. We apply the following version of Equation (4):

$$I_t^{\Omega} = \frac{1}{\Omega}\left[\sum_{\theta_t=1}^{\theta_t+\Omega}\left(\prod_{j=1}^{N} S_{j\theta_t} + \prod_{j=1}^{N}\left(1-S_{j\theta_t}\right)\right)\right] = I^{\Omega}_{t,\mathrm{inc}} + I^{\Omega}_{t,\mathrm{dec}} \text{for } \theta_t = \{1, \dots, T-\Omega\}, \tag{5}$$

where Ω denotes the length of the window. Given only six observations available for the period of the invasion, we set the window length Ω to be 6 months.

Recall that Equation (3) allows for assessing whether the trajectories of the indices $i^{t*}_{j,2010}$ move in the same direction, which we refer to as synchronisation in the direction of price developments. As the magnitudes of the changes matter (World Bank, 2022b; Figures 2 and 3), we generalise Equation (3) as follows:

$$Z_{jt} = \begin{cases} 1 & \text{if } |\, i^{t*}_{j,2010} - i^{t-1*}_{j,2010} \,| > z \\ 0 & \text{otherwise} \end{cases}, \tag{6}$$

where the absolute value of the difference between subsequent realisations must be larger than a constant z such that $Z_{jt} = 1$. Hence, we extend the notion of synchronisation in the direction of development to synchronisation in the magnitudes of price changes defined as the share of periods during which they simultaneously change by more than z units. As the price indices $i^{t*}_{j,2010}$ are measured in percentage points, we set z such that it can separate periods during which the indices show large changes from 1 month to another from periods during which changes are small. We set

[8]Fliessbach and Ihle (2022) illustrate several stylized cases of such a comovement.

z to be three and five percentage points.[9] These minimum month-to-month changes (values for z) represent substantial magnitudes as $Z_{jt} = 1$ only if all price indices in this set jointly change by a large magnitude, which is an unlikely event, as their subindices must experience a sufficiently large change. The corresponding concordance index has the form:

$$H_N^T = \frac{1}{T}\left[\sum_{t=1}^{T}\left(\prod_{j=1}^{N} Z_{jt}\right)\right]. \tag{7}$$

Furthermore, to test whether the directions and magnitudes of global price comovement differ from their levels before the invasion, we first calculate the indices $I_{N_k}^1$ for every observation quantifying the concordance in each observed period $t = 1, \ldots, T$ of all series $i_{j,2010}^{t*}, j = 1, \ldots, N_k$ belonging to index set k.[10] We collect all indices $I_{N_k}^1$ for the set k, $k = 1, \ldots, K$ into a vector $\mathbb{I}_k$ with T elements.[11] We stack all the vectors, as in Equation (8), into one vector $\mathbf{I}$ with $T \times K$ elements and regress it on a constant and a dummy variable D_{invasion}. This variable takes unity for all monthly observations after January 2022, to indicate observations during the invasion. Consequently, we first estimate the pooled regression:

$$\mathbf{I} = \begin{bmatrix} \mathbb{I}_1 \\ \ldots \\ \mathbb{I}_K \end{bmatrix} = \alpha_1 + \alpha_2 D_{invasion} + e_{kt}, \tag{8}$$

where α_1 denotes the average level of synchronisation $\overline{S} = \alpha_1$ of all indices $I_{k,t<\text{Feb2022}}$ before the invasion. The coefficient α_2 denotes the difference in synchronisation before and during the invasion.[12] Thus, if α_2 is significantly larger than zero, it implies robust statistical evidence that synchronisation during the invasion has been stronger than before the invasion across all price index sets considered.

We estimate Equation (9) for tailored statistical evidence on the hypotheses. Equation (9) estimates set-specific differences in average synchronisation before and during the invasion for all 13 price index sets k (labelled as M1 for $k = 1$ to M13 for $k = 13$):[10]

$$\mathbf{I} = \begin{bmatrix} \mathbb{I}_1 \\ \ldots \\ \mathbb{I}_K \end{bmatrix} = \beta_1 + \sum_{k=2}^{K} \beta_k D_k + \sum_{k=1}^{K} \gamma_k D_k D_{\text{invasion}} + e_{kt}, \tag{9}$$

which is Equation (8) amended by the variable D_k that takes unity for all observations of $\mathbb{I}_k$. This model allows for estimating set-specific degrees of synchronisation $\overline{S}_{k,t<\text{Feb2022}} = \beta_1 + \beta_k$ before the invasion.[13] If β_k is significantly different from zero, the average synchronisation $\overline{S}_k$ in the price

[9]A joint change of several global price indices of more than three percentage points represents *a rare event* which only occurs in 6.5% of all cases considered. Thus, most of the underlying prices - being aggregated into the global indices - must have changed considerably. If such a joint change exceeds five percentage points, it is *an extremely rare event* in global commodity markets, as it occurs in 1.8% of all concordance indices calculated.

[10]For the exact definition of all 13 index sets, see Table 3. The base set M1 comprises the IGC maize, wheat and barley indices, which are commodities most immediately affected by the disruptions of supply chains originating from Ukraine. Sets M2 to M13 add one or more indices to this base set to assess the synchronisation among each set of commodity price indices.

[11]For estimating synchronisation in the magnitude of price changes via Equations (6) and (7), we follow the identical approach described here for H_N^T.

[12]We tailor the testing set-up in Equations (8) and (9) to the hypotheses of interest. Explaining the trajectories of the price indices in detail is scope for future research beyond this study. Thus, Models (8) and (9) do not contain any other variables potentially explaining the price indices.

[13]For this study, it is central to subdivide the number of observations $T = 153$ into the period before the invasion ($t <$ Feb 2022) and observations from the first 6 months of the invasion ranging from February to July 2022.

index set k differs from the synchronisation $\overline{S}_{M1,t<\text{Feb2022}} = \beta_1$ between the global wheat, maize and barley prices before the invasion. The sign of β_k indicates the direction of the statistically significant difference. Equation (9) allows for deducing the degrees of synchronisation of global commodity price indices during the invasion $\overline{S}_{k,\text{invasion}} = \beta_1 + \beta_1 + \gamma_k$[14] for $k > 1$ relative to the synchronisation $\overline{S}_{M1,t<\text{Feb2022}} = \beta_1$ of the benchmark set M1 comprising the IGC indices of global wheat, maize and barley prices. The sign and significance of coefficients γ_k reveal whether the synchronisation in price index set k since February 2022 statistically differs and in which direction it differs from the average synchronisation in the years before.

6 | RESULTS

The empirical analysis follows the three hypotheses while considering the direction of synchronisation via I_N^T and the magnitude of the resulting joint trajectories via H_N^T. Table 2 outlines the results of the pooled regression model (Equation 8) for all three dimensions of synchronisation considered: whether the global price indices move jointly in the same direction and whether the changes of the indices from 1 month to another jointly exceed three and five percentage points, respectively. From Table 2 (last column), synchronisation in all three dimensions was higher by a multiple during the invasion than for the average prior period. While the indices in each of the 13 index sets moved in parallel in 46% of the months, this comovement jumped across all 15 global price indices to 78% during the invasion. The series within the index sets showed joint changes from 1 month to another of more than three (five) percentage points only for 5% (0.7%) of the months before the invasion. Notably, this jumped to 41% (28%) during the invasion. It implies that the global commodity price indices moved more strongly into a joint (upward) direction during the invasion, and the incidence of joint month-to-month changes of large and extremely large magnitude was much more common than in the years before.

We visualise selected time-varying concordance indices by decomposing $I_N^{\theta_t}$ as in Equation (4). This gives insight into the periods of jointly increasing ($I_{N,\text{inc}}^T$) and decreasing synchronisation trajectories ($I_{N,\text{dec}}^T$). We plot both components to provide graphical evidence of when the series that belong to a certain index set k jointly increased or decreased.

TABLE 2 Results of the testing for a general effect of the invasion

Model	Synchronisation strength: Before the invasion	Synchronisation strength: During the invasion	Percentage change
Synchronised trajectory direction	0.46***	0.78***	+70%
Synchronised trajectory change of more than three percentage points (rare magnitude of change)	0.05***	0.41***	+688%
Synchronised trajectory change of more than five percentage points (extremely rare magnitude of change)	0.007**	0.28***	+3929%

Note: *, ** and *** denote significance at the 10%, 5% and 1% levels, respectively. Table S4 presents detailed results.
Source: Authors.

[14]For the benchmark set, M1, comprising the IGC maize, wheat and barley indices (see Table S3), holds that $\overline{S}_{M1,t<\text{Feb2022}} = \beta_1$ and $\overline{S}_{M1,\text{invasion}} = \beta_1 + \gamma_1$.

We first assess the time-varying synchronisation in the direction of price trajectories for the set M1 comprising the IGC wheat, barley and maize price indices. Recall that for these three commodities, Ukraine has significant world market shares, and their maritime export has been completely blocked since 24 February 2022. Figure 4 shows that the three indices jointly moved upward since February 2022 before they synchronously decreased in July. Since 2010, the three indices jointly moved upward for at least six consecutive months (the dashed line being at 1) only during three periods: in late 2010 and early 2011, from late 2020 to June 2021 and in 2022. The gap between the end of the first phase of perfect synchronisation and the beginning of the second phase of 113 months suggests that these phases are rare. Still, a third phase occurs only 5 months after the second phase. Such a speedy re-occurrence is of low likelihood and plausibly induced by the invasion. The areas shaded in dark (light) grey in Figure 4 mark periods during which wheat, maize and barley are jointly increasing (decreasing) in more than 50% of the past 6 months, visible via the dashed (dotted) line exceeding 0.5. During the periods marked in white, they were barely or not at all synchronised. Each of these three periods of full, partial and no synchronisation accounts for about one-third of the observed time.

Next, we assess the synchronisation of the three indices with the World Bank indices for global energy prices and global fertiliser prices (set M2). Figure 5 shows that comovements of the five global commodity prices are much less frequent than between the three grain prices only. All five prices rise jointly in only 20% of the observed time and jointly fall in 15%. In two-thirds of the time, their trajectories barely or not at all develop in the same direction. Phases with joint increases are rarer, as for set M1, but occur extensively in 2021 and 2022. During the Russian invasion, global grain prices experience a sustained upward movement jointly with global energy and fertiliser prices only 5 months after the preceding joint increase had ended.

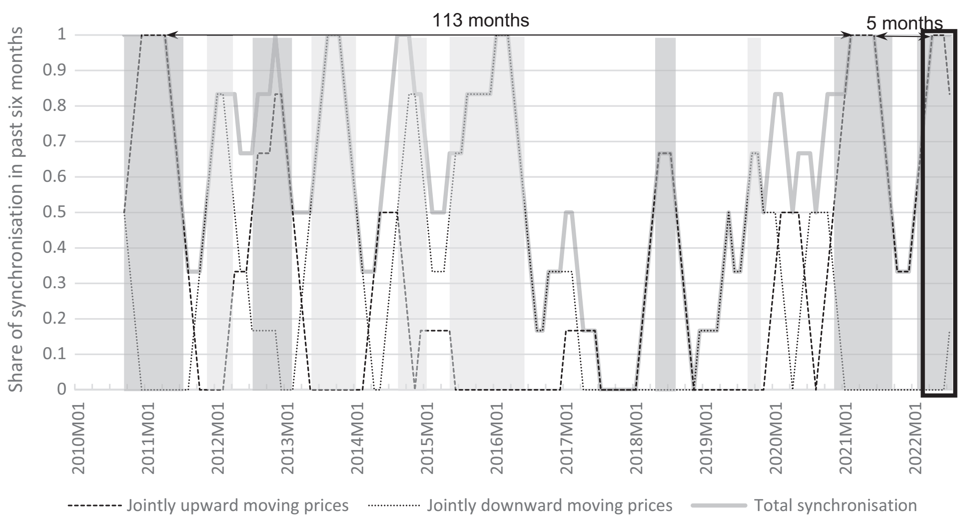

FIGURE 4 Synchronisation in increasing and decreasing global wheat, maize and barley prices. *Note*: This graph characterises time-varying synchronisation in the direction of the price index developments of the commodities belonging to set M1 (see Table 3). It shows the share of months during the past half year during which all three price indices either jointly increased or jointly decreased. The period highlighted with a thick black frame marks the invasion. The thin black dashed (dotted) line denotes the rolling window values $I_{t,inc}^{\Omega=6}$ ($I_{t,dec}^{\Omega=6}$) and the solid grey line denotes $I_{t}^{\Omega=6} = I_{t,inc}^{\Omega=6} + I_{t,dec}^{\Omega=6}$; that is, the vertical sum of the dashed and dotted lines. If a line takes the maximum of 1 (minimum of 0), then the indices have perfectly (not) been moving in the same direction during the past 6 months. The graph suggests that the three indices are rarely perfectly synchronised, and if they are moving in the same direction, then typically for only a few months. Table S6 shows that the three indices were in perfect synchronisation (in any direction) in 19% of all periods observed (each of 6-month duration). *Source*: Authors.

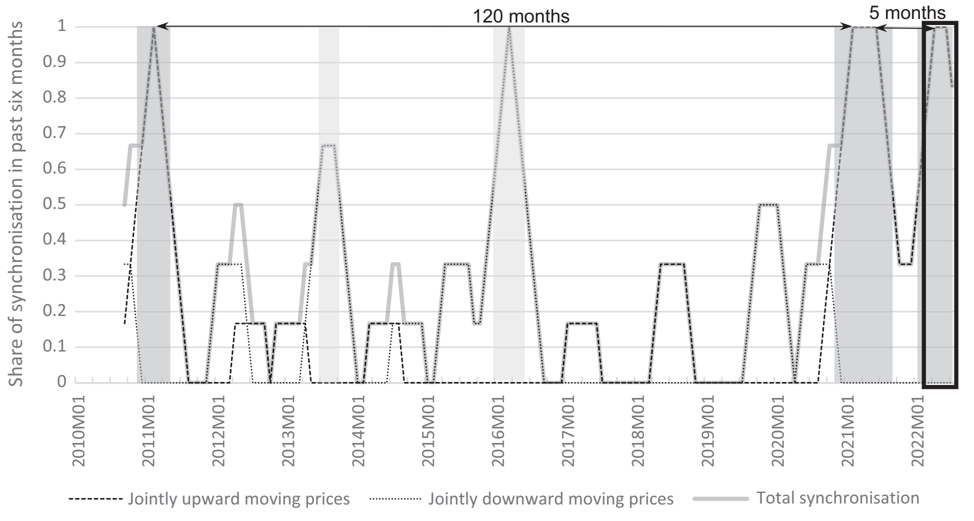

FIGURE 5 Synchronisation in global wheat, maize, barley, energy and fertiliser prices. *Note*: This graph characterises time-varying synchronisation in the direction of the price index developments of the commodities belonging to set M2. Table S6 shows that these indices were in perfect synchronisation (in any direction) in 7% of all periods observed (each of 6-month duration). *Source*: Authors.

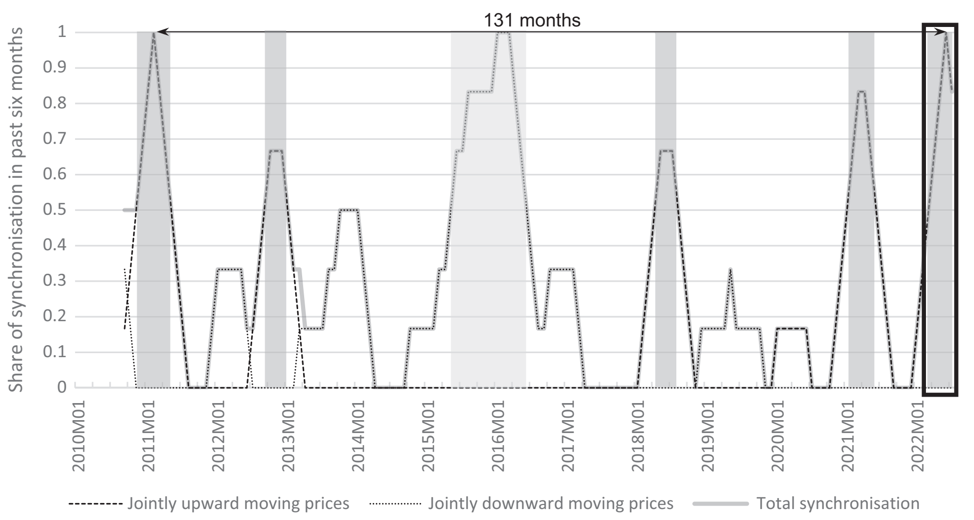

FIGURE 6 Synchronisation in global wheat, maize, barley, rice and soybean price indices. *Note*: This graph characterises time-varying synchronisation in the direction of the price index developments of the commodities belonging to set M3. Table S6 shows that these indices were in perfect synchronisation (in any direction) in 3% of all periods observed (each of 6-month duration). *Source*: Authors.

In set M3, we assess whether the synchronisation between the initial indices of set M1 resulted in spillovers towards the direction of the trajectories of the two remaining IGC sub-indices of soybeans and rice. As the latter commodities closely associate with the former, spillovers are likely. Figure 6 reiterates the patterns observed in the previous two graphs. In 65% of the time, the five indices move barely or not at all in the same direction. The complete synchronisation between all five commodity indices is approximately half as frequent as that for wheat, maize and barley (set M1). Periods of perfect comovement tend to be short and rare. In June 2022, all five commodity prices moved globally upwards for six subsequent months for the first time since 2011. This finding implies that the market situation from blocked Ukrainian wheat, maize, barley and sunflower oil exports has yielded strong spillover effects on rice and soybeans prices even though their supplies have not been impeded by the warfare in Ukraine.

We complete the analysis with assessing the synchronisation of wheat, maize and barley prices with the remaining global price indices of the World Bank (2022c) classification: the IGC GOI (set M4); global food price index (set M5); beverages price index (set M6); agricultural prices index (set M7); raw materials price index (set M8); metals and minerals price index (set M9); nonfuel price index (set M10); precious metal price and energy and nonfuel prices indices (sets M11 and M12) and all subindices in the World Bank agricultural price index (set M13). Patterns of all the index sets resemble those discussed. We posit that Russia's invasion of Ukraine induced all sets of global price indices to follow a strongly or perfectly synchronised development. Moreover, the tendency is visible that the more diverse the commodities an index set includes, the weaker the synchronisation. The Appendix S1 provides these graphs for the remaining index sets.

Table 3 outlines the results of Equation (9) for synchronisation in the direction and magnitude of monthly index changes. Synchronisation differs significantly across the sets of global price indices. Before the invasion, it was strongest for global wheat, maize and barley prices (M1) in all three dimensions. Many of the remaining index sets had a significantly weaker synchronisation. Only the synchronisation in direction between the prices of the three commodities with the IGC grains and oilseed index (M4) and the World Bank indices for global food prices (M5), agricultural prices (M7) and nonfuel prices (M10) is not significantly smaller than that between the three grain prices in M1.

Table 3 confirms the three research hypotheses. First, we find that the global prices of three grains in M1, for which Ukraine is a major exporter, experienced large and extremely large synchronous changes significantly more often during the invasion than before. Moreover, all three global price indices of M1 developing in the same direction were more frequent during the invasion (Table S5). We find an identical pattern of significantly higher synchronisation of these three indices with the indices of global energy prices and fertiliser prices in M2, providing strong evidence that those five commodity groups have jointly moved up at large magnitude during the invasion. In the decade before, they have occasionally moved synchronously but virtually never with such large monthly rates of change as currently observed.

The results in Table 3 also confirm the third hypothesis, as most of the index sets other than those considered in the first hypothesis have experienced significantly higher degrees of synchronisation at the 5% level during the invasion in direction and magnitude. This holds for the three grain price indices and the IGC GOI (M4), the food price indices (M5), the agriculture price indices (M7) and the precious metals price indices (M11) in all three dimensions. No difference in synchronisation before and during the invasion exists for the sets of grain price indices and beverage price indices (M6), raw materials price indices (M8), energy, nonfuel and precious metals price indices (M12), and food, beverages and raw materials price indices (M13). For M3, M6, M9 and M10, synchronisation is higher in at least one of the dimensions.

These results provide robust empirical evidence that the concerns about global grain markets and global food security that emerged since the start of the invasion have significantly spilled over to many other commodity markets monitored by World Bank (2022c) and IGC (2022). In most such markets, the concerns have produced price trajectories that are synchronous with price trajectories in grain markets where global supply chains were cut off. This insight holds, especially, for the World Bank global food price index.

TABLE 3 Results of the testing for index-set-specific effects of the invasion

Index set		Synchronised direction		Synchron. change >3 percentage points		Synchron. change >5 percentage points	
Set of global price indices	**Code**	**Before invasion**	**During invasion**	**Before invasion**	**During invasion**	**Before invasion**	**During invasion**
Wheat, maize and barley	**M1**	**0.61*****	1.00*	**0.15*****	0.83***	**0.04****	0.67***
M1 and energy and fertiliser	**M2**	0.33***	0.83**	0.02***	0.67***	0.00***	0.50***
M1 and rice and soybeans	**M3**	0.32***	0.83**	0.01***	0.00	0.00***	0.00
M1 and ICG GOI	**M4**	0.56	1.00**	0.13	0.83***	0.03	0.67***
M1 and food	**M5**	0.56	1.00**	0.06***	0.67***	0.01	0.50***
M1 and beverages	**M6**	0.47**	0.33	0.02***	0.00	0.00***	0.00
M1 and agriculture	**M7**	0.57	1.00**	0.04***	0.67***	0.00***	0.17***
M1 and raw materials	**M8**	0.49**	0.83*	0.03***	0.00	0.00***	0.00
M1 and metals & minerals	**M9**	0.42***	0.67	0.07***	0.67***	0.01	0.50***
M1 and nonfuel commodities	**M10**	0.54	0.83	0.05***	0.50***	0.00***	0.50***
M1 and precious metals	**M11**	0.39***	0.83**	0.07***	0.33**	0.01	0.17***
M1, energy, nonfuel and precious metals	**M12**	0.29***	0.67*	0.01***	0.17*	0.00***	0.00
M1, food, beverages and raw materials	**M13**	0.37***	0.33	0.01***	0.00	0.00***	0.00

Note: For each of the three models, *, ** and *** denote significance of the differences from the average synchronisation in the benchmark set M1 before the invasion marked in bold (being the $\widehat{\beta}_1$ of Equation [9]) at the 10%, 5% and 1% levels, respectively. For the bold estimates, the asterisks denote the significance from zero. Table S5 presents detailed results. For the series included in each index set, see Table S3. M12 (M13) corresponds to the nonenergy (agriculture) commodity aggregations of World Bank (2022c).

Source: Authors.

7 | CONCLUSION

On 24 February 2022, the Russian Federation invaded Ukraine. A major global repercussion was that it completely blocked Ukrainian maritime trade routes. This study provides the first quantitative analysis of the effect of the invasion on the synchronous development of global commodity prices. We focus on the effects on goods for which Ukraine and Russia account for major global exports and assess to what extent price developments spilled over to commodity groups for which the two countries do not play a role in global exports.

We analyse 15 indices published by World Bank (2022c) and IGC (2022) that represent global price developments for specific grains and a wide range of other internationally traded commodities. For most global price indices, periods in which they jointly move upwards or downwards for at least six subsequent months are rare and short-lived. Joint month-to-month changes in large magnitude occur even more rarely. Furthermore, the analysis finds that the more diverse the set of commodity prices, the less frequent such phases appear, and the shorter they are.

Before the invasion, synchronisation between closely related commodities such as wheat, maize and barley was quite strong in all dimensions. The trajectories of most sets of price indices are substantially stronger or even perfectly synchronised since the start of the invasion than during the previous years. Global commodity price indices moved in a parallel, upward-trending direction during the first 5 months of the invasion, and joint month-to-month changes in large magnitudes were more common than in prior years. The synchronisation of price trajectories regarding their direction and magnitude spilled over from commodities whose supply chains were interrupted for months due to the Russian blockade of the Ukrainian Black Sea coast (grains and oilseeds) or due to economic sanctions against Russia (energy commodities and fertilisers) to commodities whose markets were not directly affected by the invasion.

The results affirm the findings of Ai et al. (2006) and Lescaroux (2009) that global prices of commodities whose supply chains experienced the covariate disruption from the invasion are significantly stronger synchronised. Our results also confirm the excess comovement hypothesis of Pindyck and Rotemberg (1990) as global price synchronisation has been found to have substantially increased for those commodities whose supply chains were not disrupted by the invasion. Thus, Russia's invasion of Ukraine represents a covariate shock to global commodity markets, as prices of most internationally traded commodities show stronger synchronisation since February 2022. This shock structurally increased synchronisation between global wheat, maize and barley prices and global energy and fertiliser prices, global grain prices represented by the grains and oil seed index of the IGC, global food and global agricultural products prices, and global precious metal prices.

We obtain robust evidence that the effects of the type of supply chain disruption such as Russia's invasion are not limited to the commodities that are immediately affected by transport restrictions. It creates a contagion across numerous food and nonfood markets, thus creating food insecurity and inflationary pressures at broad scale. The simultaneous increase in most global food prices reduces consumer ability to compensate for the resulting negative effects by substituting for alternative cheaper foods. This aggravates and creates new food insecurity for the poor and vulnerable in the Global South, who must spend large shares of their income on food expenditures and can only receive limited support from the barely existing national social security systems. This challenge adds further strain to the multitude of existing problems in the Global South from more extreme weather patterns given climate change or violent political conflict. Promising options to tackle this issue could be market interventions at governmental level and resilience interventions at household level. Governments could be tempted to interfere in markets and exercise price or trade controls, as reported by Glauber et al. (2022). The establishment of strategic staple food stocks at the national level is another option that would balance farmers' selling prices and, if distributed in a targeted way to the poor, ease food insecurity for the most vulnerable.

The resilience of global food supply chains must be sustainably improved at the national level to minimise the adverse effects of possible multiple simultaneous crises. Accordingly, the government can promote the productivity of national agriculture to reduce import dependence (Veninga & Ihle, 2018) or raise demand for food not being traded on international markets but regionally produced and consumed. For example, the African Development Bank has established the African Emergency Food Production Facility worth $1.5 billion to help Africa's smallholder farmers to feed the continent (AFDB, 2022).[15] Such a structural transformation of Africa's food system can be an opportunity (UNSDG, 2022) but could also bring sizable negative externalities for the environment and the use of additional natural resources. So, there are no clear-cut solutions to this complex problem.

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DATA AVAILABILITY STATEMENT

The data that support the findings of this study are openly available in World Bank Commodity price Data at https://www.worldbank.org/en/research/commodity-markets and in International Grains Council Grains and Oilseed Index at http://www.igc.int/en/markets/marketinfo-goi.aspx.

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SUPPORTING INFORMATION

Additional supporting information can be found online in the Supporting Information section at the end of this article.

Appendix S1

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