Norwegian University
of Life Sciences

Master's Thesis 2024 30 ECTS
School of Business and Economics

Price Dynamics in Agriculture: Investigating Relationships between Fertilizer, Energy, and Grain Prices

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Master of Science in Applied Economics and Sustainability

Abstract

This thesis investigates the complex relationships between agricultural commodity prices (wheat, corn, soybeans), key fertilizer components (urea, Diammonium phosphate (DAP)), and energy sources (natural gas prices from Henry Hub and Title Transfer Facility (TTF)) from 2009 to 2023. Employing robust econometric techniques including cointegration analysis, Granger causality tests, and Autoregressive Distributed Lag (ARDL) models, the study examines both long-term equilibria and short-term dynamics within these markets. A focused sub-analysis from 2017 to 2023 highlights the intensified market dynamics during significant global economic disruptions such as the COVID-19 pandemic and geopolitical tensions from the Russia-Ukraine conflict, which have emphasized the critical interdependencies and heightened volatility across the examined markets.

The findings reveal substantial long-run cointegrating relationships between natural gas, fertilizer, and agricultural commodity prices, highlighting the sensitivity of grain prices to changes in energy and fertilizer markets. Short-run dynamics indicate that price volatilities across these markets are significantly driven by sudden energy price changes, with pronounced ripple effects observed in the fertilizer and agricultural sectors. Furthermore, the sub-sample period analysis provides valuable insights into the adaptive behaviors and strategic responses within the agricultural sector in response to external economic shocks.

By unveiling these intricate relationships and dependencies, this study contributes to the academic field by enhancing the understanding of the interactions between these critical commodities. Furthermore, it offers practical insights for policymakers, investors, and stakeholders within the agricultural sector. Recognizing these relationships empowers stakeholders to make more informed decisions regarding production planning, risk management, and policy formulation, aimed at enhancing food security and market stability in the face of future economic uncertainties. The research enables stakeholders to anticipate and mitigate potential disruptions, fostering a more resilient and sustainable agricultural supply chain.

Acknowledgments

This thesis concludes my master's program in Economics at NMBU School of Economics and Business. Working on this thesis has been both educational and challenging. I learned a lot about commodity markets and how to analyze them.

I would like to extend my heartfelt gratitude to my supervisors, Ole Gjølberg and Marie Steen. Their invaluable guidance, insightful comments, and prompt responses to my queries have been instrumental in the successful completion of this thesis. I am immensely grateful for their continuous support and the time they dedicated to helping me navigate the complexities of this research.

Additionally, I would like to express my sincere appreciation to Muhammad Yahya as his expert advice and assistance was crucial at various stages of my research, and his support significantly contributed to the overall quality of this thesis.

Finally, I would like to thank my parents for their prayers and moral support that will be part of my life forever. My heartful gratitude goes to my friend Simpoli for her patience and care throughout my thesis. I am also thankful to my friends, family, and my precious bird Rajkumari for their support and love.

All errors or inaccuracies that remain are fully my own.

Nimra Arshad
Ås, May 2024

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1. **Introduction**

This study analyzes the long-term and short-term price relationships among fertilizer components such as urea and Diammonium phosphate (DAP), natural gas, and wheat, corn, and soybeans. Understanding these relationships is crucial for forecasting agricultural commodity prices, managing market risk, and developing effective policies to ensure food security and economic stability.

Among the key factors influencing agricultural commodity prices, the prices of fertilizers and energy resources play a significant role. Scenario analyses by United Nations (2023) estimate that a 1% increase in fertilizer prices could lead to a 0.2% rise in agricultural commodity prices. Additionally, the commodity markets experienced a significant decline in prices and heightened volatility across various sectors (Gunzberg, 2016). Such enormous price volatility in commodity markets can have significant negative impacts on agricultural commodity prices and market risk management, especially for developing countries and those heavily reliant on agricultural commodity trade. Furthermore, the dynamics of commodity prices exert substantial effects on the overall stability of economies, as well as income and consumer purchasing power. These effects are particularly pronounced in developing countries, where a significant portion of household income is devoted to food expenses (Lucotte, 2016).

A large body of literature has investigated the determinants of agricultural market prices, with a majority focusing on the impact of the US dollar exchange rate (Stuemer, 2016), global demand shocks on commodity markets, and excessive speculation in these markets (Boyd et al., 2018). However, the extent to which input prices drive fluctuations in agricultural commodity markets has received considerably less attention. Input prices are crucial factors in agricultural production, impacting the supply of commodities and, consequently, market prices (Etienne et al., 2016).

The fertilizers examined in this study are urea and DAP, which are nitrogen-based granular fertilizers. The production of these nitrogen-based fertilizers primarily relies on air and natural gas as inputs. The energy price considered is the price of natural gas, recognized as the cleanest fossil fuel. According to a study by Flores et al. (2022), global fertilizer prices are closely linked to global natural gas prices. Their findings indicate that due to the impacts of COVID-19 and the Russian-Ukraine war, both global fertilizer prices and natural gas prices have been fluctuating since late 2020. This relationship between fertilizer and natural gas prices underscores the importance of understanding the dynamics between energy inputs and agricultural commodity prices.

The grain prices examined in this study are those of wheat, corn, and soybeans. While soybeans are often categorized as oilseeds, we will collectively refer to wheat, corn, and soybeans as grains for this study. Furthermore, the decision to cultivate food crops like wheat and corn or oil crops like soybeans is often influenced by factors such as limited acreage (Alexandratos & Bruinsma, 2012)and market demand dynamics (Rapsomanikis et al., 2015). Wheat and corn require significant amounts of nitrogen fertilizers for optimal growth, particularly during the vegetative and reproductive stages. In contrast, soybeans, being a leguminous crop, require less nitrogen fertilizer due to their nitrogen-fixing ability through symbiotic relationships with soil bacteria.

Fertilizers and grains have an input-output relationship, where fertilizers serve as crucial inputs for grain production. Consequently, there should be a direct connection between fertilizer and grain prices. Baffes and Kabundi (2023) show that when fertilizer prices increase, driven by rising natural gas prices (a key input in fertilizer production), the grain prices are likely to follow suit, although the timing and extent of this pass-through may vary depending on the industry's ability to respond to increases in input costs (Baffes & Dennis, 2014). Despite the recognized significance of fertilizers and energy inputs in agricultural production, there is a significant knowledge gap in comprehending the direct interdependencies and causal linkages between fluctuations in urea, DAP, and natural gas prices, and how they impact the price movements of wheat, corn, and soybeans (Nazlioglu et al., 2013) .

This study seeks to investigate the relationships and interdependencies between energy prices, fertilizer prices, and grain commodity prices in the global market. Specifically, it aims to examine how fluctuations in natural gas prices, influence the prices of urea and DAP – two widely used nitrogen-based fertilizers – and subsequently impact the prices of major grains such as wheat, corn, and soybeans.

Motivated by the need to bridge the knowledge gap in understanding the complex interplay between energy prices, fertilizer costs, and grain commodity prices, this study seeks to address the following key research questions:

RQ1: What are the long-term equilibrium relationships, if any, between natural gas prices, urea and DAP prices, and wheat, corn, and soybean prices in the global market?

RQ2: How do short-term fluctuations in natural gas prices impact urea and DAP prices, and subsequently influence short-term movements in wheat, corn, and soybean prices?

RQ3: What is the direction and magnitude of causal links and price transmission mechanisms among these commodity markets?

RQ4: Can changes in natural gas, urea, and DAP prices be effectively utilized to forecast fluctuations in wheat, corn, and soybean prices?

The findings of this research may hold significant importance for various stakeholder groups. For producers, including farmers and agricultural practitioners, the insights gained from this study can be leveraged to plan and hedge price risks more effectively. By understanding the intricate relationships between energy prices, fertilizer costs, and grain commodity prices, producers can make more informed decisions regarding planting, procurement, and risk management strategies. Consumers, on the other hand, can better anticipate changes in food prices and adjust their consumption patterns accordingly, thereby mitigating potential economic impacts. Moreover, the study's findings will be valuable for governments and policymakers, as they can utilize them to inform policies aimed at enhancing food security, managing market risks, and promoting sustainable agricultural practices. This is particularly crucial for developing countries, where a significant portion of household income is devoted to food expenses. Lastly, speculators and investors involved in agricultural and commodity markets can make more informed investment decisions based on a comprehensive understanding of the price dynamics and drivers uncovered by this research.

The thesis progresses as follows: Section 2 reviews the relevant literature, while Section 3 provides a background on key commodities. Section 4 discusses the theoretical framework, and Section 5 details the methodology used. Section 6 presents the data, followed by Section 7 which offers an econometric analysis of the findings. The thesis concludes with Section 8, synthesizing insights and suggesting future research directions.

2. Literature Review

Extensive research has been conducted to examine the co-movement of prices across various commodity markets, including agriculture, minerals, and energy. This chapter provides an overview of the relevant literature and theory concerning commodity price movements. The chapter begins with seminal contributions on general commodity markets and then transitions to recent research specifically addressing grain markets, as well as the relationships among grain, fertilizer, and energy markets.

The expanding literature on fertilizer price developments, energy price formation, and their interactions with grain prices highlights important trends and interdependencies. Studies have explored various aspects, such as the long-run relationship between fertilizer and natural gas prices, and their impact on commodity prices (Gary, 2016; Ott, 2012). Additionally, research has examined price interdependencies across different energy markets (Perifanis & Dagoumas, 2018; Serletis & Herbert, 1999; Siliverstovs et al., 2005). While some studies have focused on specific relationships among fertilizers, natural gas, and agricultural commodities, many have concentrated on the dynamics between the two commodities.

For instance, Huang and Wen-Yuan (2007) analyzed the influence of natural gas prices on ammonia prices using co-integration analysis, demonstrating that rising natural gas prices led to a significant decline in ammonia production. Ott (2012) provided evidence that increasing oil and natural gas prices triggered higher nitrogen nutrient prices, as their production is heavily reliant on energy inputs. Allen et al. (2018) employed bivariate cointegration and impulse response analyses, revealing that agricultural commodity prices are closely aligned with energy prices. Chiou-Wei et al. (2023) applied a DCC-MGARCH model to assess the interconnectedness among energy and commodity prices, identifying varying degrees of co-movement in both the short and long run.

Similarly, numerous studies have examined the relationship between energy prices and agricultural commodity prices, although the specific commodities studied have varied. Chowdhury et al. (2021) found that a positive change in energy prices has a stronger and longer-lasting impact on agricultural commodities compared to a negative change, which has a shorter-lived effect. Radmehr and Henneberry (2020) employed Pedroni cointegration tests and dynamic fixed effects models, finding that food prices increase in response to rises in energy prices in both the short and long term. Su et al. (2019) investigated causalities between energy and agricultural prices, discovering a bidirectional positive causality. Koirala et al. (2015) used high-frequency data and contemporary methodologies to demonstrate a significant positive relationship between agricultural commodities and energy futures prices, which are highly correlated. Cabrera and Schulz (2016) employed a multivariate multiplicative volatility model to assess short- and long-run linkages between energy and agricultural commodity prices, concluding that they move together in the long run, while in the short run, agricultural commodity prices are less responsive to changes in energy prices. Baffes and Haniotis (2016) analyzed six agricultural commodities to identify the key drivers of their prices and concluded that increases in energy prices were the main factor behind rising agricultural commodity prices during a recent boom. Baffes and Dennis (2014) examined the role of various sectors in agricultural commodity price increases using the reduced-form econometric model and found that more than 50% of these increases can be attributed to energy prices.

Fertilizer prices experienced significant increases during the recent price spike, contributing to the intricate interplay between energy and agricultural commodity prices. A comparative study of food, oil, and fertilizer prices revealed that between 2003 and 2008, while the prices of food and precious metals doubled and energy prices increased by 230 percent, fertilizer prices experienced a fourfold increase (Piesse & Thirtle, 2009). Heady and Fan (2008) estimated that fertilizer prices alone account for over a third of total operating costs and 15-20 percent of total costs in US corn and wheat production. Their estimation suggests that between 2001 and 2007, if the increase in fuel, fertilizer, and oil-related farm production costs were disregarded, the expenses of corn and wheat production in the US would have been 30-40 percent lower. Wongpiyabovorn (2021) examined structural changes in the relationship between nitrogen and natural gas prices and found that natural gas prices significantly affect nitrogen fertilizer product prices and anhydrous ammonia prices, although more recent data indicated that other factors might have a greater impact on these prices. Humber (2014) estimated the impact of the 2010 merger using a structural vector autoregressive model. The results showed that fertilizer prices increased by 75 percent due to the merger, with unidirectional causality from natural gas to fertilizer prices and bidirectional causality between corn and fertilizer prices. A study by Sanyal et al. (2015) showed that changes in energy prices significantly impact fertilizer prices, suggesting that the volatility effects of energy prices on fertilizer prices are substantial.

Rezitis (2015) used VAR methods and Granger causality tests to analyze the relationship between agricultural commodity prices, crude oil prices, and exchange rates, finding bidirectional causality effects between crude oil prices and agricultural prices. Headey and Fan (2008) provided a comprehensive overview of the 2007-2008 price hikes, highlighting the substantial influence of energy prices, particularly oil and fertilizer prices, on agricultural commodity prices. Similarly, Khan et al. (2010) applied the ordinary least squares method and discovered that fertilizers are highly energy- and gas-intensive, with recent increases in energy and gas prices, subsequently affecting fertilizer prices, leading to higher input prices for agricultural commodities and consequently elevated agricultural prices. Wang and McPhail (2014) employed a structural VAR model to examine the effects of energy price shocks on agricultural commodity prices, finding that energy shocks accounted for approximately 50% of commodity price changes in the long run. Ripplinger et al. (2017) applied cointegration, causation, and correlation analyses to study the relationships between fertilizer, natural gas, and corn prices, revealing strong linkages among these commodities.

Recent research has continued to emphasize the intricate dynamics between energy and agricultural prices. Vatsa et al. (2023) used structural VAR autoregression to analyze the effects of changes in natural gas and nitrogenous fertilizers on major commodities, finding that commodity prices respond rapidly to price changes in energy and fertilizers. Similarly, Etienne et al. (2016) investigated price and volatility transmission between natural gas, ammonia, and corn markets, discovering strong long-run and short-run linkages between fertilizer and corn markets, although only mild linkages in prices and volatility existed between those markets and natural gas prices.

Various time series techniques have been employed to empirically examine the relationships between these variables. The error correction model is commonly used to investigate both short- and long-run relationships among natural gas, fertilizer, and corn prices (Beckman & Riche, 2015; Etienne et al., 2016). Lucotte (2016) found empirical evidence on the crude oil and food price nexus using VAR models to assess their co-movements. Nazlioglu and Soytas (2012) examined the price transmission mechanism between world oil and three agricultural commodity prices using linear and non-linear cointegration and causality methods. Gnutzmann and Spiewanowski (2016) applied a cointegration approach to examine the impact of changes in crude oil prices on the causal relationship between fertilizer and food prices, finding a significant impact of fertilizer prices on food prices, even more so than direct energy prices. Geng et al. (2017) investigated the causality relationship between pairs of variables, uncovering unidirectional linear Granger causality from the crude oil market to North American and European markets. Similarly, Nazlioglu (2011) found unidirectional causality from oil prices to agricultural commodities using linear and non-linear cointegration and causality methods. Zeneli (2022) used time series models and several techniques, including cointegration and causality, to assess the relationships between crude oil, natural gas, and grain prices. Lahmiri (2017) used cointegration and causal linkages among different fertilizer markets, finding that these markets are closely linked. Another study by Nazlioglu and Soytas (2012) reported unidirectional causality from oil prices to agricultural commodities using linear and non-linear cointegration and causality methods.

To conclude, the literature on commodity price co-movement highlights the intricate and varied relationships among energy, fertilizer, and agricultural commodity markets. While many studies have provided valuable insights, their findings offer mixed evidence regarding the nature of these relationships, emphasizing the need for further investigation. This study aims to fill this gap, utilizing a comprehensive approach to better understand these dynamics. The impact of recent global events, such as the COVID-19 pandemic and the Russia-Ukraine conflict, has further underscored the importance of examining these interconnected markets, as disruptions in one can significantly affect the others, impacting food security and economic stability.

3. Background

Natural Gas

Natural gas is a fossil fuel primarily composed of methane, a colorless and odorless gas. It is typically extracted from subterranean reservoirs, often located near oil deposits, through drilling processes. Natural gas plays a crucial role as an energy source for diverse applications, including industrial processes like the manufacturing of fertilizers and chemicals.

This vital connection between natural gas and fertilizers extends into the agricultural sector, illustrating the deep interdependence between energy and agricultural markets. Both sectors are subject to the same economic forces as agricultural production relies heavily on energy products such as oil and natural gas. Variations in these energy prices can significantly influence the costs associated with agricultural inputs and transportation. Consequently, increases in oil and gas prices encourage the adoption of biofuels and other alternative energies and also lead to higher prices for agricultural commodities, particularly affecting food prices (Chiou-Wei et al., 2023).

Natural gas markets are often divided into three major regional markets: North America, Europe, and Asia-Pacific. In terms of market size, The United States is the largest consumer of natural gas, accounting for about 20% of global consumption in 2023, while Russia and China account for about 11% and 7% of global consumption, respectively (Review, 2024). The European Union is a significant importer, with the United Kingdom and the Netherlands as the main producers of natural gas in Europe. The North American market is centered on the US, which has a substantial domestic production of almost 978 billion cubic meters of gas annually. In Asia-Pacific, Japan and South Korea are by far the largest importers of natural gas (Enerdata, 2022a). The leading natural gas producers globally are the United States, Russia, Iran, and China, which collectively account for nearly 50% of the world's natural gas production (Enerdata, 2023).

The price of natural gas is of significant economic interest, and understanding price formation at liberalized natural gas hubs is complex due to a variety of influencing factors. The world's largest natural gas hub is Henry Hub in the United States. Compared to the natural gas Title Transfer Facility (TTF), which is the main reference virtual market for gas trading in Europe, the prices at Henry Hub have increased more aggressively over time (Enerdata, 2022b). The fluctuations in natural gas prices can be attributed to several factors, including natural gas consumption, natural gas gross withdrawals, monthly West Texas Intermediate (WTI) crude oil spot prices, and weather fluctuations (Li et al., 2021).

The crucial role of natural gas in bridging agricultural and energy commodities is evident through its integral use in the production of key agricultural inputs. Serving as a primary feedstock for nitrogenous fertilizers, natural gas significantly boosts agricultural productivity and growth. The AGA (2023) notes that natural gas is essential to the U.S. economy, particularly through its role in enabling the production of agrochemicals that enhance crop yields. Over the past 15 years, the expansion of domestic natural gas production has significantly boosted fertilizer production in the U.S.

Natural gas is essential for synthesizing nitrogen, a major component of fertilizers, alongside phosphate and potash. It serves as the primary input for ammonia synthesis in the Haber-Bosch process, facilitating the mass production of fertilizers and increased crop yields. An estimated 70 to 80% of the energy required to produce vital fertilizers for crops like wheat, soybeans, corn, rice, and oats comes from natural gas. This has led to marked yield improvements, especially for staple grains such as wheat. Moreover, the agrochemical industry relies heavily on natural gas not only as a fundamental ingredient for chemical synthesis but also as a vital source of process heat and steam, crucial for maintaining controlled crop cultivation environments. According to EIA (2023), natural gas prices can be influenced by various factors, among which weather patterns, storage levels, trade dynamics, and economic growth are among the most common and influential determinants.

Fertilizers

Fertilizers are essential components in enhancing plant productivity and development. By increasing soil fertility, fertilizers play a crucial role in promoting robust plant growth.

Fertilizers are classified by their content of three principal nutrients: nitrogen, phosphorus, and potassium, which are critical for plant health. In the broader field of agrochemicals, a diverse range of fertilizers contribute significantly to agricultural productivity and effective crop management. The demand for these essential nutrients has notably surged in recent decades. A report by GECF (2024) indicates that the consumption of fertilizer nutrients has quadrupled since 1960 and is projected to continue its upward trend in the coming years.

This study specifically narrows its focus to urea and DAP, two of the most widely used fertilizers globally. The selection of urea and DAP is driven by their high nitrogen content and their critical role in the agricultural nutrient supply chain. By focusing on these two fertilizers, the research aims to explore the importance of nitrogen in agriculture and examine its impact on the dynamics of the fertilizer market and overall agricultural productivity.

Diammonium phosphate

Diammonium phosphate (DAP) is the most widely used fertilizer in global agriculture, primarily due to its dual nutrient content of nitrogen and phosphorus. This granular, water-soluble fertilizer is derived from ammonia and phosphoric acid, enabling easy application and rapid nutrient release.

Phosphorus, a crucial component of DAP, plays a vital role in energy transfer, photosynthesis, and nutrient movement within plants. This makes DAP particularly beneficial during the critical early stages of root and shoot development. The nitrogen content further enhances plant growth and health. DAP's versatility extends to a wide range of crops and soil types, making it a favorable choice for farmers across diverse agricultural settings.

Chemically, DAP is formulated as $NH_4H_2PO_4$, containing 18% nitrogen in the Ammonim, $(NH_4 +)$ form and 46% phosphorus pentoxide (P_2O_5). This balanced nutritional profile makes DAP an excellent choice for establishing a strong foundation for their crops. Commonly applied to wheat, corn, rice, and barley, DAP meets the substantial phosphorus needs of these crops during critical early growth stages. Upon application, DAP temporarily elevates soil pH, further enhancing its versatility for various farming activities, including pre-sowing cultivation, spring sowing, and autumn tilling.

The production of DAP is highly energy-intensive, heavily reliant on natural gas both as a key raw material for synthesizing ammonia and as an energy source throughout the manufacturing process. Therefore, the prices of DAP are closely tied to natural gas prices. Fluctuations in natural gas prices can significantly influence the production costs of DAP, thereby affecting its market price. The pricing dynamics are also influenced by factors such as the cost of raw materials, geopolitical tensions, unexpected shifts in demand and supply, and fluctuations in exchange rates (Beckman et al., 2013). . This complex interplay of elements makes the DAP market dynamic and unpredictable.

Urea

Urea, with its chemical formula $CO(NH_2)_2$, stands out as the world's most popular nitrogen fertilizer, boasting a remarkable nitrogen content of 46.6%. Its synthesis is achieved through the renowned Haber-Bosch process, a method still widely employed for industrial ammonia production, which is a key ingredient in urea production (Britannica, 2024). The Haber-Bosch process combines ammonia and carbon dioxide under high pressure and temperature. Given its energy-intensive nature, urea production is significantly linked to the price fluctuations of natural gas, as it serves as a primary feedstock in the form of ammonia and plays a pivotal role in the manufacturing process.

Granular urea, characterized by its dryness and high resistance to moisture, facilitates easy transportation and storage. This form has emerged as the dominant choice for nitrogen fertilizers in recent years, nearly replacing ammonium nitrate. Unlike ammonia, which is typically injected into or incorporated within the soil, granular urea is applied to the soil's surface, where it reacts with water to form ammonia. However, leaving urea on the surface in warmer conditions poses a risk of considerable nitrogen loss into the air, making it less effective than ammonia in such environments. Nonetheless, for in-season fertilizer applications, urea is often favored due to its high nitrogen efficiency, crucial for meeting the nitrogen demands of growing crops (Zhang et al., 2021).

The price dynamics of urea, like those of DAP, are closely tied to the energy markets, particularly natural gas prices (Beckman et al., 2013). This cost affects the overall structure of grain production, as urea is a major input for crops such as wheat, corn, and soybeans. Fluctuations in urea prices significantly impact grain prices. These prices are influenced by various factors including global supply-demand imbalances, trade policies, and geopolitical issues that affect supply chains (Beckman et al., 2013; Huang & Wen-yuan, 2009). The global nature of the urea market makes it sensitive to events in key producing regions, leading to swift and sometimes unpredictable price changes.

Grain Market

The grain market is a vital component of the global commodities trade, representing the convergence of agricultural production, international commerce, and global food security. Grains are crucial trade commodities due to their ability to be stored and transported with minimal spoilage. In recent times, international commodity markets have become an integral part of the food industry, playing a pivotal role in grain pricing. The grain market operates within a complex supply chain system influenced by factors such as demand and supply dynamics, production conditions, and policy frameworks. Its ability to manage both microeconomic decisions and macroeconomic shifts, while balancing agricultural production, international trade, and global food security, highlights its significance in shaping global food systems.

Wheat, corn, and soybeans serve as key drivers in the global grain market. According to Alexandratos and Bruinsma (2012), the world demand for wheat and other grains has tripled since 1960 and is expected to increase more by the middle of the 21st century. In the selection of crops for this study, wheat, and corn were chosen for their high nitrogen requirements, as they are heavy consumers of nitrogenous fertilizers, such as urea as they are unable to fix atmospheric nitrogen. In contrast, soybeans can take atmospheric nitrogen through symbiotic relationships with bacteria in the soil which makes them less dependent on nitrogenous fertilizers.

Corn

Corn stands as the most vital grain in the global trade of feed grains (corn, sorghum, barley, and oats), accounting for 95 percent of the overall volume traded worldwide during the past decade (USDA, 2023). This staple crop requires a balanced supply of essential nutrients such as nitrogen, phosphorus, potassium, and various micronutrients to achieve optimal growth and yield. Farmers determine the nutrient levels in their fields through soil tests and then select appropriate fertilizers based on the soil.

Figure 1 illustrates an upward trend globally in corn production over the years with annual figures consistently hovering around 1200 million metric tonnes. However, the graph highlights significant fluctuations, with production rising to remarkable levels of 1,223 million metric tonnes in 2021, followed by a decline in 2022/2023, and then a resurgence in 2023/2024. This variability can be attributed to factors such as weather conditions, shifts in global demand, and the adoption of advanced agricultural technologies and improved cultivation practices. Despite these fluctuations, the overall trend indicates an increase in corn production over the years, facilitating its widespread utilization across diverse sectors.

Corn's versatility extends far beyond its traditional domains of food and feed. Its importance in the biofuel sector as a key feedstock for ethanol production, an environmentally friendly alternative to petroleum, cannot be overstated. Additionally, corn finds applications in the production of corn syrup, a cost-effective sweetener widely used as a substitute for sucrose. Its edible oil is incorporated into various products, including soaps, paints, inks, certain insecticides, and even biodiesel manufacturing. The versatility of corn extends beyond these applications, highlighting its significance as a multifaceted crop with far-reaching implications across diverse industries.

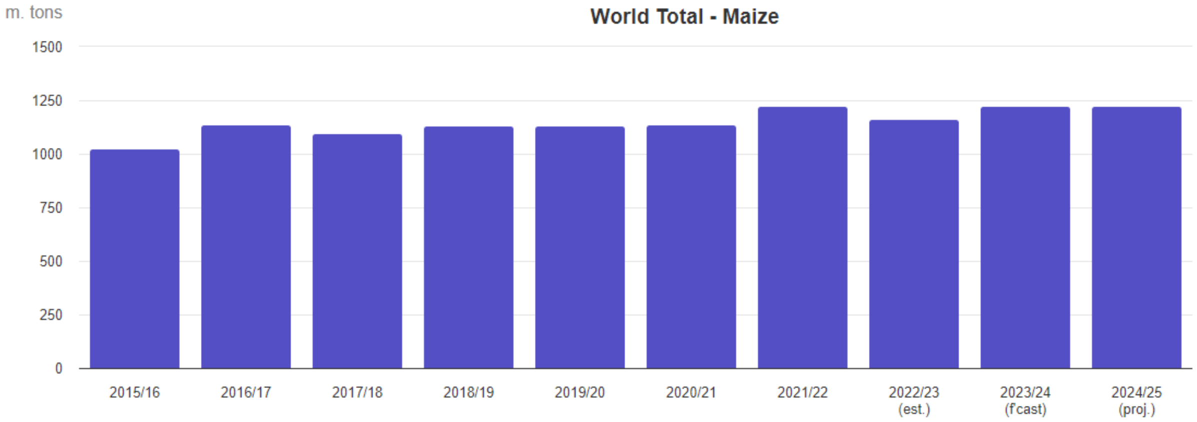

Figure 1: Total global production of corn (Metric Tonnes) for the past 10 years. Source International Grains Council (IGC, 2024a).

Wheat

Wheat stands as one of the most crucial crops worldwide, both in terms of tradable value and its status as a dietary staple for billions of households globally. The consistent production trends depicted in Figure 2, illustrating global wheat production over the past decade, underscore its enduring importance. Wheat is a nutritional powerhouse, serving as a rich source of protein, fiber, essential nutrients, and beneficial phytochemicals for populations across the globe. According to FAO (2023), the world wheat production in 2021 was 773 million tonnes which makes it the second most-produced cereal after corn.

The graph in Figure 2 reveals a relatively stable pattern in wheat production, with annual figures hovering around 700 million metric tonnes, culminating in the noteworthy 771 million tonnes produced in 2021. Despite occasional fluctuations, the data underscores wheat's critical role as a pillar of the agricultural economy and a vital staple in global diets, providing sustenance to billions of people worldwide.

Wheat cultivation is heavily dependent on the availability and cost of nitrogen and phosphorus fertilizers. Nitrogen plays an indispensable role throughout the growth stages of wheat; inadequate nitrogen can lead to detrimental consequences, such as low protein content, reduced tillering, and stunted growth, ultimately impacting yields and quality. Phosphorus fertilizers, on the other hand, play a pivotal role in mitigating soil acidity, enhancing moisture retention, and optimizing water use efficiency, thereby fostering optimal wheat production (Stewart, 2012).

Market prices for wheat are subject to volatility, influenced by a complex interplay of factors, including geopolitical events, trade policies, currency fluctuations, climate conditions, yields, oil and fertilizer prices, and natural gas costs – particularly those linked to the Henry Hub and TTF indices. This interconnectedness highlights the complexity of the wheat trade and its susceptibility to global economic and environmental changes. (Enghiad et al., 2017)

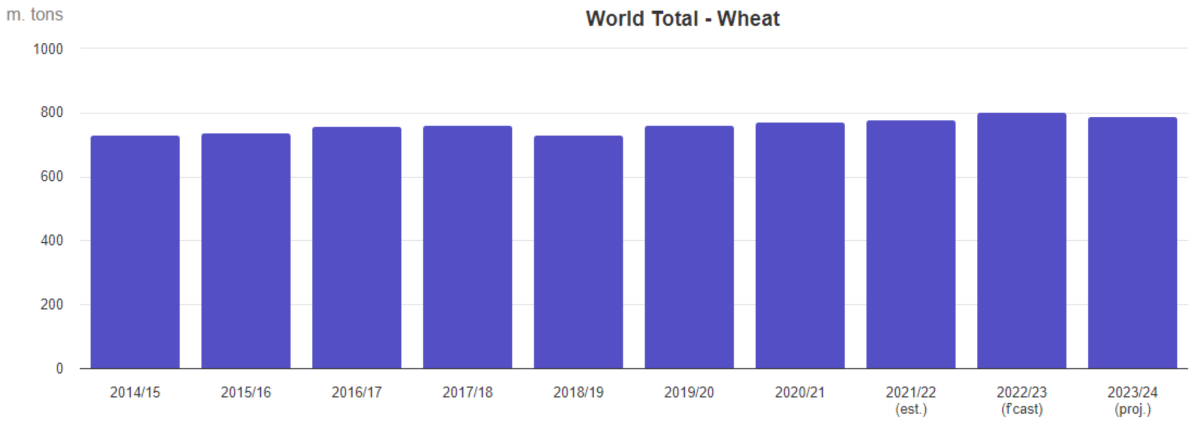

Figure 2: Total global production of Wheat (Metric Tonnes) for the past 10 years. Source International Grains Council (IGC, 2024c).

Soybean

Soybean, a staple in global agriculture, has been cultivated for over 5,000 years but gained prominence only in the last two centuries. Renowned for being both economical and rich in nutrients, soybeans play a vital role in the diets of humans and animals alike. Soybean seeds comprise 17 percent oil and 63 percent meal, with approximately half of the meal being protein. After harvesting, processing plants extract about 11 pounds of crude soybean oil and 47 pounds of soybean meal from every 60-pound bushel. Due to its high protein content, soybeans are utilized in products ranging from animal feed to biodiesel and eco-friendly industrial supplies like paints and cleaners.

As depicted in Figure 3, the global demand for soybeans has exhibited fluctuations over the past decade but has ultimately increased from 317 million metric tons in 2015/16 to a projected 413 million metric tons in 2024/25. This overall growth reflects the crop's well-established role in global agriculture and its diverse applications.

Soybean prices are typically highly correlated with and affected by other grains such as wheat and corn which highlights the complexity of the global agricultural commodities trade. Other key factors influencing soybean market dynamics include fluctuating exchange rates, varying market demands, and the presence of alternative oils. These elements collectively impact soybean pricing and, consequently, the broader agricultural commodities market dynamics.

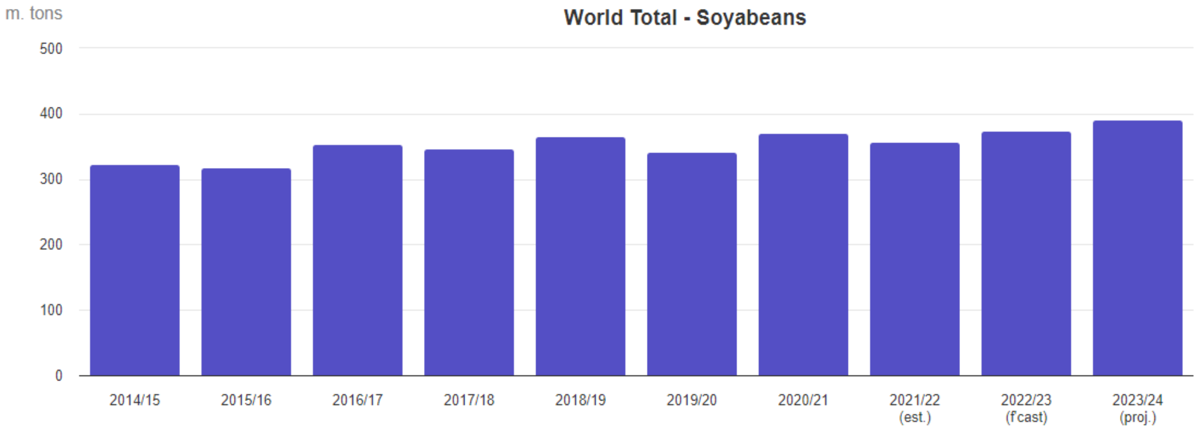

Figure 3: Total global production of Wheat (Metric Tonnes) for the past 10 years. Source International Grains Council (IGC, 2024b)

4. Theoretical Framework and Basic Facts on Price Relationships

This chapter provides a foundation to understand the mechanisms that derive the phenomena under study, utilizing established economic theories to analyze and interpret the empirical findings concerning the price relationships among agricultural commodities, fertilizers, and energy prices. The theoretical framework employed in this study is specifically drawn upon the principle of demand and supply, and market efficiency, providing essential insights into market dynamics and their interdependencies. These theories are essential to understanding the dynamics of markets and their effects on each other and also provide a framework to identify the drivers of price deviations between them.

Economic Theory of Supply and Demand

The theory of supply and demand is a fundamental concept in economics that describes the price formation in markets operating without external interventions. This principle is based on two interrelated forces named demand and supply (Whelan et al., 2001). The volume of goods or services that the manufacturers are willing or able to sell at a given price is referred to as supply. According to the law of supply an increase in price results in an increased quantity supplied, assuming other factors remain constant, and vice versa for a price decrease.

The concept of demand refers to the amount of a product that the consumers are willing to or able to purchase at a particular price. The law of demand states that as prices rise, consumer demand falls, and as prices drop, demand increases, again assuming all other factors are constant.

The intersection of the demand and supply curve determines the equilibrium price of a good or service in the market. If the the price of a good or service is below or above the equilibrium level, there will be excess demand or excess supply in the market respectively. Changes in demand and supply can also result in shifts in the respective curves which further leads to alterations in the equilibrium price and quantity. For example, an increase in consumer income can increase demand which will in return cause a rise in the equilibrium price and quantity.

When it comes to agricultural commodities, the theory of demand and supply plays a crucial role in understanding the impact of changes in input costs, such as those related to fertilizers (urea, DAP) and energy (natural gas), on the supply of grains like wheat and corn. It is essential to comprehend how these input costs influence the supply of grains. Additionally, various other factors like transportation and distribution infrastructure, the level of economic activity, weather conditions, government regulations, and geopolitical events can also impact the demand and supply of agricultural commodities in general.

The demand for agricultural commodities can be influenced by factors such as the price of the commodities themselves, fertilizer prices, energy prices, consumer preferences, and income levels. On the supply side, factors such as commodity prices, fertilizer prices, energy prices, labor costs, weather conditions, and technological advancements can affect the quantity supplied.

To analyze the demand and supply of agricultural commodities, a new model can be derived:

$$D_{agri} = f\left(P_{agri}, P_{fert}, P_{ener}, X_D\right) \tag{1}$$

$$S_{agri} = g\left(P_{agri}, P_{fert}, P_{ener}, X_S\right) \tag{2}$$

Equation (1) shows that the demand for agricultural commodities (D_{agri}) might be influenced by the price of agricultural commodities (P_{agri}), fertilizer prices $\left(P_{fert}\right)$, energy prices (P_{energy}), and other factors affecting demand (X_D), such as consumer preferences and income levels.

Equation (2) indicates that the supply of agricultural commodities (S_{agri}) can be affected by the price of agricultural commodities $\left(P_{agri}\right)$, fertilizer prices (P_{fert}), energy prices (P_{energy}), and other factors affecting supply (X_s), such as labor costs, weather conditions, and technological advancements.

It is important to note that the demand and supply of agricultural commodities can exhibit different elasticities in the short and long run. In the short run, demand and supply may be relatively inelastic due to limited substitution possibilities and fixed production capacities. However, in the long run, demand and supply can become more elastic as consumers and producers adjust to changing market conditions.

Additionally, storage capabilities can play a role in price volatility and supply management. If storage facilities are readily available, surplus production can be stored and released into the market during periods of scarcity, potentially stabilizing prices and reducing volatility.

In summary, the economic theory of supply and demand provides a framework for understanding the intricate relationships between input costs (such as fertilizers and energy), production levels, and commodity prices in the agricultural sector. By analyzing the factors influencing demand and supply, policymakers and market participants can make informed decisions to enhance the efficiency and sustainability of agricultural commodity markets.

Input-Output Price Transmission

This theory explores how changes in input costs influence output prices. In the context of agricultural economics, this theory plays a significant role in understanding how the prices of crucial inputs such as fertilizers and energy prices influence the prices of agricultural commodities. A central element of this theory is the price transmission elasticity, which measures how sensitive output prices are to variations in input costs. The degree to which the input price changes are transmitted to the output prices can vary depending on factors like market structure, and price stickiness. In this study, the Input-Output Price Transmission theory is instrumental in analyzing the effects of fluctuating fertilizer and energy costs on agricultural production expenses.

Market Integration and Independence Theories

Market integration measures the interconnectedness and interdependence among different markets, particularly focusing on how prices in one sector influence others. This concept is pivotal for understanding the relationships between agricultural commodities, fertilizers, and energy prices. By examining the degree to which prices in these sectors move together, this theory provides insights into how a change in energy prices might affect fertilizer costs, and subsequently, the prices of agricultural commodities. In this study, the market integration theory is utilized to explore the ripple effects of fluctuations in one market on others, highlighting the complex web of dependencies among fertilizer, energy, and grain markets. This analysis helps to delineate the broader agricultural market dynamics, revealing how closely these commodities are linked.

$$\ln(P_{agri,t}) = \beta_0 + \beta_1 \ln(P_{fert,t}) + \beta_2 \ln(P_{energy,t}) + \epsilon_t \tag{3}$$

Here β_0 is the intercept, β_1 and β_2 measure the elasticity of agricultural commodity prices relative to changes in fertilizer and energy prices, respectively. This model is essential for evaluating market integration by observing the significance of the coefficients, which indicate how closely linked these markets are.

Conversely, the Market Independence Theory posits that prices in different markets may move independently, suggesting that shifts in one market, such as energy prices, may not necessarily impact prices in other markets like agricultural commodities and fertilizers, due to barriers or unique market dynamics that hinder the transmission of price signals across sectors. This perspective is crucial for identifying scenarios where despite potential connections, changes in one market do not affect others, providing a nuanced understanding of market behaviors.

5. Methodology

In this chapter, I will explore the essential concepts of time series econometrics that will be used for the econometric analysis in subsequent chapters. This includes a discussion of cointegration analysis, Granger causality tests, and autoregressive distributed lag (ARDL) models. Each method falls within the scope of time-series econometrics and will be briefly outlined to provide a foundation for their application in analyzing the dynamic relationships among the study variables.

An essential aspect of time series data analysis is assessing whether the data is stationary or non-stationary. Stationary data have a constant mean and variance, whereas non-stationary data exhibit changes in these statistical properties over time. Analyzing non-stationary data without adjustments can lead to spurious correlations, challenging the validity of conventional statistical tests such as F-tests and t-tests (Granger, 1986). Therefore, the first vital step in the time series econometrics is to determine if the data is stationary.

One way to check if prices are stationary is to draw a line plot. A standard test for non-stationarity is the Augmented Dicky Fuller (ADF) test developed by Dickey and Fuller (1979). This test involves regressing the first difference of the series, $\Delta \mathrm{P}_{\mathrm{t}}$, against its lagged level $\mathrm{P}_{\mathrm{t-1}}$and its lagged first differences $\Delta \mathrm{P}_{\mathrm{t-1}} \dots, \Delta \mathrm{P}_{\mathrm{t-k}}$

$$\Delta P_t = \alpha + \mu_t + \beta P_{t-1} + \gamma_1 \Delta P_{t-1} + \dots + \gamma_k \Delta P_{t-k} + \varepsilon_t \qquad (4)$$

Here, Δ signifies the difference operator, t denotes the time trend, and k represents the number of lags to accommodate serial correlation. The test includes an intercept $\alpha\alpha$ to handle non-zero means typical in econometric time series. The ADF test's null hypothesis posits that the series is non-stationary ($H_0: \beta = 0$), , against the alternative of stationarity ($H_A: \beta < 0$).

Rejecting the null hypothesis suggests that the data are stationary or integrated of order zero $P_t \sim \mathrm{I}(0)$. Failure to reject indicates potential non-stationarity, necessitating differencing to achieve stationarity, possibly leading to a series integrated of order one $P_t \sim I(1)$, if stationarity is obtained after one difference. The robustness of results is ensured by including both a constant and a time trend in the test.

The selection of the appropriate number of lags in the ADF test is vital to minimize bias from serial correlation and enhance the test's statistical power. The optimal number of lags is determined using the Akaike Information Criterion (AIC), calculated as follows:

$$\boldsymbol{AIC = ln\,(\sigma^2) + \frac{2k}{T}} \tag{5}$$

where σ^2 represents the variance of the estimated residuals, k is the number of lags, and T is the sample size. This criterion helps balance the complexity of the model against its fit, with a lower AIC indicating a preferable model.

As Gordon (1995) notes, different methods for selecting lags can yield diverse conclusions about stationarity, emphasizing the importance of method choice. Researchers must evaluate the sensitivity of ADF test results to the selected lag length and consider alternative criteria to ensure robust findings.

Cointegration analysis then becomes a pivotal method for exploring price dynamics within the agricultural sector. This approach is crucial for understanding the long-term relationships between time series, even if these series themselves are non-stationary. Cointegration indicates that despite short-term deviations, prices will revert to long-run equilibrium, indicating a persistent, stable relationship over time. This occurs when a linear combination of non-stationary variables results in a stationary series, indicating that although individual variables may trend over time, their combined movements adhere to a stable, long-term equilibrium relationship (Engle & Granger, 1987).

Two standard ways of testing for cointegration are Engle and Granger's two-step procedure (Engle & Granger, 1987) and Johansen's cointegration test (Johansen, 1988). The Engle and Granger analysis is used to test the cointegration relationship between pairs of time series, while the Johansen test can be used for both multivariate and bivariate cointegration tests. I will apply Engle & Granger's two-step procedure in my empirical analysis. To use this method, the relationship between two variables must either be defined based on economic theory (unrestricted cointegration test) or estimated through regression (restricted cointegration test). I will be using a restricted cointegration test, which is based on the regression of the following form:

$$Y_t = \beta_0 + \beta_1 x_t + \epsilon_t \tag{6}$$

Where Y_t and X_t represent the variables being examined at the time t, β_1 captures the long-term relationship, and ϵ_t is the error term indicating how much Y_t changes per unit change in X_t.

After estimating this relationship using ordinary least squares (OLS), I will compute and analyze the residuals:

$$\epsilon_t = Y_t - \beta_0 - \beta_1 X_t \tag{7}$$

Cointegration will be tested using the Engle-Granger residual-based method, applying the Augmented Dickey-Fuller (ADF) test to the residuals to check if they are stationary, with specific critical values adjusted for this context.

If the variables are cointegrated, I will proceed to estimate an Error Correction Model (ECM). This model is instrumental in integrating both the short-term deviations from equilibrium and the long-term adjustments necessary to return to equilibrium. The ECM is expressed as:

$$\triangle Y_t = \beta_0 + \beta_1 \triangle X_t + \beta_2 (Y_{t-1} - \beta_0 - \beta_1 X_{t-1}) + v_t \tag{8}$$

Where β_0 is the intercept, $\beta_1 \triangle X_t$ represents the short-term effects, and $\beta_2 (Y_{t-1} - \beta_0 - \beta_1 X_{t-1})$ is the error correction term with β_2 indicating the speed of adjustment towards equilibrium, If β_2 falls outside the range of -1 to 0, it suggests non-converging behavior, necessitating model reassessment. A properly defined ECM provides valuable insights into the equilibrium relationship and provides a fundamental aspect of understanding the price movements within the agricultural sector.

This study also employs the Autoregressive Distributed Lad (ARDL) approach to analyze the dynamics between agricultural prices and their determinants over time (Jorgenson & Griliches, 1967). The ARDL approach is particularly advantageous due to its flexibility in handling different levels of integration among variables, whether I(0) or I(1), without requiring pre-testing for unit roots. This feature simplifies the initial stages of analysis and allows for a more straightforward assessment of both short-term and long-term relationships.

In addition, the bounds-testing approach by Pesaran et al. (2001) enhances the ARDL framework by providing a robust means to test for the existence of a long-run relationship using an F-statistic to jointly test the null hypothesis that no long-run relationships exist (that $\alpha = 0$ and all coefficients $\theta_j = 0$) against the alternative hypothesis of a long-run relationship. If the null hypothesis is rejected, further tests like the t-statistic on α and z-tests on the coefficients of θ help confirm individual relationships and the model's validity.

The general ARDL model can be formulated as:

$$\triangle Y_t = \alpha + \sum_{i=1}^{p} \phi_i \triangle Y_{t-i} + \sum_{j=0}^{q} \theta_j \triangle X_{t-j} + \lambda Y_{t-1} + \sum_{k=1}^{r} \gamma_k X_{t-k} + \epsilon_t \qquad (9)$$

Where Y_t represents the first difference of the dependent variables to capture immediate changes, α is the intercept, ϕ_i are the coefficients of the lagged dependent variable differences, capturing the autoregressive nature of Y, θ are the coefficients for the differences of the independent variable X, indicating short-term effects and λY_{t-1} and $\gamma_k X_{t-k}$ represent the long-run relationship, with λ *and* γ_k representing the speed of adjustment to equilibrium.

The ARDL model can be effectively transformed into an Error Correction Model (ECM) to emphasize short-term dynamics alongside long-term equilibrium adjustments. This restructuring facilitates an integrated analysis of how variables adjust in the short run while aligning with the long-term equilibrium:

$$\Delta Y_t = \gamma_0 + \gamma_1 t + \lambda(Y_{t-1} - \theta_1 X_{t-1}) + \sum_{i=1}^{p-1} \gamma_{i+1} \Delta Y_{t-i} + \sum_{i=0}^{q-1} \delta_i \Delta X_{t-i} + \epsilon_t \qquad (10)$$

Where $\Delta \mathrm{Y_t}$ and $\Delta \mathrm{X_{j,t-1}}$ denote the first differences between the dependent and independent variables, γ_0 is the intercept and γ_1 represents a time trend component. λ represents the coefficient of the error correction term, $Y_{t-1} - \theta_1 X_{t-1}$ is the error correction term (ECT), representing the long-term relationship deviation from equilibrium at the time $t-1$ while γ_{i+1}, δ_i are the coefficients for the lagged differences of the dependent and independent variables, respectively.

The ARDL model's versatility is evident in its various forms—such as partial adjustment, finite distributed lag, static, differences, and dead start—each defined by specific restrictions on dynamic processes. For instance, the partial adjustment model suggests a decaying lag structure, while the dead start model assumes no immediate relationship between Y and X(Jorgenson & Griliches, 1967). Notably, the ARDL approach does not require pre-testing for the order of integration, facilitating the analysis under conditions where variables are either I(0) or I(1) (Banerjee et al., 1998).

When variables are $I(1)$ and cointegrated, the ARDL model can be directly applied in levels using OLS to estimate long-term relationships. Conversely, if the variables are not cointegrated or comprise a mix of $I(0)$ and $I(1)$, differencing is applied to achieve stationarity. The long-run relationships within the ARDL framework are captured as follows:

$$Y = \frac{\alpha_0}{1 - \sum_{i=1}^{p} \alpha_i} + \sum_{j=1}^{p_j} \sum_{i=0}^{p_j} \frac{\beta_{ji}}{1 - \sum_{i=1}^{p} \alpha_i} X_j \tag{11}$$

This formula highlights how deviations from equilibrium are adjusted, where $\frac{1}{1-\sum_{i=1}^{p} \alpha_i}$ serves as a transformative component from short-term impacts to long-term equilibrium, illustrating the robustness of the ARDL model in capturing the underlying dynamics of price movements.

In exploring the directional relationships among economic variables, the Granger causality test is pivotal. Originally proposed by Engle and Granger (1987), and further examined by scholars like Granger (1988), this test assesses whether the past values of one variable are useful in predicting another (Aptech, 2021).

Granger causality within a VAR model involves testing the predictive ability of one time series on another. Notably, the causality function in VAR models not only examines Granger causality but also tests for instantaneous causality—where variables exhibit immediate interdependencies without lag effects (Norrulashikin et al., 2016). This test utilizes a fitted VAR model with a specified lag order, generating a matrix of test statistics and p-values for pairwise causality assessments. The VAR model for variables Y_t and X_t is expressed as follows:

$$Y_t = \alpha_{10} + \sum_{i=1}^{p} \alpha_{1i} Y_{t-1} + \sum_{i=1}^{p} \beta_{1i} X_{t-i} + \epsilon_{1t} \tag{12}$$

$$X_t = \alpha_{20} + \sum_{i=1}^{p} \alpha_{2i} X_{t-i} + \sum_{i=1}^{p} \beta_{2i} Y_{t-i} + \epsilon_{2t} \tag{13}$$

Here α_{1i}, β_{1i}, α_{2i}, β_{2i} are the coefficients of the lagged variables in the VAR equations, indicating how past values influence current values. The null hypothesis tested is that *X* does, not Granger cause *Y* and vice versa, represented by coefficients being zero in their respective equations.

In this thesis, the use of linear Granger causality tests within the VAR framework allows for a detailed examination of how economic variables influence each other over time, enhancing our understanding of dynamic economic interactions.

6. Data

In this study, I have chosen to analyze U.S. market prices due to its significant role as one of the leading producers and exporters of agricultural commodities, energy, and fertilizers. This prominence makes the U.S. market highly influential on a global scale, and the U.S. benchmarks serve as standard references in global pricing, highlighting the relevance of U.S. market data in international trade dynamics.

The primary data sources for this study include Refinitiv, a renowned global provider of financial data, and FRED (Federal Reserve Economic Data), an extensive online database housing numerous economic data series. These sources ensure reliable and comprehensive data coverage for the commodities in question.

Table 1: Data type, sources, and Pricing unit

Commodity Name	**Type of data**	**Source**	**Pricing unit used**
Corn	Spot	U.S. Department of Agriculture	U.S. Bushel
Wheat	Spot	U.S. Department of Agriculture	U.S. Bushel
Soybean	Spot	U.S. Department of Agriculture	U.S. Bushel
Urea	Spot	Refinitiv	Metric Ton
DAP	Spot	Refinitiv	Metric Ton
Natural Gas Henry Hub	Spot	FRED	Dollars per Million BTU
Natural Gas TTF	Futures	Refinitiv	Dollars NL

When choosing a price series for natural gas, multiple options were considered based on geographical location and market relevance. I opted for Henry Hub prices because of their pivotal role in the U.S. natural gas markets. Given the U.S.'s status as a major producer and exporter, Henry Hub is not only the primary benchmark in the United States but also exerts considerable influence on global natural gas prices. To incorporate a broader international perspective and examine the impact of global energy prices on U.S. markets, I also included Natural Gas TTF (Title Transfer Facility) prices in my analysis. TTF has emerged as the main benchmark for natural gas pricing in Europe, effectively supplanting other benchmarks like the UK's National Balancing Point (NBP), thus offering a comprehensive view of energy price dynamics.

For this study, I have selected wheat, corn, and soybean, which rank among the world's six most important agricultural commodities by value. The specific grades chosen—No.2 Soft Wheat, No. 2 Yellow Corn, and No. 1 Yellow Soybeans—are not only widely traded but also serve as benchmarks in the U.S. market. These selections provide a robust dataset for conducting detailed price analysis, offering insights into significant market trends and price movements.

Among fertilizers, urea and DAP were chosen due to their extensive global usage. The selected price points for these fertilizers in the thesis are Urea Granular CFR (Cost and Freight) New Orleans and DAP New Orleans CFR Barge. These are specifically quoted for the New Orleans market, a strategic choice due to the city's critical role as a major shipping and logistics hub in the United States. The location's significance stems from its extensive network and infrastructure that support the distribution and trading of agricultural inputs like fertilizers. This strategic positioning makes the pricing and delivery terms from New Orleans particularly relevant for analyzing market dynamics and supply chain factors in the fertilizer industry.

Selecting the appropriate data frequency is a crucial step in time series analysis. High-frequency data, such as daily or weekly, can introduce significant noise, complicating the analysis with short-term fluctuations that may not be relevant to long-term trends. Conversely, low-frequency data, like annual series, while less noisy, require extending the historical data range to gather enough observations for robust analysis (Pindyck, 1999).

In this thesis, after considering various options—including annual, weekly, monthly, and daily frequencies—I opted for monthly time series data. This frequency strikes an optimal balance, offering sufficient detail to discern emerging price relationships while avoiding the excessive noise typical of higher-frequency data sets. Monthly data are not only more readily available but also widely employed in commodity price co-movement research, facilitating comparisons with existing studies. This frequency choice supports a focused examination of newer price relationships, providing a contemporary snapshot of market dynamics without the need for extensive historical data.

Following the choice of commodities and data frequency, the next critical step is to define the period for analysis. For this analysis, I have selected monthly time series data spanning from January 2009 to December 2023, encompassing U.S. spot prices for corn, wheat, soybean, urea, DAP, and natural gas at Henry Hub. Spot prices are used instead of futures due to their ability to reflect current market conditions. Spot prices directly capture real-time market events, offering a clearer view of market dynamics and reducing the distortions caused by speculative activities that can lead to excessive volatility. This approach ensures a more accurate representation of market-clearing equilibriums and inter-commodity relationships (Gardebroek & Hernandez, 2013). However, for natural gas TTF (Title Transfer Facility), I have opted to use futures prices. This decision is based on the structure of the natural gas market, which predominantly relies on futures contracts for trading. Futures prices are typically used in this context to ensure security of supply and price stability, features that are crucial given the market's orientation towards long-term contracts. This methodological choice allows for an analysis that is aligned with the prevailing market practices for natural gas trading in Europe.

Given the dynamic nature of global markets, this analysis incorporates an extended investigation into two distinct periods, each marked by unique economic and geopolitical conditions The first period spans from January 2009 to December 2023, providing a comprehensive view with a total of 180 observations. This extensive timeline ensures a robust dataset that captures long-term trends and cyclic behaviors in commodity prices.

The second, more focused period, runs from 2017 to 2023, encompassing 84 observations. This recent timeframe is particularly significant due to the heightened economic fluctuations and geopolitical tensions that have reshaped market dynamics. Notable events such as the COVID-19 pandemic and various geopolitical conflicts have dramatically impacted commodity supply chains and price levels, introducing new price relationships and market dependencies, especially with the increased use of natural gas. These changes suggest potential new correlations and impacts, especially within the agricultural sector, which warrant closer examination.

This study aims to analyze two periods and understand the market forces behind them. By doing so, it aims to differentiate between short-term impacts and enduring trends. This approach helps us understand how recent global events have affected commodity markets. It provides valuable insights that are essential for stakeholders to navigate the current economic landscape with precision and accuracy.

Descriptive statistics and detailed analysis for both periods will be elaborated upon in subsequent chapters, offering a comparative perspective on how market conditions have evolved and highlighting significant shifts in price behaviors and market interrelations.

Descriptive statistics

In this study, descriptive statistics and stylized facts will be presented for both the level data and the log-first differences of the data across two distinct periods: 2009-2023 and 2019-2023. The use of logarithmic transformations is pivotal for this analysis, as it enables the capture of proportional, rather than absolute, changes over time. This approach is particularly valuable for time series data that exhibit large fluctuations, as it reflects percentage changes, providing a clearer understanding of market dynamics (MURPHY, 2024).

The table below provides a comprehensive view of the descriptive statistics for 2009-2023 for the prices of all commodities studied. This includes agricultural commodities like wheat, corn, and soybean; fertilizers such as urea and DAP; and energy sources like Natural Gas (Henry Hub and TTF).

Table 2: Descriptive statistics for level values 2009-2023.

	Wheat	**Corn**	**Soybean**	**Urea**	**DAP**	**Natural Gas (HH)**	**Natural Gas(TTF)**
Mean	5.88	4.69	11.55	351.38	459.34	3.46	31.44
SD	1.52	1.51	2.57	134.74	151.07	1.25	33.76
Skewness	0.70	0.69	0.38	1.89	1.55	1.50	3.48
Excess Kurtosis	0.58	-1.01	-1.52	3.74	2.32	3.17	12.73

Notes. *The table provides an overview of the stochastic properties for the level values between 2009 and 2023. SD represents the standard deviation of the underlying series.*

The descriptive statistics of the annualized returns for various commodities and energy prices over the selected period are presented in Table 2. Wheat, corn, and soybeans, key agricultural commodities, showed average annualized returns of 5.88%, 4.69%, and 11.55%, respectively, reflecting moderate to high profitability in agricultural investments. Urea and DAP, two crucial fertilizers, reported significantly higher annualized means of 351.38 and 459.34, respectively, indicating volatile markets with potential for high returns.

In terms of volatility, measured by the annualized standard deviation (SD), soybeans demonstrated the highest fluctuation among the agricultural commodities at 2.57, suggesting greater price variability. However, the volatility was even more pronounced for Urea and DAP, with SDs of 134.74 and 151.07, respectively. This extreme volatility reflects the unpredictable nature of fertilizer markets, which may be influenced by factors such as supply chain disruptions, global demand shifts, and changes in input costs.

The skewness and kurtosis of various commodity price distributions provide insights into market dynamics. Natural Gas TTF, Urea, and DAP exhibit positive skewness, suggesting frequent occurrences of lower prices with high spikes, indicating potential market shocks or abrupt supply-demand shifts. Wheat and Corn also show moderate positive skewness, reflecting occasional higher-than-average returns. Conversely, Soybeans display minimal skewness, indicating a more balanced and stable pricing structure. Regarding kurtosis, Corn and Soybeans exhibit negative excess kurtosis, signifying distributions concentrated around the mean with fewer extreme values, suggestive of more consistent and regulated market conditions. In contrast, commodities like Natural Gas TTF and Urea have high positive excess kurtosis, pointing to peakier distributions with fatter tails and a higher probability of extreme price deviations, reflecting volatile market conditions. These statistical characteristics underscore varying risk profiles and necessitate tailored risk management strategies for each commodity.

Following the same structure, this table provides statistics for the more recent period 2017-2023, highlighting how market conditions have evolved in the face of recent global challenges.

Table 3: Descriptive statistics for level values 2017-2023

	Wheat	*Corn*	*Soybean*	*Urea*	*DAP*	*Natural Gas (HH)*	*Natural Gas(TTF)*
Mean	*6.02*	*4.58*	*11.31*	*376.45*	*512.01*	*3.37*	*42.78*
SD	*1.52*	*1.42*	*2.85*	*178.32*	*196.62*	*1.55*	*46.65*
Skewness	*1.35*	*0.72*	*0.47*	*1.37*	*0.82*	*1.80*	*2.14*
Excess Kurtosis	*1.82*	-0.91	-1.26	*0.72*	-0.37	*2.67*	*3.93*

Notes*. The table provides an overview of the stochastic properties for the level values between 2017 and 2023. SD represents the standard deviation of the underlying series.*

Table 3 provides the descriptive statistics for the level prices of all commodities from 2017-2023. Overall the results highlight distinct patterns in the distribution of prices across the commodities. The mean prices for all commodities are generally stable compared to the overall 2009-2023 period, except for the natural gas TTF prices which have increased relative to other commodities in recent years. This increase highlights TTF's growing significance in the energy market. While the volatility for agricultural commodities remained relatively stable, there was a marked increase in the volatility for fertilizers and both Henry Hub and TTF natural gas prices during this period, suggesting heightened market sensitivity or external market pressures.

The skewness values indicate that in both periods, most commodities exhibit positive skewness which suggests a potential for price spikes. However, the prices for wheat, corn, and soybean in the 2019-2023 period display negative skewness which indicates a shift towards lower prices in recent years. The kurtosis values show that TTF natural gas prices exhibit heavy tails in the 2019-2023 period, highlighting extreme price variations. Table 4 examines the first difference log values, providing insights into the immediate changes in prices between consecutive months, which can be critical for understanding the impact of short-term market events.

Table 4: Descriptive statistics with log first-differences for 2009-2023 & 2019-2023

For 2009-2023-First Differences log values

	Wheat	***Corn***	***Soybean***	***Urea***	***DAP***	***Natural Gas (HH)***	***Natural Gas(TTF)***
Annualized Mean	0.016	0.010	0.014	0.018	0.048	-0.048	0.036
Annualized SD	0.31	0.27	0.20	0.34	0.20	0.48	0.55
Skewness	-0.11	-0.09	-0.29	0.22	1.24	-0.07	0.23
Excess Kurtosis	0.61	0.65	0.53	1.53	5.68	5.08	3.66

For 2017-2023-First Differences log values

	Wheat	***Corn***	***Soybean***	***Urea***	***DAP***	***Natural Gas (HH)***	***Natural Gas(TTF)***
Annualized Mean	0.0096	0.006	0.072	0.096	0.144	-0.036	0.12
Annualized SD	0.38	0.41	0.27	0.65	0.38	0.79	1.10
Skewness	-0.13	0.28	0.42	-0.08	0.42	-0.58	-0.01
Excess Kurtosis	0.03	0.16	0.27	0.06	1.02	2.36	0.13

Notes. *The table provides an overview of the descriptive statistics for the first difference log values for the whole sample and the subsample, respectively.*

Table 4 provides an in-depth analysis of the descriptive statistics for the first-differenced prices of agricultural commodities, fertilizers, and energy across two distinct periods: 2009-2023 and 2017-2023. During the 2009-2023 period, the annualized mean first differences indicate relatively minor year-over-year price changes in agricultural commodities such as wheat, corn, and soybean. Conversely, fertilizers like urea and DAP exhibited higher mean changes of 0.048 for DAP, signaling increased price volatility. Notably, natural gas prices showed divergent trends; Henry Hub natural gas experienced a decline with a mean change of -0.048, while TTF natural gas recorded a slight increase of 0.036. In the more recent period of 2017-2023, there was a noticeable rise in the annualized mean changes for urea (0.096) and DAP (0.144), suggesting heightened market dynamics possibly driven by supply disruptions or fluctuating demand.

The volatility, as measured by the annualized standard deviations, remained higher for energy products, with Henry Hub natural gas at 0.48 and TTF at 0.55, reflecting more significant price fluctuations during 2009-2023. Additionally, DAP's distribution displayed a notable positive skewness of 1.24, indicative of more frequent higher price changes, and an exceptionally high excess kurtosis of 5.68, pointing to a higher likelihood of extreme price variations.

For the 2017-2023 period, the standard deviation for TTF natural gas was particularly high, denoting considerable market instability. The skewness values across most commodities were moderate, with Henry Hub natural gas showing a noticeable negative skewness, suggesting a trend toward lower price changes. DAP's kurtosis remained elevated, reaffirming the potential for extreme price movements.

Stylized Facts of Prices

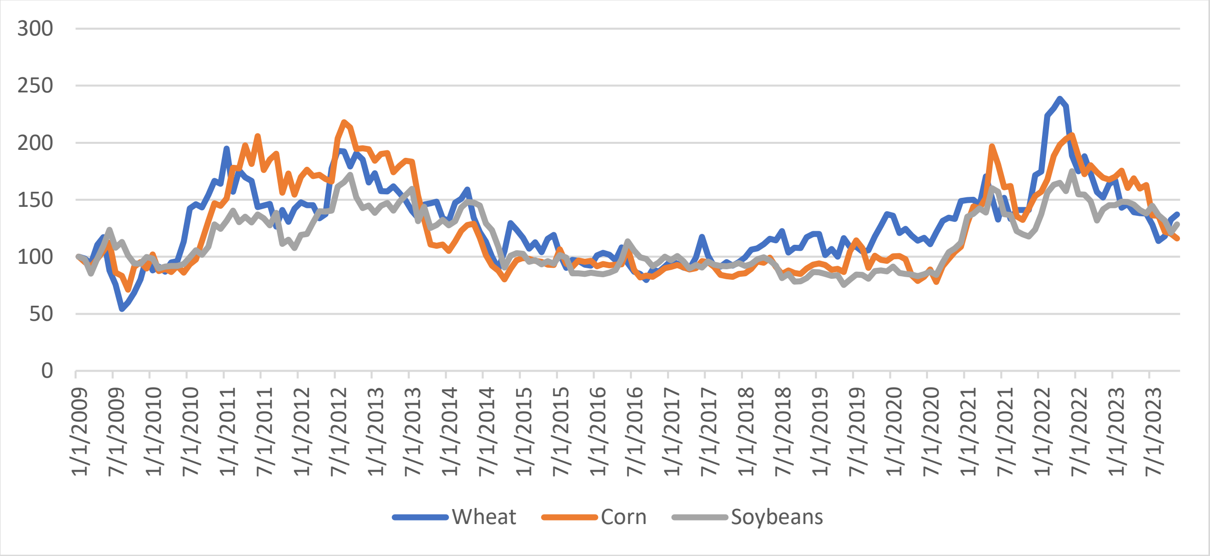

Figure 4: Indices for Grain prices for 2009-2023.

Figure 3 displays the price trends of three agricultural commodities: wheat, corn, and soybeans over a period from 2009 to 2023. Grain prices move together in the long run. There have been some price bumps over the 14 years. This graph shows significant fluctuations that are typical of the cyclical nature of commodity markets, influenced by a mix of demand and supply shocks, varying weather conditions, and geopolitical events.

There are two dominant spikes in the graph 2011 to 2014 and 2021 to 2023. Several factors have been pointed out as reasons for price increases in both periods. The rise in agricultural prices from 2011 to 2014 is accounted for several reasons including the drought of 2012, global weather events, biofuel demand, the declining value of the U.S. dollar, policies adopted by importers and exporters to reduce home food price inflation (Nigatu et al., 2020). However, the price rise in 2021 to 2023 can be accounted for by factors including supply chain disruptions due to COVID-19, adverse weather conditions, increased input costs, and geopolitical events like the Russia-Ukraine Conflict (Gong & Xu, 2022; Xu et al., 2020). The common thread in both periods was the influence of external shocks and disruptions highlighting the sensitivity of agricultural markets.

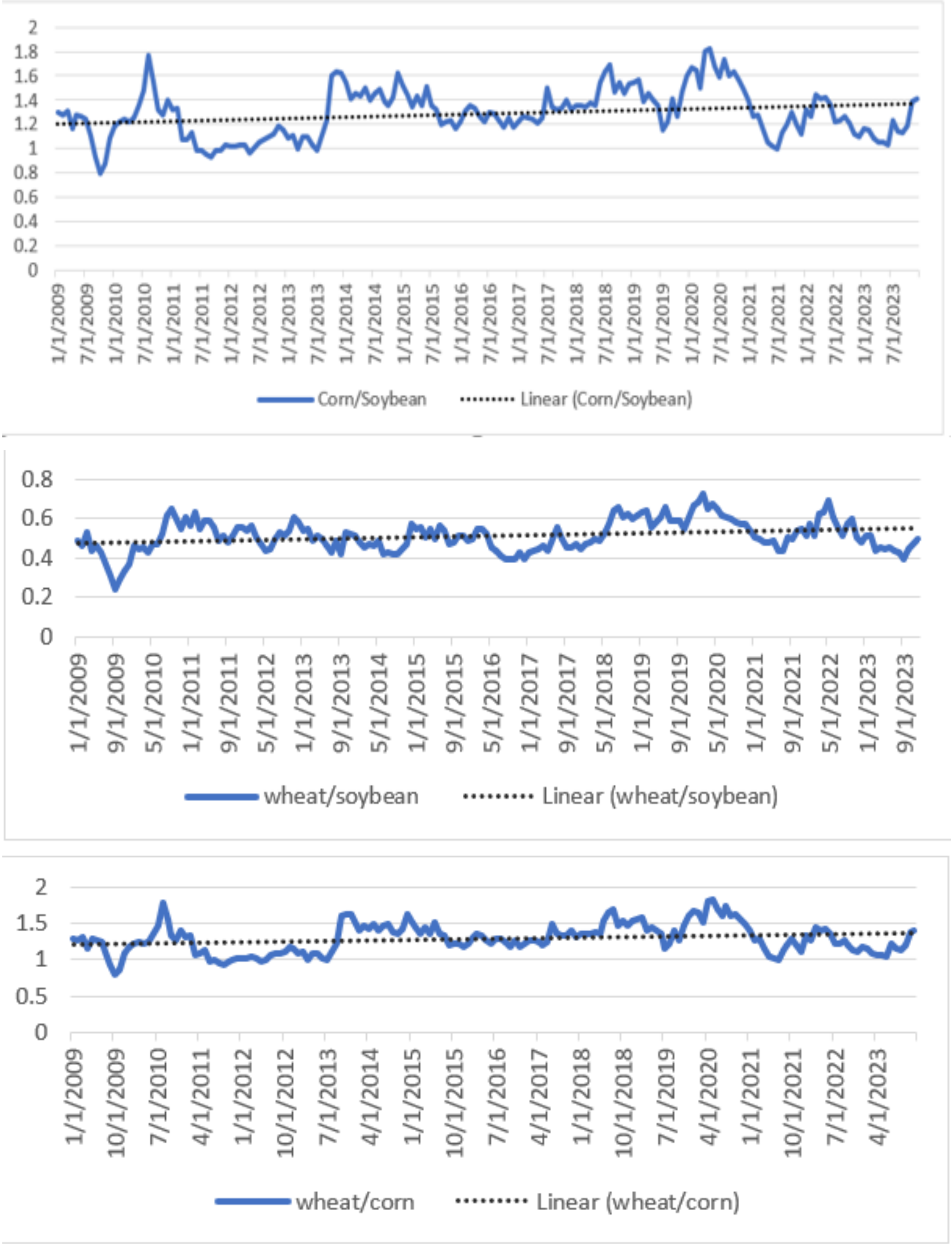

Figure 5: Grain price ratios, 2009-2023.

Relative prices are of more significant interest than absolute values as we can check for trends in price ratios. A trend in this context implies a divergence in pricing between commodities. Despite short-term fluctuations, the prices for commodities have remained stable over time without displaying any long-term trends in favor of one commodity over the other. This absence of long-term deviations is likely because farmers adjust their crop choices to capitalize on more profitable grains, thereby normalizing the relative prices to a long-term average. This stability suggests that these markets are influenced by similar factors and respond to the broader economic and environmental conditions in a balanced manner.

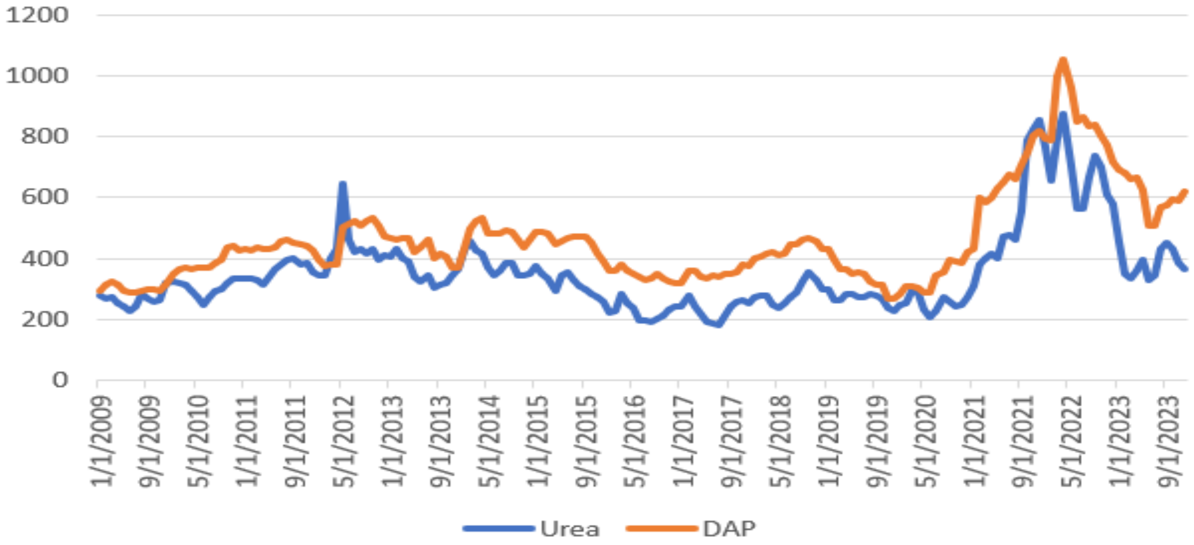

Figure 6: Indices for fertilizer prices, 2009-2023.

The fertilizers, urea, and DAP, exhibit distinctive price trends, shaped by various economic and geopolitical influences. The prices of Urea and DAP have experienced significant fluctuations with peaks occurring during 2012 and 2021-2022 which is quite similar to the peaks occurring for agricultural commodities prices observed in Figure 3. Several factors contribute to these spikes, including fluctuations in natural gas prices, geopolitical tensions, the impacts of the COVID-19 pandemic, and shifts in global demand. The differences in urea and DAP reflect their unique market dynamics and also highlight the interconnectedness of global energy and commodity markets and their impact on agricultural prices.

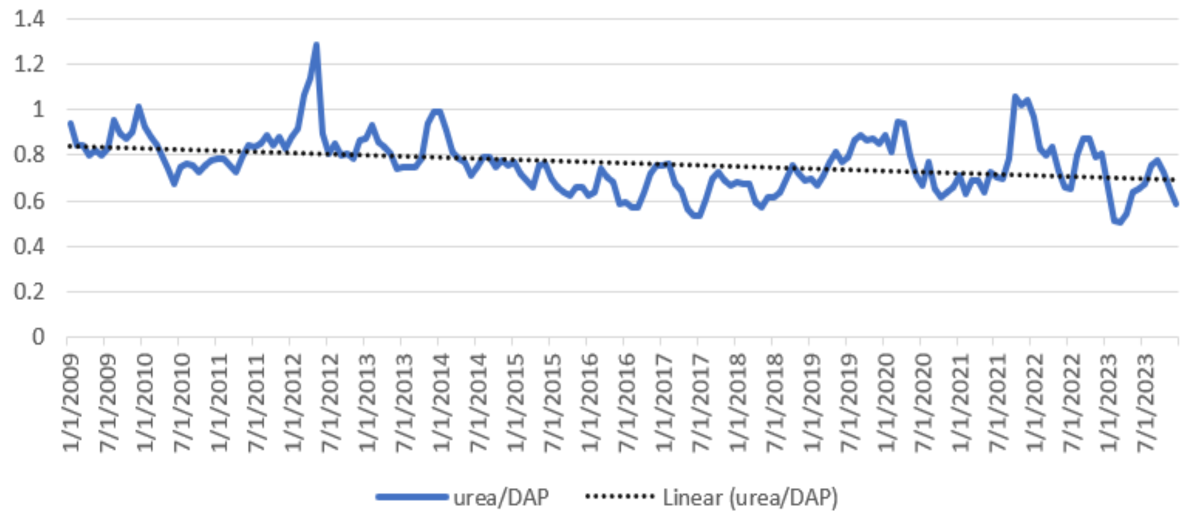

Figure 7: Fertilizer price ratios, 2009-2023.

The urea and DAP price ratio highlights the distinct market dynamics of the two fertilizers where the ratio exhibits a peak around 2012 and 2021 indicating that urea was relatively more expensive compared to DAP. In 2012, urea prices spiked due to increased global demand and supply disruptions, and in 2021, the ratio peaked again as urea prices surged due to rising natural gas prices and supply chain issues while the DAP prices did not increase drastically.

Figure 8: indices for Natural gas Henry hub prices (dollars per million BTU),1/1/ 2009 to 9/1/2023.

Figure 9: indices for Natural gas TTF prices (dollars per million BTU),1/1/ 2009 to 9/1/2023.

From the data presented in Figure 8, Henry Hub prices show fluctuations over the years but remained mostly within a range of $2 to $8 per million British Thermal Units (MMBtu) until a significant spike around 2022. This upward trend could be attributed to various factors including shifts in demand, changes in supply dynamics, regulatory changes, or geopolitical events affecting the North American market.

In contrast, Figure 9 illustrates the indices for TTF natural gas prices, which maintained a relatively stable pattern at lower levels until around late 2020. Post-2020, there is a sharp increase, with prices reaching as high as approximately $60 per MMBtu by mid-2022 before declining. The spike in TTF prices is notably more pronounced than in the Henry Hub, suggesting higher volatility and potentially tighter supply conditions in Europe, or stronger reactions to geopolitical tensions and supply uncertainties, particularly those influenced by European dependence on gas imports.

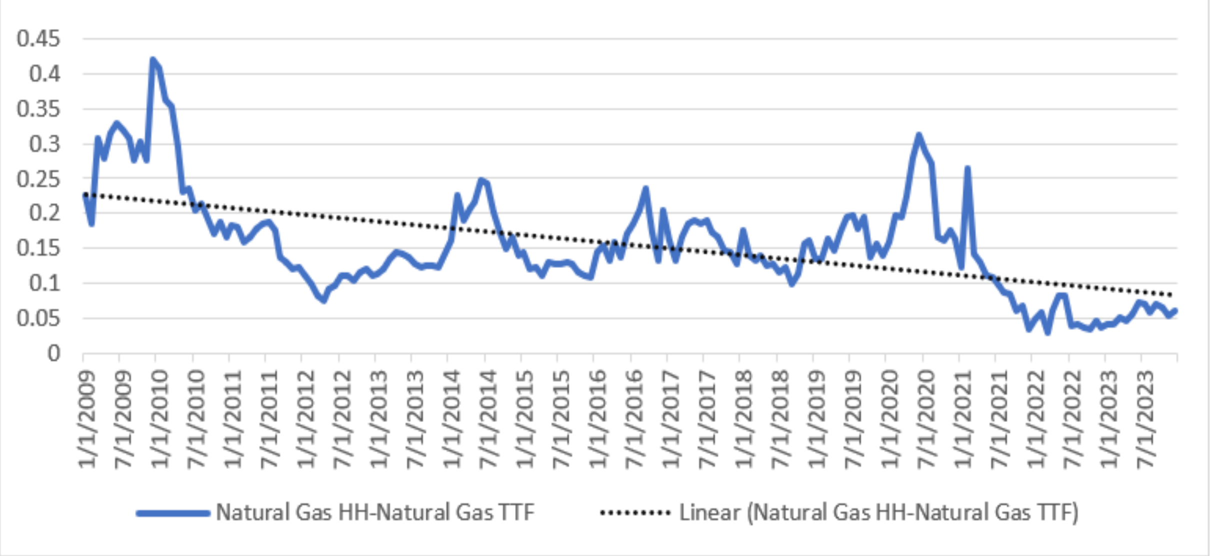

Figure 10: Energy price ratios, 2009-2023

The ratio demonstrates considerable volatility from 2009 to 2013, followed by a period of relative stability, with noticeable fluctuations reemerging in 2023. The peaks indicate the periods when the natural gas TTF prices were significantly higher than the natural gas Henry hub prices reflecting the market dynamics in both markets The U.S., as a major producer, relies heavily on its natural gas production, while Europe, more dependent on imports—particularly from Russia—is more subject to geopolitical tensions and supply disruptions. These factors contribute to heightened volatility and price spikes in the TTF market. Thus, the price ratio between natural gas Henry Hub and natural gas TTF highlights the differences in market conditions, supply and demand dynamics, and geopolitical influences in the U.S. and Europe.

7. Econometric Analysis

In this chapter, an econometric analysis will be conducted to explore the long-term relationships among agricultural commodities, fertilizers, and energy markets. Initially, the analysis will assess the stationarity characteristics of the dataset utilizing the Augmented Dickey-Fuller (ADF) test. Subsequently, I will study the price connections between agricultural, fertilizers, and energy markets through the application of different time series econometric analyses.

Stationarity

In this analysis, the Augmented Dickey-Fuller (ADF) test was utilized to determine whether the price series for commodities exhibit stationarity in both their logarithmic levels and first differences. Each variables were transformed using the natural logarithm and by taking the first difference of the natural log. The ADF tests were conducted both with and without a trend and constant and the optimal number of lags, up to a maximum of 10, was determined using the Akaike Information Criterion (AIC). This approach ensures a robust assessment of stationarity across the series, taking into account potential variations in data trends and volatilities

Table 5: ADF for the period (2009 to 2023).

Variable	Level values		First Differences	
	Constant + trend	Constant	Constant + trend	Constant
Wheat	-2.63	-2.60	-12.95***	-12.98***
Corn	-1.92	-1.94	-13.23***	-13.26***
Soybean	-2.13	-2.13	-13.87***	-13.91***
Urea	-2.23	-2.21	-10.93***	-10.96***
DAP	-1.72	-1.54	-10.86***	-10.89***
Natural gas HH	-3.26	-3.29	-14.14***	-14.17***
Natural gas TF	-1.96	-1.72	-11.81***	-11.84***

Notes. H0: Not cointegrated against HA: Cointegrated. Critical values of test statistic from MacKinnon (1991): ** denotes significance at the 10% level, ** at the 5% level, and *** at the 1% level. The critical values are -3.53 (1%), -2.90 (5%), and -2.58 (10%).*

Table 6: ADF for the period, 2019-2023.

Variable	Level values		First Differences	
	Constant + trend	Constant	Constant + trend	Constant
Wheat	-2.41	-2.00	-9.52***	-9.55***
Corn	-1.51	-1.35	-8.220***	-8.40***
Soybean	-1.84	-1.08	-8.66***	-8.72***
Urea	-1.55	-1.44	-6.37***	-6.41***
DAP	-1.17	-1.10	-7.59***	-7.65***
Natural gas HH	-2.150	-2.12	-10.07***	-10.12***
Natural gas TF	-1.43	-1.11	-7.88***	-7.93***

Notes. H0: Not cointegrated against HA: Cointegrated. *Critical values of test statistic from MacKinnon (1991): * denotes significance at the 10% level, ** at the 5% level, and *** at the 1% level. The critical values are -3.53 (1%), -2.90 (5%), and -2.58 (10%).*

The sensitivity of results to the selection of lag length, with and without a trend, was examined to ensure robust inferences about the characteristics of the data. All the variables are found to be non-stationary and integrated of the same order i.e. $I(0)$ as can be observed from the table in their level values for both periods 2009-2023 and 2017-2023. After the first differencing, the ADF test confirms stationarity at $I(1)$ for all the variables at a 1% significance level which means that we can use cointegration as an appropriate method to examine the long-run relationship between these variables. This behavior is normal for commodity time series data which display persistent movements or trends. According to economic theory, the prices of commodities are likely to follow random walks or near random walks due to certain factors including market efficiency, and changing supply and demand dynamics.

In light of these results, the first-differenced series will be used in further analysis to avoid spurious regression and to capture the relationship between agricultural commodities and their influencing factors accurately.

Cointegration Analysis

To thoroughly examine the dynamic relationships between agricultural commodities and key market factors, a bivariate Engle-Granger cointegration test was performed, covering the period from 2009 to 2023, followed by a focused sub-sample analysis from 2017 to 2023. The Augmented Dickey-Fuller (ADF) test results indicated that all variables achieved stationarity at their first differences. This finding allows for their inclusion in a comprehensive bivariate cointegration analysis alongside the prices of staple agricultural commodities such as wheat, corn, and soybean.

The analysis for each of these commodities—wheat, corn, and soybean—was detailed in separate tables, highlighting their interactions with other agricultural commodities, fertilizers, and wheat prices. For all the tests, Robust t-values are computed using Newey-West standard errors to account for heteroscedasticity and autocorrelation (HACSE). This structured approach helps to explore the various economic interdependencies influencing these commodities over the specified periods. Each table presents a nuanced analysis of these relationships, providing insights into the underlying economic forces at play.

Wheat

The bivariate cointegration results for wheat, detailed in Table 7, reveal significant long-term equilibrium relationships with other commodities, fertilizers, and energy prices across the periods 2009-2023 and 2017-2023.

During the period 2009-2023, the cointegration statistics in the table reveal a statistically significant long-run equilibrium relationship between wheat prices and other commodities, fertilizers, and energy prices. The cointegration results for 2017-2023 also showed significance, although the strength of cointegration generally weakened slightly. The commodities pairs have a negative cointegration statistic with values ranging from -3.60 to -4.30 which indicates a statistically significant long-run equilibrium with the prices of wheat. Wheat showed strong cointegration with urea with the cointegration statistic of -4.30 and -3.649 for the periods 2009-2023 and 2017-2023 respectively. The relationship for urea weakened in the more recent period and the long-run relationship also dropped from 0.53 to 0.43. Wheat also showed a robust cointegrating relationship with DAP, corn in both periods under study. For 2009-2023, the test statistics showed a very positive relationship between two commodities with a long-run relationship of 0.90 but the relationship is not significant in the analysis of 2017-2023.

However, wheat showed a significant relationship with Natural gas Henry Hub and natural gas TTF in the period 2009-2023 but the test statistic for 2017-2023 was -2.99 and -2.94 respectively which indicates no significant cointegration.

The Engle-Granger cointegration analysis over the two distinct periods, 2009-2023 and 2017-2023, illuminates key dynamics in the speed of adjustment and long-run relationships for wheat with various commodities. Throughout both periods, the error correction coefficients remained significant at the 1% level, establishing a robust error correction mechanism to manage deviations from long-term equilibrium. Notably, the speed of adjustment for urea increased from -0.13 to -0.21, indicating more rapid corrections to deviations in the recent period, even as the long-run relationship with wheat weakened from 0.53 to 0.43. A similar pattern was observed in the wheat-DAP relationship, where the speed of adjustment increased from -0.12 to -0.19, and the strength of the long-run relationship concurrently diminished.

The analysis for natural gas Henry Hub revealed an interesting shift; despite no significant cointegration in the 2017-2023 period, the speed of adjustment increased. Across all agricultural commodities, a faster response to equilibrium deviations was noted in the more recent period, suggesting improved market efficiencies. The robustness of these findings is further reinforced by the robust t-values associated with the coefficients, affirming the statistical significance of the speed at which wheat prices revert to their long-run path.

The cointegration analysis exhibits notable shifts in the long-run relationships. This parameter represents the degree of responsiveness from the agricultural commodities, fertilizers, and energy prices to the wheat price. The results suggest that 2017-2023 showed a positive relationship between the wheat prices and the agriculture and energy market prices at the 1% significance level. For 2009-2023, the highest long-run relationship appears to be from the soybean and wheat prices at 0.90 suggesting that a 1% increase in soybean prices is associated with a 0.90% increase in wheat prices in the long run while the lowest long-run relationship of wheat prices is with Natural Gas Henry Hub and Natural Gas TTF. For wheat and urea, the long-run relationship declined from 0.53 in the earlier period to 0.43 in the latter indicating a reduced impact of urea prices on wheat prices. The long-run relationship for DAP, corn, soybean, and natural gas TTF also decreased indicating a weakening in the latter period but still held a long-term relationship with the wheat prices. In contrast, the long-run relationship for Natural gas Henry hub-wheat increased from 0.25 to 0.34 suggesting a stronger long-term effect of natural gas prices on wheat in the latter period. The positive coefficients signify a direct and proportional relationship, indicating that the commodities move with wheat prices over the extended period. Moreover, the significance of these β coefficients, as indicated by the near-zero p-values, lends robustness to these long-term relationships.

Table 7: Engle-Granger results for wheat with selected commodities, 2009-2023 & 2017-2023

	2009-2023			2017-2023		
Wheat	Cointegration statistic	Speed of adjustment	Long-run relationship (β)	Cointegration statistic	Speed of adjustment	Long-run relationship (β)
Urea	-4.30***	-0.13 (-3.70)	0.53 (7.87)	-3.649**	-0.21 (-3.93)	0.43 (5.98)
DAP	-3.77**	-0.12 (-3.80)	0.59 (8.37)	-3.13*	-0.19 (-3.04)	0.50 (6.36)
Natural gas HH	-3.04*	-0.084 (-2.42)	0.25 (3.01)	-2.99	-0.11 (-2.41)	0.34 (4.12)
TTF	-3.60**	-0.12 (-3.80)	0.244 (6.77)	-2.94	-0.14 (-2.70)	0.18 (5.41)
Corn	-3.89**	-0.15 (-3.05)	0.71 (13.40)	-3.32*	-0.22 (-3.30)	0.69 (9.11)
Soybeans	-3.605**	-0.12 (-3.30)	0.90 (11.03)	-2.93	-0.16 (-2.99)	0.76 (7.50)

Notes: ** denotes significance at the 10% level, ** at the 5% level, and *** at the 1% level. The critical values are -3.958 (1%), -3.370 (5%), and -3.068 (10%). Robust t-values, indicated in parentheses next to the coefficients in the table, are computed using Newey-West standard errors to account for heteroscedasticity and autocorrelation (HACSE).*

Corn

We now proceed to analyze the results of bivariate cointegration analysis between corn prices and other commodity prices under study. For the 2009-2023 period, the cointegration test statistic indicates a significant cointegrating relationship between the commodity pairs with urea-corn having a strong cointegration statistic at -3.58 which weakened significantly in the 2017-2023 period and reached -3.11. The cointegration statistic for DAP also weakened from -3.06 in the 2009-2023 period to -2.69 in the latter period. For natural gas Henry hub and natural gas TTF, the cointegrating statistic was significant at a 10% level indicating a marginally significant relationship but the statistic weakened significantly, and the results for 2017-2023 indicate that the relationship was not significant. The relationship for wheat-corn and wheat-soybean also decreased like other commodities which shows that the cointegrating relationship generally weakened except for urea and wheat which retained a marginally significant relationship.

The coefficients for the speed of adjustment are all significant showing robust adjustments towards the equilibrium. The speed of adjustment values across all commodity pairs indicates a faster correction of deviations from the long-run equilibrium in the 2017-2023 period compared to 2009-2023. Although the speed of adjustment increased for all commodity pairs, the pairs of Corn-DAP and Corn-Wheat showed a marked increase in the speed of adjustment. These figures suggest that the markets for these commodities are highly efficient where the prices quickly adjust to the new situation and return to equilibrium faster than the other markets. In contrast natural gas Henry hub and natural gas TTF display slower adjustment speeds of -0.046 and -0.06, respectively in both periods. This suggests that the long-run relationship between corn and the selected commodities has weakened over time but the markets have become more responsive in short-term deviations from equilibrium.

The long-run coefficients are significant for all variables indicating a strong and statistically significant long-term relationship. The long-run relationship between corn-urea and corn-soybean and corn-natural gas TTF weakened in the period 2017-2023 while the long-run relationship for other commodity pairs increased. The relationship with wheat which was already strong further increased in strength and reached 1.12 from 1.02. These findings suggest that the long-run relationships between corn and these selected commodities have sustained, indicating robust interconnections in these markets.

Table 8: Engle-Granger results for Corn with selected commodities, 2009-2023 & 2017-2023

	2009-2023			2017-2023		
Corn	Cointegration statistic	Speed of adjustment	Long run	Cointegration statistic	Speed of adjustment	Long run relationship
Urea	-3.58**	-0.09 (-2.75)	0.65 (9.15)	-3.11*	-0.13 (-3.19)	0.58 (8.93)
DAP	-3.06*	-0.07 (-2.56)	0.68 (11.45)	-2.50	-0.19 (-3.20)	0.50 (12.54)
Natural gas HH	-3.50**	-0.04 (-2.01)	0.31 (4.87)	-2.30	-0.06 (-1.87)	0.45 (6.25)
TTF	-3.20*	-0.06 (-2.21)	0.29 (10.91)	-2.45	-0.08 (-1.55)	0.27 (12.45)
Wheat	-3.44**	-0.10 (-3.46)	1.02 (12.38)	-2.80	-0.15 (-3.23)	1.12 (14.25)
Soybean	-3.40**	-0.086 (-2.41)	1.21 (17.72)	-3.13*	-0.20 (-3.14)	1.08 (17.46)

Note: ** denotes significance at the 10% level, ** at the 5% level, and *** at the 1% level. The critical values are -3.958 (1%), -3.370 (5%), and -3.068 (10%). Robust t-values, indicated in parentheses next to the coefficients in the table, are computed using Newey-West standard errors to account for heteroscedasticity and autocorrelation (HACSE).*

Soybean

The results for cointegration tests along with ECM for various commodities relative to corn prices for the periods 2009-2023 and 2017-2023 are given in the table. The variables under study show a strong cointegration with corn prices, especially urea and corn which are statistically significant at a 1% level. For 2009-2023, all variables except natural gas TTF showed a significant cointegration statistic and indicated a strong cointegrating relationship. However, the cointegrating relationship weakened for all commodity pairs in 2017-2023, and the analysis shows that soybean lost its cointegrating relationship with urea, DAP, natural gas Henry hub, wheat, and corn in the latter period. The relationship with TTF was not significant in either period. These findings suggest that while the long-run equilibrium relationships existed in the 2009-2023 period, they generally weakened or disappeared due to fluctuating market dynamics or weaker interconnections in the more recent period.

The speed of adjustment term further reveals how quickly these commodities efficiently correct deviations from long-term equilibrium. For the 2009-2023 period, significant cointegrating relationships existed between soybeans and the selected commodities with varying speeds of adjustment. In the recent period 2017-2023, the speed of adjustment decreased with the disappearing cointegrating relationships across all pairs. The speed of adjustment indicated a slower rate of correction towards the equilibrium. During the period 2017-2023, natural gas Henry hub and natural gas TTF had the lowest speed of adjustment at -0.02 and -0.03 respectively. While the speed of adjustment for all commodity pairs weakened the speed of adjustment for soybean-corn strengthened from -0.13 to -0.15. This changing speed of adjustment among all the pairs suggests that while stable, long-term relationships existed in the period 2009-2023, they have weakened in recent years and the market is taking a longer time to adjust to short-term deviations. In summary, the increasing long-run relationship with disappearing cointegration and slower speed of adjustment suggests that while related commodity prices maintain strong proportional relationships, the markets have become more volatile to changes that disrupt stable long-term equilibria.

Table 9: Engle-Granger results for soybean with selected commodities, 2009-2023 & 2017-2023

	2009-2023			2017-2023		
Soybean	Cointegration statistic	Speed of adjustment	Long run	Cointegration statistic	Speed of adjustment	Long run relationship
Urea	-3.76**	-0.09 (-0.14)	0.46 (7.99)	-2.49	-0.06 (-1.71)	0.45 (7.49)
DAP	-3.21*	-0.07 (-2.46)	0.51 (11.31)	-2.95	-0.07 (-1.75)	0.58 (14.43)
Natural gas HH	-3.14*	-0.05 (-1.86)	0.29 (4.82)	-1.92	-0.02 (-0.92)	0.35 (5.78)
TTF	2.94	-0.06 (-2.25)	0.21 (9.14)	-2.19	-0.03 (-0.87)	0.21 (10.28)
Wheat	-3.26*	-0.11 (-3.72)	0.66 (16.50)	-2.33	-0.08 (-2.45)	0.87 (10.70)
Corn	-3.53**	-0.13 (-3.75)	0.63 (18.42)	-3.01	-0.15 (-2.89)	0.78 (25.15)

Note: ** denotes significance at the 10% level, ** at the 5% level, and *** at the 1% level. The critical values are -3.958 (1%), -3.370 (5%), and -3.068 (10%). Robust t-values, indicated in parentheses next to the coefficients in the table, are computed using Newey-West standard errors to account for heteroscedasticity and autocorrelation (HACSE).*

Auto-regressive Distributed Lag (ARDL)

To deepen the understanding of the price dynamics between various commodity pairs, I employed autoregressive distributed lag (ARDL) models, focusing on their long-run relationships and speed of adjustment. The auto-regressive distributed lags (ARDL) model results for various commodity pairings over the period 2009-2023 reveal distinct dynamics in cointegration and long-run relationships, complemented by the heteroscedasticity and autocorrelation consistent standard errors (HACSE) obtained using Newey-West methodology. I used the log values for the ARDL model as taking the first difference can affect the magnitude of estimated price transmission elasticity. The table also reports the Ramsey test of model specification by J.B.Ramsey (1969) testing the model specification.

The cointegration statistics for different commodity pairs are given in the first column showing that wheat has a cointegrating relationship with all other commodities. However, the cointegration relationship of corn and soybeans is not significant with all commodities. Specifically, the DAP, natural gas Henry hub, and, natural gas TTF prices show no significant relationship with corn and soybean.

The analysis of the ARDL (Autoregressive Distributed Lag) model results reveals varying degrees of price elasticity and interdependence among major agricultural commodities like soybeans, corn, and wheat. For example, a 1% rise in soybean prices is associated with a 0.68% increase in wheat prices, while a similar 1% gain in corn prices leads to a 0.65% uptick in wheat prices in the long run. These relationships highlight the interdependence between these agricultural commodities likely driven by the same factors such as input costs and market conditions. In contrast, the long-run relationship between agricultural commodity prices and energy prices, particularly natural gas (Henry Hub and TTF), appears to be comparatively weaker. This suggests that natural gas prices are not directly related to agricultural inputs and outputs, unlike fertilizer prices which exhibit a moderately strong long-term relationship with agricultural commodity prices.

The speed of adjustment coefficients suggests that the markets correct deviations from the long-term equilibrium relatively quickly. Wheat-corn pair has the highest speed of adjustment at -0.17 meaning that 17% of any disequilibrium is corrected each period. All the speed of adjustment coefficients are negative ranging from -0.04 to -0.17 indicating that any deviations from equilibriums are corrected in subsequent periods.

The last column shows the Ramsey RESET test result which provides indications about the accuracy of econometric model specification. The null hypothesis for the Ramsey Reset test is that the model has no omitted variables and the functional form is correct while the alternate hypothesis suggests misspecification. For most commodity pairings, the RESET test shows a high p-value which means that the models are well-specified without any evident misspecifications. For example, the pairing of wheat-soybean exhibits a p-value of 0.94 which indicates that the model is well-specified for these variables. However, the pairs wheat-corn and corn-soybean with p-values of 0.20 and 0.28 respectively suggest that these models might need some crucial variables or that the model structures are not fully capturing the underlying relationships.

Table 10: Auto-Regressive distributed lags model for all commodities (ARDL), 2009-2023

	Cointegration statistic	Long run relationship	Speed of Adjustment	RESET (Ramsey Reset)
Wheat-Urea	F = 6.987**	0.56 (8.96)	-0.13 (-3.70)	0.16 (0.68)
Wheat-DAP	F = 5.822**	0.54 (8.37)	-0.12 (-3.44)	0.04 (0.83)
Wheat-Natural gas HH	F = 4.545*	0.33 (3.57)	-0.08 (-2.87)	0.15 (0.69)
Wheat-TTF	F = 6.371**	0.26 (7.84)	-0.12 (-3.52)	0.30 (0.58)
Wheat-Corn	F = 6.374**	0.65 (13.40)	-0.17 (-2.99)	5.19 (0.02)
Wheat-Soybeans	F = 6.445**	0.68 (11.03)	-0.12 (-3.49)	0.004 (0.94)
Corn-Urea	F = 4.855***	0.74 (13.35)	-0.09 (-3.15)	0.79 (0.37)

Corn-DAP	F = 2.611	0.56 (9.15)	-0.06 (-2.32)	1.28 (0.25)
Corn- Natural gas HH	F = 2.221	0.34 (10.91)	-0.04 (-2.08)	0.36 (0.54)
Corn-Natural gas TTF	F = 2.793	0.27 (3.58)	-0.06 (-2.36)	0.47 (0.49)
Corn-Wheat	F = 5.877**	1.15 (12.38)	-0.10 (-3.45)	4.07 (0.04)
Corn-Soybean	F = 3.509	0.98 (13.32)	-0.08 (-2.66)	5.46 (0.02)
Soybean-Urea	F = 4.530***	0.45 (7.99)	-0.10 (-3.00)	1.12 (0.29)
Soybean-DAP	F = 3.327	0.39 (11.31)	-0.08 (-2.79)	0.31 (0.57)
Soybean-Natural gas HH	F = 2.184	0.30 (4.82)	-0.06 (-2.11)	1.09 (0.29)
Soybean-Natural gas TTF	F = 2.616	0.14 (9.14)	-0.04 (-2.33)	1.21 (0.27)
Soybean-Wheat	F = 7.917*	0.88 (8.87)	-0.11 (-4.01)	3.33 (0.36)
Soybean-Corn	F = 5.879**	0.68 (14.82)	-0.12 (-3.49))	2.26 (0.17)

Note: ** denotes significance at the 10% level, ** at the 5% level, and *** at the 1% level. The critical values from Kripfganz and Schneider (2020) are 4.071–4.821, 4.974–5.797, and 6.992–7.949 for 10%, 5%, and 1% significance levels, respectively. Robust t-values, indicated in parentheses next to the coefficients in the table, are computed using Newey-West standard errors to account for heteroscedasticity and autocorrelation (HACSE).*

ARDL 2017-2023

In this analysis, I focus on the period from 2017-2023 evaluating potential changes in the cointegration relationships, long-run relationships, and error correction speed. By doing a subsample analysis for 2017-2023, I aim to study distinct patterns or trends that may have emerged in the more recent period.

During the 2017-2023 period, the analysis of cointegration statistics across various agricultural commodity pairings indicates diverse levels of integration. While Wheat paired with Urea and DAP showed strong cointegration, with significant F-statistics of 6.146 and 5.097 respectively, indicating robust long-term relationships, other pairings exhibited more variability. For instance, commodities involving natural gas, such as Wheat-Natural Gas HH and Soybean-Natural Gas HH, displayed notably weaker cointegration, with F-statistics of 2.811 and 0.671 respectively, falling below conventional significance thresholds. This suggests less stable or evolving relationships, possibly due to the volatile nature of energy prices and their indirect impact on these agricultural commodities. However, a distinct observation was made for soybeans, which showed no significant cointegration with any other commodity, highlighting its unique market dynamics and potential independence from the factors influencing other agricultural markets.

The speed of adjustment results display significant and negative error correction terms across all commodity pairs indicating stability and tendency to return to equilibrium after disturbance. The significant negative values range from -0.02 to -0.22 where soybean-natural gas TTF has the lowest speed of adjustment at -0.02 while wheat-DAP has the lowest speed of adjustment while Wheat-DAP has the highest speed of adjustment at -0.22. These results highlight that despite short-term fluctuations and no cointegration, there is a strong tendency for these commodity prices to return to equilibrium in the long run.

Across the examined pairings, several significant long-run relationships have been identified indicating stable and long-run connections across certain commodities. For example, the pairing of soybean-wheat exhibits a long-term relationship of 1.10 while the soybean-TTF exhibits the lowest long-run relationship at 0.04. Overall, the significant long-run relationships observed in some commodity pairs highlight the importance of interconnected markets and also underscore the complex yet stable nature of agricultural commodity markets.

The Ramey Reset test also shows non-significant results across the commodity pairings which indicates that the models are appropriately specified. These results collectively suggest that the

ARDL models used in the subsample analysis are robust and support the reliability of the long-run relationships and speed of adjustment results.

Table 11: Auto-Regressive distributed lags (ARDL), 2017-2023.

	Cointegration statistic	*Long run relationship*	*Speed of Adjustment*	*RESET*
Wheat-Urea	*F = 6.146***	*0.42* *(5.98)*	*-0.17* *(-3.43)*	*0.01* *(0.89)*
Wheat-DAP	*F = 5.097***	*0.46* (6.36)	*-0.22* *(-3.15)*	*0.001* *(0.96)*
Wheat-Natural gas HH	*F = 2.811*	*0.27* *(4.12)*	*-0.10* *(-2.26)*	*0.33* *(0.56)*
Wheat-TTF	*F = 3.809*	*0.17* *(5.41)*	*-0.14* *(-2.69)*	*0.14* *(0.70)*
Wheat-Corn	*F = 5.567***	*0.61* *(9.11)*	*-0.21* *(-3.26)*	*0.55* *(0.45)*
Wheat-Soybeans	*F = 4.371**	*0.66* *(7.50)*	*-0.16* *(-2.97)*	*0.03* *(0.85)*
Corn-Urea	F = 3.677	0.62 (8.93)	-0.13 (-2.76)	0.10 (0.74)
Corn-DAP	F = 6.229**	0.75 (12.54)	-0.19 (-3.62)	0.03 (0.85)
Corn- Natural gas HH	F = 1.279	0.38 (6.25)	-0.05 (-1.56)	0.14 (0.70)
Corn-Natural gas TTF	F = 1.604	0.22 (12.45)	-0.08 (-1.78)	0.07 (0.78)

Corn-Wheat	F = 4.887*	1.29 (14.25)	-0.15 (-3.16)	0.10 (0.74)
Corn-Soybean	F = 4.524*	1.12 (17.46)	-0.20 (-3.06)	0.02 (0.87)
Soybean-Urea	F = 2.048	0.38 (7.49)	-0.08 (-2.03)	3.08 (0.08)
Soybean-DAP	F = 1.218	0.35 (14.43)	-0.07 (-1.57)	0.69 (0.40)
Soybean-Natural gas HH	F = 0.671	0.16 (5.78)	-0.03 (-1.10)	1.36 (0.24)
Soybean-Natural gas TTF	F = 0.659	0.04 (10.28)	-0.02 (-1.09)	1.45 (0.23)
Soybean-Wheat	F = 2.323	1.10 (10.70)	-0.08 (-2.36)	3.54 (0.06)
Soybean-Corn	F = 1.165	0.66 (18.15)	-0.09 (-1.53)	6.18 (0.01)

Note: *: * denotes significance at the 10% level, ** at the 5% level, and *** at the 1% level. The critical values from Kripfganz and Schneider (2020) are 4.095–4.860, 5.032–5.875, and 7.163–8.148 for 10%, 5%, and 1% significance levels, respectively. Robust t-values, indicated in parentheses next to the coefficients in the table, are computed using Newey-West standard errors to account for heteroscedasticity and autocorrelation (HACSE).*

Granger Causality

The Granger causality is a statistical hypothesis test to determine if one time series can predict another. In the context of analysis, I have provided the analysis of agricultural commodities prices i.e. wheat, corn, soybean in separate tables with other agricultural commodities, fertilizer, and energy prices for the period 2009 to 2023 and from 2017 to 2023. The null hypothesis in one variable does not Granger to cause the other.

For many of the pairings such as urea and DAP, the tests reveal that these fertilizers Granger cause wheat prices in both periods 2009-2023 and 2019-2023, highlighting their predictive influence. The relationships involving energy commodities like natural gas Henry Hub and natural gas TTF exhibit weaker or bidirectional causalities with natural gas Henry predicting wheat prices in 2009-2023 and wheat predicting the natural gas TTF prices in both periods. In the case of agricultural commodities, corn is the only commodity causing the wheat prices in the longer period 2009-2023.

Table 12: Granger causality for wheat with commodities, 2009-2023 & 2017-2023.

Wheat	**2009-2023**		**2017-2023**	
Null Hypothesis	**Chi2**	**Prob.**	**Chi2**	**Prob.**
UREA does not Granger Cause WHEAT	11.26	0.03	15.04	0.02
WHEAT does not Granger Cause UREA	1.45	0.96	1.19	0.97
DAP does not Granger Cause WHEAT	13.28	0.03	13.23	0.03
WHEAT does not Granger Cause DAP	6.48	0.37	3.15	0.79
Natural gas Henry Hub does not Granger Cause WHEAT	11.35	0.03	7.85	0.24
WHEAT does not Granger Cause Natural gas Henry Hub	5.49	0.48	8.36	0.23
Natural gas TTF does not Granger Cause WHEAT	13.62	0.07	9.08	0.16
WHEAT does not Granger Cause Natural gas TTF	14.07	0.02	14.16	0.02
Corn does not Granger Cause WHEAT	13.82	0.03	5.30	0.50
WHEAT does not Granger Cause Corn	3.291	0.77	3.08	0.79
Soybean does not Granger Cause WHEAT	2.85	0.82	11.18	0.08
WHEAT does not Granger Cause Soybean	6.97	0.32	3.45	0.75

This table provides Granger Causality results for corn with all other commodities under study. In the case of fertilizers, we find no evidence of Granger causality among corn, urea, and DAP prices in the periods 2009-2023 and 2017-2023. For the period 2009-2023, corn was the only commodity found to be causing soybean and wheat prices suggesting that the fluctuations in corn prices could be used to forecast changes in other crops. Interestingly, natural gas Henry hub was also found to granger-cause corn, indicating the potential influences of energy prices on agricultural commodities. In the period 2017-2023, the only significant finding was that corn Granger causes soybean prices, highlighting the interdependency between these two crops.

Table 13: Granger causality for corn with commodities, 2009-2023 & 2017-2023.

2009-2023			**2017-2023**	
Null Hypothesis	**Chi2**	**Prob.**	**Chi2**	**Prob.**
UREA does not Granger Cause corn	13.89	2.33	9.42	0.15
Corn does not Granger Cause UREA	5.58	0.15	7.98	0.24
DAP does not Granger Cause corn	10.29	0.11	10.65	0.10
Corn does not Granger Cause DAP	9.64	0.14	5.40	0.49
Natural gas Henry Hub does not Granger Cause corn	12.96	0.04	9.18	0.163
Corn does not Granger Cause Natural gas Henry Hub	1.83	0.93	10.175	0.11
Natural gas TTF does not Granger Cause corn	12.98	0.81	10.95	0.15
Corn does not Granger Cause Natural gas TTF	6.62	0.35	5.40	0.24
Wheat does not Granger Cause corn	3.29	0.77	3.08	0.79
Corn does not Granger Cause Wheat	13.82	0.03	5.30	0.50
Soybean does not Granger Cause Corn	3.19	0.78	6.29	0.39
Corn does not Granger Cause Soybean	17.72	0.00	16.89	0.010

This table provides the Granger causality results for soybean prices with other agricultural, fertilizer, and energy prices. In the period 2009-2023, both fertilizers, urea, and DAP are found to be causing the soybean prices. Moreover, the corn prices are found to cause the soybean prices. For the period 2019-2023, the urea, DAP, and corn prices are found to be causing the soybean prices like the 2009-2023 period results. These findings highlight the significant predictive relationships between Urea, DAP, and corn with soybean prices. The results suggest that the price changes in soybean can be predicted with urea, DAP, and corn prices across both periods analyzed.

Table 14: Granger causality for soybean with commodities, 2009-2023 & 2017-2023.

	2009-2023		**2017-2023**	
Null Hypothesis	**Chi2**	**Prob.**	**Chi2**	**Prob.**
UREA does not Granger Cause soybean	17.89	0.00	16.08	0.01
Soybean does not Granger Cause UREA	6.01	0.42	6.87	0.33
DAP does not Granger Cause soybean	18.26	0.003	21.20	0.002
soybean does not Granger Cause DAP	11.73	0.06	7.78	0.25
Natural gas Henry Hub does not Granger Cause soybean	7.03	0.97	9.61	0.14
Soybean does not Granger Cause Natural gas Henry Hub	11.73	0.06	10.21	0.11
Natural gas TTF does not Granger Cause soybean	7.03	0.31	7.78	0.25
Soybean does not Granger Cause Natural gas TTF	9.60	0.14	7.95	0.24
Wheat does not Granger Cause soybean	6.97	0.32	3.45	0.75
Soybean does not Granger Cause Wheat	2.85	0.82	11.18	0.08
Corn does not Granger Cause soybean	17.72	0.00	16.89	0.01
Soybean does not Granger Cause Corn	3.19	0.78	6.29	0.39

8. **Conclusion**

Throughout this thesis, I have analyzed the relationships between key agricultural commodities—wheat, corn, and soybeans—and essential market inputs such as urea, diammonium phosphate (DAP), and natural gas prices from Henry Hub and TTF from 2009 to 2023. Employing a robust econometric framework that included cointegration analysis, Granger causality tests, and Autoregressive Distributed Lag (ARDL) models, the study has highlighted significant relationships that exist both in the long-term equilibrium and in response to short-term market fluctuations.

The findings demonstrate a stable long-term relationship among the prices of natural gas, fertilizers, and agricultural commodities, confirming that fluctuations in natural gas prices—as a critical input for fertilizer production—directly influence the cost structures within the agricultural sector. Particularly illuminating was the sub-sample analysis from 2017 to 2023, which revealed increased market sensitivity to geopolitical events and global economic disruptions, including the COVID-19 pandemic and the Russia-Ukraine conflict. It was observed that short-term fluctuations in natural gas prices significantly impact the prices of urea and DAP, subsequently affecting the prices of major agricultural commodities. The study has documented notable ripple effects across the fertilizer and agricultural markets prompted by sudden changes in energy prices, highlighting their critical role in agricultural price formation and the consequent impact on food security and economic stability. Furthermore, the analysis confirms that the agricultural commodities prices are not only influenced by fertilizer and natural gas prices but also exhibit significant long-term relationships with other commodities, suggesting a persistent interdependence over the long run.

For producers and agricultural practitioners, the insights provided by this study are crucial for effective planning and risk management. Agricultural producers face numerous uncertainties related to input costs and market prices. By understanding the intricate relationships between energy prices, fertilizer costs, and grain market prices, producers can develop more informed strategies for planting, procurement, and hedging. For example, farmers can make better decisions regarding the timing and type of fertilizers to use based on energy prices, which directly impact fertilizer costs. Furthermore, the findings may facilitate policymakers in understanding the dynamics between energy, fertilizers, and agricultural commodity prices, as these sectors are crucial for food security and economic stability. The study's findings can inform policies aimed at stabilizing food prices, managing market risks, and promoting sustainable agricultural practices. For instance, policymakers can use the insights to develop strategies for mitigating the impact of energy price shocks on fertilizer costs and, subsequently, on food prices. For investors, the insights provided by this study are valuable for making informed investment decisions in agricultural and commodity markets. Investors can use the understanding of price dynamics and drivers uncovered by this research to identify potential investment opportunities and manage risks effectively. For example, investors might anticipate that rising natural gas prices will lead to increased fertilizer costs and, subsequently, higher grain prices. By understanding these interconnected markets, investors can develop strategies to capitalize on price movements and mitigate potential losses.

While this study provides a comprehensive analysis, it acknowledges the limitation that the econometric models employed, predicated on linear relationships, might not fully capture potential non-linear interactions prevalent in commodity markets. To address this limitation, future research should utilize advanced modeling techniques to capture complex non-linear market dynamics.

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