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The impact of the 2008 financial crisis on the food-energy-agricultural inputs nexus and implications for economic resilience

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Abstract

We use multivariate copula models to assess the asymmetries in tail dependence between agricultural commodity prices (i.e., cereals and meats) and production input prices (i.e., fertilizers, seeds, animal feed and energy). We use monthly observations between January 2000 and May 2022 and split the time in 2009 to assess the results of the financial crisis. We find upper tail dependence between cereals and fertilizers in the pre-2009 period and upper tail dependence between seeds and fertilizers, and energy and fertilizers post-2009. Furthermore, we find strong and symmetric tail dependence between cereals and seeds in both periods. Our findings suggest that the protective nature of CAP has led to moral hazard effects depriving farmers from the incentives that enhance the sector resilience. Furthermore, agro-chemical companies do not seem to exploit the oligopoly market structure and raise prices arbitrarily. Finally, based on our results, we infer on the economic resilience of the agricultural sector.

Keywords: *Agricultural commodity prices, Input prices, Economic resilience, Price co-movement, Copula models.*

1. Introduction

The food price rally in late 2021 and the subsequent invasion of Russia in Ukraine have renewed interest in the price linkages between production inputs including energy and agricultural markets. Russia is the world leader in the export of fertilizers and a key player in the global energy markets, whereas Ukraine is a major cereals producer and exporter. The specific conflict combined with the adverse effects of climate change jeopardize the food supply of wheat and basic grains (Ibrahim, 2024). In this context, the interrelations between agricultural commodity and input prices such as fertilizers, seeds, animal feed and energy have drawn considerable attention, especially given the concerns for many countries, which dependent on food and imports of crude oil, fertilizers, etc. Nevertheless, it is worth noting that even though nominal grain prices have risen dramatically since the 1960s, in real terms they have actually fallen against oil prices and to a lesser extent against the fertilizer prices (Dorward, 2013), which may pose

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threats relating to the economic resilience of farms and agricultural communities. This paper examines the impact of the 2008 financial crisis on the price dependence relationships between the prices of agricultural commodities (cereals and meats), energy and agricultural inputs (fertilizers, seeds and animal feed) and subsequently discusses the implications on economic resilience for the Greek agricultural sector. The profound effects of the crisis combined with the intrinsic characteristics of the food-energy-agricultural inputs nexus, including the oligopolistic nature of the inputs markets are expected to have borne considerable changes on the Greek agricultural sector and its economic resilience.

The food-energy-agricultural inputs price nexus provides various prospects for empirical research. The energy-intensive nature of agriculture stems from the direct link between energy and agricultural production (Koirala *et al*., 2015). Increasing oil prices incur rises in the agricultural input costs and thus yield rises in the commodity prices. Nevertheless, the intensity of such impacts is affected by various factors, including the relative importance of oil in the cost of production and the market power in the agricultural sector (Koirala *et al*., 2015). Furthermore, energy and agricultural markets are closely connected on the demand side (Reboredo, 2012). Increased oil prices lead to significant raises in the demand for biofuels. This is particularly relevant in periods of increasing biofuel production when the demand for agricultural commodities is exacerbated (Chen *et al*., 2010). Moreover, Chen *et al*. (2010) shows that changes in the prices of corn, soybean, and wheat are affected by increased crude oil prices, especially when increased oil prices have led to increased derived demand for corn and soybean, and to more intense competition for the areas cultivated with other grains. Therefore, several studies show that oil prices are critical in determining the agricultural commodity prices (e.g., FAO, 2008; Mitchell, 2008; OECD, 2008; Piesse and Thirtle, 2009).

Furthermore, agriculture consumes energy indirectly, through the production of fertilizer. Manufacturing inorganic nitrogenous fertilizer is an energy-intensive process, typically requiring significant use of energy from fossil fuels (World Bank Group, 2007) and despite the increasing application of machinery in the agriculture of high-income countries, fertilizer still accounts for almost half of agriculture's demand for energy (Dorward, 2013). Therefore, shocks to fertilizer markets are expected to incur wide economic impacts, which have not been adequately acknowledged. With empirical research so far focusing on direct oil cost-push or demand shocks due to biofuel production, the fertilizer channel is a new element on the food-energy-agricultural inputs nexus, which has been largely overlooked. In this context, competition in the fertilizer industry becomes highly relevant. Gnutzmann and Spiewanowski (2016) point the long history of cartel behavior in the specific industry and relate this behavior to the lack of competition for nitrogen, for mineral reserves such as phosphorus and potash which are geographically concentrated and exploited by export cartels, and for nutrients which are production compliments. Furthermore, we emphasize the importance of seeds and animal feed for agricultural production. Seeds comprise a crucial and expensive factor with the corresponding market being highly concentrated on a global level (USDA, 2023). Animal feed is the largest single cost item for livestock and poultry production, accounting for 60 to 70 percent of the total cost, and what is more, animal producers cannot simply pass cost increases on to consumers, since they act as price takers in competitive markets (Lawerence *et al*., 2008). The respective index involves cereals such as corn, barley, wheat, sorghum, and oats but also includes pasture forage, hay, silage, vitamin and mineral supplements, the prices of which are not captured in the cereals index.

The Greek agricultural sector contributes more than 4.5 percent to the country's GDP (European Commission, 2021) and employs approximately 400,000 people, which is 10 percent of its total employment (European Commission, 2023). The sector comprises a total of 700,000 farms, which are mainly small family holdings, averaging a size of about 7 hectares, while more than 70 percent of these farms occupy less than 5 hectares each (European Commission, 2023). Furthermore, more than 70 percent of the agricultural area faces natural or other constraints including extreme slopes, low temperatures, dryness of soil, unfavorable soil texture, borderline areas, island regions, which bears significant impacts in the farming process. Rural areas account for 63 percent of the total area and agricultural land amounts to 5.3 million hectares. Regarding agricultural inputs, Greece has very little indigenous oil production and the demand for oil is covered by imports (OECD, 2020). According to Eurostat (2023) oil and petroleum products (excluding biofuels) account for 56 percent of the total direct consumption of energy in the agricultural and forestry sector, and even though this share is considerably lower for the Greek agricultural sector, these factors still remain important for agricultural production. Furthermore, the Greek agricultural sector is heavily dependent on imports of fertilizers, seeds, and animal feed. In 2019, the imports of fertilizers amounted to 34000 tons (WITS, 2019), whereas those of soybean and soybean meals (i.e., the main ingredients in animal feed), raised above 300,000 metric tons (USDA, 2021). In addition, Greece is a net importer of planting seeds, averaging imports of $68 million (USDA, 2015). With fertilizers bearing a cost share of 44 percent in food commodity prices, which far exceeds the share of direct energy (Gnutzmann and Spiewanowski, 2016), their prices are of strategic importance to the producers. Moreover, the market of seeds is highly concentrated with 5 firms dominating the global market (USDA, 2023). Given this oligopolistic market structure, price formation exhibits particular interest, especially since seeds are critical for agricultural production. In this context, we seek to shed light into the interdependencies between agricultural commodity prices and input prices, in the Greek agricultural sector.

Bristow (2010) defines economic resilience as 'the capacity of a system to absorb disturbance and reorganize while undergoing change, so as to still retain essentially the same function, structure and feedbacks' and associates it with the firm's ability to adapt so they maintain an acceptable growth in output, employment and wealth over time (Martin, 2012). It has typically been studied through employment indicators (Martin and Sunley, 2015; Angelopoulos *et al.*, 2023), macroeconomic and accounting measures such as gross value added (Sdrolias *et al.*, 2022) and gross agricultural output value (Yang *et al.*, 2022). Nevertheless, in the context of agriculture, not much attention has been placed explicitly on the cost factors, which are crucial for agricultural production and may challenge the farms and the agricultural sector in general. Even though these costs are implicitly accounted for, these measures include several other factors as well, making them unsuitable for our cause. In this regard, we aim to assess the price interrelations between agricultural inputs (i.e., fertilizers, seeds, energy, and animal feed) and agricultural commodity prices (i.e., cereals and meats), before and after the 2008 financial crisis and subsequently, infer on economic resilience of the Greek agricultural sector.

The interrelations between energy and food prices have traditionally been examined via linear and nonlinear methods. Nazlioglu (2011) employs linear and nonparametric causality methods to examine the causal relationships between world oil and agricultural commodity prices. This study finds that oil and agricultural commodity prices do not influence each other but there are nonlinear feedbacks between them and there exists persistent unidirectional nonlinear causality from oil to corn and soybeans prices. Nazlioglu and Soytas (2011) investigate the short- and long-run interrelationships between world oil prices, exchange rates, and individual agricultural commodity prices in Turkey. This study employs causality and impulse-response analysis, and its findings support neutrality of agricultural commodity markets to both direct and indirect effects of oil price changes. Zhang *et al.* (2010) examine cointegration and multivariate short-run interactions between fuels and agricultural commodities and find no direct long-run and limited direct short-run relations between fuel and agricultural commodity prices. Cheng and Cao (2019) investigate the dynamic relationship between crude oil prices and food price indices applying cointegration, linear Granger causality, threshold vector autoregressive and threshold vector error correction models and find nonlinear causal relationship between the variables, concluding that the adjustment of the food price indices towards equilibrium is persistent and grows faster than oil prices when a threshold is reached. However, studies employing causality analysis or linear correlation-based methods pose certain limitations. In more detail, the results of causality analyses rely on arbitrarily calibrated price elasticities (Reboredo, 2012). On the other hand, correlation is considered an inadequate dependence measure since it provides no information regarding the dependence structure. Furthermore, linear correlation is not invariant under nonlinear and strictly increasing transformations, which implies that returns may be uncorrelated even though prices are correlated or vice versa (Koirala *et al*., 2015). Therefore, studies applying non-linear methods, including copula-based methods, are needed for the analysis of commodity and resource prices, the dependence structures of which typically exhibit nonlinear traits.

In this context, copula-based studies include Mensi *et al*. (2017) combining wavelets with static and time-varying copulas to analyze the dependence structure between the volatility indices of oil, wheat and corn and finding evidence of asymmetric tail dependence between the cereals and oil in different time horizons. Furthermore, Reboredo (2012) employs both static and time-varying copulas to assess the co-movements between Brent spot prices and global prices for corn, soybean and wheat. This study finds weak oil-food dependence but no extreme market dependence, which indicates that food price spikes are not caused by positive extreme oil price changes. Koirala *et al*. (2015) employs the Clayton and the Clayton–Gumbel copulas to investigate the relationship between the prices of various energy and agricultural commodity futures. They find that agricultural commodity and energy future prices are highly correlated and exhibit positive and significant dependence. This finding is attributed to the connection between energy prices and agricultural production costs, which for increasing energy prices yields decreasing planted acreage and reduced supply of agricultural commodities. Furthermore, this outcome implies that significant utilization of agricultural commodity inputs in the production of energy may lead to greater energy self-sustainability. Finally, in a broader context, Chavas *et al*. (2022) use a quantile autoregressive model to estimate univariate yield distributions for corn and wheat in seven regions of Italy and employ a nonparametric copula model to investigate the co-variability of yield risk across the crops and across the regions. This study finds that yield co-variability decreases between more distant regions, thus providing opportunities for regional diversification to reduce risk in the global food supply.

The present study contributes to the empirical literature towards at least three perspectives. The effects of the 2008 financial crisis have been studied via a wealth of methods and in various contexts (e.g., Kapelko *et al*., 2017; Zhu *et al*., 2021 and Ghazani *et al*., 2023). Nevertheless, the effects of the crisis with regards to agricultural prices and their interconnections with energy and inputs prices have been largely neglected. To this end, this is the first study applying copulas to analyze the changes in the price linkages between agricultural commodities and agricultural input prices, in the aftermath of the crisis. Furthermore, to the best of our knowledge, this is the only study including the price indices of seeds and animal feed in analyzing the food-energy-agricultural inputs price nexus. Finally, relevant analyses regarding the Greek agriculture are limited and we seek to fill this gap. Our findings are of particular interest, given that Greek producers are evidently price takers regarding energy, fertilizers, seeds and to a large extent animal feed. In this respect, the price interplay between food, energy and agricultural inputs is essential for understanding food markets. The rest of the paper is organized as follows: Section 2 presents the methods we apply and discusses the main features of the data we use, Section 3 outlines the empirical results and provides a discussion of our findings, and finally, Section 4 concludes the paper.

2. Materials and methods

2.1. *The marginal models*

Following the semi-parametric approach of Chen and Fan (2006a; 2006b) we first specify a GARCH model which we fit to the price changes, subsequently we convert the standardized residuals of the filtered data into copula data (i.e., data lying on (0,1)), and finally we estimate the copula models by applying the maximum-likelihood estimator on the copula data. We utilize ARMA(p,q)-GARCH(1,1) and GJR(p,q)-GARCH(1,1) models, and select the most appropriate models based on the usual information criteria (Akaike, Bayes, Shibata, and Hannan-Quinn).

2.2. *Copula models, selection, estimation and testing*

In order to investigate the price interdependencies between the variables, we employ copulas. The general idea underlying a copula is to separate the dependence structure from the marginal distributions. A copula depicts how the marginal distributions are linked in the joint distribution and therefore, copulas are applied to assess dependencies between multivariate marginal distributions and detect price co-movements. A marginal distribution function is associated with each of the components (prices) in a random vector and the copula captures the dependence structure between the individual components.

Vine copulas are a class of models which decompose a multivariate model into a group of bivariate copulas. This decomposition is not unique, but all possible decompositions can be organized as a graphical model (i.e., a collection of nested trees) called the regular vine, where each of the edges corresponds to a pair of random variables conditioned on some others (Nagler *et al*., 2022). A D-vine is a special case of regular vine where each tree is a path, that is, each of the vertices is connected to at most two other vertices. The specific structure is natural when there is a natural ordering of the variables. Another special case of regular vine is the C-vine, where each tree is a star, that is, there is one vertex which is directly connected to all other vertices. The specific structure applies when there is a single variable driving the others.

Each pair-copula can be modeled separately and therefore, regular vines are very flexible in describing complex dependence structures which capture asymmetries and extreme tail dependence. Furthermore, analyzing the price linkages based on bivariate copulas may lead to misleading outcomes, especially in the case of prices which are not directly connected, but for which price co-movements exist given a conditioning market. Aguiar-Conraria and Soares (2014) demonstrate that the co-movement between two prices conditioned on a third price, if modeled directly may be distorted and appear more intense or weaker. Nevertheless, a positive price association between separated markets normally leads to weaker co-movement after conditioning (Diβmann *et al*., 2013; Kellner and Rösch, 2016). Thus, higher numbered trees usually involve the independence copula and become redundant.

For the pair connections of the trees, we consider various static bivariate copula models which can capture diverse patterns of tail dependence, including independence, symmetric, and asymmetric upper or lower tail dependence. More precisely, we apply elliptical (Gaussian and Student's t) and Archimedean bivariate copulas (Clayton, Gumbel, Frank, Joe, Clayton-Gumbel, Joe-Gumbel, Joe-Clayton, and Joe-Frank). This battery of copulas provides sufficient flexibility which allows effectively capturing diverse non-zero lower- and upper-tail dependence structures. Moreover, we consider the rotated Clayton, Gumbel, Joe, Clayton-Gumbel, Joe-Gumbel, Joe-Clayton, and Joe-Frank copulas. A 180 rotated copula corresponds to the respective survival copula, while the 90 and 270 rotated copulas enable modelling negative dependence structures.

To select the most appropriate copula model for each of the pairs of price series we use the Akaike information criterion (AIC). Furthermore, we apply the maximum likelihood estimation method to obtain the parameters of each specified copula model. Finally, we perform the goodness-of-fit tests of Huang and Prokhorov (2014) for the vine copulas we obtain, to confirm the validity of the selected models.

2.3. *Measuring dependence*

We use Kendall's τ to assess the degree of overall dependence. This measure ranges between -1, which indicates perfect dis-concordance, and +1, which indicates perfect concordance. Furthermore, we use the lower- and upper-tail coefficients, taking values in [0,1], to measure tail dependence. If λ_L (λ_U) is positive, then there is lower or left (upper or right) tail dependence, otherwise there is lower (upper) tail independence.

2.4. *Data*

We empirically investigate the tail dependence relationships between agricultural commodity prices, that is cereals (wheat, corn, and barley) and meats (beef and veal, pork, lamb and goat) and input prices (energy, fertilizers, seeds, and animal feed) using monthly data covering the period between January 2000 and May 2022. We utilize agricultural commodity prices instead of consumer or processor prices, given our interest in economic resilience in the agricultural sector and thus, in the farmers' income. The data for cereals, meats, seeds, fertilizers, and animal feed are monthly price indices obtained from the databases of the Hellenic Statistical Authority with base year 2015 (2015=100). As a proxy for the energy prices, we use Europe Brent crude oil prices which are obtained from the official website of the U.S. Energy Information Administration. These are free-on-board (FOB) spot prices reported daily that are averaged on a monthly basis. Moreover, they are initially expressed in US dollars per barrel and are converted in EUR per barrel using the exchange rates obtained from the website of macrotrends. Cereals, meats, fertilizers, seeds, animal feed and oil price returns (r_t) are computed on a continuous compounding basis as $r_t = ln(P_t / P_{t-1})$, where P_t and P_{t-1} are the current and one-period lagged monthly prices. We use monthly observations instead of weekly given the nature of our variables (agricultural commodities exhibit seasonal production and therefore their prices are usually recorded in lower frequencies) and because it is less noisy.

Figure 1 - Development of log-prices for the agricultural commodities and the production inputs.

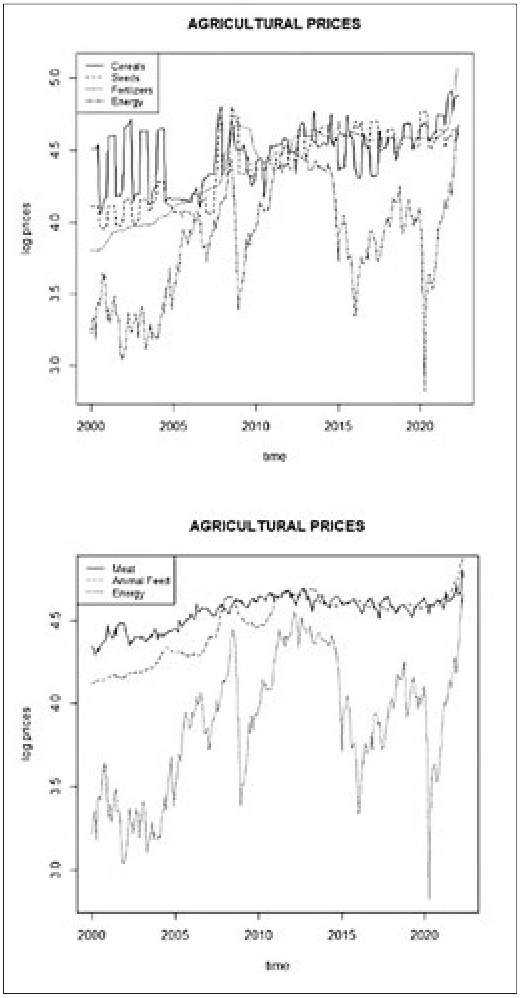

Figure 1 plots the price series under consideration whereas the corresponding descriptive statistics are presented in Table 1.

Table 1 - Descriptive statistics of price returns (raw price shocks).

	cereals	*meats*	*fertilizers*	*seeds*	*animal feed*	*energy*
mean	0.0014	0.0015	0.0048	0.0020	0.0028	0.0054
std. dev.	0.1099	0.0274	0.0184	0.0732	0.0119	0.1056
min	-0.5511	-0.0678	-0.0738	-0.4124	-0.0430	-0.5674
max	0.4348	0.1062	0.1850	0.4641	0.0677	0.4636
observations	268	268	268	268	268	268

Note: Monthly data between 01/2000 and 05/2022.

Table 2 - ADF and Phillips-Perron test results.

	cereals	*meats*	*fertilizers*	*seeds*	*animal feed*	*energy*
Test statistic	-10.9670	-9.9601	-3.1371	-11.3720	-3.9080	-6.5078
Z(alpha)	-235.0800	-332.3400	-189.6700	-244.2700	-105.5900	-178.4200

Note: Null hypothesis: the series has a unit root. Test critical values: 1% level –2.58, 5% level –1.95, and 10% level –1.62.

These figures highlight that it is not uncommon for input price indices to surpass agricultural commodity price indices. Furthermore, energy clearly exhibits larger price variation compared to the indices. This is due to the volatile nature of crude oil prices and to averaging when computing price indices, which tends to reduce large variations.

We examine the stationarity properties of the log-returns applying the augmented Dickey-Fuller (ADF) and the Phillips-Perron unit root test. The respective results are presented in Table 2 and confirm that all the series are stationary on the first differences.

3. Results and discussion

3.1. *Results for the marginal models*

We initially obtain the filtered rates of the price changes. To this end, we fit ARMA(p,q)-GARCH(1,1) and GJR(p,q)-GARCH(1,1) models to each of the price series and select the most appropriate among the different models based on four information criteria (Akaike, Bayes, Shibata, and Hannan-Quinn). The selected models are ARMA(1,0)-GARCH(1,1) for the prices of cereals, meats, fertilizers and seeds, ARMA(2,0)-GARCH(1,1) for the prices of animal feed and ARMA(2,3)-GARCH(1,1) for the prices of energy. We then calculate the empirical distribution functions and obtain the copula data, using the standardized residuals. We do not present the results of the respective models in full detail for the sake of brevity. However, they are available on request.

3.2. *Results for the copula models*

In the first subperiod (2000 to 2008), we find that the D-vine structure best captures the interdependencies between the variables. The only central market is cereals which establishes direct connections with fertilizers and seeds. This implies that the market of cereals receives/transmits strong price signals from/to these markets. The protective nature of the CAP measures in place throughout the respective period could have allowed farmers to determine the prices of cereal considering both the cost-push and the demand-pull effects. On the other hand, the prices of fertilizers and seeds which are both imported, have been determined on the global markets and, to a large extent, irrespective of the domestic demand. Therefore, the price interrelations between cereals and fertilizers/seeds have been stronger, making cereals the central market.

Furthermore, we find that the survival Clayton copula best captures the price linkages between cereals and fertilizers, with Kendall's τ=0.1014. This copula indicates asymmetric upper tail dependence, implying that the prices of cereals and fertilizers boom together but they do not crash together, and that price increases are passed on to a larger extent than price decreases. This finding is consistent with Chowdhury *et al.* (2021) which finds that positive price changes of fertilizers bear larger effects on food (including wheat and corn) prices than negative price changes. To explain this asymmetry, we resort to the EU intervention policies in place throughout the period 2000 to 2008, which seem to have provided some level of protection to the prices of cereals against dropping below certain levels. Therefore, during periods of price surges in the fertilizers markets the prices of cereals increased to accommodate the higher input costs, but during periods of price falls the cereal prices did not match the falls in the fertilizers markets. More particularly, before 2003, support for the production of cereals involved measures such as coupled crop-specific payments, supply control (e.g., set-aside obligation), production refunds for starch processors, intervention buying, and border measures such as import tariffs, tariff rate quotas for imports designed to protect the internal market from lower-priced world market imports, and export refunds (European Commission, 2012). Moreover, the 2003 Mid Term Review introduced the decoupled Single Payment Scheme, which provided income support regardless of the type or level of production in a specific year (European Commission, 2012). The protective nature of these measures is likely to have prevented the cereal prices from dropping below certain levels during periods of price falls, which in turn resulted in the positive asymmetry we observe between cereals and fertilizers. Furthermore, this asymmetry may be explained as the outcome of the farmers' incentives to use fertilizers. In more detail, in case of high fertilizer prices farmers may hold off from their use in the hope of price decreases. This may result in productivity reductions which in turn, lead to lower productions and thus higher prices. Therefore, we observe increased correlation in the high tail. On the other hand, in case of low fertilizer prices, farmers can use only a certain amount of them without damaging soil health (e.g., altering soil pH, acidification, soil crust, etc.). Therefore, low fertilizer prices do not yield productions beyond, and in response, cereal prices below certain levels. Thus, the correlation in the low tail of prices does not meet the one in the high tail. Finally, this upper tail asymmetry highlights that farms in Greece have not been exposed to potentially low cereal prices, since they have been protected by the respective measures. The agricultural sector has largely relied on the EU support and did not have much incentive to develop appropriate mechanisms to absorb disturbances and reorganize after an external shock. Therefore, economic resilience of the sector cannot be warranted due to moral hazard effects.

Moreover, we find symmetric upper and lower tail dependence for the pair cereals-seeds with the Student-t copula being selected. We observe a considerable degree of price dependence with Kendall's τ=0.2917. This symmetry is unexpected given the high market concentration observed in the specific sector. With six companies (i.e., BASF, Bayer, Dow Chemical, DuPont, Monsanto, and Syngenta) dominating the global markets for seeds and agricultural chemicals and five of them proceeding in mergers and acquisitions in 2015 and 2016 (USDA, 2023), the exercise of some degree of market power followed by the subsequent price asymmetries would be expected. However, OECD (2018) finds no significant correlation between market concentration and seed prices for field crops in European countries, which is consistent with symmetric price transmission and confirms our findings. This strong and symmetric price association entails important implications for the resilience of the farms, which on the one hand, are highly dependent on the few providers of seeds but on the other hand, do not seem to be threatened by the oligopoly of the specific market. More precisely, the efficient price transmission between seeds and cereals implies that agro-chemical companies do not exploit price asymmetries to materialize excessive profits and farmers do not have incentives to maintain seed stocks for future productions. Therefore, the ability of farms to absorb disturbances and reorganize is not jeopardized by the oligopolistic nature of this strategic market.

On the other hand, we find no tail dependence (i.e., the Independence copula) in the pairs seeds-energy, seeds-fertilizers, cereals-energy, fertilizers-energy, meats-energy, animal feed-energy, and meats-animal feed. The independence we observe between energy and cereals supports the neutrality hypothesis, which implies that oil prices do not have a significant effect on agricultural commodity prices and is consistent with Reboredo (2012), Gardebroek and Hernandez (2013), and Fowowe (2016). The results for the first subperiod are summarized in Table 3.

In the second subperiod (2009 to 2022) a C-vine structure is selected with seeds being the central market establishing direct connections to cereals and fertilizers. However, the 90 rotated Gumbel copula is selected for the pair seeds-fertilizers, with Kendall's τ=-0.0774. This copula indicates discordance which is consistent with no tail dependence.

Moreover, the Student-t copula is selected for the pair cereals-seeds, which indicates symmetric upper and lower tail dependence. This dependence is slightly lower than in the first subperiod with Kendall's τ=0.2372, which may relate to the development of prices differing for cereals and seeds. In more depth, between 1990 and 2020, prices paid for seeds increased by 270 percent, whereas the prices for seeds with genetically modified traits rose by 463 percent, which was substantially higher compared to the increases in the commodity output prices (USDA, 2023). These increases in the seed prices are of particular interest since they reflect productivity gains from cultivating improved crop varieties, which bring forth the return on investments for research and development costs. Even though cereal prices rose as well, their increases were not on par with the increases in seed prices, which may have led to the minor drop in the price dependence between cereals and seeds we observe from the first subperiod to second.

Furthermore, we find some level of upper tail dependence selecting the Joe copula for the pair fertilizers-energy, with Kendall's τ=0.0925. This finding confirms, to a large extent, Khalfaoui *et al*. (2021) who find evidence of price dependence between energy and fertilizers in the high tail, especially in the short and the long term. The fertilizer industry is a prominent energy user and will procure energy even at excessive prices, to ascertain a level of production that meets its demand. In a scenario of high energy prices, the energy-dependent industry of fertilizers, will accommodate a significant surge in the cost of production and in return, will increase the fertilizer prices accordingly (Khalfaoui *et al*., 2021). Thus, we observe increased dependence between energy and fertilizer prices in the high tail. Regarding the lower price tail, it has been emphatically acknowledged that European traders engage in dumping, especially with their Russian and Ukrainian counterparts, which allows the fertilizer prices to reach artificially low levels (Fertilizers Europe, 2013; 2017; 2019; 2021), regardless of the energy prices, and thus provides the grounds for the positive asymmetry we observe. In terms of economic resilience, both these agricultural inputs are covered mainly by imports and therefore, the Greek agricultural sector is vulnerable to price changes of both. This implies that fluctuations of fertilizer or oil prices may threaten economic resilience, without the farmers being able to materialize profits directly from the price interplay between them. On the other hand, engaging in the trade of fertilizers during periods of price crashes could allow farmers to benefit from the low fertilizer prices and prepare for periods of price booms, thus enhancing economic resilience of the sector.

The Frank copula is selected for the pair meats-animal feed, indicating intermediate price dependence with Kendall's τ=0.0884. This price dependence is increased compared to the first subperiod when these prices were independent. The 2008 financial crisis may have played a role in strengthening the price linkages between meats and animal feed through two mechanisms. First, the meat industry agents were expected to overcome the temporarily negative medium-term outlook in the aftermath of the crisis, through focusing on core business activities and cost controls, which enhance efficiency (Lohmann Breeders, 2009). Second, the crisis severely restricted the access to credit and capital markets. Even though credit from banks was still available, banks became more selective in lending or increasing credit, and this resulted in increased costs for borrowing and reduced available credit. Thus, the risk profile of many agents in the meat industry, including farmers was raised. Reduced availability of financing led to difficulties in running or expanding existing operations (Lohmann Breeders, 2009). Therefore, the crisis incentivized farmers to reduce nonvalue adding activities such as storage of animal feed, which reduced their capacity to benefit from price decreases and realize production based on cheaply obtained resources. This in return, led to strengthening the price linkages between meats and animal feed. Furthermore, a symmetric price transmission process is consistent with the notions of economic resilience, since it does not offer opportunities for excessive profits during price booms or crushes, to any of the trading agents. In this respect, farmers are not threatened by booming animal feed prices which essentially are passed on to the meat prices.

Finally, we find no tail dependence (i.e., Independence copula) for the pairs seeds-energy, cereals-fertilizers, cereals-energy, meats-energy, and animal feed-energy. The independence we observe between cereals and energy in both periods is in contrast with the conclusion of Han

Table 3 - Results for the copulas, subperiod 2000-2008.

pair	*Family*	*Parameter(s)*	*SE*	*Kendall's τ*	*Tail dependence*
cereals–fertilizers	Sur. Clayton	0.2258	0.1289	0.1014	$\lambda_U = 0.0464$
cereals–seeds	Student-t	0.4423, 2.001	0.0000, 0.0000	0.2917	$\lambda = 0.3604$
seeds–energy	Independence	-	-	0	-
seeds–fertilizers | cereals	Independence	-	-	0	-
cereals–energy | seeds	Independence	-	-	0	-
fertilizers–energy | cereals, seeds	Independence	-	-	0	-
meats–energy	Independence	-	-	0	-
animal feed–energy	Independence	-	-	0	-
meats–animal feed | energy	Independence	-	-	0	-

Note: Parameters, standard errors, Kendall's τ, and tail dependence coefficients are reported.

Table 4 - Goodness of fit tests for the vine copulas, subperiod 2000-2008.

	AIC	*BIC*	*LL*	*GoF test*	*p-value*
Vine copula	-51.7626	-43.7441	28.8813	0.6555	0.8800

Note: The GoF test for bivariate copulas is introduced by Huang and Prokhorov (2014) and based on the White's information matrix equality.

Table 5 - Results for the copulas, subperiod 2009-2022.

pair	*Family*	*Parameter(s)*	*SE*	*Kendall's τ*	*Tail dependence*
cereals–fertilizers | seeds	Independence	-	-	0	-
cereals–seeds	Student-t	0.3641, 2.001	0.0908, 0.0000	0.2372	$\lambda = 0.3222$
seeds–energy	Independence	-	-	0	-
seeds–fertilizers	90° rot. Gumbel	-1.0839	0.0590	-0.0774	$\lambda = 0.0000$
cereals–energy | seeds	Independence	-	-	0	-
fertilizers–energy | cereals, seeds	Joe	1.1781	0.0919	0.0925	$\lambda_U = 0.1990$
meats–energy	Independence	-	-	0	-
animal feed–energy | meats	Independence	-	-	0	-
meats–animal feed	Frank	0.8035	0.4992	0.0884	$\lambda = 0.0000$

Note: Parameters, standard errors, Kendall's τ, and tail dependence coefficients are reported.

Table 6 - Goodness of fit tests for the vine copulas, subperiod 2009-2022.

	Family	*AIC*	*BIC*	*LL*	*GoF test*	*p-value*
Vine copula		-60.9233	-48.5977	34.4617	1.5359	0.6650
meats–animal feed	Frank	-0.6015	2.4799	1.3007	0.0841	0.1200

Note: The GoF test for bivariate copulas is introduced by Huang and Prokhorov (2014) and based on the White's information matrix equality.

et al. (2015), which finds that the 2008 global financial crisis exerted the most powerful impact on the relationship between agricultural commodities (i.e., wheat, soybean, and corn) and energy prices. We summarize the results for the second subperiod in Table 4.

4. Conclusions

The food–energy–agricultural inputs nexus is of crucial interest and entails various implications for the domestic economies as well as for international trade. It involves several agents along the agricultural supply chains and as such it affects the welfare of large populations. In this regard, the price linkages between agricultural commodities and production inputs, and between production inputs themselves have received considerable attention amongst the research community.

The present research investigates the price dependence relationships between agricultural commodity and agricultural input prices, against the 2008 financial crisis, taking a further view on the implications regarding agricultural economic resilience. To this end, we use static vine copulas and split the time period in 2009, to investigate the effects of the 2008 financial crisis. Our results indicate (i) upper tail dependence in the pair cereals–fertilizers before 2009, (ii) upper tail dependence in the pairs seeds–fertilizers and energy–fertilizers after 2009, and (iii) strong and symmetric tail dependence in the pair cereals–seeds in both periods. Overall, our results suggest that the protective nature of the CAP has shielded Greek farmers from high inputs prices, but at the same time, it has created moral hazard effects depriving them from the incentives to develop appropriate mechanisms which enhance resilience of the sector; the few agro-chemical companies supplying seeds, even though enjoy a predominant position in the food supply chain, they do not seem to exploit this position and engage in price raises irrespective of the farmer income.

Our findings are largely in support of the neutrality hypothesis between energy and cereals, and between energy and meats, implying that oil prices do not significantly affect food prices or in other words, fluctuations in agricultural commodity prices are not driven by oil price movements. This finding is of particular interest to policy makers since it implies that policies seeking to reduce food prices or price variability, do not need to consider the dynamics in the global oil market. Instead, the surges in food prices should be addressed focusing on the forces of supply and demand in the agricultural markets. More particularly, oil price spikes are not shown to be connected to food price spikes, which in turn affect disproportionally the lower incomes since a larger share must be spent on food. Therefore, short-run policies seeking to alleviate the corresponding adverse impacts on the financially challenged, such as food subsidies, should be implemented regardless of extreme oil price shifts. Moreover, food price stabilization policies which aim to control price volatility, including price controls and trade barriers, should differentiate between average oil price movements, which probably bear permanent impacts and extreme oil price shocks, which probably bear no impact on food prices. Furthermore, the independence between energy and agricultural commodity markets entails important implications for risk management, especially regarding the agricultural commodity markets which have gained momentum in recent years. The tail independence shown both before and after the structural break, suggests that risk-averse investors may choose to include assets from both markets to diversify their risk and hedge against it.

Finally, we note that our findings should be further confirmed via different approaches. This study uses exclusively static copula models which is a limitation. The application of time-varying copula models may be more relevant, especially in the case of dynamic price linkages, and as such, it provides a promising strand for prospective research.

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