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Agriculture under pressure: anthropogenic flows and global risks

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Abstract

The article addresses the significant impact of human-driven factors – material, energy, demographic, and economic – on modern agriculture within a multipolar world. It highlights the relevance of anthropogenic flows in understanding the vulnerabilities of agricultural systems, particularly in the context of geopolitical instability, supply chain disruptions, and demographic shifts. The purpose of the article is to analyse how these flows influence agricultural resilience in Germany, France, Spain, and Russia from 2000 onward, using four analytical models: Material Flow Analysis (MFA), Demographic Flow Model (DFM), Supply Chain Vulnerability Model (SCVM), and Economic Impact of Sanctions Model (EISM). The methods involve quantitative analysis of resource use, migration patterns, supply chain risks, and economic impact of sanctions, based on data derived from FAOSTAT, Eurostat, and national reports. The results reveal varying degrees of vulnerability across the studied countries, with Germany and Spain heavily reliant on external inputs, France maintaining stability through energy efficiency, and Russia facing significant challenges due to sanctions and rural depopulation. The article concludes with policy recommendations towards enhance agricultural resilience, emphasizing diversification, sustainable practices, and local food sovereignty.

Keywords: anthropogenic flows, agroecology, geopolitics, material flow analysis, Supply Chain Vulnerability

INTRODUCTION

Agriculture has long been shaped by human-driven flows of people, resources, and knowledge—what we call anthropogenic flows. These flows generate economic value and shape agricultural systems. Recent geopolitical disruptions, particularly since 2022, have impacted these flows, especially in Europe and Russia, influencing trade and production (Zachmann et al., 2022). This study examines these dynamics through a comparative analysis of Germany, France, Spain, and Russia – key players in global agriculture – dividing the timeline into a stable pre-2022 phase and a disrupted post-2022 phase marked by sanctions, war, and supply chain disruptions.

Based on mathematical modelling and quantitative analysis, this work investigates how material and energy flows, demographic transitions, and geopolitical factors interact with agricultural resilience. As Gudeman (2001) argues, agriculture lies at the intersection of environment, economy, and politics, shaped by global mobility. Current study integrates anthropogenic perspectives – cultural ecology, political economy, agroecology, food sovereignty, and globalization – to assess the vulnerability of modern agriculture.

Anthropogenic flows, encompassing global movement of energy, people, and knowledge, are central to agricultural dynamics (Escobar, 1995). McMichael (2009) highlights how the "corporate food regime" generates dependencies that render agriculture vulnerable to global shocks. Thus, analyzing these flows is critical for system resilience evaluation. Cultural ecology (Steward, 1955; Conklin, 1957; Dove, 1983; FAO et al., 2024) reveals how agriculture adapts to environmental limits.

Smallholder resilience (Netting, 1993) contrasts with vulnerability induced by the global markets (Mintz, 1986; Wolff, 1982; Salamon et al., 2017). Agroecology, integrating local knowledge and ecological science, fosters sustainable systems (Rosset & Altieri, 2017; Gliessman, 2014; Altieri, 2018; Toledo & Barrera-Bassols, 2008). The food sovereignty movement, led by La Vía Campesina, confronts agribusiness and defends traditional systems and marginalized identities (Gray, 2010; Schanbacher, 2010; Pimbert, 2018; Wittman et al., 2010; Desmarais, 2007; Shiva, 1991; Holt-Giménez & Shattuck, 2011).

Globalization diminishes local biodiversity and traditional knowledge (Pretty, 2002; Van der Ploeg, 2010), though traditional systems continue to adapt (Nazarea, 2005). Ferguson (1994) and Akram-Lodhi (2018) show how migration and mobility affect agrarian labor and sustainability. Industrial agriculture's reliance on external inputs (González-Torres et al., 2022) and fossil fuels increases volatility and ecological risk (Altieri, 1995; Friedmann, 2005). Though smallholders display adaptability (Netting, 1993), they remain exposed to market shocks and structural dependency (Borras et al., 2017; Shiva, 1991; Mintz, 1986; Clapp, 2020; Perfecto et al., 2019).

Urbanization and labor shifts undermine rural economies and food systems (Bernstein, 2010; Patel, 2007), while demographic transitions, energy regimes, and cultural shifts redefine agricultural trajectories (Oosterveer & Sonnenfeld, 2011). Conflicts and sanctions accelerate food insecurity and population displacement (Duncan, 2015; Desmarais, 2007), calling for new strategies for territorial resilience (Wolf, 1982).

Geopolitical instability disrupts trade and access to essential input. Hawkes & Popkin (2020) link conflict and climate to food system risk. Sanctions and political tensions, especially post-2022, have destabilized cereal markets (Lécuyer & Chatellier, 2014; Smith, 1984; Mintz, 1986; Warman, 2003; Thompson, 2010; Popescu et al., 2022). Thus, agriculture is deeply embedded in cultural, economic, and geopolitical structures. As Goodman & Redclift (1991) argue, sustainability requires reconnecting agriculture with local autonomy and resilience. Current study contributes to this agenda and aim to analyse the resilience under anthropogenic and geopolitical pressures across four critical agricultural systems.

MATERIALS AND METHODS

To assess agricultural vulnerabilities this study employs correlation analysis and four analytical models: Material Flow Analysis (MFA), Demographic Flow Model (DFM), Supply Chain Vulnerability Model (SCVM), and Economic Impact of Sanctions Model (EISM). Each model evaluates different aspects of resource use, demographic trends, and geopolitical risks. The analyses focus on Germany, France, Spain, and Russia from 2000 to 2023. These countries were selected based on their significant roles in European and global agriculture, as well as their varying degrees of exposure to geopolitical risks, energy dependencies, and demographic shifts.

Material Flow Analysis (MFA) systematically track the use of critical agricultural resources such as water, nutrients, and energy. The study used data derived from FAOSTAT, Eurostat, and national agricultural reports in order to quantify input-output balances in agricultural systems. Given that increasing geopolitical shifts affect resource availability (Brunner & Rechberger, 2003) this approach helps the evaluation of agricultural sustainability in a multipolar world. The MFA model incorporates a resource efficiency assessment, where we analysed fertilizer use trends, water consumption, and energy input across the four selected countries. Correlation analysis was conducted to examine the relationships between input levels and agricultural productivity.

Demographic Flow Model (DFM) was used for analyses of migration patterns and their impact on the agricultural workforce. Human migration and population changes significantly affect agricultural productivity, particularly as rural labor shifts to urban areas or emigrates. Data from the United Nations Population Division, Eurostat, and national census reports were utilized to monitor rural depopulation and labor shortages. This model quantifies the movement of people and their influence on labor availability in agriculture, which also helps us to assess the impact of demographic shifts on agricultural GDP.

Supply Chain Vulnerability Model (SCVM) was implemented in order to evaluate the impact of geopolitical disruptions. Agricultural supply chains are increasingly vulnerable to trade sanctions, energy crises, and market fluctuations. This model assesses risk levels in different geopolitical contexts by measuring the trade dependencies and supply chain disruptions. The model integrates OECD trade data, World Bank commodity reports, and national trade statistics from Eurostat and Rosstat to quantify the degree of risk that agricultural supply chains face. All that combined serves as a reliable tool to anticipate potential disruptions under different geopolitical scenarios.

Finally, Economic Impact of Sanctions Model (EISM) was developed to quantify the direct economic consequences of sanctions on agricultural GDP. Sanctions can restrict access to markets, financial resources, and essential agricultural inputs such as fertilizers and machinery. Data from Eurostat, Rosstat, and IMF economic reports were used to estimate GDP fluctuations in the agricultural sector due to sanctions. A panel data analysis was performed to assess the statistical significance of these economic impacts across the four selected countries.

By integrating the correlation analysis and these four models, the study aims to provide a comprehensive assessment of agricultural vulnerabilities, with particular attention to energy dependencies, supply chain fragility, and labor migration trends. The interaction between these models was carefully examined to ensure that each aspect of the analysis contributes to a holistic understanding of agricultural resilience in a rapidly changing geopolitical landscape.

While the models used offer valuable insights, they are subject to limitations, including the assumptions of linear correlation, the granularity of national-level datasets, and the inherent uncertainty in geopolitical trends projecting.

RESULTS AND DISCUSSION

The results are presented model by model, followed by an integrated cross-model synthesis to illustrate interdependencies between energy, demographic, and geopolitical pressures. The findings are derived from the application of correlation analysis and four analytical models: Material Flow Analysis (MFA), Demographic Flow Model (DFM), Supply Chain Vulnerability Model (SCVM), and Economic Impact of Sanctions Model (EISM). Correlation analysis was conducted to examine the relationships between input levels and agricultural productivity. The correlation coefficients, ranging from 0.74 to 0.97, indicate a strong positive relationship between energy consumption and agricultural output in all four countries, highlighting the importance of energy efficiency in maintaining productivity.

To provide a more comprehensive analysis the findings for each model which integrated the methodological framework with the graphical data are presented. The MFA model tracks the use of critical agricultural resources such as water, nutrients, and energy across Germany, France, Spain, and Russia from 2000 to 2023. The results reveal varying degrees of dependency on external inputs, with significant implications for agricultural productivity and sustainability.

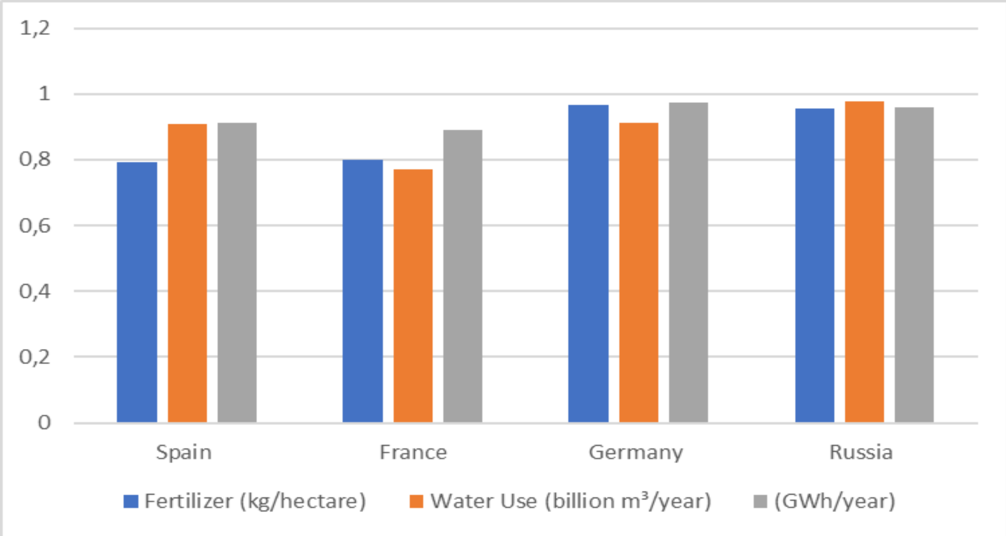

Figure 1. Correlation – Productivity vs. resource consumption.
Source: Own calculations

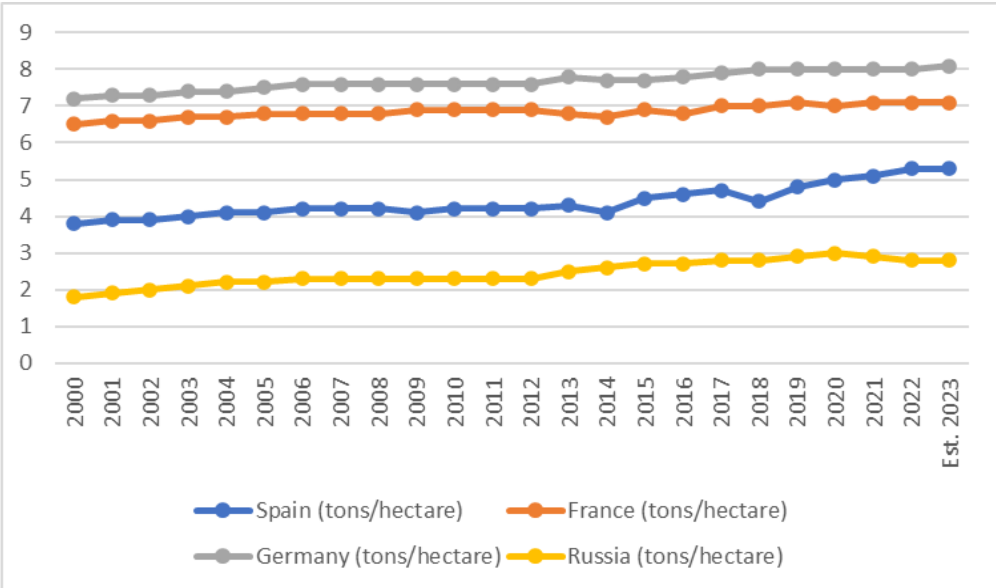

Figure 2. Wheat yield.
Source: Adapted from Ahmad & Zhang, 2020; Perdana & Schenckery, 2022; Dogan & Ongan, 2017; Balezentis & Streimikiene, 2023

The MFA reveals a direct correlation between energy consumption and yield output (Fig. 2). Germany and Spain show steady increases in wheat yield, driven by high energy and fertilizer inputs. In contrast, Russia's yield fluctuations are more pronounced, reflecting the impact of geopolitical changes, particularly post-2014 sanctions. France maintains stable yields, supported by efficient resource management and energy independence.

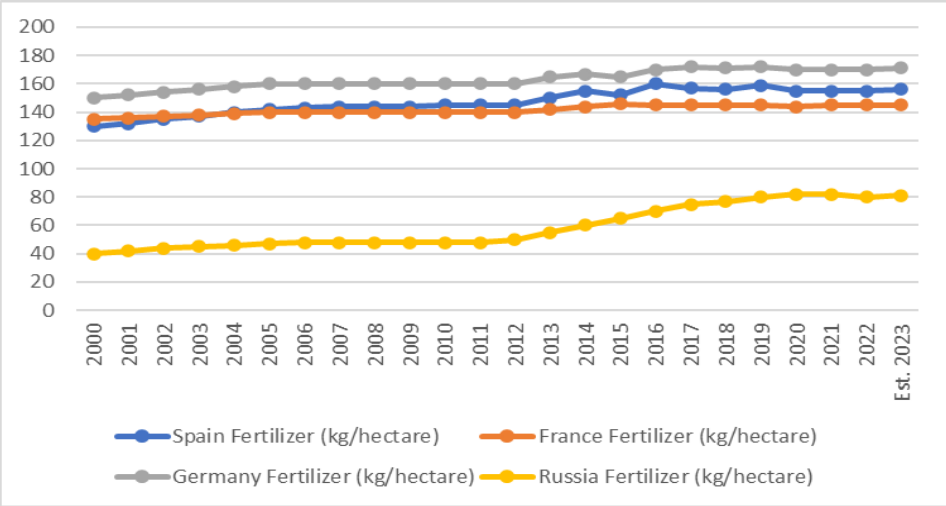

Figure 3. Fertilizer utilization.

Source: Adapted from Ahmad & Zhang, 2020; Perdana, & Schenckery, 2022; Dogan & Ongan, 2017; Balezentis & Streimikiene, 2023

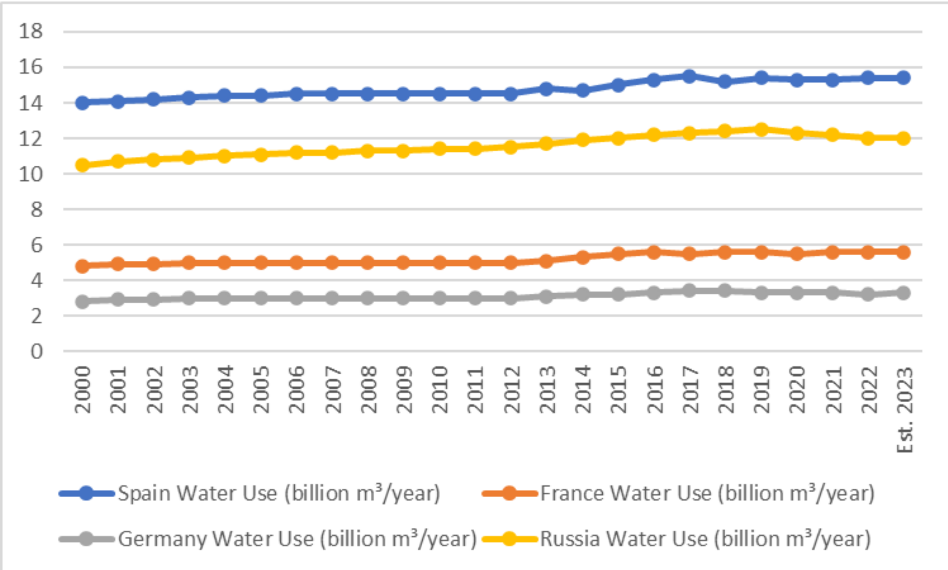

Figure 4. Water consumption.

Source: Adapted from Ahmad & Zhang, 2020; Perdana, V., & Schenckery, 2022; Dogan, I. & Ongan, 2017; Balezentis, R. & Streimikiene, 2023

The data from the MFA indicate a heavy reliance on chemical fertilizers in Germany and Spain, with significant increase in the utilization levels over the study period (Fig. 3). France, however, demonstrates more stable fertilizer use, reflecting its focus on sustainable agricultural practices. Russia's fertilizer use spikes post-2014, as the country attempts to compensate for yield losses caused by labor shortages and sanctions.

The trends of another MFA element we have included, water use, highlight the sustainability challenges faced by Spain, where increasing water consumption signals rising stress on resources. France's stable water use reflects efficient irrigation practices, while Russia's increased water usage, despite lower yields, suggests inefficiencies in water management (Fig. 4).

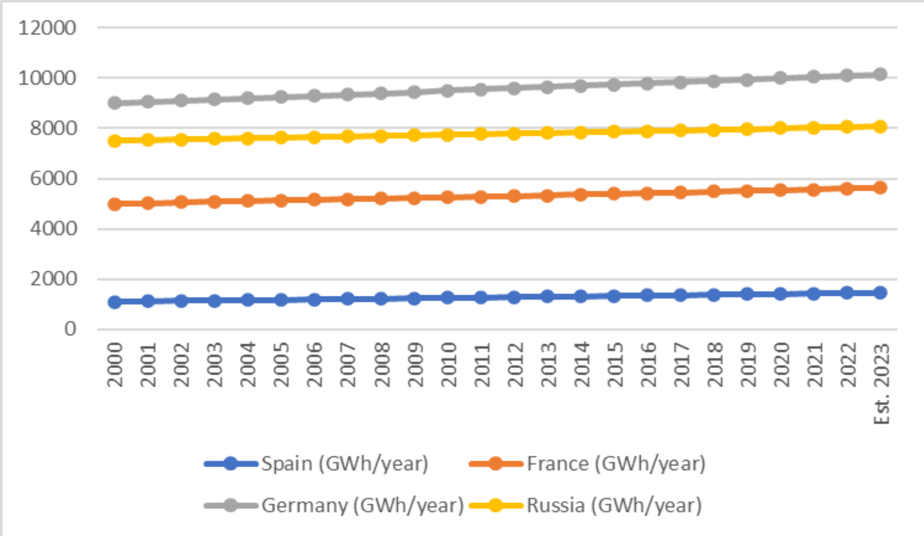

Figure 5. Energy consumption.
Source: Adapted from Ahmad & Zhang, 2020; Perdana & Schenckery, 2022; Dogan & Ongan, 2017; Balezentis & Streimikiene, 2023

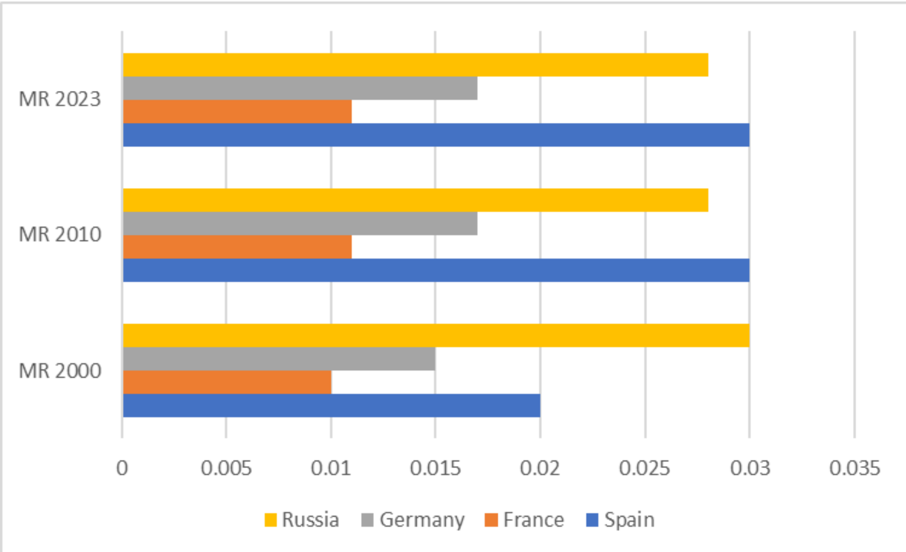

Figure 6. Migration rate trends.
Source: The United Nations, 2020

A pivotal element of the MFA, energy consumption, reveals trends which underscore the vulnerability of Germany and Russia to energy price fluctuations (Fig. 5). Germany's reliance on energy-intensive agricultural practices makes it particularly susceptible to supply chain disruptions, as seen in the post-2022 energy crisis. On the contrary, France's reliance on nuclear energy provides stability and protection of agricultural sector from external shocks.

The DFM analyses migration patterns and their impact on the agricultural workforce. Rural depopulation is a significant challenge across all four countries, with varying degrees of severity (Fig. 6).

The demographic model presented as time series highlights significant patterns in rural-to-urban migration, showing a continuous decline in rural populations across the studied countries from 2000 to 2023. The DFM reveals pronounced rural depopulation in Germany and

Spain, driven by economic factors and urbanization. Russia also faces severe rural depopulation, exacerbated by socio-political instability and limited rural development. France, however, shows a slower decline in rural population, supported by policies that preserve agricultural labor and traditional practices. In particular, the demographic flow model indicates that Germany and Spain show pronounced demographic shifts, with significant population losses in rural areas. In Russia depopulation is more severe, exacerbated by socio-political factors such as geopolitics, economic instability and limited rural development.

The SCVM assesses the vulnerability of agricultural supply chains to geopolitical disruptions, including trade sanctions and energy crises. In the following graphs, are provided risk analysis based on statistical trends, using authors` own vulnerability scale, which categorizes agricultural risk levels according to the intensity of material usage, including energy, fertilizers, water, and external inputs. This scale allows for a comparative assessment of agricultural resilience across Germany, France, Spain, and Russia, reflecting how dependence on these resources influences overall stability and exposure to geopolitical disruptions.

Applying the SCVM, Spain's agricultural sector demonstrates a high degree of sensitivity to energy price changes and renewable energy policy shifts, both of which have significant implications for productivity and sustainability. Data from 2000 to 2023 reveals that agricultural productivity in Spain is highly correlated with water and energy use, therefore cost, with a correlation coefficient of 0.90 and 0.91, underscoring the country's heavy dependence on energy for irrigation, particularly in arid southern regions. The share of renewable energy in Spain's energy mix rose from 15% in 2000 to 42% in 2023, a diversification that has mitigated some effects of fossil fuel price volatility.

SVCM shows that France's agricultural sector promotes considerable resilience compared to other countries, largely due to the stability of its energy policy and reliance on nuclear power (Fig. 8). The share of nuclear energy in France's total energy consumption has remained stable at around 70% over the past two decades.

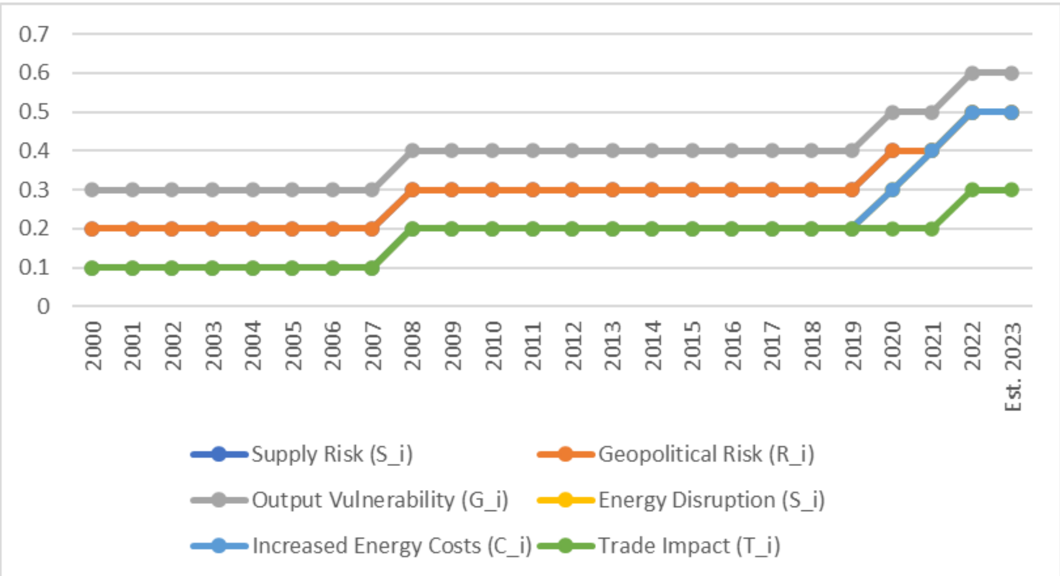

Figure 7. Risk Levels - Spain
Source: World Bank, 2020

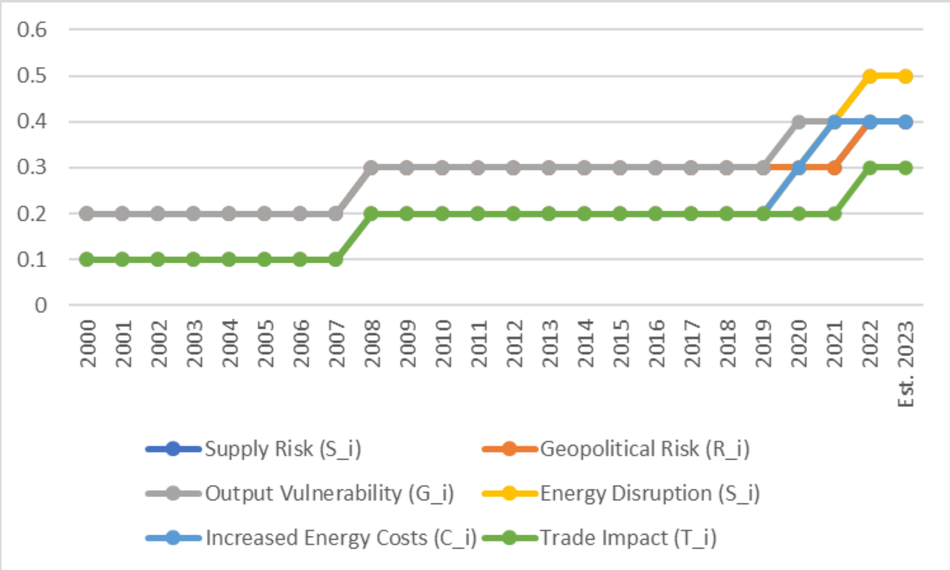

Figure 8. Risk Levels - France
Source: World Bank, 2020

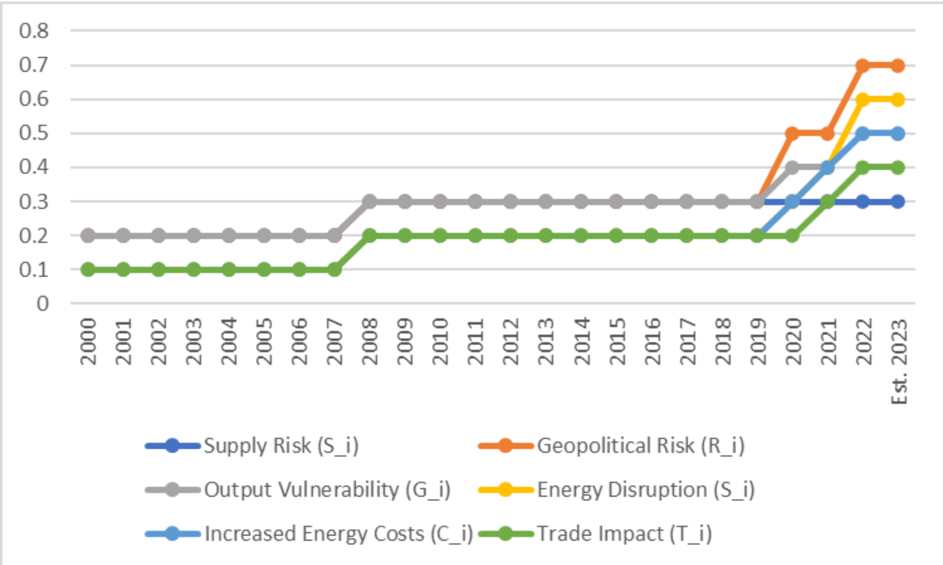

Figure 9. Risk Levels - Germany
Source: World Bank, 2020

This stability, along with France's closure of its market to Ukrainian wheat, has helped mitigate the effects of global energy price spikes, as reflected by minimal fluctuations in agricultural output, with wheat yield variations staying below 3% from 2020 to 2023. The correlation coefficient between the share of nuclear energy in total energy consumption and agricultural productivity is 0.65, suggesting a significant positive impact of stable energy policy on maintaining agricultural output. Additionally, France's targeted policies have helped slow rural depopulation. As a result, France has been more resilient to demographic shifts.

SCVM clearly indicates that Germany's agricultural sector exhibits pronounced vulnerability to energy supply disruptions, particularly after 2022 (Fig. 9). The sharp rise in energy costs following the disruption of natural gas imports – previously comprising nearly 50% of Germany's gas supply from Russia – illustrates this risk. Post-2022, can be seen significant cost increases for energy-intensive agricultural inputs such as fertilizers and irrigation. The correlation analysis of energy consumption and agricultural productivity reveals coefficient of 0.97, indicating that energy price increases can be linked to declines in productivity, especially for intensity-dependent crops such as wheat. This trend underscores Germany's heavy dependence on energy-linked agricultural inputs. This confirms the earlier observed correlation coefficient of 0.97 about energy inputs and productivity, reinforcing SCVM's identification of Germany's acute vulnerability to energy shocks.

The agricultural sector in Russia has faced significant challenges due to sanctions and trade disruptions, which have directly impacted the availability of essential agricultural inputs. The SCVM clearly indicated that following the imposition of sanctions in 2014 and their intensification in 2022, there has been a marked decline in agricultural GDP, which fell by 12% in 2022 compared to the previous year (Fig. 10). Efforts to counteract export restrictions included an 18% increase in domestic fertilizer production in 2022 and 2023, where total agricultural output continues to rise. Russia has high potential risk of labor shortages due to significant rural depopulation trends.

EISM model tracks the effect of sanctions on GDP in the agricultural sector. Through the Economic Impact of Sanctions Model (EISM) we quantify the economic losses in agricultural GDP resulting from trade sanctions, energy disruptions, and the reduced availability of key agricultural inputs. Data from Eurostat and Rosstat clearly show that Russia demonstrates exceptional agricultural resilience (+1.50%), attributed to resource self-sufficiency (energy/fertilizers) and insulation from global supply chain disruptions. On the other hand, Germany shows severe systemic fragility (-1.50%), driven by import dependencies and concentrated export models vulnerable to anthropogenic flows. Spain and France show moderate vulnerability (-0.35% to -0.50%), reflecting climate stressors in Mediterranean agriculture (Spain) and EU policy/energy constraints (France). The nearly 3% resilience gap between Russia and Germany underscores how sanctions and energy decoupling (2022–2023) radically redistributed agricultural risks across Europe.

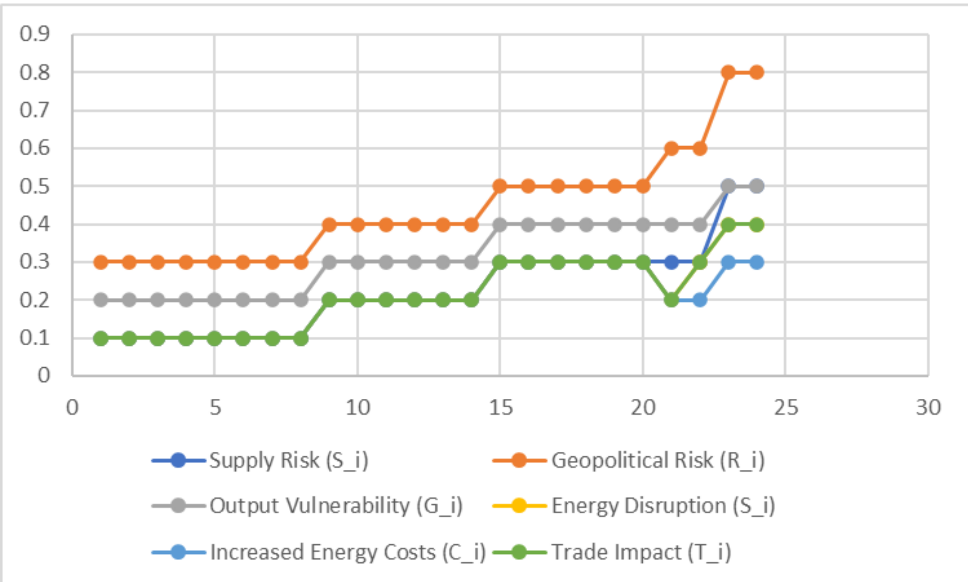

Figure 10. Risk Levels - Russia
Source: World Bank, 2020

Through the EISM in the current study is quantified the economic impact of sanctions on agricultural GDP, revealing significant losses in Germany, somewhat moderate impacts in France and Spain, and following a brief decline, substantial increase in Russia's agricultural GDP. This trend indicates that, while Western European countries face rising input costs and supply chains disruptions, Russia has benefited from redirected trade flows, increased domestic production, and government-backed agricultural subsidies, mitigating external pressures.

The findings of the current study contribute to the growing body of literature on agricultural resilience by highlighting the interplay between material movements, demographic shifts, and geopolitical risks. The results underscore the importance of diversifying energy sources, optimizing resource use, and addressing rural depopulation to enhance global food security.

CONCLUSIONS

The results from analysis in the current study are country specific and model derived. In the context of Material Flow Analysis (MFA), Spain’s agricultural productivity steadily increased, primarily due to high energy and fertilizer inputs. The MFA reveals a direct correlation between energy consumption and yield output, demonstrating how external input reliance boosted productivity. However, the Demographic Flow Model (DFM) indicates that rural depopulation, which typically threatens labor availability, was probably counterbalanced by mechanization and economic growth, ensuring continued agricultural output. The Supply Chain Vulnerability Model (SCVM) identifies Spain’s heavy dependence on external energy sources, rendering its agricultural sector highly susceptible to global crises. This vulnerability was further confirmed by the Economic Impact of Sanctions Model (EISM), which shows that disrupted energy supply chains moderately reduced agricultural GDP most likely due to rising input costs. France demonstrates exceptional agricultural stability, as evidenced by the MFA, which highlights steady productivity sustained by energy efficiency and strategic resource management. The country’s reliance on nuclear energy insulated its agricultural sector from external shocks, as confirmed by SCVM, which shows low supply chain vulnerability. DFM analysis further reveals that France’s government policies slowed rural depopulation, ensuring a stable agricultural workforce, a key factor in maintaining long-term productivity. The EISM model further supports these findings, showing that agricultural GDP remained largely unaffected during crises, reinforcing the resilience of France’s energy-independent agricultural sector.

Germany’s high agricultural efficiency, as demonstrated by MFA, was heavily dependent on external energy and fertilizer imports, which became critical risk factors post-2022. DFM findings indicate that while rural depopulation was moderate, it increased reliance on mechanization, intensifying Germany’s dependence on energy-intensive agricultural production. The SCVM reveals that Germany’s vulnerability peaked following sanctions on Russian energy imports in 2022, which severely disrupted fertilizer supply chains. This is corroborated by EISM, which quantifies significant agricultural GDP losses post-2022, highlighting Germany’s susceptibility to geopolitical instability.

MFA results indicate severe constraints on agricultural productivity in Russia post-2014 due to sanctions restricting fertilizer exports and machinery imports. The DFM model identifies severe rural depopulation, further exacerbating labor shortages and weakening productivity in key agricultural regions. SCVM analysis reveals that widespread sanctions amplified supply chain disruptions, making Russia’s agricultural sector one of the most vulnerable among the studied countries. Finally, EISM confirms that post-2022, despite that economic sanctions on Russia in the agricultural sector have surged, the development of trade channel alternatives diminished the impact of trade restrictions, resulting in higher GDP.

Key Policy Recommendations

- **Spain** is encouraged to reduce its dependence on external fertilizers by fostering the adoption of sustainable alternatives, such as organic fertilizers, and promoting crop diversification where feasible.
- **Germany** may consider broadening its energy supply sources to enhance resilience against geopolitical disruptions, with a particular focus on expanding renewable energy integration.
- **France** could further strengthen its resilience strategy by implementing enhanced rural development initiatives aimed at sustaining labor availability in the agricultural sector.
- **Russia** has demonstrated agricultural self-sufficiency; optimizing domestic fertilizer production and reinforcing external supply chains may further support stability in response to sanctions.

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