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Ensuring the security of the clean energy transition: Examining the impact of geopolitical risk on the price of critical minerals

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ABSTRACT

We use constant and time-varying parameter local projection (TVP-LP) regression models to examine the effect of geopolitical risk on prices of six critical minerals: aluminium, copper, nickel, platinum, tin and zinc. We propose a conceptual framework in which the responsiveness of prices for critical minerals to geopolitical risk depends on the non-technical risk associated with procuring each critical mineral and geopolitical threats have a bigger effect on critical mineral prices than geopolitical acts. Our results are generally consistent with these predictions. We find considerable evidence that the effect of geopolitical risk on the prices of critical minerals is time varying, with the Gulf War, 9/11 terrorist attacks and COVID-19 pandemic each having a significant effect. We find that shocks due to geopolitical threats are generally bigger in magnitude than geopolitical acts and that prices respond more quickly to geopolitical threats.

1. Introduction

There is no universal definition of a critical mineral. In part, this reflects that which specific minerals are considered as being critical depends on the needs of different countries. For example, the European Union (EU) (2024) states that "critical raw materials are raw materials of *high economic importance* for the EU, with a *high risk of supply disruption* due to their concentration of sources and lack of good, affordable substitutes" (emphasis in original). The Energy Act (2020) in the United States "defines a 'critical material' as: any non-fuel mineral, element, substance, or material that the Secretary of Energy determines: (i) has a high risk of supply chain disruption; and (ii) serves an essential function in one or more energy technologies, including technologies that produce, transmit, store, and conserve energy" (United States Department of Energy, 2024). The EU lists 34 critical minerals, while the United States lists 50 critical minerals. In practice, most metals and minerals that are generally regarded as critical fall into one of three categories: (a) minerals needed to facilitate the clean energy transition to carbon net zero by 2050; (b) minerals used in defence and security applications; and (c) minerals employed in communication and entertainment technologies (see e.g. McNulty and Jowitt, 2021; Ramdoo et al., 2023).

The literature on energy security has traditionally focused on fossil fuels, but growing recognition that critical minerals are essential to developing renewable energy sources needed to realize clean energy transition targets, along with the importance of critical minerals to strategic defence objectives, has highlighted the importance of critical minerals for global energy security (Hotchkiss et al., 2024). As Gaspar Filho and Santos (2022, p. 16) succinctly put it: "Ensuring a stable supply of critical non-fuel minerals at an affordable price is essential for the current energy transition to take place".

The United States under the Biden administration was reluctant to mine for critical minerals (Ali, 2023), making it increasingly dependent on imports for critical minerals (Majkut et al., 2023). This has made the United States especially vulnerable to supply chain risks, which are exacerbated by geopolitical tensions with China that plays a key role in the supply chain of many critical minerals (Purdy and Castillo, 2022). Geopolitical risk (GPR) is defined "as the risk associated with wars, terrorist acts, and tensions between states that affect the normal and peaceful course of international relations" (Caldara and Iacoviello, 2022). Given geopolitical rivalry to secure critical minerals (Khurshid et al., 2023; Vivoda, 2023; Vivoda and Matthews, 2023) and the potential for violent conflict, supply chains are particularly susceptible to GPR (Dou and Xu, 2023; Renneboog et al., 2022). For instance, the Russia-Ukraine war is a source of GPR to critical mineral markets

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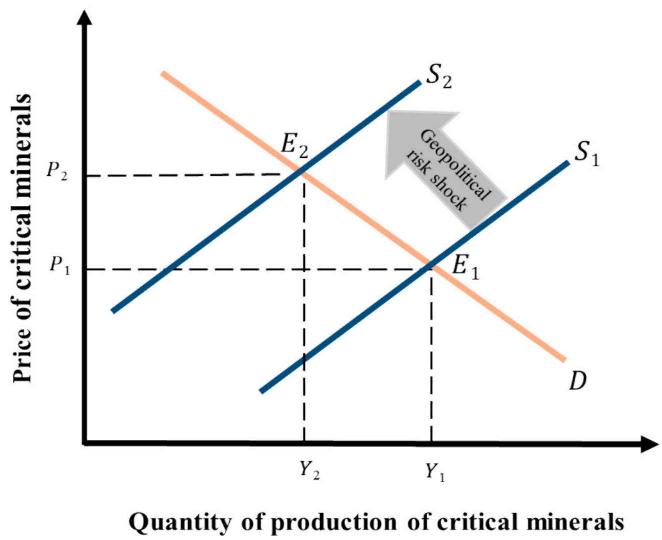


Fig. 1. The impact of geopolitical risk shocks on critical minerals markets.

because Russia is a major producer of cobalt and nickel (Khurshid et al., 2023, 2024; Pata et al., 2024). The spike in lithium and nickel prices attributable to the disruption in supply chains due to the COVID-19 pandemic and the Russia-Ukraine war resulted in acute supply shortages in the European electric vehicle market (Considine et al., 2023).

Beyond the immediate threat of shortages due to supply chain risk, the fact that global production of critical minerals is concentrated in a few countries contributes to GPR (Nygaard, 2023; Berahab, 2022; IRENA, 2023). Many of the countries in which critical mineral production is centred in Africa and South America have experienced civil conflict and exhibit high levels of non-technical risk, such as threats of nationalization and red tape (Trench et al., 2014). Non-technical risks exacerbate the back-ended risk premium for critical minerals (Vespignani and Smyth, 2024), contributing to suboptimal levels of investment in critical minerals, creating excess demand that drives up prices.

In this paper, we use constant and time-varying parameter local projection (TVP-LP) regression models (Inoue et al., 2024) to examine the effect of geopolitical risk on prices of six critical minerals: aluminium, copper, nickel, platinum, tin and zinc. Each of these six minerals are included in the United States list of 50 critical minerals and four of the six minerals (aluminium, copper, nickel and platinum) are on the EU list of 34 critical minerals. We focus primarily on supply-side disruptions, while demand-size factors receive less attention. The choice of critical minerals was dependent on data availability. We included all critical minerals for which there was a long monthly time series of prices. Each of these minerals have renewable energy applications that are important for realizing carbon net zero targets. Aluminium, copper and nickel are key inputs into several low-carbon technologies (Pata et al., 2024). Aluminium, copper and zinc are important for the production of solar and wind energy. Nickel is important in the production of solar energy, as well as being used in energy storage and in the production of electric vehicles. Platinum is an essential input into green hydrogen technologies, which have various uses, including fuel cell vehicles. Tin is utilized in the production of solar panels and as a protective barrier to increase the life of batteries, assisting with energy storage (IRENA, 2023; Pata et al., 2024).

Our contribution connects with several strands of literature. One set of studies to which our paper is related are those on various aspects of prices for critical minerals. Studies have examined interconnectedness between prices of critical minerals (Bastianin et al., 2023) and spillover effects between demand for fossil fuel and renewable energy products and prices for critical minerals (Attílio et al., 2024; Zhang et al., 2024). Related studies have forecast the price of critical minerals (Choi and Kim, 2024; Esangbedo et al., 2024; Li et al., 2023) or considered the implications of a shock to critical mineral prices on outcomes such as global oil prices and inflation (Considine et al., 2023; Miranda-Pinto et al., 2024) and green investments (Sohag et al., 2023). Yet other studies have examined the effect of government policies on prices for critical minerals (Dou et al., 2024; Romani and Casoli, 2024).

Our study also contributes to the literature that has examined the implications of GPR for a range of energy and environment-related outcomes. One strand of this literature has examined the effects of GPR on carbon emissions (Anser et al., 2021; Chen et al., 2024; Ding et al., 2023; Pata and Ertugrul, 2023). Another strand of the literature has considered the effects of GPR on prices for natural resources and energy commodities (Aloui et al., 2023; Bouoiyour et al., 2019; Ding et al., 2023a; Evrim Mandaci et al., 2023; Gkillas et al., 2022; Gong and Xu, 2022; Khurshid et al., 2024; Liu et al., 2019; Mignon and Saadaoui, 2024; Zhao, 2023). A related set of studies examine the effect of GPR on oil stock returns (Alqahtani et al., 2020; Antonakakis et al., 2017; Kumar et al., 2021; Smales, 2021), oil price futures (Mei et al., 2020; Zheng et al., 2023) and critical mineral and renewable energy stock returns (Yang et al., 2021; Zhou et al., 2020). Other studies have examined the implications of GPR for a range of other energy-related outcomes, such as energy security risk (Ullah et al., 2024); renewable energy generation,

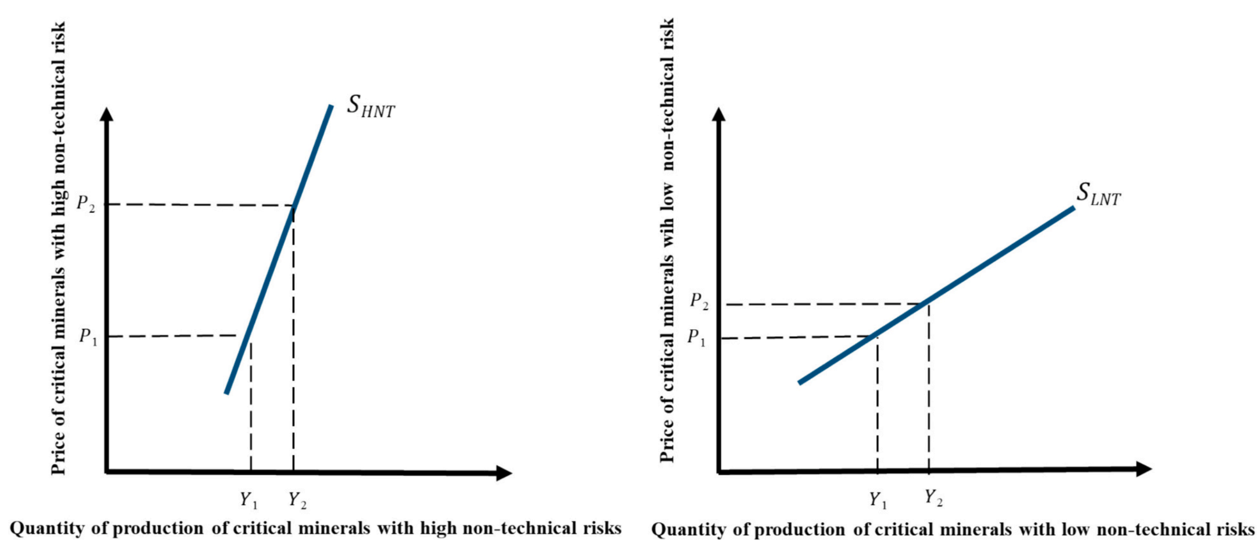


Fig. 2. High vs. low critical minerals prices response to geopolitical risk shocks.

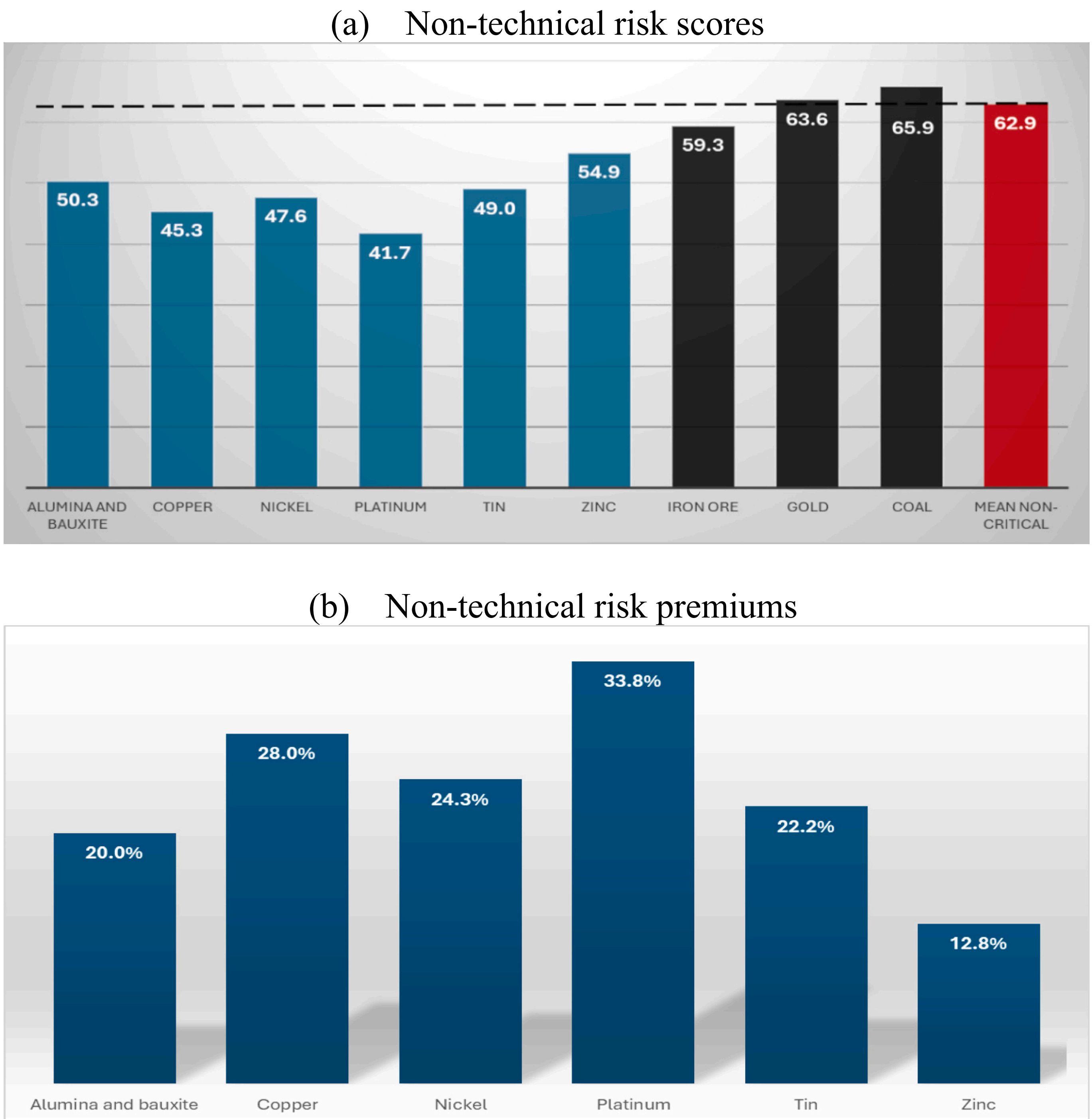


Fig. 3. The non-technical risk scores and premiums of selected critical minerals (2023).

deployment, consumption and use (Alsagr and Van Hemmen, 2021; Cai and Wu, 2021; Islam et al., 2023; Sweidan, 2021); and trade in critical minerals and energy-related products (Li et al., 2021; Zhang et al., 2024a).

The extant literature on the effect of GPR on different aspects of prices for critical minerals is mostly recent and relatively scant (Aloui et al., 2023; Khurshid et al., 2023; Pata et al., 2024; Wang et al., 2023; Zhang et al., 2024b; Zhao, 2023). Compared with these studies, our approach and our results analyse in a more systematic way the instability of impulse response functions (IRF) on a larger sample of critical minerals. Wang et al. (2023) and Zhang et al. (2024b) examine how GPR affect prices for a single critical mineral and the focus in Wang et al. (2023) is on price bubbles which is different to us. Our approach has methodological advantages compared with Aloui et al. (2023) because we do not rely on a sub-sample that results in loss of power; and Zhang et al. (2024b) because we do not rely on time-varying algorithms, given that the literature is unclear about which algorithms are most appropriate in rolling regressions. Compared to Khurshid et al. (2023) and Pata et al. (2024) whose focus is on the effect of the Russia-Ukraine War on critical minerals prices, we examine a broader set of geopolitical events and analyse more systematically the differences in IRFs. Perhaps closest to what we do in terms of coverage is Zhao (2023), but very importantly, methodologically, we differ from that study in that we test for statistical differences between IRFs, which Zhao (2023) does not do.

Another point of difference with each of these studies is that, in our conceptual set up, we extend on Vespignani and Smyth's (2024) recent work to consider how non-technical risk affects the extent to which GPR shocks lead to changes in prices of critical minerals. Non-technical risks in mining refer to the various challenges and uncertainties that arise outside of the technical and operational aspects of a mining project. These risks typically involve social, environmental, political, and economic factors that can impact the viability, success, and sustainability of mining operations. The main categories of non-technical risks in mining are political and regulatory risk, social risk and environmental risk (Trench et al., 2014). Vespignani and Smyth (2024) show that 16 critical minerals, representing 90 % of the total market value of the 50 critical minerals listed by the United States Department of Energy, had higher non-technical risks than a benchmark non-critical mineral composite, consisting of coal, gold and iron ore. We examine the extent to which differences in non-technical risk, which will be reflected in the elasticity of the supply curve for each critical mineral, magnifies the effect of shocks to GPR on prices.

We are the first to examine the extent to which the effect of GPR on critical mineral prices is time varying with different effects across time horizons using the TVP-LP framework proposed by Inoue et al. (2024). This framework is particularly well suited to examining GPR, in which the environment is likely to be unstable. In doing so, we build on a small number of previous studies that have used this framework to examine the macroeconomic effects of fiscal policy shocks (Inoue et al., 2024) and the effect of GPR on monetary policy (Ginn and Saadaoui, 2024) and oil prices (Mignon and Saadaoui, 2024).

2. Conceptual framework

Geopolitical tensions have caused significant disruptions in the supply of critical minerals due to increased investment uncertainty, export restrictions and supply chain fragmentation. These factors lead to price volatility and supply shortages (Wang et al., 2024; Liu et al., 2022). In Fig. 1, the impact of GPR shocks on critical minerals is depicted. Starting at equilibrium E_1, where the price is P_1 and the output is Y_1, an increase in GPR results in a supply shortage. Consequently, supply shifts from S_1 to S_2. At this new equilibrium E_2, the quantity produced declines from Y_1 to Y_2 and prices increase from P_1 to P_2.

In Fig. 2, we show the differential response of critical mineral prices to supply shocks (GPRs). For simplicity, we show in panel (a) critical minerals with high non-technical risks (or inelastic supply) compared to panel (b) low non-technical risk (or elastic supply). This figure shows that the same change in production of critical minerals leads to notably different prices. Prices are more responsive to GPR when non-technical risks are high (panel a) than when they are low (panel b).

Next, we provide estimates of the non-technical risk for aluminium, copper, nickel, platinum, tin and zinc - the six critical minerals that we consider in this study. Vespignani and Smyth (2024) proposed a methodology to estimate non-technical risks and non-technical risk premiums.

Formally,

$$Non-technical\ risk = \sum_{c=1}^{n} w_{c,m} * s_{c,m} \tag{1}$$

Eq. (1) describes the total value of non-technical risk, aggregated across all countries c for a given mineral, m, where n is the total number of countries, $W_{c,m}$ is the weight assigned to country c for proven reserves of critical mineral c and $S_{c,m}$ is the score or level of non-technical risk for country c of mineral m. This score is based on the country-level investment attractiveness index compiled by the Fraser Institute's (2022) Annual Survey of Mining Companies.

We use the non-technical risk scores to calculate the non-technical risk premium, which is the critical mineral non-technical risk expressed as a percentage of the non-technical risk of the non-critical front-ended mineral benchmark. Consistent with Vespignani and Smyth (2024), we use the average non-technical risk of coal, gold and iron ore to represent the non-critical front-ended mineral benchmark.

Formally,

$$Non-technical\ risk\ premium = \frac{(IAI_{NC,} - IAI_C)}{IAI_{NC}} \tag{2}$$

Where *IAI* is the investment attractiveness index and NC and C denote non-critical minerals and critical minerals, respectively.

There are some similarities, but also differences, with the notion of the risk premium in financial markets. In financial markets, the risk premium represents the additional return that investors demand for taking on extra risk compared to a risk-free investment. The risk premium compensates investors for various uncertainties, including market volatility, liquidity risks and economic downturns. In the context of critical minerals, the non-technical risk premium is analogous, but reflects sector-specific uncertainties rather than broad market conditions. It encompasses factors such as political instability, regulatory challenges, environmental liabilities, and socio-economic dynamics tied to mining projects. These risks vary significantly based on the geographic and institutional contexts of the mining operations.

In Fig. 3a, we report non-technical risks for the six critical minerals, coal, gold and iron ore. Lower values represent a lower investment attractiveness index, and higher non-technical risk, for the relevant mineral. The non-technical risk of each of the six critical minerals was higher than coal, gold or iron ore in 2023. In Fig. 3b we present the non-technical risk premiums of our six critical minerals. The non-technical risk premium reflects the additional risk in the project development of each critical mineral compared to the benchmark of iron ore, gold, and coal. According to Fig. 3b, platinum (33.8 %), copper (28.0 %), and nickel (24.3 %) exhibit the highest non-technical risk premiums among critical minerals. This is followed by tin (22.2 %), aluminium (20.0 %), and zinc (12.8 %).[1]

In appendix A, we undertake the same exercise, but using the separate components of the investment attractiveness index (best practices and policy perception) shows that policy perception is the key driver of non-technical risk in the selected critical minerals. Fig. 4 shows risk premiums for those minerals, distinguishing between best practices and policy perception premiums.[2] For most minerals, policy perception premiums are higher, indicating greater perceived investment risk compared to productivity-based risks. Notably, platinum has the highest policy perception premium (0.340), while nickel and copper also have significant disparities between the two measures. Tin's difference is smaller, and zinc is the only mineral where the best practices premium (0.184) exceeds the policy perception premium (0.175), suggesting slightly higher productivity-driven risk than perceived investment risk.

Caldara and Iacoviello (2022) find that geopolitical acts (i.e. the realization of a geopolitical threat) have smaller effects than the threat itself on prices for several economic and financial variables using a VAR analysis. Wang et al. (2024) find that geopolitical threats hinder the clean energy transition, defined as the share of renewable energy consumption in total energy consumption, more than geopolitical acts using

[1] An important caveat is that platinum can be substituted by several other metals depending on the application, though these alternatives often come with trade-offs. In catalytic converters, palladium is the most common substitute, particularly for gasoline engines, while rhodium is sometimes used for reducing nitrogen oxides. In electronics, nickel and silver can replace platinum in connectors and capacitors, but they are less corrosion resistant. In chemical catalysis and fuel cells, palladium and nickel are sometimes used as cheaper alternatives, though they are generally less efficient than platinum.

[2] Note that the average of the best practices index and the policy perspective index does not exactly match the investment attractiveness index. This discrepancy arises because some firms do not respond to all survey questions required for constructing all indices in the Fraser Institute's Annual Survey of Mining Companies. As a result, there are slight differences between the overall composite investment attractiveness index and its two components.

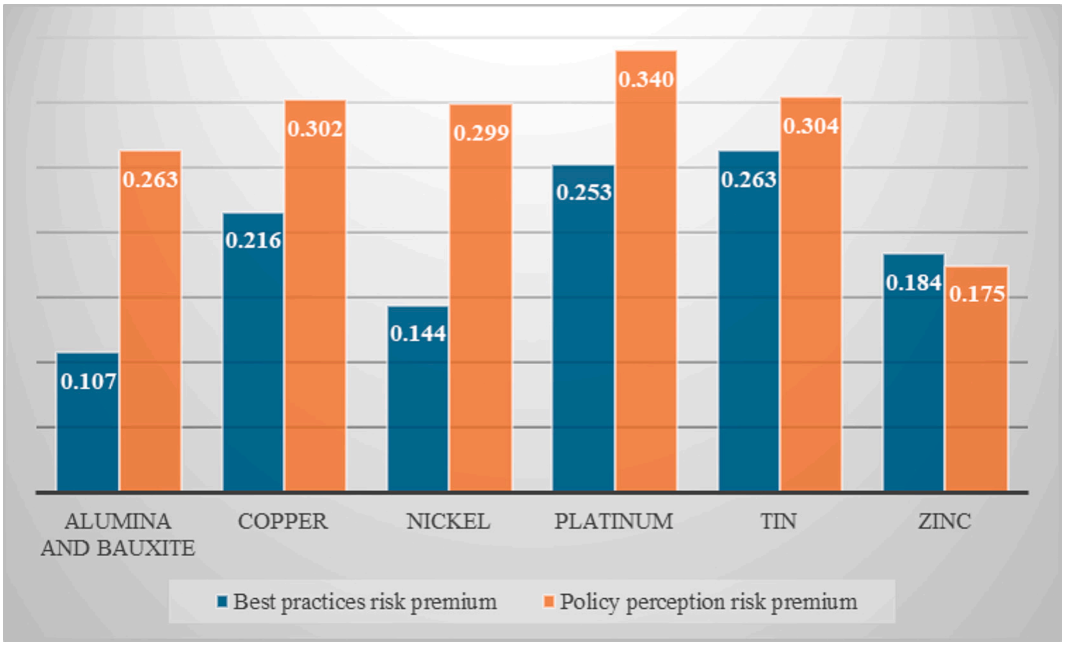


Fig. 4. The non-technical risk premiums decomposition (2023).

panel cointegration techniques and dynamic panel estimates with threshold effect tests. In a related study, Sohag et al. (2023) show that the heightened uncertainty associated with geopolitical threats, but not geopolitical acts, increases the cost of investing in green technologies.

The theoretical explanation for these results centre on the manner in which firms form expectations when faced with differing levels of uncertainty (Ilut and Schneider, 2014). The models in Bloom et al. (2007) and Dixit and Pindyck (1994) illustrate the basic point that firms prefer less complexity, and associated uncertainty, when making investment decisions. Uncertainty surrounding geopolitical threats is much more complex for firms to deal with than geopolitical acts. Indeed, there is a reduction in uncertainty when the conflict starts, as the firm can make cost-advantage calculations on a more solid basis than faced with a scenario in which the firm does not whether the conflict will start or not. Bouoiyour et al. (2019) suggest that prolonged threats lead to more extensive disruptions because market participants factor in long term risks and avoid commitments in uncertain environments, exacerbating supply chain vulnerabilities.

In Fig. 5(a) and 5(b), we distinguish between responses to geopolitical threats and acts, respectively. In panel (a), a geopolitical threat leads to a large disruption in the supply chains of critical minerals, causing a reduction in supply from S_1 to S_2 and shifting to a new equilibrium from E_1 to E_2. In panel (b), a geopolitical act leads to smaller disruptions in the supply chains of critical minerals, resulting in a reduction in supply from S_1 to S_2 and a shift in equilibrium from E_1 to E_2. Panel (a) demonstrates that threats cause larger shifts in the supply compared to panel (b), resulting in moderate supply shocks reflected in smaller increases in prices for acts and larger price increases for threats.

Drawing this together, suggests two hypotheses that we test in the empirical section. First, Fig. 2 suggests that critical mineral prices are more responsive to GPR when non-technical risks are high than when they are low. This leads us to hypothesise that in response to a shock in GPR prices for platinum will be most responsive, followed by prices for copper, nickel, tin, aluminium and zinc. Second, Fig. 5 suggests that prices will be more responsive to geopolitical threats than geopolitical acts.

3. Data and methodology

3.1. Data

We utilize monthly prices from January 1985 to January 2024 for aluminium, copper, nickel, platinum, tin and zinc. The prices for these six critical minerals were obtained from the World Bank's "pink sheet" and we used data for all critical minerals available from this source. The data on economic activity is sourced from Baumeister and Korobilis (2022), while information on GPR, geopolitical actions, and threats is sourced from Caldara and Iacoviello (2022). Global inflation data is obtained from the Federal Reserve Bank of Dallas, Database of Global Economic Indicators.

Fig. 6(a) shows the time series of GPR, geopolitical acts, and geopolitical threats from 1985 to 2024. The vertical axis represents the intensity or index values, while the horizontal axis represents time in monthly intervals. Geopolitical threats (light blue line) are characterized by sharp spikes, notably around the late 1990s and early 2000s, as well as during the early 2020s. The peak in the early 2000s is the highest observed, indicating a period of intense geopolitical tensions. Geopolitical acts (black line) generally exhibit a similar pattern to geopolitical threats, with high peaks during the same periods, although they are slightly lower in magnitude. This correspondence suggests that significant geopolitical actions, such as sanctions or conflicts, coincided with periods of increased threats.

Fig. 6(b) presents a time series comparison of global economic conditions in red and global inflation, (in light blue) from 1985 to 2024. The vertical axis measures changes, ranging from −4 to +2, while the horizontal axis represents time in monthly intervals. Global economic conditions fluctuate significantly over time, showing periods of both positive and negative growth. Notable declines are observed during global financial crises, with sharp drops in the late 2000s (reflecting the 2008 financial crisis) and during 2020 (corresponding to the COVID-19 pandemic). The most significant drop occurs around 2020, indicating a severe economic downturn. Following the 2020 dip, economic conditions recovered but remained volatile. Global inflation also exhibits fluctuations over the same period, although with generally smaller variations compared to economic conditions. Inflation is relatively stable around the zero mark but increases noticeably in the late 2000s and again during the early 2020s, reflecting periods of rising inflation often

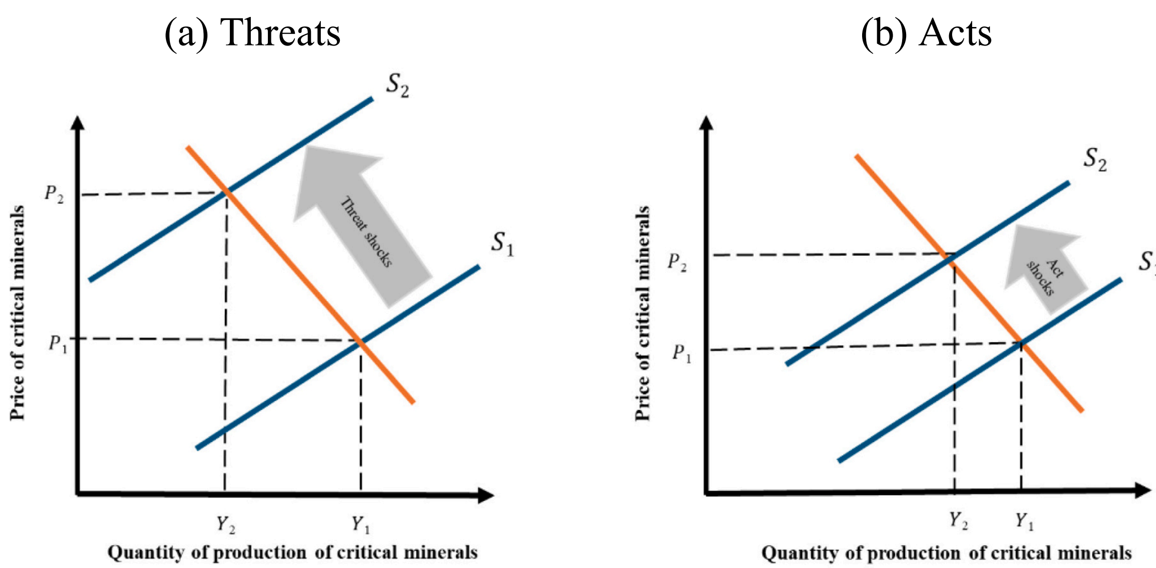


Fig. 5. The impact of geopolitical threats and acts on selected critical minerals.

linked to economic instability. The inflation rate appears to increase substantially during the post-pandemic recovery period, coinciding with the sharp drop and subsequent recovery of economic conditions.

Fig. 6 (c) displays the critical mineral prices from 1985 to 2024. The vertical axis denotes prices, while the horizontal axis represents time at monthly intervals. The nickel price (black line) exhibits the most significant fluctuations, with two major spikes: one around 2007–2008, and the other from 2020 to 2024. The price reached peaks of around $50,000 per unit,[3] reflecting high volatility and large swings during these periods. The tin price (grey line) also experienced noticeable increases, particularly in 2010 and 2022, where the price exceeded $30,000 per unit. Tin generally exhibits more stability compared to nickel, but still had significant spikes. The copper price (light blue line) has experienced steady growth with moderate fluctuations, peaking at around $10,000 per unit, particularly during the 2005–2008 and 2020–2025 periods. The zinc price (cyan line) exhibits moderate variability with noticeable peaks around 2006–2007 and 2022, where prices also approached the $10,000 mark. The aluminium price (red line) and platinum price (purple line) have been relatively stable compared to the other metals, with smaller fluctuations. Aluminium prices peaked around 2007–2008 but remained much lower in magnitude compared to nickel and tin.

As emphasised by Mignon and Saadaoui (2024), these GPR shocks may reflect fear of supply disruption for firms and, at the same time, as recalled above, induce investment uncertainty. In this respect, Mignon and Saadaoui (2024) provide empirical evidence that identified GPR shocks Granger cause the aggregate prospect of "business expectations (BCI) and, more significantly, markets' expectations (CLI) from the 2000s" using OECD survey data and time-varying causality tests. In this sense, GPR shocks act as negative supply shocks that reflect the expectation of supply disruptions. Accordingly, we expect that these shocks, depending on their size, will produce an increase in the critical mineral price.

3.2. Methodology

We use the TVP-LP approach, pioneered by Inoue et al. (2024), to examine the effects of GPR shocks on critical mineral prices. Methodologically, the LP approach (Jordà, 2005) has several advantages, including estimation by single equation OLS at each horizon, a simple inference for impulse response coefficients, the effects being local to each horizon (i.e., no cross-period restrictions) and that the estimation of very nonlinear and flexible models is straightforward in this setup. In addition, Montiel et al. (2024, p.2) recently provide "a formal proof of Jordà's claim that conventional LP confidence intervals for impulse responses are surprisingly robust to misspecification." Regarding our research question, all features of the TVP-LP approach enable us to provide time-varying dynamic evidence on the causal impact of GPR shocks. The TVP-LP is especially relevant in the context of our research question due to the evolving geopolitical context. In contrast to other VAR/LP-based models that allow for time variation (such as TVP-(B)VAR, state-dependent LPs), the TVP-LP approach does not require one to specify parametrically the exact form of the instability process. More intuitively, the TVP-LP approach will estimate a path estimator for each time horizon.[4] For example, at horizon 1, we have $T = 476$ months (from January 1985 to August 2024) in our sample and the horizon is equal to $h = 1$ month. Thus, we will have $T - h = 476–1 = 475$ impulse response functions at horizon 1 in the first row and first column panels of Appendix B to D. That means that this path estimator does not constrain the response to be the same for each time horizon, allowing for smooth and flexible time-variation. For example, GPR shocks that occur during episodes of high financial stress may have different effects than in normal conditions. The standard local projections cannot uncover these differences, and, similarly, the state-dependent local projections constrain the response to be the same in each state. With these different estimates for the impulse response at each time horizon, it is possible to construct an interval estimator to detect the presence of instabilities / time-varying effects in the impulse response at each time horizon.

We examine the effect of a one-unit identified geopolitical risks

[3] Critical mineral prices are expressed in US dollar per metric ton, except for the platinum price, which is expressed in US dollar per troy oz.

[4] The step-by-step implementation of the TVP-LP estimator is described in Section 2.2 of Inoue et al. (2024).

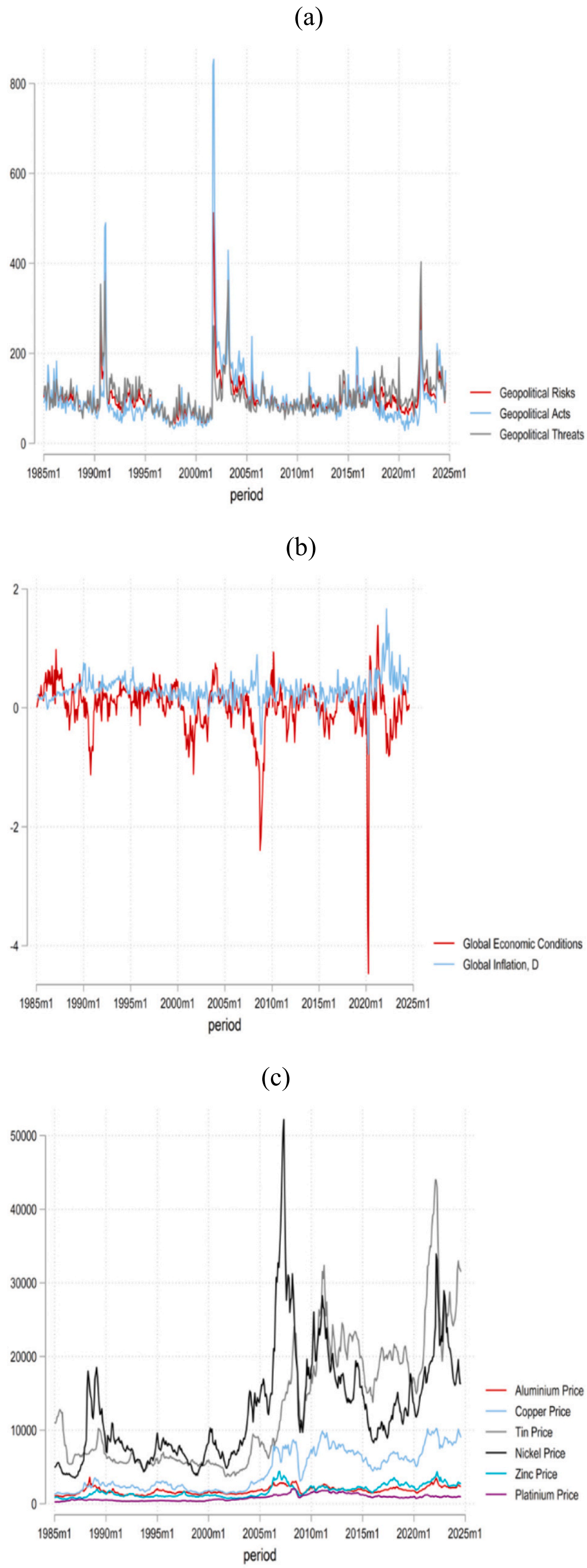


Fig. 6. Data description.
Note: the sources of the data are fully described at the beginning of section 3.

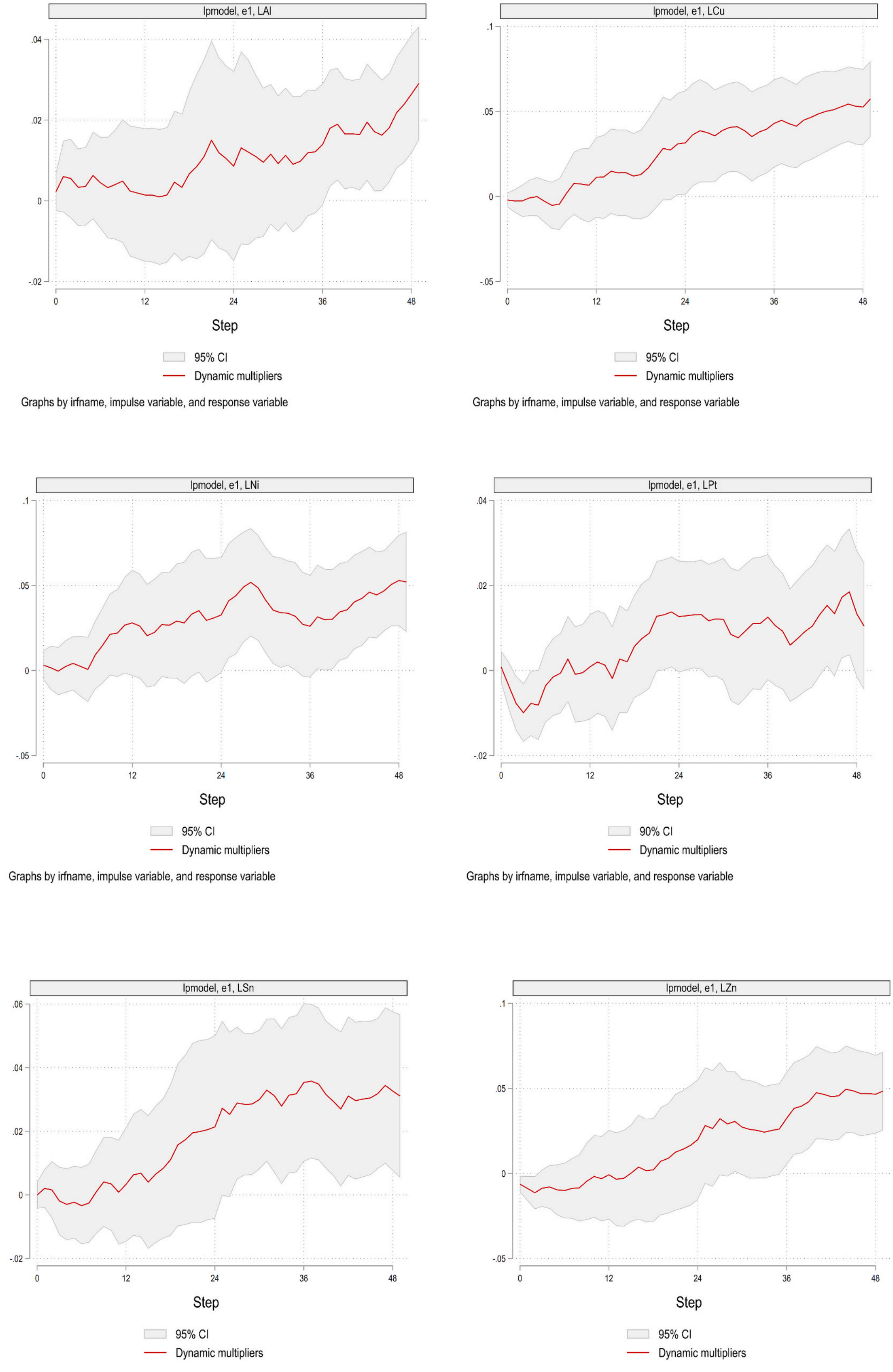


Fig. 7. Response of individual critical minerals to geopolitical shocks (GPR).
Note: the dynamic multipliers retrace the reaction of critical mineral price to an identified GPR shock, see footnote 2.

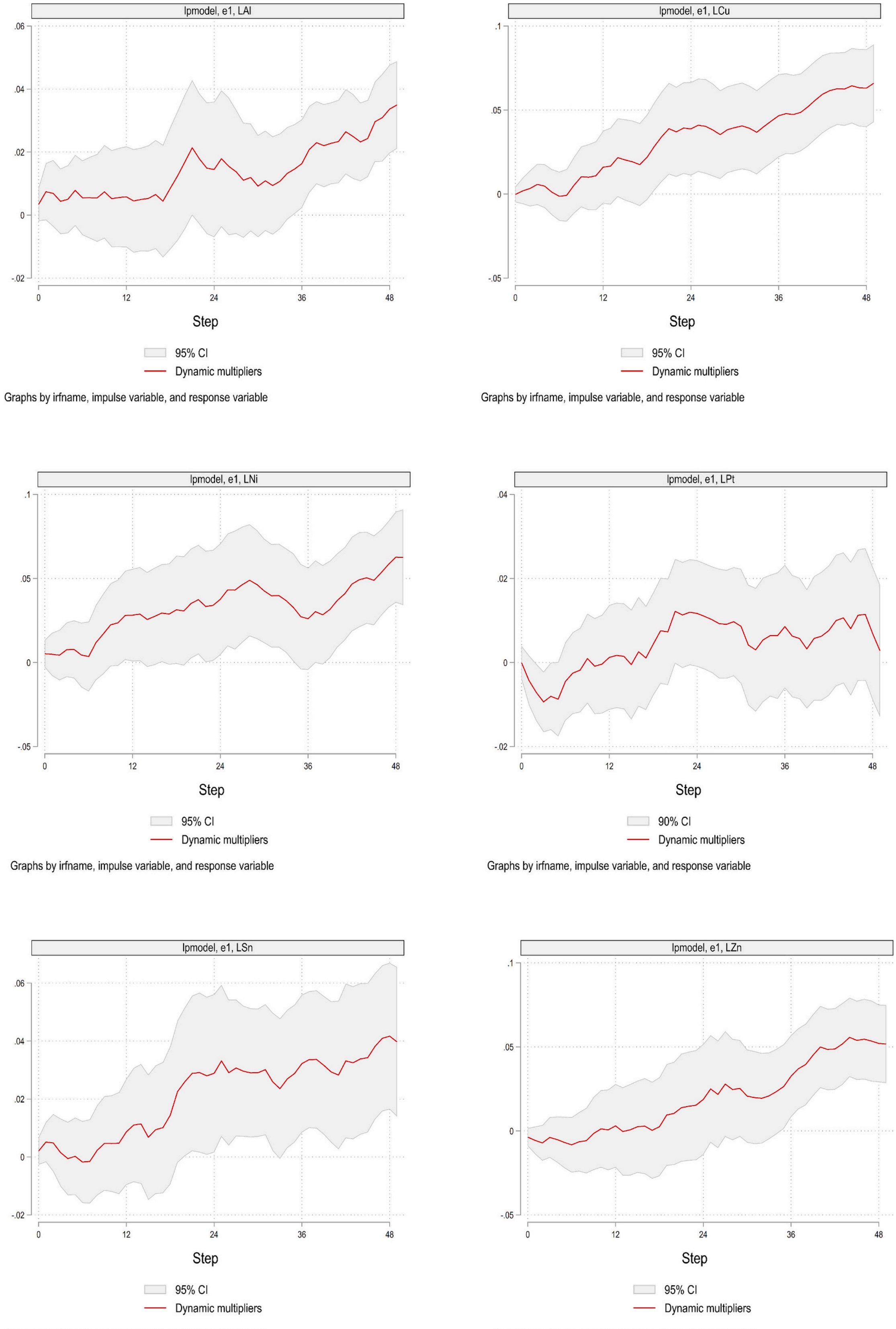


Fig. 8. Response of individual critical minerals to geopolitical threat shocks (GPRT).
Note: the dynamic multipliers retrace the reaction of critical mineral price to an identified GPR threat shock, see footnote 2.

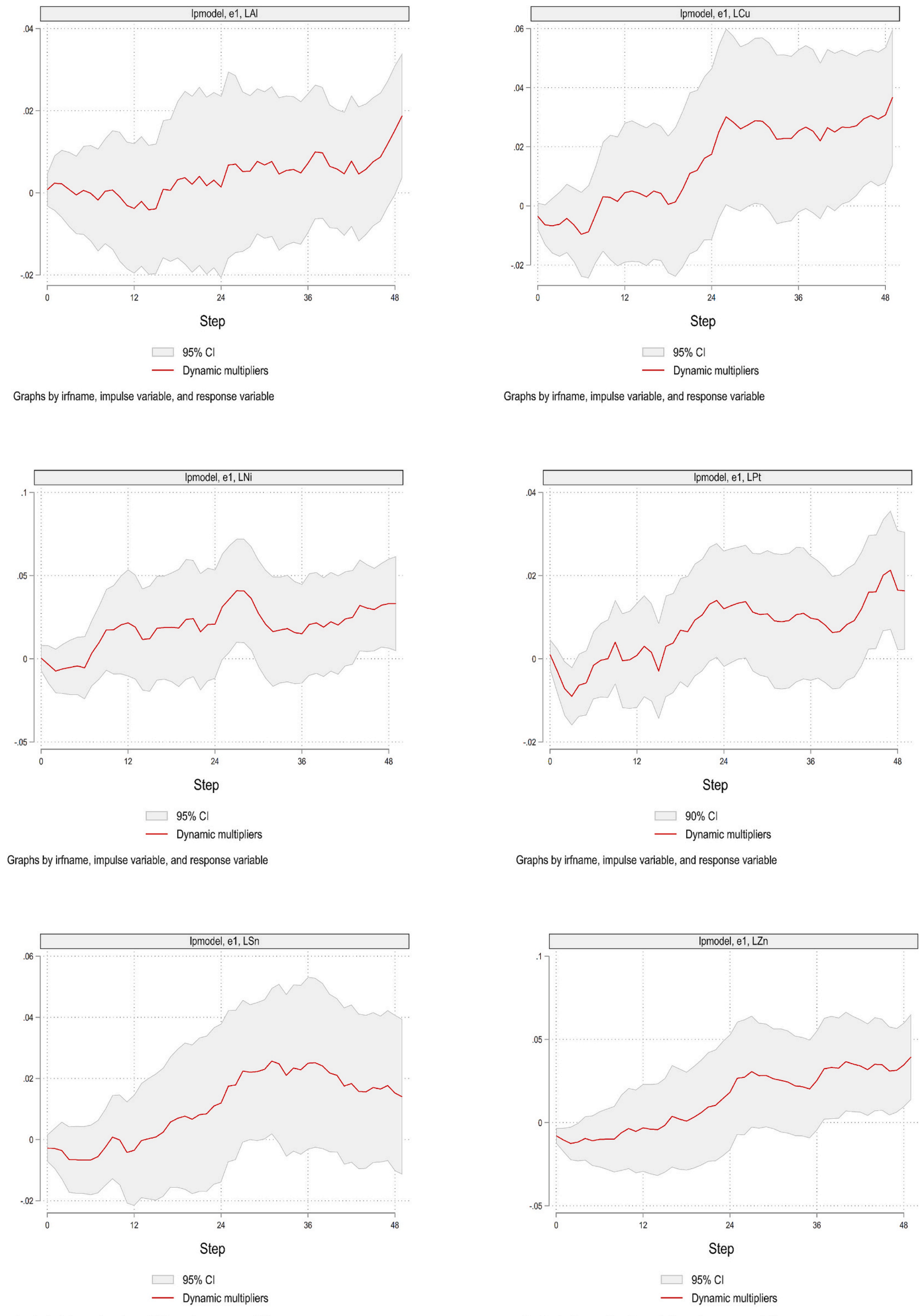


Fig. 9. Response of individual critical minerals to geopolitical act shocks (GPRA).
Note: the dynamic multipliers retrace the reaction of critical mineral price to an identified GPR acts shock, see footnote 2.

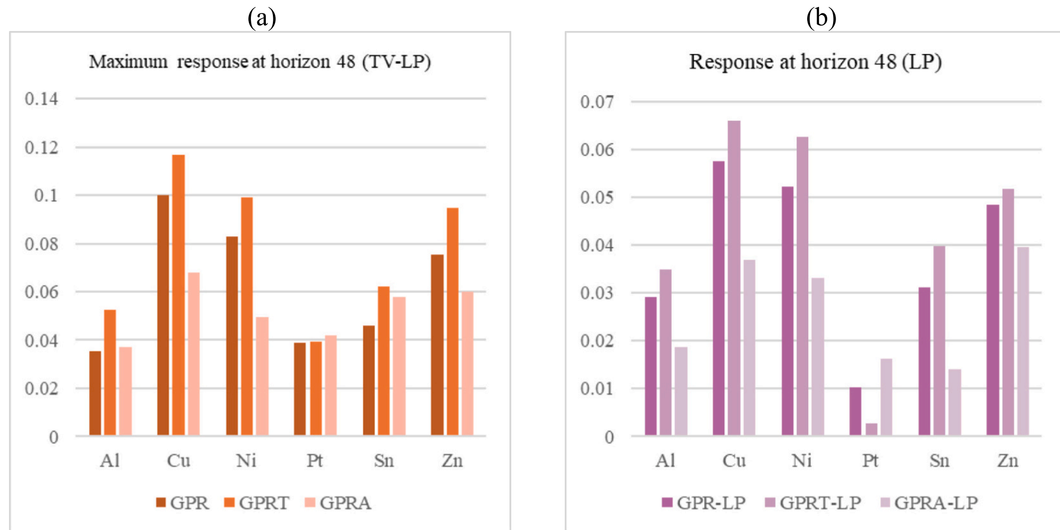


Fig. 10. Long-term (48 month) responses to geopolitical risk, threats, and acts.
Note: these long-term (48 month) responses to geopolitical risk, threats, and acts and their significance levels can also be found in Figs. 7 to 9 and Appendix B to D. In Figs. 7 to 9, these long-term (48 month) responses are shown in horizon 48. In Appendix B to D, the maximum response can be found in the last panel by looking at the global maximum for the plain curve.

shocks[5] (ϵ_{gpr}) on the price of critical minerals (*cms*). Thus, we can formulate the TVP-LP approach as follows:

$$cms_{t+h} = c_{t+h} + \beta_{h,t+h}\epsilon_{gpr_t} + \sum_{j=1}^{12} \alpha'_{j,t+h}\mathbf{z}_{t-j} + v_{t+h} \quad h = 0, 1, \dots \tag{3}$$

$$\text{IRF}(h) = \beta_{h,t+h}$$

where $\mathbf{z} = (cms, gecon, ginf, \epsilon_{gpr})'$. The parameter of interest is the time-varying impulse response $\beta_{h,t+h}$. The explained variable, the price of the six critical minerals, are designated by *cms*. We use successively the price of aluminium, copper, nickel, platinum, tin and zinc, as the explained variable. Other terms are defined as follows: c is a constant term, *gecon* denotes global economic conditions; *ginf* is the global inflation rate; h is the horizon; ϵ_{gpr} is the impulse variable (SVAR-identified geopolitical risks shocks); $\mathbf{z}$ is a vector of control variables; IRF, stands for the impulse response function and v, is the error term.

4. Results

4.1. Impulse responses of selected critical minerals to geopolitical risks, threats and acts

In Figs. 7 to 9, a general pattern clearly emerges in the (time-invariant) local projections. In the medium-to-long run, geopolitical risk has a positive impact on the price of five of the six critical minerals, with the exception being platinum. Following a unit shock of geopolitical risk to the aggregate GPR index in Fig. 7, the impulse response functions become significant after 24 to 36 months. The critical mineral prices that are influenced the most are copper, nickel and zinc with a maximum response around 5 %, which is significant at the 5 % level. While it is difficult to directly compare these results with previous studies because of methodological differences in approach and slightly different research questions, the general conclusion that an increase in GPR has a positive effect on critical mineral prices is qualitatively consistent with Aloui et al. (2023) (copper and zinc prices), Wang et al. (2023) (nickel prices) and Zhao (2023) (copper, nickel and zinc prices).

These dynamics are very similar for a unit-shock of geopolitical threat in Fig. 8. However, the impulse response for prices of aluminium, copper, nickel and tin are generally more reactive to geopolitical threats than to the aggregate GPR index. In Fig. 8, the long-run effect of geopolitical threat on the nickel price seems to be more pronounced from the 24th month to the 48th month, suggesting a time-varying pattern in the long run. In Fig. 9, the unit shocks of geopolitical acts seem to have less significant effects on each of the critical mineral prices, which is in line with the literature. However, the price of copper, nickel and, more strongly, zinc show a positive significant reaction to geopolitical acts in the long run.

4.2. Long term (48-month) responses of selected critical minerals to geopolitical risks, threats and acts

In Section 2, we hypothesised that critical minerals with higher non-technical risk premiums would show a stronger price response to GPR shocks. Except for platinum, our findings are broadly consistent with this hypothesis. Specifically, copper and nickel exhibit relatively high non-technical risks (0.11) and significant price responses to GPR shocks (28.0 %). In contrast, aluminium, tin, and zinc show moderate non-technical risks (0.05, 0.06, and 0.07, respectively) and moderate price responses to GPR shocks (20.0 %, 22.2 %, and 12.8 %, respectively). Note, that in terms of relative responsiveness of critical mineral prices to a GPR shock, there are some similarities and some differences with Zhao (2023), who finds that GPR has the biggest effect on prices for aluminium and copper, with less significant effects on prices of nickel and platinum over the period October 1992 to October 2022. Specifically, while our results for the relative importance of copper and platinum are similar, we differ on the ordering of aluminium and nickel. Zhao (2023) does not frame his study in terms of the relevance of non-technical risk, but we believe that our results are more consistent with the underlying non-technical risk for five of the six critical minerals.

The exception is platinum prices. Platinum differs from the other critical minerals that we consider in that it has suffered a negative demand shock from the electric vehicle revolution. Catalytic convertors used to clean exhaust fumes by the automobile sector are responsible for

[5] The series of GPR shocks, ϵ_{gpr}, are obtained for each critical mineral and the different GPR index using a SVAR(12) and the following recursive ordering: *cms*, *gecon*, *ginf*, *gpr*; where *cms* is the price of different critical minerals and *gpr* is alternatively the GPR index, the GPR Threat index or the GPR Act index. Overall, we have six critical minerals and three GPR indexes. Thus, we have 18 series of different GPR shocks.

40 % of the demand for platinum and 80 % of demand for palladium offtake, but this process is not required in pure electric vehicles (Devitt and Shivaprasad, 2024). The increase in global sales of pure electric vehicles means, in the case of platinum, that the shift in the supply curve to the left due to geopolitical risk in Fig. 1, has been accompanied by a downward shift in the demand curve offsetting the supply side shock.

In Section 2 we hypothesised that critical minerals prices would be more responsive to geopolitical threats than geopolitical acts. In Fig. 10, the impact of geopolitical threats seems more pronounced than geopolitical acts, indicating that the anticipation or risk of geopolitical tension has a larger effect on these markets than actual events. This is true to both specifications TVP-LP and LP.

The aluminium prices response to geopolitical threats is 5.27 %, while the response to geopolitical acts is lower at 3.73 %, indicating a significant difference and higher sensitivity to threats. Copper exhibits the highest sensitivity overall, with a geopolitical threats' response of 11.67 %,[6] compared to a geopolitical acts' response of 6.81 %. The response of nickel prices to geopolitical threats is 9.90 %, whereas the response to geopolitical acts is 4.95 %. Nickel displays a marked increase in response when faced with threats compared to acts. Tin shows a geopolitical threats response of 6.24 %, slightly higher than the geopolitical acts response of 5.98 %. Zinc responds at 9.50 % to geopolitical threats, which is considerably higher compared to a geopolitical acts response of 5.98 %. Platinum's response to geopolitical threats is 4.21 %, while its response to geopolitical acts is only marginally smaller at 3.90 %. Overall, the responses in the first figure (TVP-LP) are generally higher than those in the second fig. (LP), indicating that the model using TVP-LP captures stronger responses to geopolitical risk factors across all critical minerals.

5. Robustness analysis and state dependence analysis

In Appendices B, C, and D, we present a robustness and state dependence analysis of various specifications of our benchmark model for GPR, geopolitical acts and geopolitical threats for each of aluminium, copper, nickel, platinum, tin and zinc. The first set of figures for each critical mineral illustrates different specifications of the benchmark model to facilitate comparisons, consisting of the TVP-local projection, high GPR risk response, the response following the Global Financial Crisis (GFC) and low global economic conditions (GECON). Low-GECON, in this context, refers to the economy being in a recessionary state. The subsequent six figures for each critical mineral demonstrate different state dependencies observed at different time intervals - one, six 12, 24, 36, and 48 months - respectively.

5.1. Robustness analysis

The impulse response function results in Figs. 7 to 9 suggest a long-run positive effect of GPR shocks on critical mineral prices after 24 to 36 months. The TVP local projection estimates confirm these results in the first column of the upper panels in Appendix B. We find that these long-run effects are more important after the Global Financial Crisis when the geopolitical context changed - for example, the rivalry between China and the United States intensified after the Global Financial Crisis (see eg. Garrett, 2010; Lee et al., 2018) - in the second column of the upper panels of Appendix B. This is particularly evident for nickel prices and zinc prices with a long-run impact of 4 %, 48 months after the GPR shocks. Quite remarkably, the effect of high GPR (above the ninth decile for GPR) and the effect of deep recessions (below the first decile for global economic conditions) is similar in the second and third columns of the upper panels in Appendix B. However, we observe slight differences for the aluminium price and the tin price. These two critical minerals are positively impacted by the GPR shock at longer horizons.

Does this general pattern change with geopolitical acts and geopolitical threats? The general point that comes through Appendices C and D is that the effects of shocks to geopolitical threats (GPRT) are stronger than GPR and that the effects of GPR are stronger than geopolitical acts (GPRA). In Appendix C, the main difference between shocks to geopolitical acts and GPR is in the period following the Global Financial Crisis in the second column, where the effects for geopolitical acts are more dispersed than for GPR and have large positive effects only for tin and the platinum. In Appendix D, for geopolitical threats the general pattern observed for GPR shock is confirmed and the effects are mostly stronger with the long-run impact of geopolitical threats between 5 and 10 %, with the notable exception of platinum prices.

5.2. Time-varying analysis

In terms of state dependence for a GPR shock in the lower panels of Appendix B, we can clearly observe that the impulse responses are significantly unstable when the confidence interval between the two dotted lines does not include zero. When we reject the null of a stable impulse response function, then we detect time-varying effects. Overall, we detect time-varying effects for the aluminium price during the Gulf War, with an elasticity of 4 %, 48 months after the shock. For the copper price, we detect time-varying effects for more than 10 years, between 1985 and 1995, with an elasticity fluctuating between 5 % and 10 %, 48 months after the shock. For the nickel price, we also detect time-varying effects around the Gulf War, with an elasticity of around 8 %, 48 months after the shock. For the tin price, we find a time-varying effect around the 9/11 attacks, with an elasticity around 10 %, 36 months after the shock. Similarly, we find time-varying effects around the Gulf War for the zinc price, with an elasticity of around 7 %, 48 months after the shock.

How do the results for geopolitical acts and threats differ in the lower panel of Appendices C and D? Overall, we detect several time-varying effects for geopolitical shocks, which differ from those for geopolitical risk shocks. For the aluminium price, we find a time-varying effect around the start of the COVID-19 pandemic, with an elasticity around −3 %, six months after the shock. We also find a time-varying effect around the start of the COVID-19 pandemic for the copper price, with an elasticity around 5 %, six months after the shock. For the tin price, we find multiple time-varying effects at different time horizons. During the COVID-19 pandemic, for the tin price we observe an elasticity in excess of 5 %, six months after the shock. This time-varying effect is still observable 12 months after the shock. The tin price is positively affected by geopolitical act shocks during the months surrounding the 9/11 attacks, with an elasticity above 10 %, 36 months after the shock. For zinc prices we detect time-varying effects for around 10 years, between 1985 and 2000, with an elasticity fluctuating between 1 % and 4 %, 36 months after the shock. For geopolitical threat shocks, the pattern observed for GPR shock is confirmed and even stronger. For the price of aluminium, we find a time-varying effect during the Gulf War and between 2015 and 2018, with an elasticity of 5 %, 48 months after the shock. Similar to aluminium price, nickel prices react more strongly to threats. The effects of a shock to geopolitical threat on the copper price are stronger than the effect of GPR shocks, with elasticities above 10 % between 1985 and 1995, 48 months after the shock. We detect a time-varying effect for the platinum price at the end of the 1990s. The elasticities are around 5 %, 24 months after the shock. Lastly, the zinc price reacted strongly to threats during the periods surrounding the Gulf War and the 9/11 attacks, with elasticities ranging from 5 to 10 %, 48 months after the shock.

[6] The level of significance for the elasticities can be seen in Appendix B to D. For example, the maximum elasticity of copper prices to geopolitical threats is equal to 11.67 % as shown in the first row and first column panel of Appendix D for copper prices. In the last row and last column panel of Appendix D for copper prices, it can be seen that the maximum elasticity is during the Gulf War at the beginning of the 1990s and is statistically significant at the 5 % level.

6. Conclusion

The traditional focus of the literature on energy security has been on fossil fuels. However, more recently, given growing recognition of the essential role of critical minerals for realizing carbon net zero targets, the importance of ensuring a stable supply of critical minerals is increasingly being acknowledged as vital to maintaining energy security (Nature, 2023). Maintaining supply chains for critical minerals in order to ensure energy security has brought the issue of GPR into sharp focus. The United States, in particular, is worried about the implications of escalating GPR for supply chains of critical minerals for both the clean energy transition and defence applications and what this might mean in terms of escalating prices. This is particularly evident in the push for friend-shoring agreements, such as the Minerals Securities Partnership, which is an initiative launched in June 2022 by the United States and its allies, designed to mitigate GPR due to China's dominance in the processing and supply of many critical minerals (Vivoda, 2023).

In this paper, we employed constant and time-varying parameter local projection (TVP-LP) regression models, recently proposed by Inoue et al. (2024), to examine the effect of GPR on prices of aluminium, copper, nickel, platinum, tin and zinc. In so doing, we contribute to a small number of studies that have examined the effect of GPR on prices for critical minerals (Aloui et al., 2023; Khurshid et al., 2023; Pata et al., 2024; Wang et al., 2023; Zhang et al., 2024b; Zhao, 2023).

We extend this literature in two main directions. The first is that we introduce a conceptual set up which predicts that the responsiveness of prices for critical minerals to GPR will depend on their respective non-technical risk. Using the method suggested in Vespignani and Smyth (2024) we provide estimates of the non-technical risk and non-technical risk premium for each of the six critical minerals. We then show that, with the exception of platinum, prices of critical minerals which exhibit higher non-technical risk are more responsive to GPR, consistent with the prediction of our theoretical set up. The fact that the findings for platinum prices do not conform with our theoretical prediction can be explained by platinum suffering a demand side shock due to the expansion of the electric vehicle market, which has offset the supply side shock due to GPR, meaning that prices have not risen like the other critical minerals in the study.

The second way in which we extend our understanding of the relationship between GPR and prices of critical minerals is through distinguishing between the effects of geopolitical acts and geopolitical threats. Drawing on an existing theoretical and empirical literature in other contexts, which suggests that geopolitical threats have a more adverse effect on investment decisions through contributing to greater uncertainty than geopolitical acts, we posit that geopolitical threats will have a bigger effect on the price of critical minerals than geopolitical acts. Our results are consistent with this conjecture.

We observe considerable time varying effects in the response of prices of critical minerals to GPR shocks. Previous research has shown that critical mineral prices have responded to recent GPR shocks, such as the Russian-Ukraine conflict (Khurshid et al., 2023; Pata et al., 2024). Our analysis shows the time varying responses of prices of each of the critical minerals studied to a number of events generating shocks to GPR over an extended period, including the Gulf War, 9/11 terrorist attacks and COVID-19 pandemic. We find that shocks due to these events have different effects across geopolitical acts and geopolitical threats.

Our results have important implications for our understanding of the role of critical minerals in ensuring energy security and realizing the clean energy transition. Importantly, they suggest that the effect of GPR (including geopolitical acts and threats) on the prices of critical minerals can be mitigated through reducing non-technical risk. In terms of the components of non-technical risk, our analysis reported in Appendix A suggests that the highest marginal returns lie with focusing on policy perceptions, rather than best practices. We conclude through offering some suggestions regarding specific strategies for policymakers and firms to address these challenges effectively. Policymakers could reduce non-technical risk by promoting greater openness and transparency; seeking greater stakeholder engagement in decision-making; acting proportionately and consistently in dealing with managing risk; employing evidence-based decision-making; allocating responsibility for managing risks to those best placed to control them and enhancing regulatory clarity (see eg. Aven and Renn, 2018). For the individual firm, there is often a tendency to treat non-technical risk as being exogenous to the investment decision - i.e. as being beyond the firm's control. Trench et al. (2014) are critical of this mindset and stress the importance of firms taking ownership of non-technical risk. Specifically, Trench et al. (2014) emphasise that the uncertainty generated by non-technical risk to the firm can be reduced by considering non-technical risk early - i.e. non-technical risks should be assessed, monitored and discussed from the exploration stage to assist with stage-gating of project decisions. Individual firms can employ a range of strategies to mitigate non-technical risk. Some of these can mirror strategies being adopted by nation states in the form of friendshoring agreements, such as fostering international collaboration to stabilize supply chains and diversifying sourcing regions.

A limitation of the paper is that our sample is limited to six materials, which reflects data availability. While this is a bigger sample than that employed in previous studies of this sort, given that the EU lists 34 critical minerals and the United States lists 50 critical minerals, the sample size potentially limits the study's ability to generalize findings across a broader set of critical metals. Examining how the findings might generalize to other critical materials is an extension for future research.

CRediT authorship contribution statement

Jamel Saadaoui: Writing – original draft, Formal analysis, Data curation, Conceptualization. **Russell Smyth:** Writing – original draft, Conceptualization. **Joaquin Vespignani:** Writing – original draft, Formal analysis, Conceptualization.

Appendix A. Alternative measures of non-technical risks (best practices and policy perception risks)

A.1. Policy perception

Fig. A1(a) displays non-technical risk (policy perception) scores for each critical mineral, in which a higher score indicates a lower risk. Aluminium, copper, nickel, platinum, tin and zinc each have higher non-technical risks (40.2 to 50.3) compared to the non-critical benchmark (60.9), indicating that they are associated with higher risk levels. Fig. A1(b) shows the non-technical risk premiums for each of the six minerals. Platinum has the highest risk premium at 34.0 %, indicating the highest compensation for risk, followed by tin (30.4 %) and copper (30.2 %). Nickel has a similar premium at 29.9 %, while the risk premium for aluminium is slightly lower at 26.3 %. Zinc, with the lowest non-technical risk premium at 17.5 %, suggests the least compensation needed for risk. This indicates varying levels of non-technical risk across these minerals, with platinum carrying the highest and zinc the lowest.

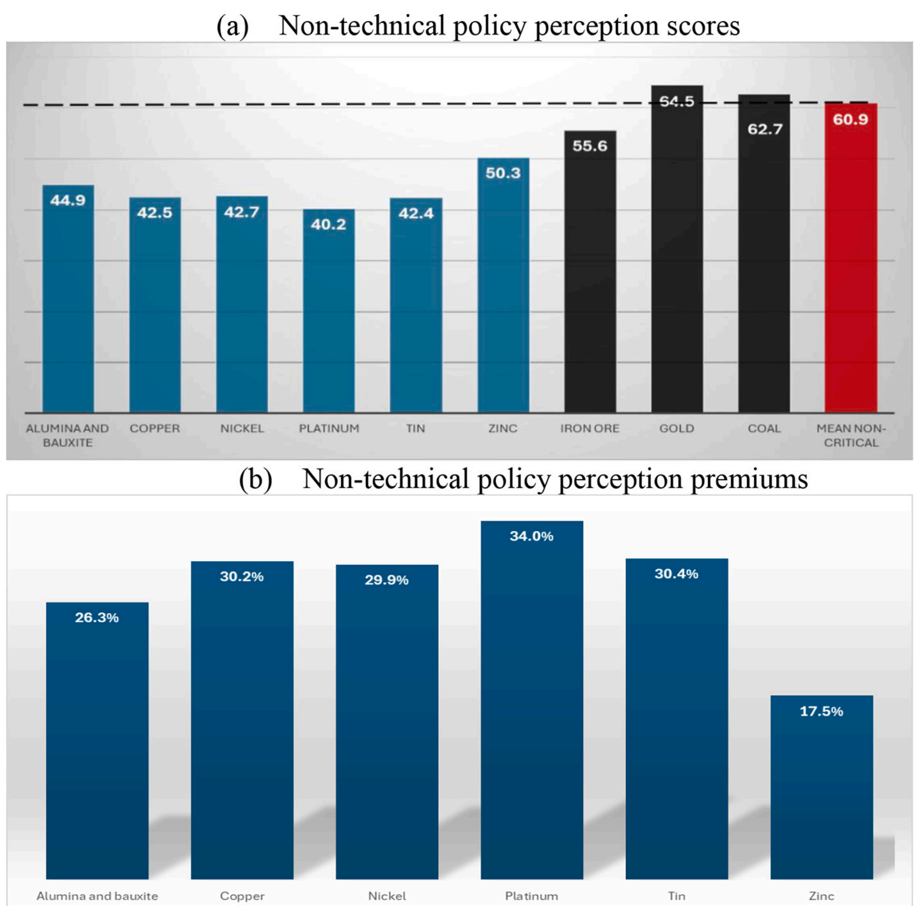


Fig. A1. The non-technical risk (policy perception scores) and premiums of selected critical minerals (2023).

A.2. Best practices

Fig. A2(a) presents non-technical risk scores for each of the critical minerals based on the best practices subcomponent. The picture that emerges is similar to that with the policy perceptions subcomponent and for the overall non-technical risk scores presented in Fig. 3. Specifically, the scores for these six critical minerals range from 44.1 to 53.4, while the mean score for the non-critical benchmark is 59.9. Fig. A2(b) shows the non-technical best practice risk premiums. Tin has the highest risk premium at 26.3 %, indicating the highest level of expected compensation for associated risks. Platinum follows with a risk premium of 25.3 %, while copper has a premium of 21.6 %. Zinc and nickel have relatively moderate premiums at 18.4 % and 14.4 %, respectively. Aluminium has the lowest risk premium at 10.7 %, suggesting the lowest compensation needed for risk among these minerals. This range of risk premiums suggests varying levels of non-technical risks across these minerals, with tin and platinum having the highest expected compensation and aluminium the lowest.

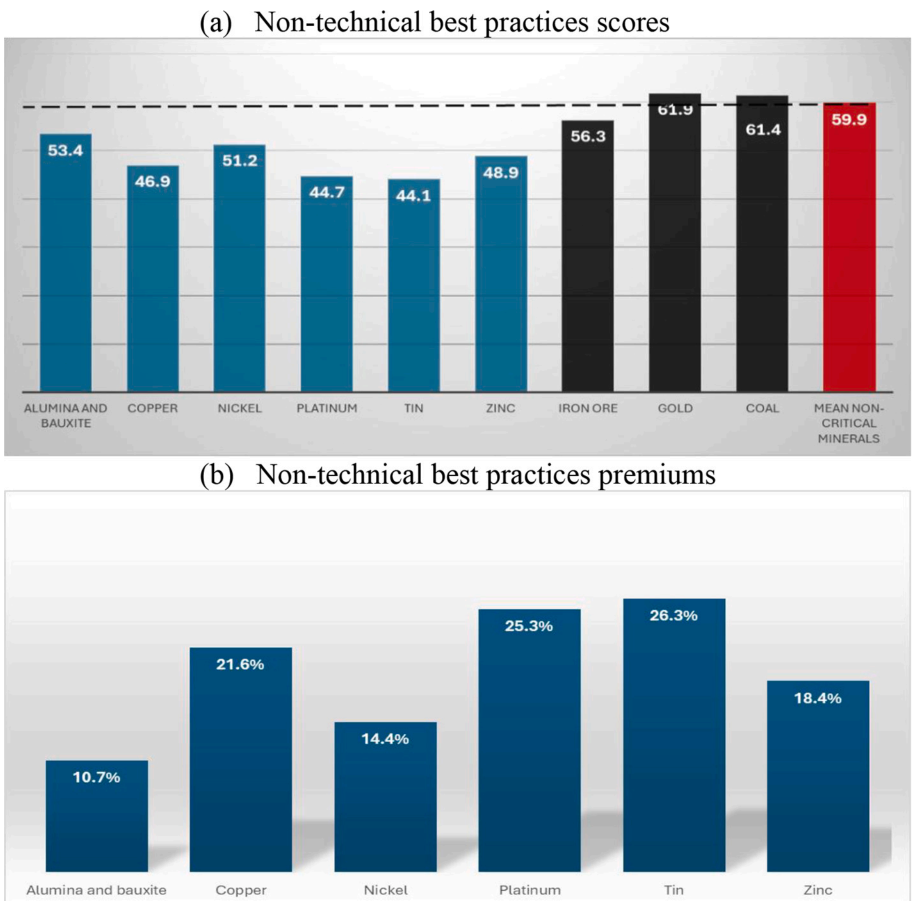
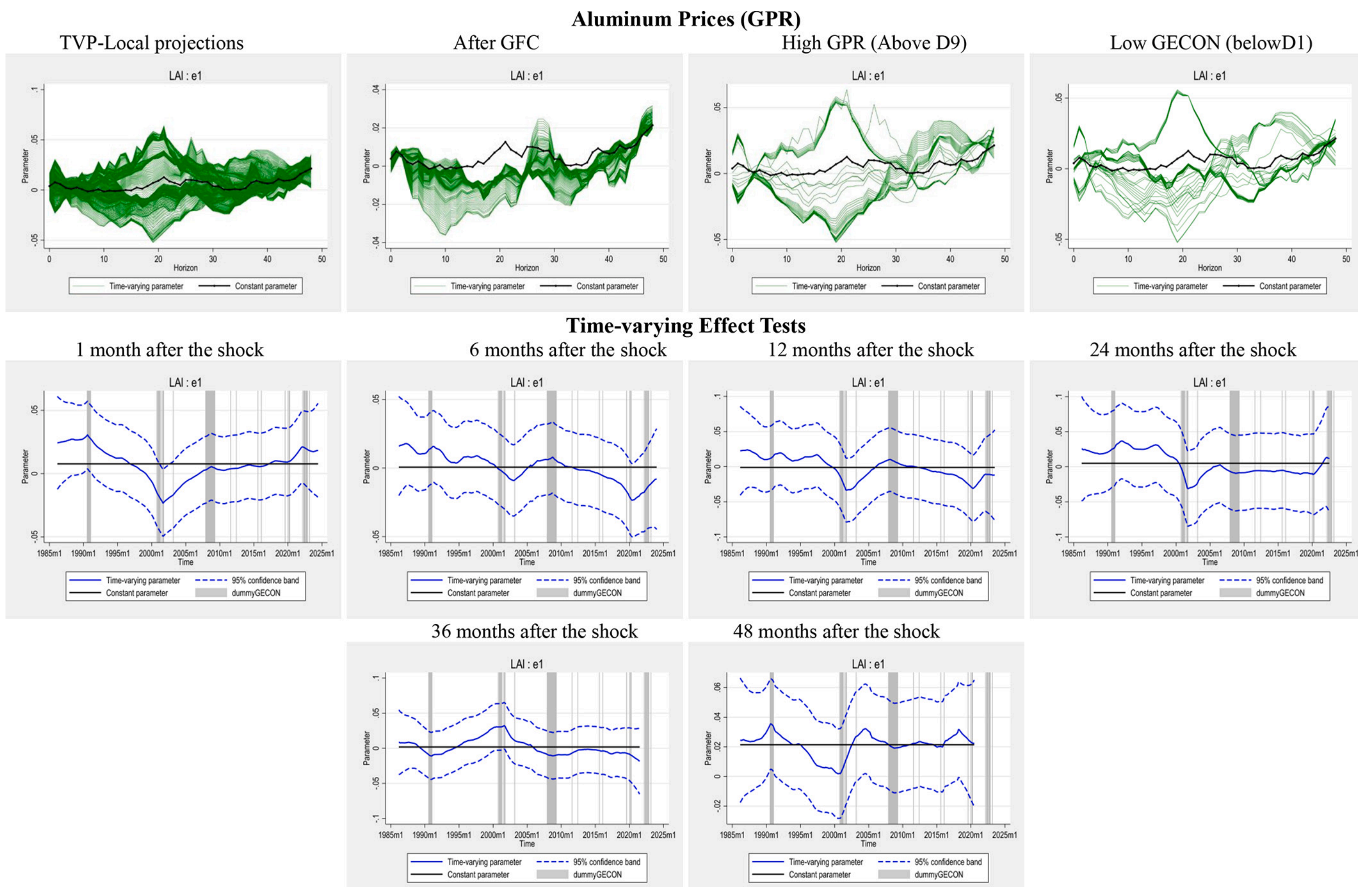
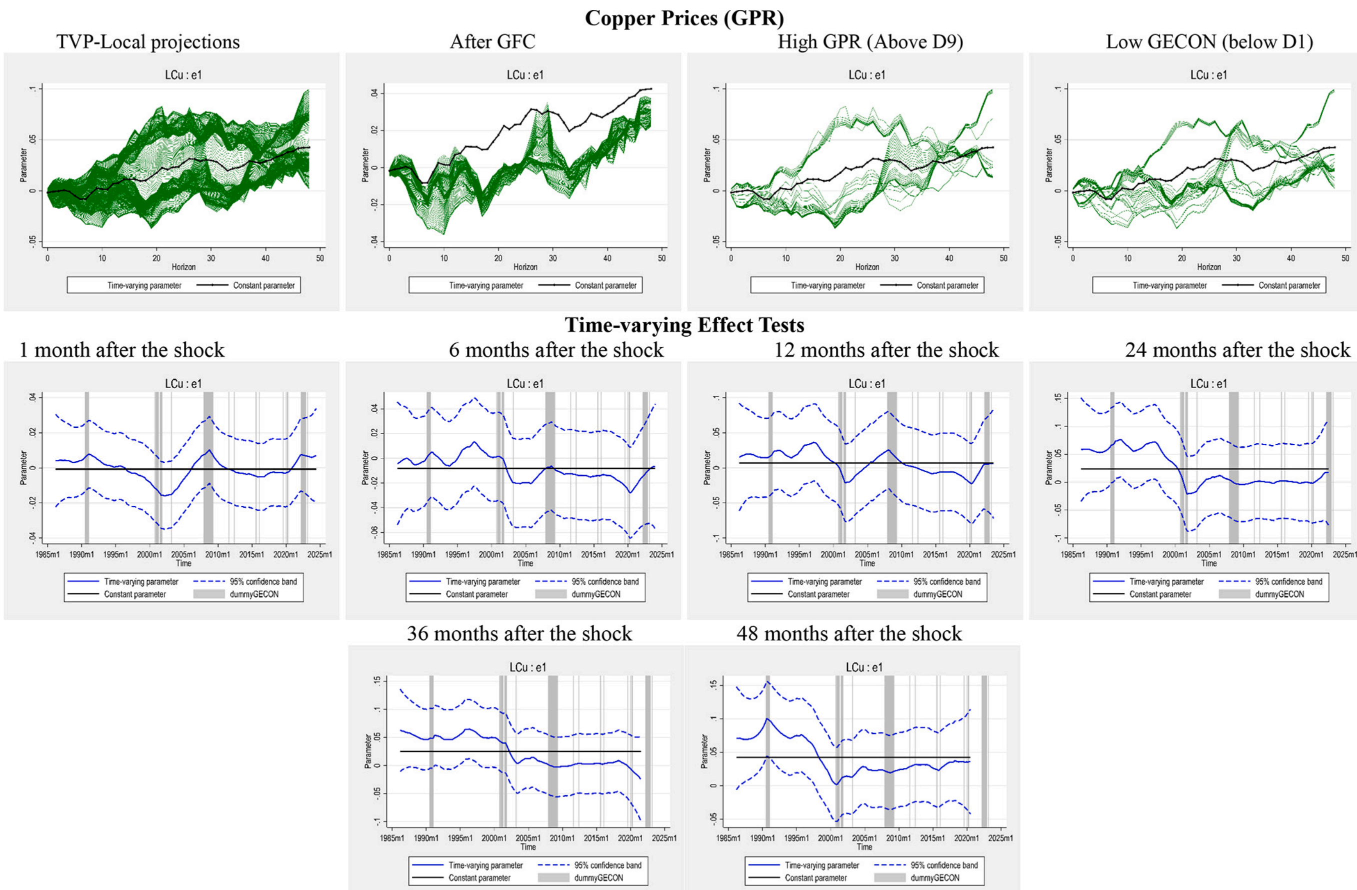


Fig. A2. The non-technical risk (best practices scores) and premiums of selected critical minerals (2023).

Appendix B. Robustness Analysis: Impulse responses of critical minerals to global geopolitical risk and instability analysis



Note: the first row and first column panel compare the TVP-LP estimates with the LP estimates for price elasticity of the critical mineral. The next three figures in the first row focused on different specific periods. The panels on the second and the third rows test the instability of IRF at different time horizons, when the interval formed by dotted lines does not include the zero line, then the IRF is statistically significant and time-varying effects are discovered.



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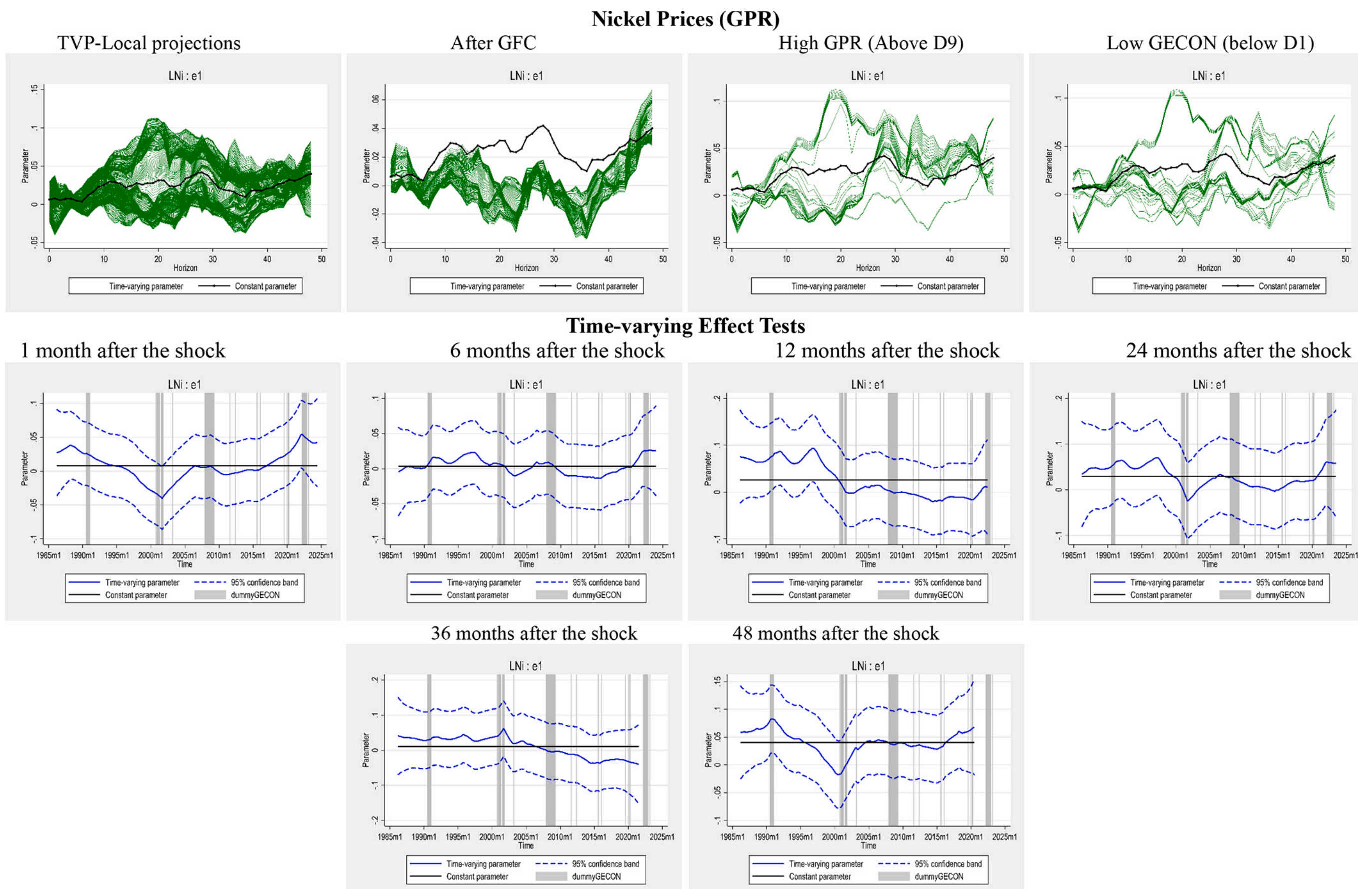
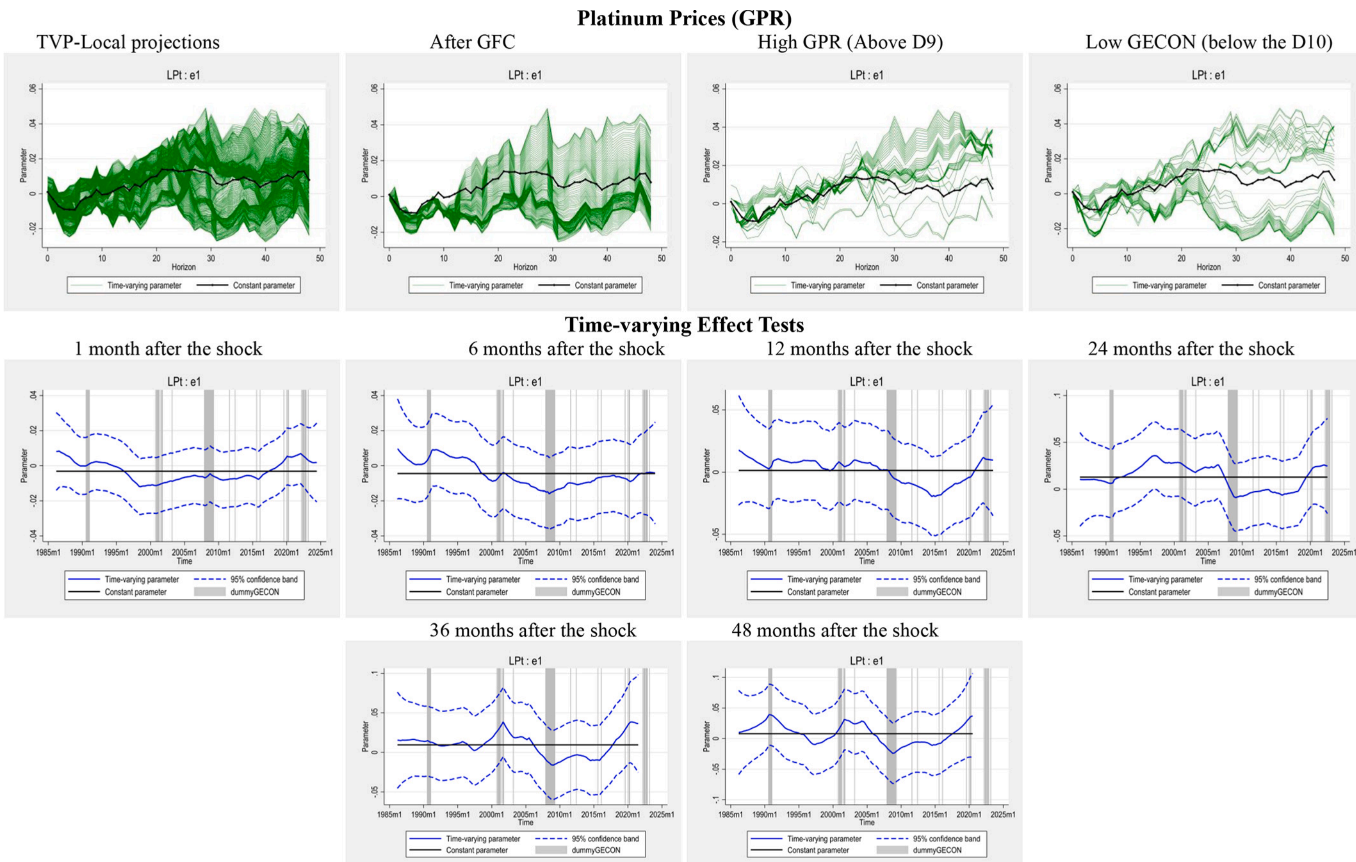

Nickel Prices (GPR)
TVP-Local projections
After GFC
High GPR (Above D9)
Low GECON (below D1)
LNi : e1
Parameter
Horizon
Time-varying parameter
Constant parameter
Time-varying Effect Tests
1 month after the shock
6 months after the shock
12 months after the shock
24 months after the shock
36 months after the shock
48 months after the shock
Time
95% confidence band
dummyGECON



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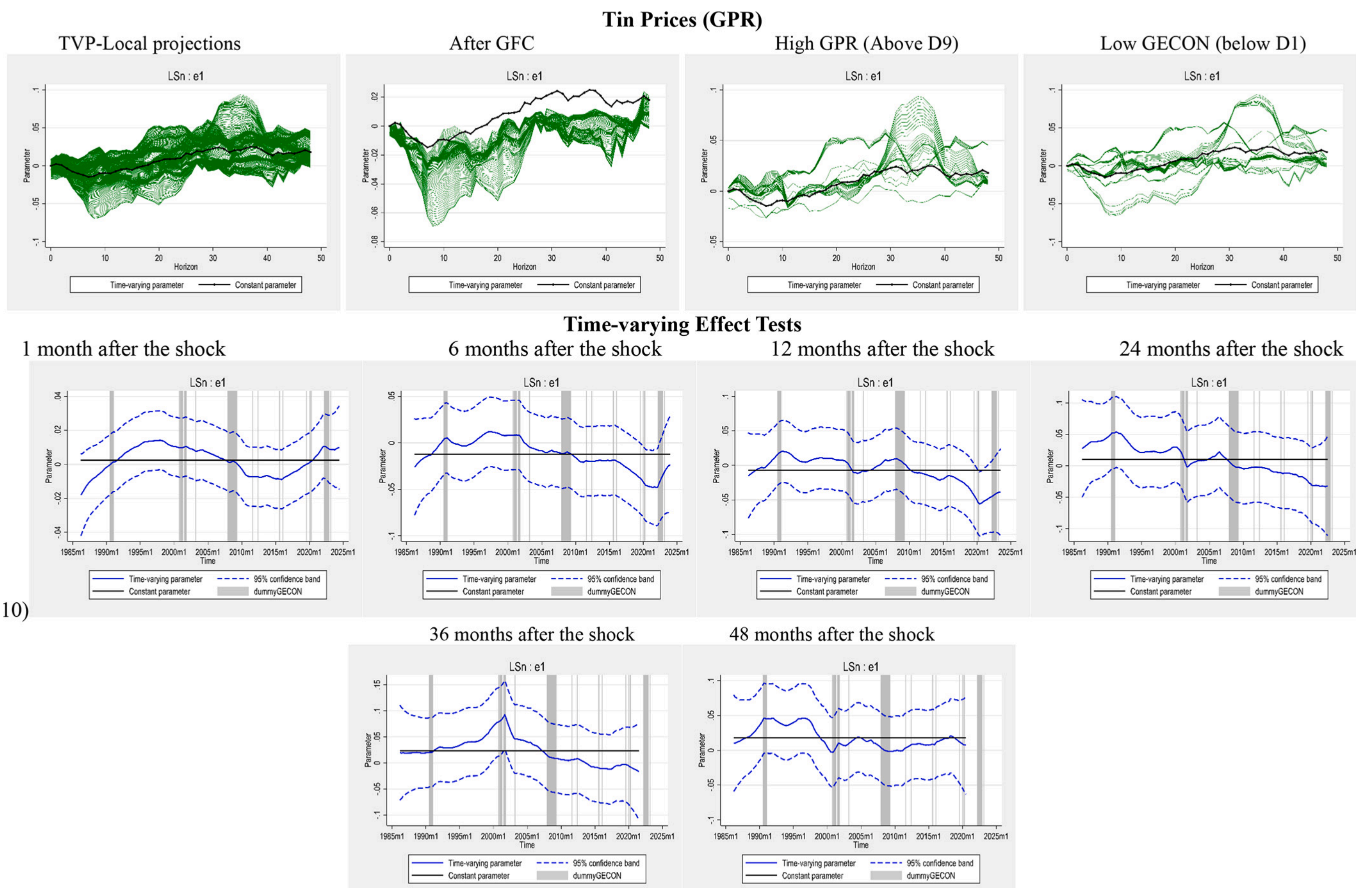

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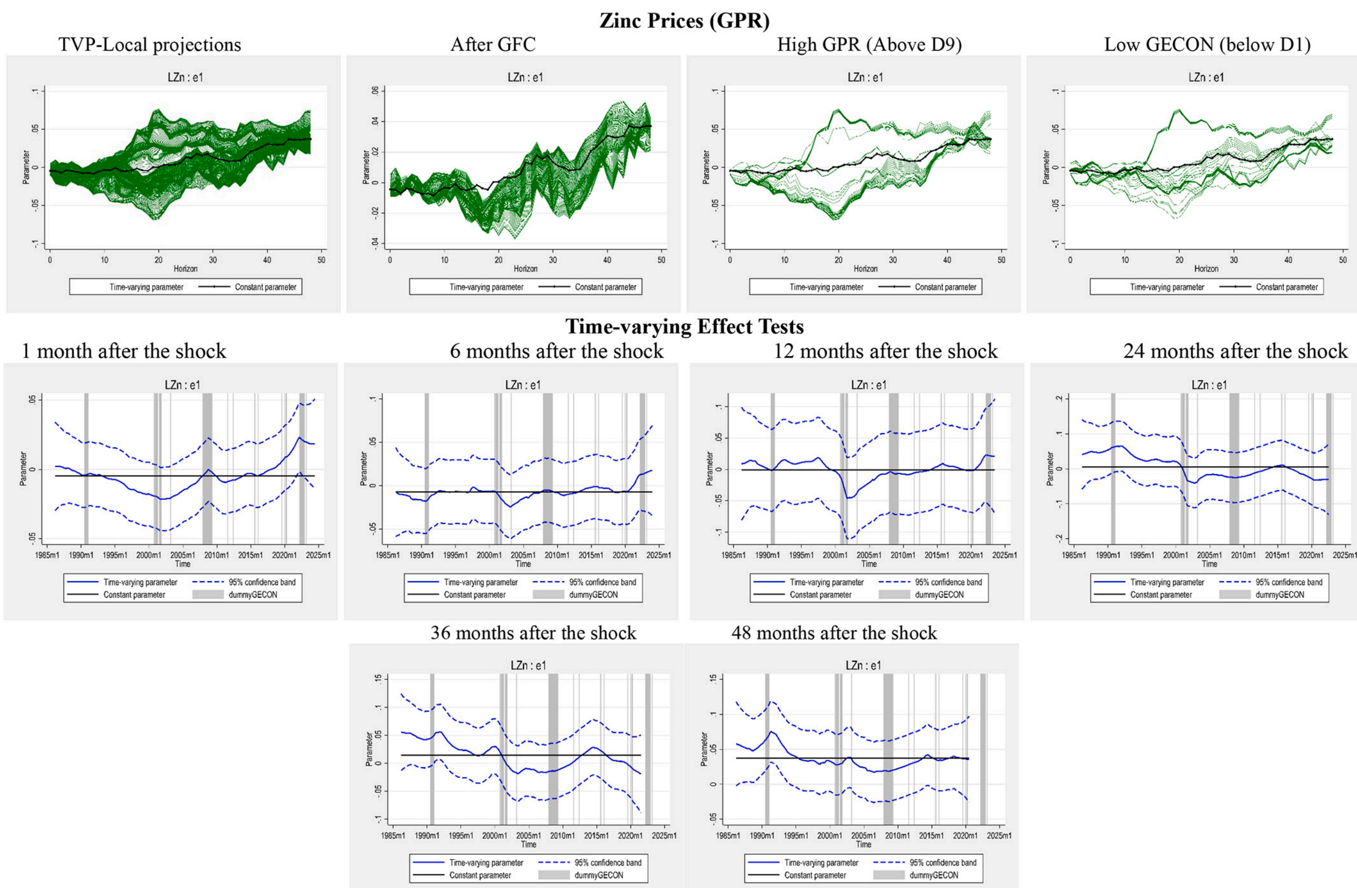

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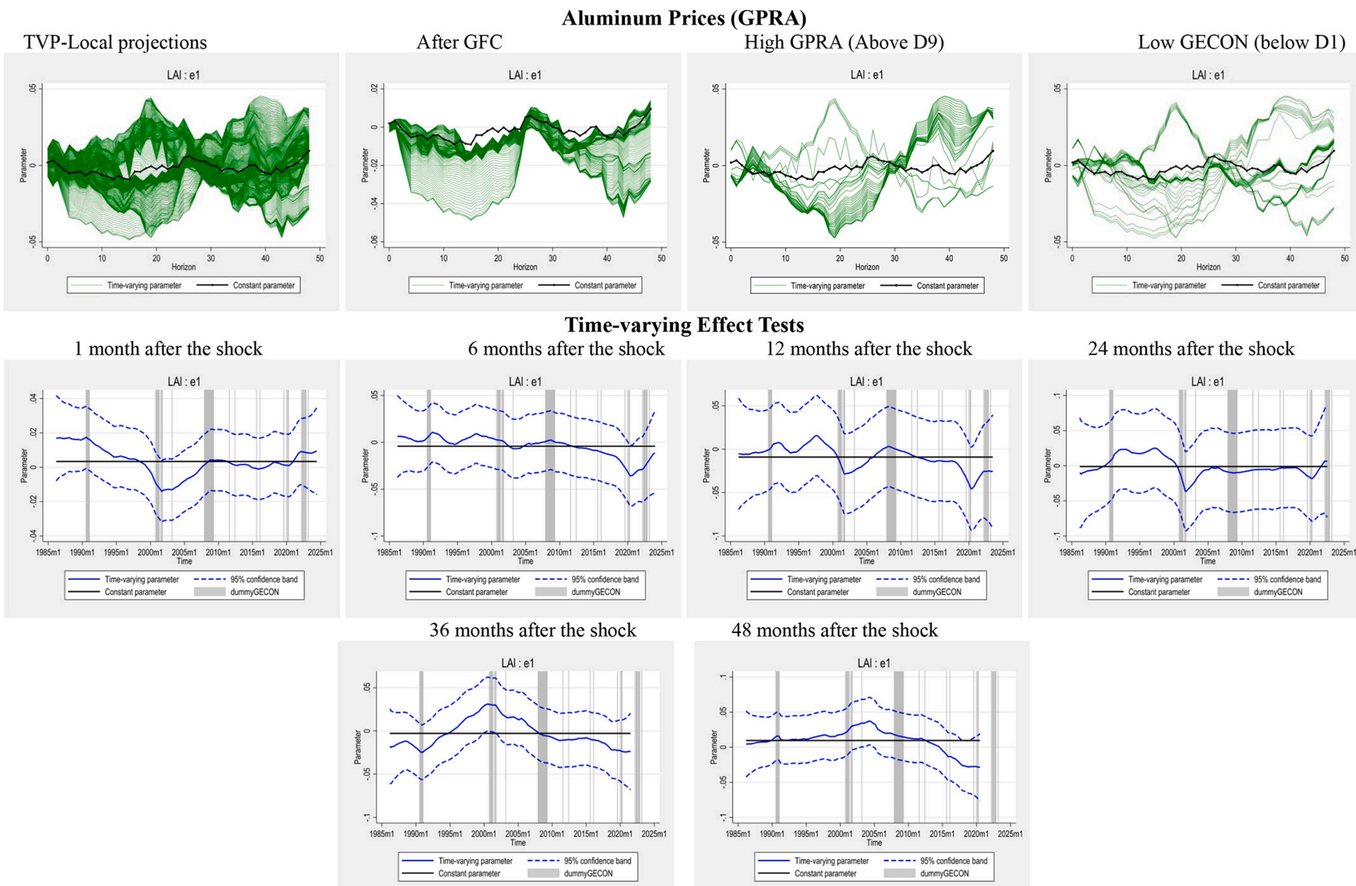

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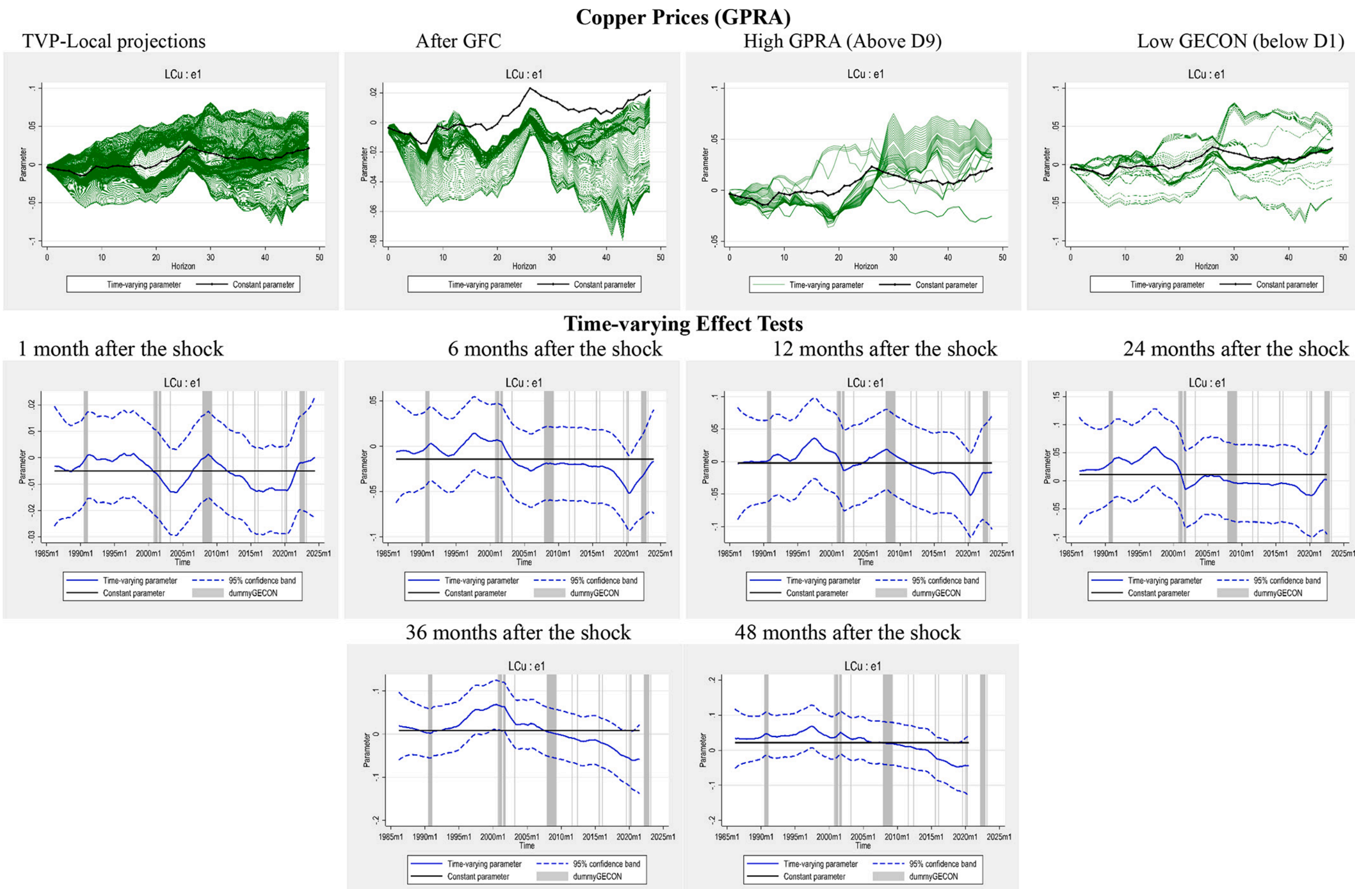
Appendix C. Robustness Analysis: Impulse responses of critical minerals to global geopolitical risk acts and time-varying analysis



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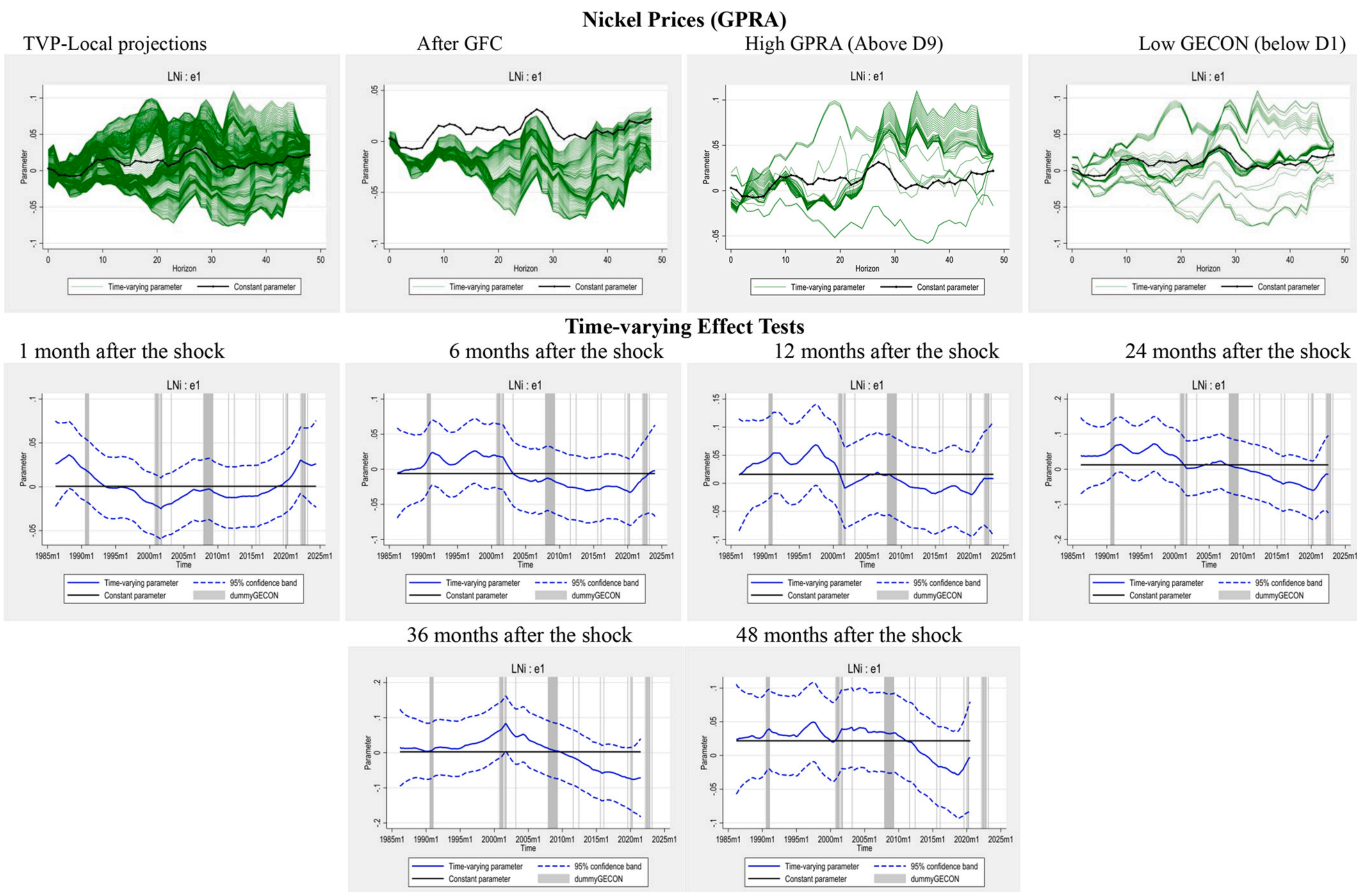

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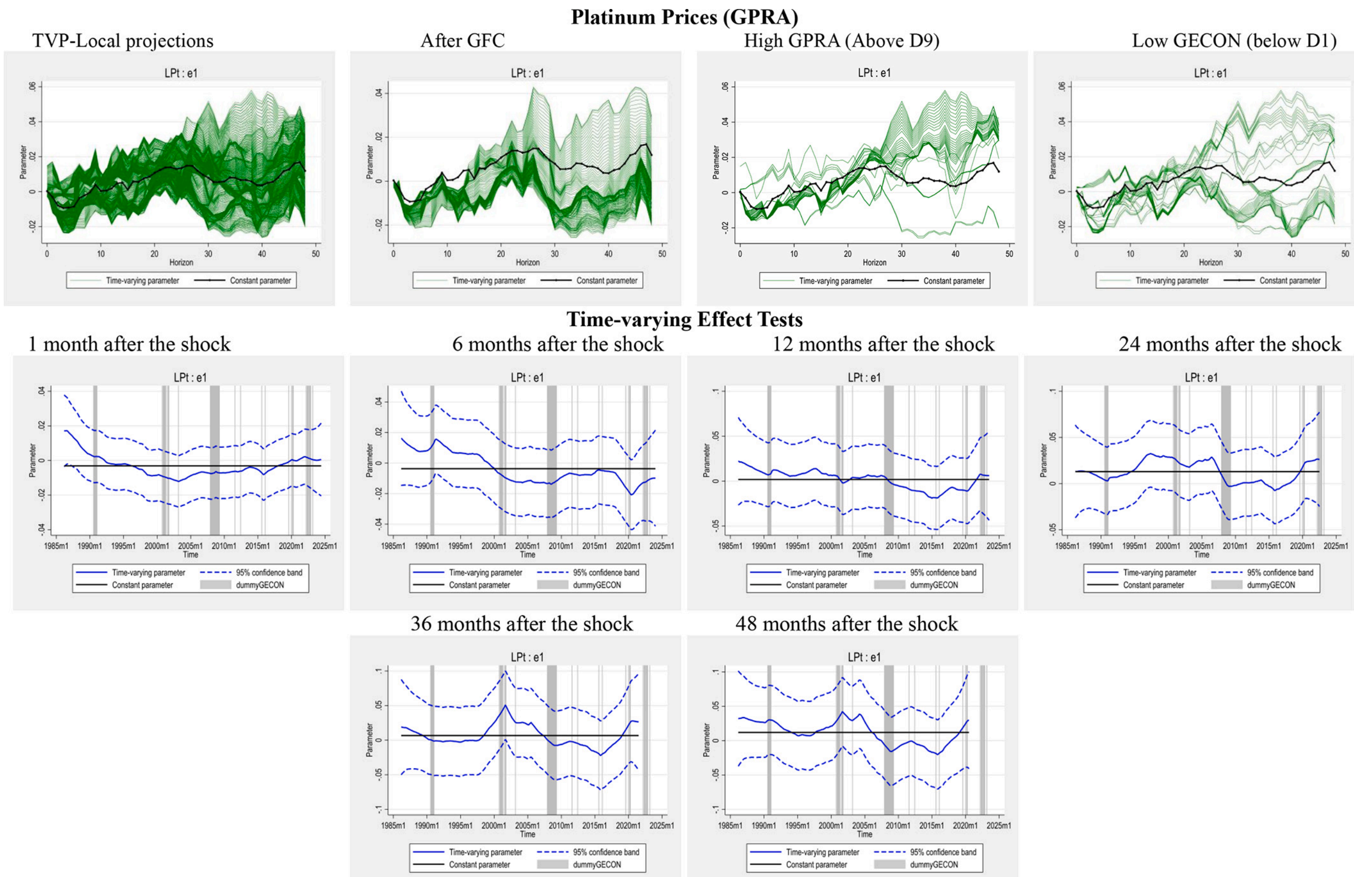

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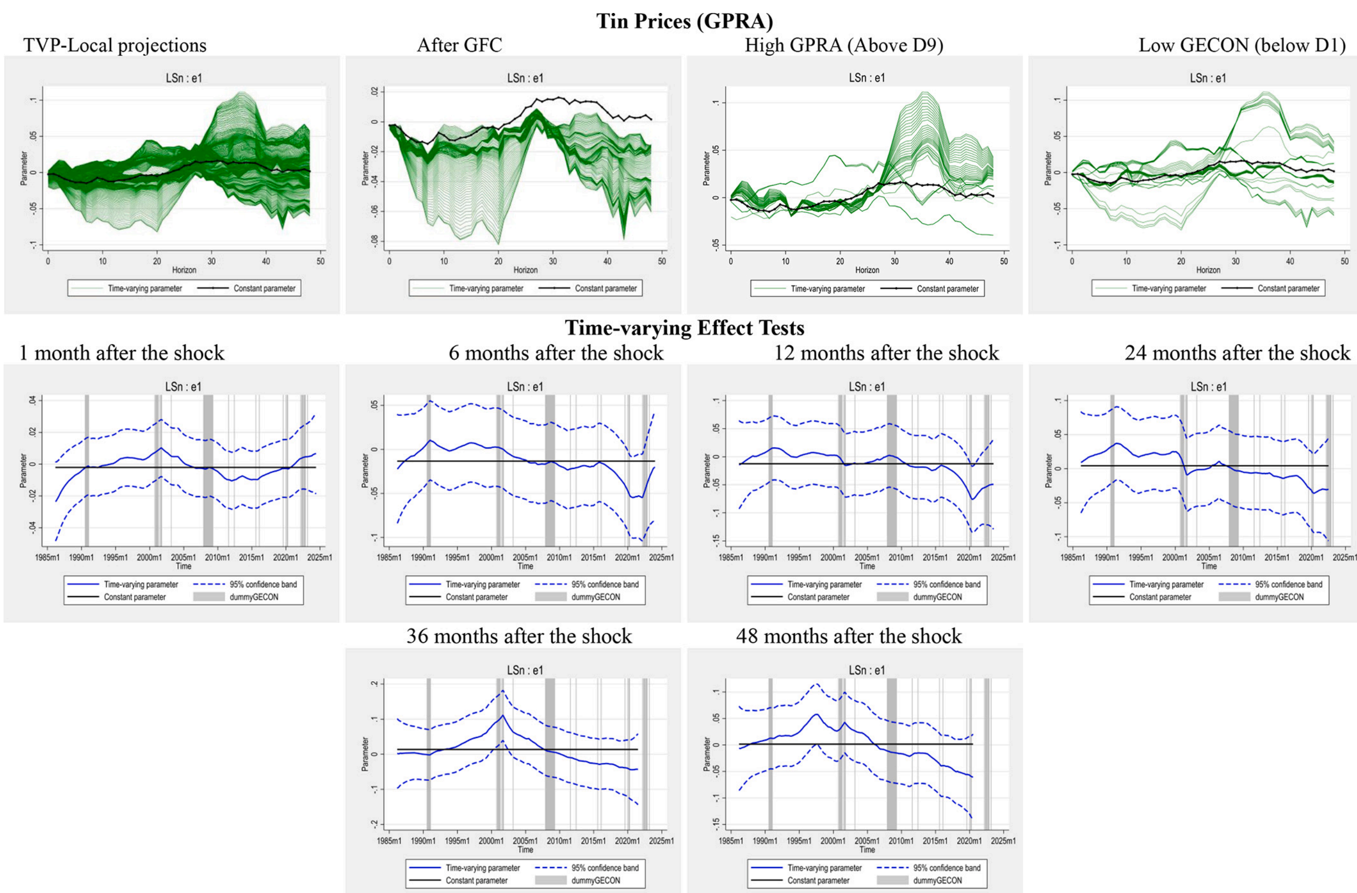

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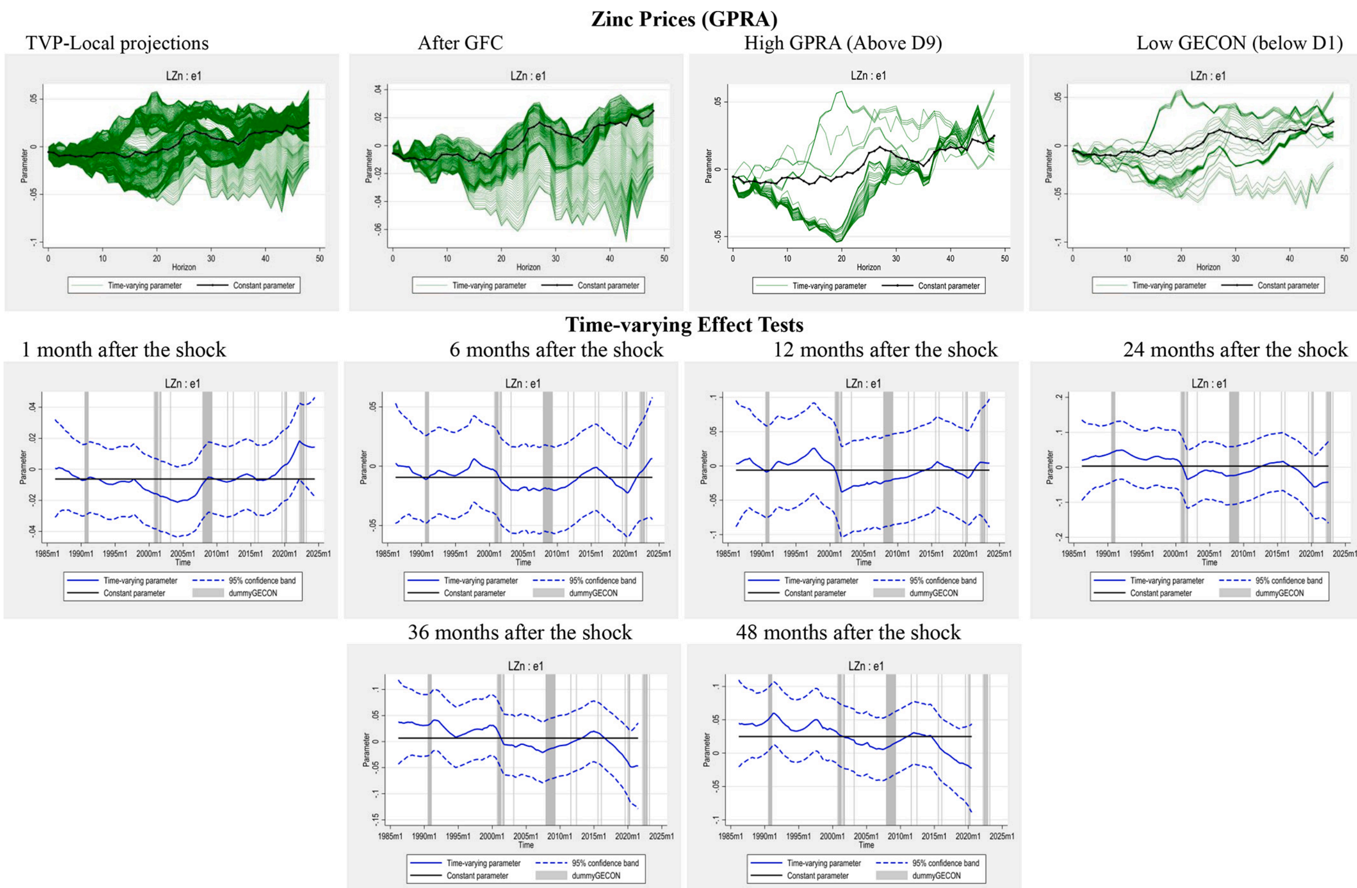

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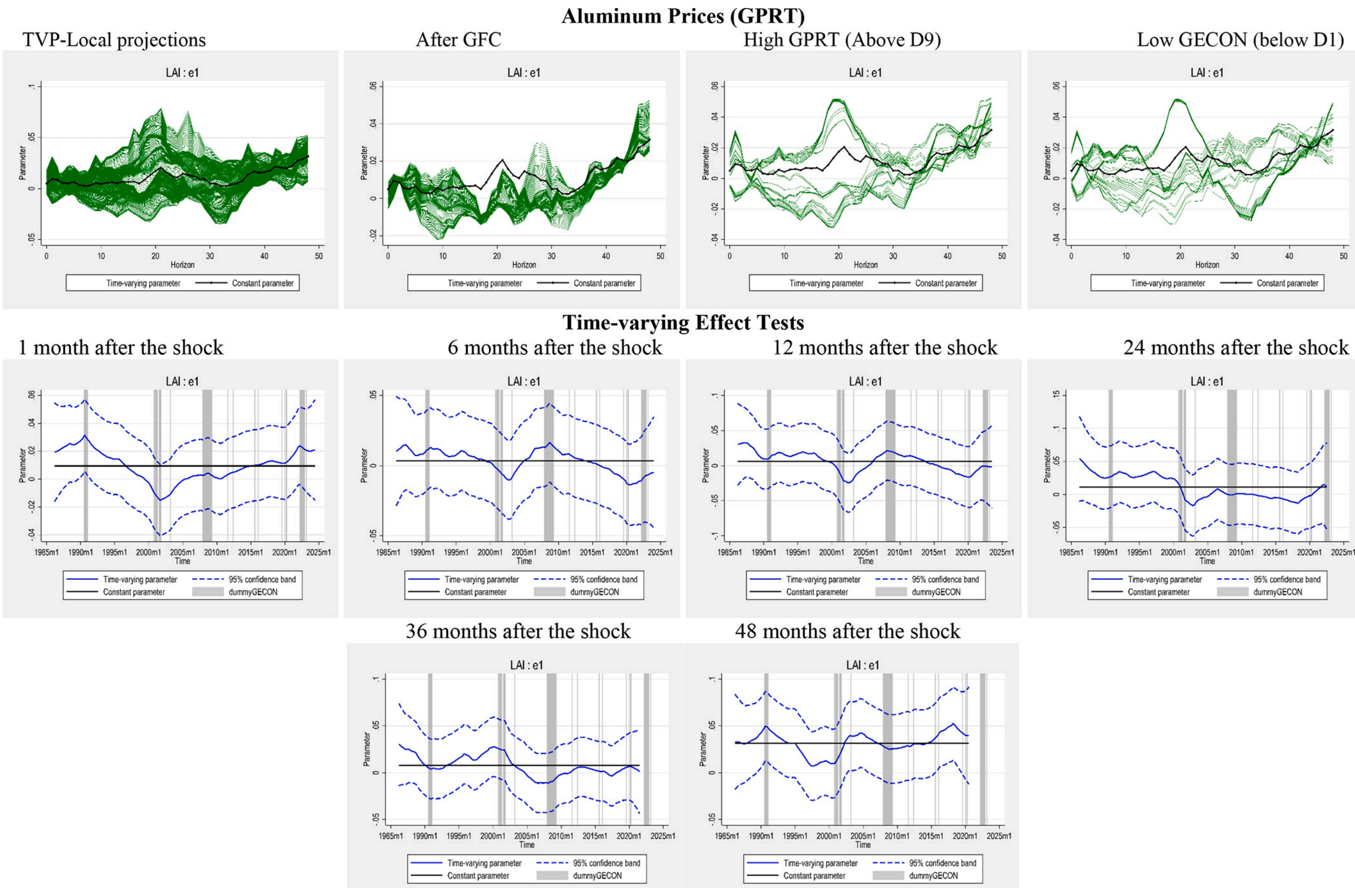
Appendix D. Robustness Analysis: Impulse responses of critical minerals to global geopolitical risk threats and time-varying analysis



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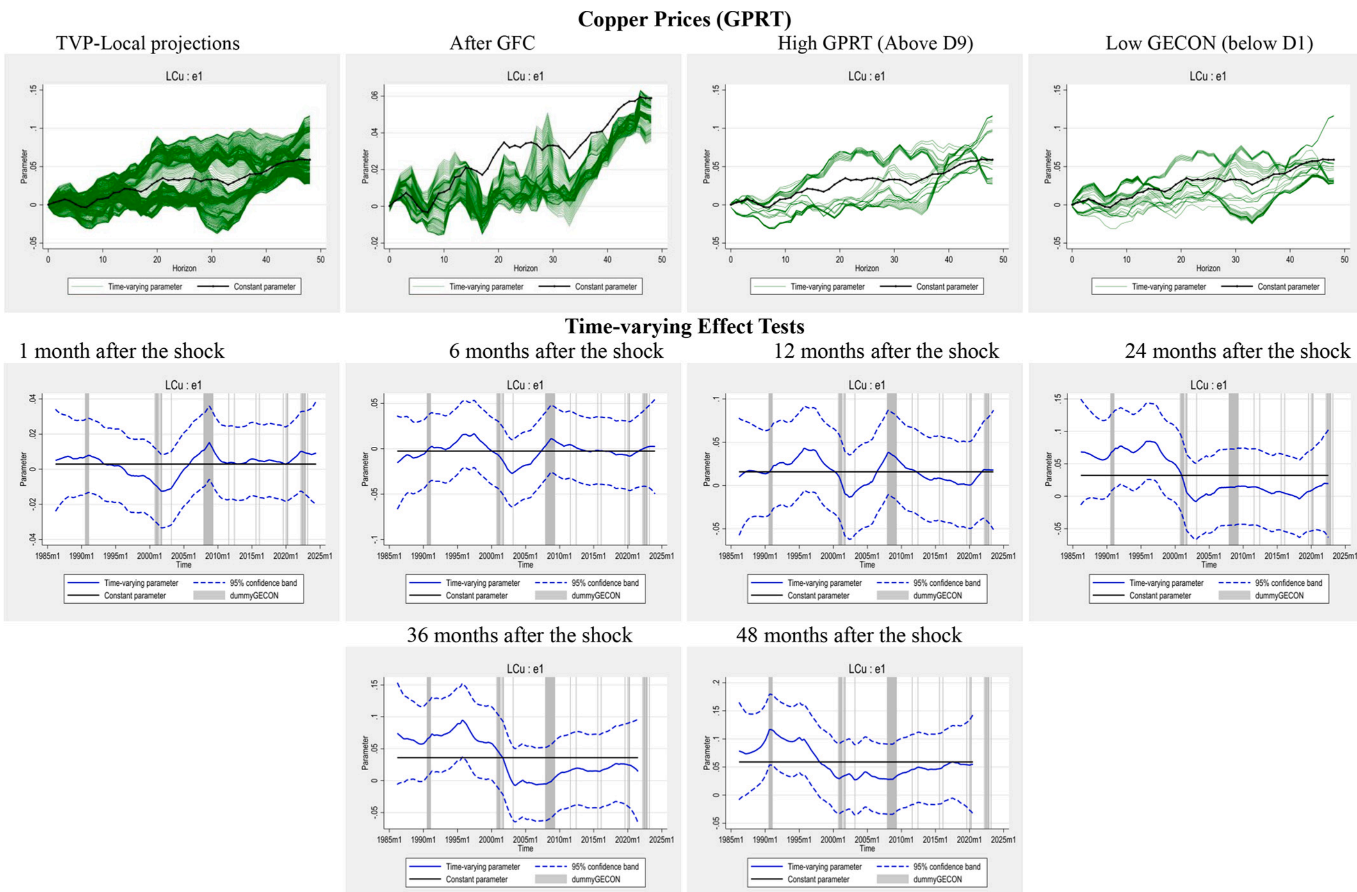

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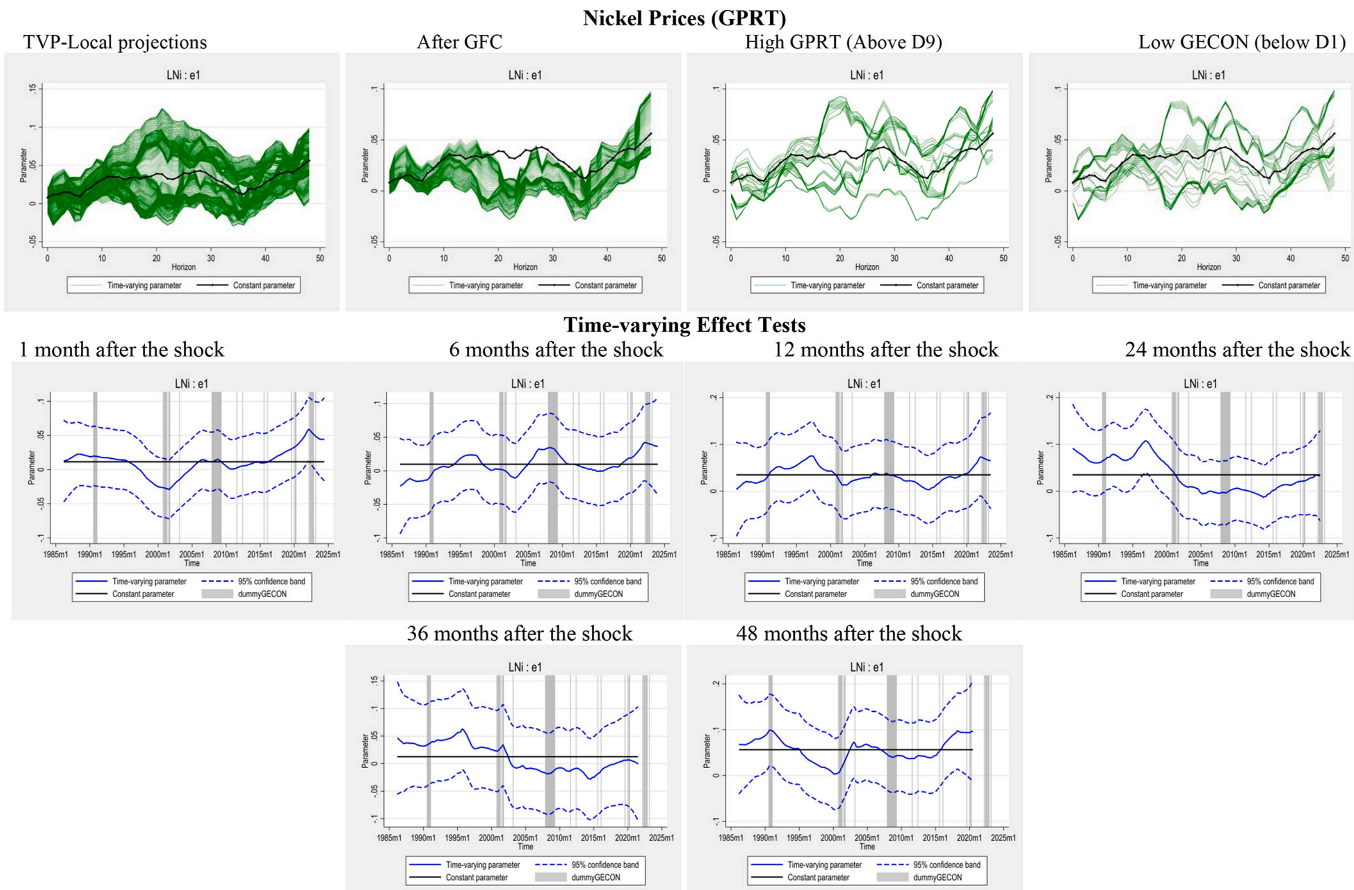
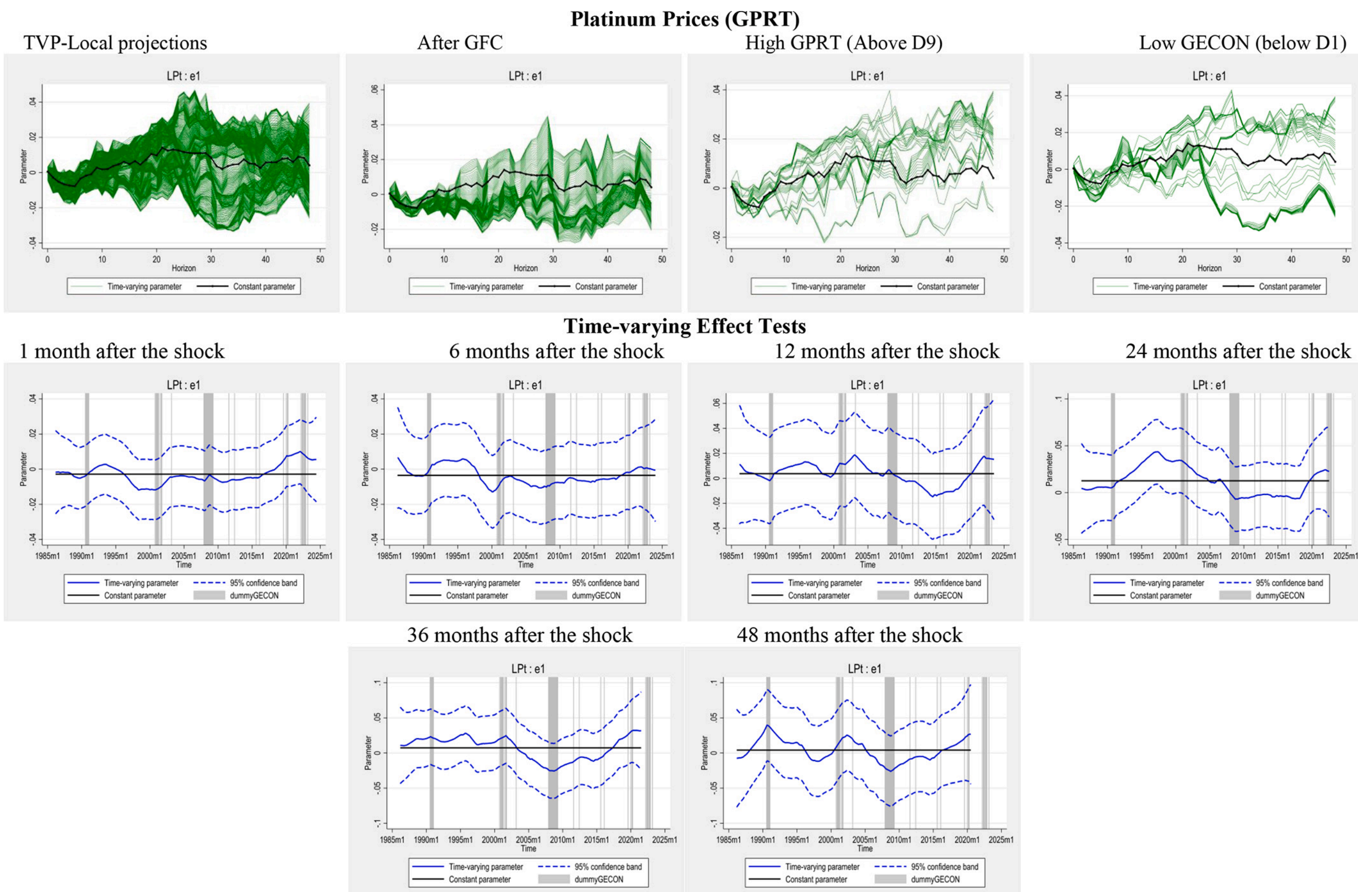
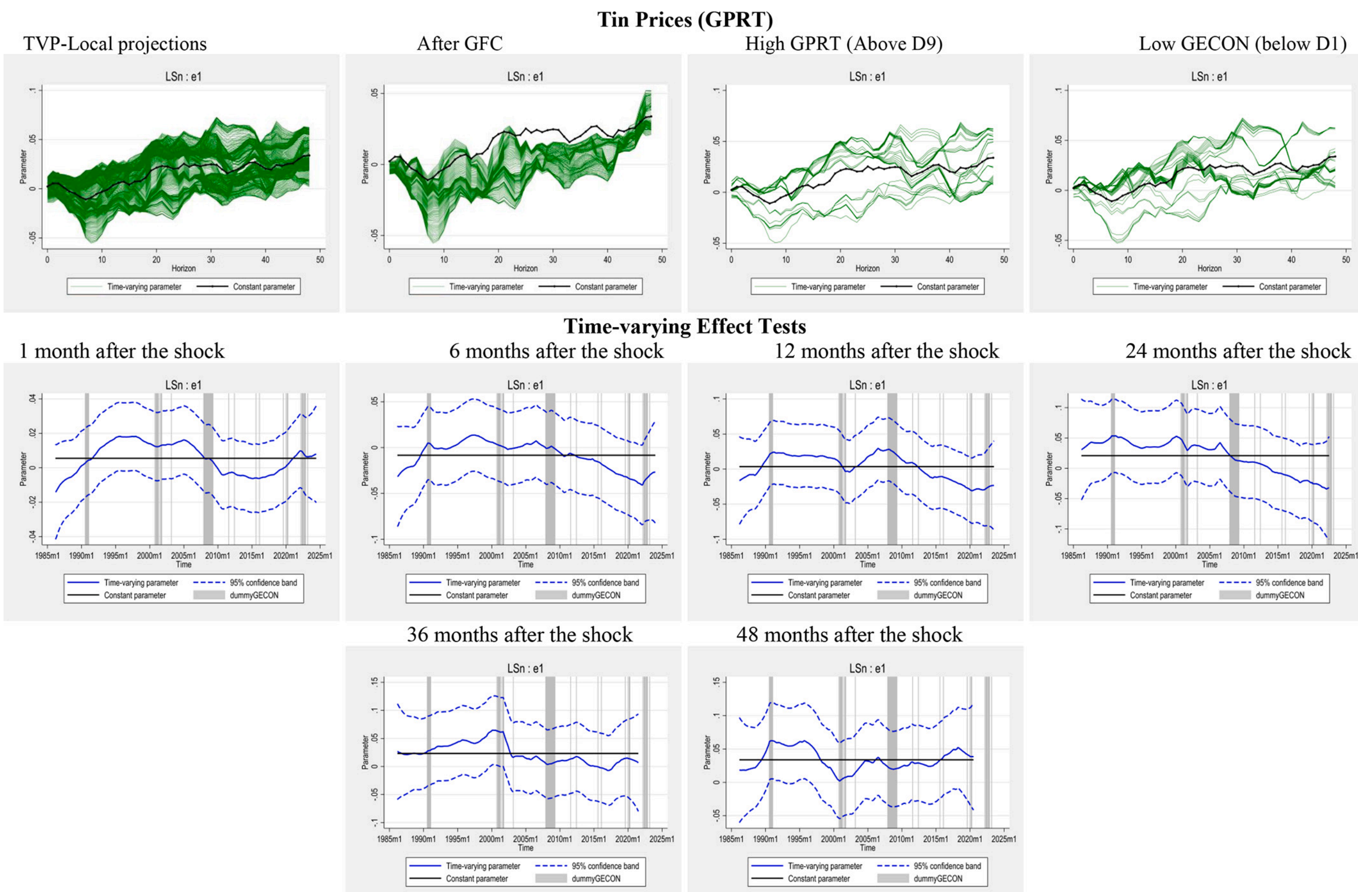


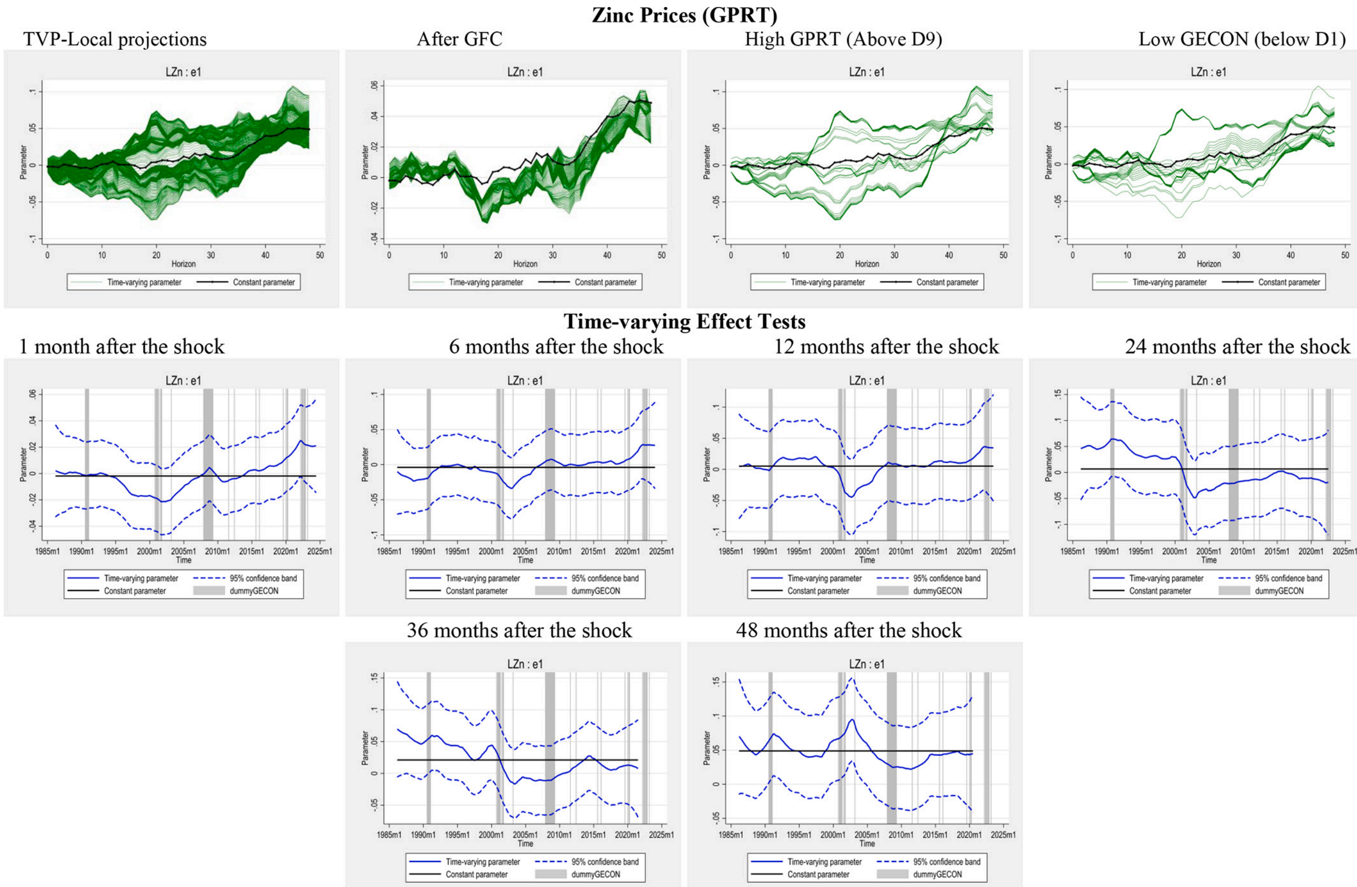
Note: the first row and first column panel compare the TVP-LP estimates with the LP estimates for price elasticity of the critical mineral. The next three figures in the first row focused on different specific periods. The panels on the second and the third rows test the instability of IRF at different time horizons, when the interval formed by dotted lines does not include the zero line, then the IRF is statistically significant and time-varying effects are discovered.



Note: the first row and first column panel compare the TVP-LP estimates with the LP estimates for price elasticity of the critical mineral. The next three figures in the first row focused on different specific periods. The panels on the second and the third rows test the instability of IRF at different time horizons, when the interval formed by dotted lines does not include the zero line, then the IRF is statistically significant and time-varying effects are discovered.



Note: the first row and first column panel compare the TVP-LP estimates with the LP estimates for the price elasticity of the critical mineral. The next three figures in the first row focus on different specific periods. The panels on the second and the third rows test the instability of IRF at different time horizons, when the interval formed by the dotted lines does not include the zero line, the IRF is statistically significant implying time-varying effects.



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Appendix E. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.eneco.2025.108195.

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