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This paper applies and extends the macroeconomic fragility framework for studying the effects of supply chain disruptions, proposed by Acemoglu and Tahbaz-Salehi (2024), to incorporate the role of stockpiling, which stabilizes critical mineral markets and reduce macroeconomic fragility. A key prediction of the macroeconomic fragility framework is that equilibrium supply chains are inherently fragile, meaning that even small shocks can trigger cascading supply chain breakdowns that can significantly magnify the discontinuous response of aggregate supply to shocks, leading to higher volatility and prices of critical minerals. We highlight the important role that the non-technical risk premium plays in magnifying global supply chain shocks in the specific case of critical minerals. Using a mixed-frequency Structural VAR model with agnostic sign restrictions and newly constructed data on non-technical risk premiums, we estimate the impact of supply chain disruption, the non-technical risk premium and their interaction on the prices and volatility of six critical minerals. We find that global supply chain disruptions, magnified by non-technical risk premiums, significantly increase critical mineral prices and price volatility for all six critical minerals studied, indicating inefficient outcomes which we interpret as macroeconomic fragility in critical minerals markets.

Keywords: Global Supply Chain Disruption, Critical Minerals, Non-technical Risk Premiums Macroeconomic Fragility

JEL Classification: F62, Q43, Q30

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The Macroeconomic Fragility of Critical Mineral Markets

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Abstract

This paper applies and extends the macroeconomic fragility framework for studying the effects of supply chain disruptions, proposed by Acemoglu and Tahbaz-Salehi (2024), to incorporate the role of stockpiling, which stabilizes critical mineral markets and reduce macroeconomic fragility. A key prediction of the macroeconomic fragility framework is that equilibrium supply chains are inherently fragile, meaning that even small shocks can trigger cascading supply chain breakdowns that can significantly magnify the discontinuous response of aggregate supply to shocks, leading to higher volatility and prices of critical minerals. We highlight the important role that the non-technical risk premium plays in magnifying global supply chain shocks in the specific case of critical minerals. Using a mixed-frequency Structural VAR model with agnostic sign restrictions and newly constructed data on non-technical risk premiums, we estimate the impact of supply chain disruption, the non-technical risk premium and their interaction on the prices and volatility of six critical minerals. We find that global supply chain disruptions, magnified by non-technical risk premiums, significantly increase critical mineral prices and price volatility for all six critical minerals studied, indicating inefficient outcomes which we interpret as macroeconomic fragility in critical minerals markets.

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1. Introduction

The global energy transition depends on the secure and sustainable supply of critical minerals, such as aluminium, copper, nickel, platinum, tin and zinc amongst others. According to the International Energy Agency (IEA, 2021), shortages in these critical inputs pose significant risks to achieving decarbonization targets, even under extended net-zero scenarios such as 2060–2070. Disruptions in critical mineral supply chains, driven by geopolitical, environmental and policy risks—collectively termed non-technical risks—can severely derail the deployment of clean energy technologies. These risks amplify supply chain fragility by increasing financial uncertainty, raising capital costs and limiting investment in critical mineral projects. It is estimated that over 80 per cent of the world's energy production must shift from fossil fuels to clean energy technologies, in order to realize carbon net zero objectives (IEA, 2023).

A key structural challenge in the clean energy transition is the disparity in development timelines between fossil fuel and critical mineral projects. As illustrated in Figure 1, fossil fuel projects such as gas, oil and coal have relatively short development cycles, taking on average two, three and four years, respectively. In contrast, critical minerals essential for clean energy technologies, such as copper, platinum, and nickel, require significantly longer lead times of 12, 11, and 10 years, respectively. Even critical minerals with simpler extraction processes, such as tin and zinc, take at least six years, which is longer than any fossil fuel project. This shift from short-term fossil fuel investments to long-duration mineral projects introduce new supply chain risks, capital costs and greater exposure to geopolitical disruptions, making strategic planning and risk mitigation crucial to ensure a stable energy transition.

Building on the work of Trench et al., (2014) and Trench and Park (2021), Vespignani and Smyth (2024) introduce a framework to estimate non-technical risk premiums for critical minerals. Non-technical risk premiums refer to the additional return that investors require to compensate for risks that are not directly related to the technical aspects of a project or investment in the mining of critical minerals. These premiums account for policy and regulatory uncertainties, geopolitical tensions and environmental risks, representing an additional risk factor compared to fossil fuel investments (Trench et al., 2014). Vespignani and Smyth (2024) argue that non-technical risk premiums are one of the most important obstacles for global decarbonization as neither government nor private companies have sufficiently invested in critical mineral project developments to the minimum level required for achieving net zero by 2050. A detailed explanation and decomposition of these risks is presented in Section 3.2 and in Appendix A.

In this paper, we extend the macroeconomic fragility framework for studying supply chain disruptions, recently proposed by Acemoglu and Tahbaz-Salehi (2024), to analyze the effects of global supply chain disruptions and non-technical risk premiums on critical mineral prices and volatility. According to Acemoglu and Tahbaz-Salehi (2024), supply chains are inherently fragile, where even minor shocks can lead to disproportionate disruptions in aggregate output and prices. In the context of critical minerals, this framework suggests that non-technical risk premiums magnify global supply chain disruptions by discouraging mining firms from adapting to disruptions through supplier diversification or capacity expansion. The result is lower supply availability, heightened price volatility and increased critical mineral cost of production. As non-technical risks rise, the production network becomes less adaptable and more prone to collapse under stress, raising the cost of project development and elevating the cost of capital, as investors demand higher returns to compensate for increased exposure to risk. We extend the macroeconomic fragility framework by showing how strategic stockpiling of critical minerals can mitigate the adverse effects of supply chain disruptions and non-technical risk premiums. By acting as a buffer against shocks, stockpiles reduce the likelihood of cascading network failures, stabilize supply, and lower the cost of maintaining supplier relationships. A formal extension of the model shows that sufficient reserves can offset rising risk exposure, preserving supplier links and maintaining aggregate productivity.

This research develops and tests three hypotheses through application of the macroeconomic fragility framework to critical mineral markets. The first hypothesis is that non-technical risk premiums (NTRP) and global supply chain disruptions (GSCD) directly increase the price volatility of critical minerals. Higher NTRP, driven by policy uncertainty, geopolitical risks and regulatory constraints, discourage investment and expansion in mining projects, leading to constrained supply and higher prices. Greater GSCD exacerbate supply shortages, amplifying cost-push inflation in critical mineral markets.

The second hypothesis is that NTRP magnifies the effect of GSCD on critical mineral price volatility. As firms face greater exposure to supply chain failures, reduced adaptability due to high NTRP increases the persistence and severity of price shocks. This leads to heightened uncertainty, prompting investors to demand higher returns, further increasing the cost of capital for critical mineral projects. The interaction of NTRP and GSCD leads to greater supply chain fragility, increasing the risk of prolonged price shocks and project delays. When NTRP are high, mining firms are less likely to mitigate disruptions through alternative suppliers or capacity expansion, making supply networks more vulnerable to external shocks, generating prolonged periods of elevated prices and volatility and further destabilizing critical mineral markets.

Our third hypothesis is that the combined effects of NTRP and GSCD are different on the price and volatility of individual critical minerals from one episode to the next, because the interaction shocks historically have been driven by varying combinations of innovations in NTRP and GSCD at different points in time. We argue that the relative importance of any one-time shock in the critical mineral market for price and price volatility tends to vary over time. Clearly, over the course of the COVID-19 pandemic from 2020 to 2022, when shocks to GSCD were more prevalent, their effects are expected to dominate the average responses to the price and volatility increases estimated for that period.

To test these hypotheses, we employ a mixed-frequency Structural Vector Autoregression (VAR) model with agnostic sign restrictions to examine the effect of NTRP and GSCD on the prices of aluminium, copper, nickel, platinum tin and zinc.[1] Our results indicate that GSCD and NTRP contribute directly to higher price volatility and that NTRP magnify the positive effect of GSCD on price volatility, leading to higher prices across the six critical minerals. In speculative asset markets, such as commodities, as price volatility rises, prices also sharply increase, potentially raising the cost of capital due to increased valuation uncertainty. Furthermore, both factors exhibit a statistically significant positive effect on critical mineral prices, reinforcing the role of supply chain fragility in shaping mineral markets. We find evidence that the relative importance of any one-time shock in the critical mineral market for price and price volatility varies over time, which is consistent with our third hypothesis.

This research contributes to multiple strands of literature by integrating the macroeconomic fragility framework with studies on critical mineral supply chains, price volatility and risk assessment. First, it

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[1] Monthly data for these critical minerals are available from the World Bank Commodity Markets. For other important critical minerals, such as lithium or cobalt, data are not available for the full period examined.

extends understanding of critical mineral price dynamics, particularly in response to geopolitical risks and supply chain fragility (Aloui et al, 2023; Gao et al 2024; Irawan and Okimoto, 2021; Khurshid et al 2023, 2024; Mandaci et al, 2023; Pata et al, 2024; Saadaoui et al, 2025; Shao et al, 2024; Wang et al, 2023; Zhang et al, 2024; Zhao, 2023). Second, it contributes to the literature on supply chain disruptions in critical mineral markets (Dou et al 2023; Dou & Xu, 2023; Durr & Dreiska 2023; Fattahi, 2021; Leruth et al 2023; Locmelis et al 2023; Majkut et al 2023; Sauer & Seuring 2017; Shao et al 2023; van den Brink et al 2019; 2020; Vekasi 2023; Vivoda, 2023; Vivoda & Matthews 2023). Third, it adds to research on project development, the cost of capital and non-technical risks in mining projects (Tufano, 1998; Trench et al., 2014; Humphreys, 2019; Trench & Park, 2021; Vespignani & Smyth, 2024; Fry-Mckibbin et al., 2025; Trench & Skykes, 2025).

The paper proceeds as follows: Section 2 outlines the conceptual framework. Section 3 describes the data and methodology used to examine the effect of NTRP, GSCD and their interaction on price volatility. Section 4 presents our results, while Section 5 discusses policy recommendations. Section 6 concludes.

2. Conceptual Framework

Modern supply chains rely on relationship-specific investments, where firms establish specialized links with suppliers to achieve productivity gains, but these relationships are costly to maintain or replace (Acemoglu & Tahbaz-Salehi, 2024). GSCD distort these links through delays, shortages and logistical bottlenecks, while a high NTRP exacerbates these challenges by amplifying the cost of maintaining or replacing them. NTRP reflect geopolitical risks, regulatory uncertainties and environmental risks which heighten supply disruptions and price volatility in critical mineral markets. Geopolitical threats, policy uncertainty and regulatory changes have a disproportionate effect on critical minerals, where market sensitivity to perceived risks often exceeds the actual impact of geopolitical events (Saadaoui et al., 2025). Inflation risk premiums further compound uncertainty, as inflation volatility increases required returns, adding another layer of unpredictability to pricing (Camba-Méndez & Werner, 2017).

Commodity price fluctuations increase investment risk and capital costs for mining firms. The shift to spot pricing has intensified market volatility, straining financial stability (Humphreys, 2019), while price swings affect stock price exposure, limiting access to lower-cost funding (Tufano, 1998). Consequently, rising financial risk, borrowing costs and uncertainty about expected uncertainty combine to drive up the cost of capital for project developments, contributing to cost-push inflation in critical mineral markets.

Formally, consider the following application of the macroeconomic fragility model to critical minerals markets. In this model, efficient aggregate output is continuous and maximized by solving:

$$Y^{eff} = \max_{G} \left(A(G)L \; - \; \Sigma_{i,j} G \; \in \left(c_{ij} + \; s_{ij} \right) \right). \tag{1}$$

G is the production network (a set of supplier-customer relationships). A(G) is aggregate productivity as a function of G; c_{ij} is the fixed cost for mining firm i to form a relationship with supplier j; and s_{ij} is the variable cost of maintaining that relationship, which increases with the NTRP and GSCD. L is the total labor supply at the equilibrium output Y^{eff}.

In equilibrium, firms form relationships only if the private benefit exceeds the cost:

$$\Delta\pi_{i(G \cup \{ij\})} - \Delta\pi_{i(G)} \geq \; c_{ij} + \; s_{ij} \; . \tag{2}$$

$\Delta\pi_i$ is the change in firm i's profit from forming a link with j. Let $s_{ij} = \; f(NTRP, GSCD \;),$ where $\frac{\partial f}{\partial NTRP} > 0 \; and \, \frac{\partial f}{\partial GSCD} > \; 0$. This denotes that the cost of production is an increasing function of GSCD and NTRP. The interaction term is $\frac{\partial^2 f}{\partial NTRP \partial GSCD} > \; 0$, implying that the combined effect of GSCD and NTRP on s_{ij} is greater than their individual effects. In equilibrium, firms dissolve links when costs exceed private benefits:

$$s_{ij} > \; \Delta\pi_i(G \; \cup \; \{ij\}) - \; \Delta\pi_{i(G)} \; . \tag{3}$$

As GSCD and NTRP increase, s_{ij} rises, leading to a critical threshold $s_{ij} *$ beyond which relationships dissolve:

$$Y^{eq}(s_{ij}) = \; f(x) = \begin{cases} A(G)L \; - \; s_{ij}, & if \; s_{ij} \; \leq \; s_{ij} \, *, \\ A(G/\{ij\}L, & if \; s_{ij} > \; s_{ij} \, *. \end{cases} \tag{4}$$

The discontinuity arises because Y^{eq} drops sharply when $s_{ij} > \; s_{ij}*$. The network effect amplifies the impact of dissolved relationships. If the link ij is severed: $A(G) \rightarrow \; A(G \;\; \{ij\})$, where $A(G \;\; \{ij\}) \; < \; A(G)$

due to the loss of productivity spillovers. If NTRP and GSCD are high, multiple links dissolve simultaneously, leading to cascading failures:

$$A(G) \rightarrow A(G'), \quad where\ G' \subset G\ and\ |G'| \ll |G|\,. \tag{5}$$

The mathematical representation shows that when the interaction term $\frac{\partial^2 f}{\partial NTRP \partial GSCD} > 0$, s_{ij} is amplified, resulting in a higher likelihood of relationship severance, cascading network breakdowns and discontinuous output drops, leading to an increase in the price of critical minerals.

2.1 Stockpiling as a strategic solution to mitigate the impact of macroeconomic fragility on critical minerals

Gorton et al. (2013) argue that commodity spot price volatilities reflect the state of inventories and are informative about commodity futures risk premiums. They suggest that stockpiling inventories can reduce the price volatility of critical minerals. The mechanism through which stockpiles reduce price volatility operates through several interconnected channels, primarily related to supply stabilization, speculative behavior and market expectations. First, inventories act as a buffer against supply shocks. When there is a sudden disruption in production (e.g. GSCD and NTRP)—whether due to geopolitical conflicts, natural disasters or technical failures—stockpiles can be released into the market to compensate for the shortfall. This prevents sudden spikes in prices by ensuring a steady flow of supply. In the context of oil, gas and coal commodities, stockpiles help moderate speculative pressures. Traders and market participants closely monitor inventory levels to gauge future supply conditions. When strategic petroleum reserves (SPR) or commercial inventories are adequately stocked, market speculation about future shortages diminish, reducing the risk of exaggerated price swings driven by panic buying or hoarding. Conversely, when inventories are low, speculators may anticipate tighter supply conditions and drive prices up through aggressive trading.

Empirical research suggests that oil stockpiles play a crucial role in stabilizing prices in the oil market. Pindyck (2004) discusses how oil inventories help hedge against price fluctuations by mitigating supply and demand shocks, thereby reducing volatility. Similarly, Liu et al. (2021) find that incorporating SPR into energy policies enhances crude oil market stability by minimizing welfare losses associated with energy price volatility. Relatedly, Baumeister and Kilian (2016) explore how the demand for above-ground oil inventories influences price movements, showing that strategic stockpiles help cushion markets from price shocks by regulating supply flows. Kilian and Lee (2014) further analyze the relationship between global oil inventories and speculative price fluctuations, suggesting that changes in stockpiles can moderate speculative pressures, thus reducing extreme price volatility. These studies indicate that both commercial and strategic oil stockpiles act as buffers against sudden changes in supply and demand, contributing to greater price stability in global oil markets.

We argue that stockpiles can equally reduce macroeconomic fragility in critical mineral markets by mitigating supply chain disruptions, lowering geopolitical risk sensitivity and stabilizing prices, thus addressing the core mechanisms outlined in Acemoglu and Tahbaz-Salehi's (2024) model. In this framework, GSCD and NTRP increase the cost of maintaining supplier relationships, denoted as $s_{ij} = f(NTRP, GSCD)$, where both factors positively contribute to rising costs. A key insight from the model is that the interaction term $\frac{\partial^2 f}{\partial NTRP \partial GSCD} > 0$, which magnifies instability, meaning that the combined effect of geopolitical and supply chain risks exceeds their individual impacts. This leads to severance of supplier relationships, a sharp drop in aggregate productivity A(G), and a cascade of broken links in the production network G, resulting in price spikes and supply shortages. Stockpiles act as a stabilizing buffer by lowering s_{ij} through supply-side adjustments. By providing an alternative source of critical minerals during GSCD-induced shortages, stockpiles reduce firms' dependence on fragile supplier relationships. This directly decreases the probability that costs exceed private benefits in Equation (3), preventing widespread dissolution of supplier links. Mathematically, maintaining reserves flattens the response function f(x), mitigating the discontinuous drop in equilibrium output Y_{eq} at the threshold $s_{ij}*$, thereby reducing cascading failures.

Formally, Let R denote the level of stockpiled reserves for a given critical mineral. We now extend the cost function to include the stabilizing effect of stockpiling:

$$s_{ij}(R) = f(NTRP, GSCD) - g(R) \tag{6}$$

Where $g(R)$ is an increasing and concave function of R, implying stockpiling reduces supplier link costs but with diminishing marginal returns, formally: $dg/dR > 0, d^2g/dR^2 < 0$.

We model the dampening effect of stockpiles with a logarithmic functional form:

$$s_{ij}(R) = f(NTRP, GSCD) - \gamma log(1 + R), \gamma > 0 \qquad (7)$$

The severance threshold condition becomes:

$$s_{ij}(R) \leq \Delta\pi_i(G \cup ij) - \Delta\pi_i(G) \qquad (8)$$

Hence, when R is sufficiently high, s_{ij} is reduced below the threshold, preserving the supplier link and preventing cascading failures. Since supplier links are preserved, aggregate productivity A(G) remains intact, and output stays continuous:

$$Y_eq(R) = A(G)L - s_{ij}(R) \qquad (9)$$

The marginal benefit of stockpiling on output is positive and decreasing:

$$dY_eq/dR = \gamma/(1 + R) > 0 \qquad (10)$$

Intuitively, stockpiles counteract the inflation risk premium and market volatility. When firms face uncertain costs due to price swings, capital expenditure becomes more expensive, raising the cost of capital and constraining investment in new projects, as described by Humphreys (2019) and Tufano (1998). By ensuring price stability, stockpiles reduce uncertainty, stabilizing required returns and mitigating the amplification effects of price volatility on financial risk. From a geopolitical perspective, stockpiles lower the sensitivity of critical mineral markets to policy shocks, reducing the market's overreaction to geopolitical threats, as described by Saadaoui et al. (2025). When strategic reserves are available, the market perceives lower risk, decreasing speculative price surges linked to NTRP fluctuations.

3. Data and Methodology

3.1 Data Source

Data for the GSCD are monthly from 1998M12 to 2022M10.[2] The GSCD, compiled by the Federal Reserve Bank of New York, integrates transportation cost data and manufacturing indicators to measure the

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[2] Our data are limited to the GEU index created by Dang, et al (2023) that is available from 1998M12 to 2022M12 and limited to the non-technical risk premium proposed by Vespignani and Smyth (2024) available from 2012 to 2022.

importance of global supply constraints with respect to economic outcomes.[3] For example as shown in Figure 2, three major episodes of global supply chain inter-linkage disruptions are the Tohoku earthquake and the following tsunami in March 2011 (Boehm et al., 2019; Carvalho et al., 2021); the obstruction of the Suez Canal in March 2021 (Furceri et al., 2023), and the zero-COVID policy imposed by authorities in Shanghai in April 2022. GSCD is strongly associated with historical inflation for both the producer price index (PPI) and consumer price index (CPI) in the United States and the Euro area.

The monthly price of aluminium, copper, nickel, platinum, tin and zinc from 1998M12 to 2022M10 are sourced from the World Bank.[4] We compute the monthly realized variance for the daily spot price of individual critical minerals from Bloomberg over the period from 1998M12 to 2022M10.

The Global Energy Uncertainty Index (GEU) and Global Real Economic Activity (GREA) index are also monthly from 1998M12 to 2022M10. The GEU index, created by Dang, et al (2023), is based on the Google search keywords that best predict energy price volatility for 28 developed and developing countries.[5] Dang, et al (2023) find that the GEU is strongly associated with oil price shocks and historical events, such as the Global Financial Crisis and the COVID-19 pandemic. Economic activities at both the country and industry levels slow as the GEU index increases. The GREA index, proposed by Kilian (2009), is a business cycle index derived from a panel of dollar-denominated global bulk dry cargo shipping rates and is viewed as a proxy for the volume of shipping in global industrial commodity markets.[6]

The NTRP for each of the six critical minerals is at annual frequency for the period 2012 to 2022. The method for constructing NTRP, and an overview of the NTRP for each of the six critical minerals, are detailed in Section 3.2. While the first year for NTRP data is 2012, we extrapolate back to 1998. Extrapolation fills in zeros for the NTRP variable before 2012. It maintains data alignment across series to mitigate estimation inefficiency due to the short time series and long lags in our structural VAR model. The monthly index for the non-technical risk premium is based on annual data that remains constant throughout

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[3] The data are from https://www.newyorkfed.org/research/policy/gscpi#/overview.
[4] The data are at https://www.worldbank.org/en/research/commodity-markets.
[5] The data are available at https://www.policyuncertainty.com/energy_uncertainty.html.
[6] The data are at https://www.dallasfed.org/research/igrea.

the year. All variables used in the Structural VAR model are z-score normalized, transforming data to have mean zero and standard deviation 1, so as to ensure comparability of different features with different scales.

In Section 5 where we examine the effect of stockpiling on price volatility of critical minerals, we employ monthly future prices for critical minerals from Investing.com and monthly data on stockpiles of critical minerals from the World Bureau of Metal Statistics (WBMS) for 2011M1 – 2022M10. Table 1 summarizes the data description, sources and frequency for each of the variables used in this study.

3.2. Non-technical Risk Premium

Non-technical risk refers to risks in mining and resource industries that are not tied to the technical aspects of extracting and processing resources. These risks stem from various factors, such as political instability, regulatory changes, geopolitical tensions and social dynamics in the countries in which critical minerals are geographically located. Vespignani and Smyth (2024) formalised this definition as follows:

$$Non-technical\ risk = \sum_{i}^{n} w_{c,m} * s_{c} \tag{11}$$

$w_{c,cm}$ is the proven reserves of critical mineral m in country c as a percentage of the world's proven reserves of minerals and S is the investment attractiveness index score for country c from the Annual Survey of Mining Companies conducted by the Fraser Institute (2022).[7] Sykes et al. (2014), Trench and Packey (2012) and Trench et al. (2014) made the empirical observation that many critical minerals exhibit back-ended risk in project development due to non-technical risks occurring in the later stages of the project. This contrasts with the risk faced by other minerals - so called front-ended risk minerals - such as gold, coal, and iron ore for which the value of the project increases rapidly during the early stages of project development (exploration). Following this rationale, Vespignani and Smyth (2024) define the non-technical risk premium as the non-technical risk of each critical mineral expressed as a percentage of the non-technical risk of a benchmark of non-critical front-ended minerals. We follow Vespignani and Smyth (2024) and use the average non-technical risk of gold, coal and iron ore as the benchmark front-ended minerals.

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[7] The investment attractiveness index, produced by the Fraser Institute, is a composite index that evaluates how appealing various jurisdictions are for mining investment. It is widely used in the mining industry as a benchmark for assessing how policy and geological potential impact investment decisions.

$$Non - technical\ risk\ premiun = \frac{(IAI_{NC,} - IAI_C)}{IAI_{NC}} \tag{12}$$

Where IAI is the investment attractiveness index and NC and C denote non-critical minerals and critical minerals respectively. We build upon the cross-sectional data for the NTRP provided by Vespignani and Smyth (2024) by first disaggregating it into two components: the non-technical risk best practice premium and the non-technical risk policy perception premium. The non-technical policy perception risk premium reflects mining executives' risk perception with respect to the policy environment, including factors such as taxation, regulatory uncertainty, environmental restrictions, political stability and the efficiency of the permit process. The non-technical best practices risk premium reflects the perception of mining executives with respect to the geological attractiveness of a country (or region), if it operates under a world-class regulatory environment and adheres to optimal mining policies. Additionally, we extend the dataset on the non-technical risk premium and its two components to cover the period 2012 to 2022 for the six critical minerals. The first year is 2012 because this is the first year in which the Fraser Institute report this survey. In Figure A1 in Appendix A, we present the NTRP, non-technical risk best practice premium and non-technical risk policy perception premium for each of the six critical minerals over the period 2012 to 2022.

The results for aluminium in Figure A1(a) show that initially from 2012 to 2014, the NTRP was negative, indicating low risks, but these turned positive after 2015, reflecting a general increase in perceived risk. Movements in the best practice and policy perception premiums for aluminium are similar - both were negative at the beginning of the timeframe but turned positive after 2015. In 2017, the NTRP for aluminium dropped significantly as Rio Tinto advanced its Amrun bauxite project in northern Queensland, Australia.[8] The development of the Amrun project promised to secure future alumina production, with bauxite reserves estimated at over 1 billion tonnes (Rio Tinto, 2017). The rise in non-technical risk associated with aluminium in 2018 was primarily due to a 10% tariff imposed by the Trump administration on aluminium imports under Section 232, which was justified by national security concerns. This tariff led to market disruptions and increased prices in the United States (U.S. Department of Commerce, 2018).

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[8] Australia is recognized for having the lowest non-technical risk due to its best practices and policy perspective, according to the Fraser Institute.

Figure A1(b) shows consistently negative values for copper from 2012 until 2020, indicating a prolonged period of low perceived non-technical risks. However, by 2021 and 2022, the premium turns positive, suggesting a marked increase in risk. This turn can be attributed to major copper-producing countries like Chile, Peru, and Mexico which faced temporary mine closures and reduced operations due to lockdowns and safety measures (Cochilco, 2020). The best practice premium is mostly negative throughout the period, with especially large negative values in 2017 and 2018, reflecting low perceived risks. It starts to increase by 2021, with positive values indicating worse outcomes from best practice adoption. The policy perception premium also trends negatively for most of the period, indicating good policy perceptions until around 2021. By 2021 and 2022, the premium turns positive, signalling a more negative policy environment.

In Figure A1(c) the non-technical risk premium for nickel exhibits varied dynamics, which is reflected in its components. The best practice premium is negative in 2015, 2016, 2018, and 2020. The policy perception premium is negative at the beginning of the timeframe, but turns positive from 2016 onwards, suggesting increase policy risk perception. In 2019, Indonesia discovered a very large deposit of nickel in the Sulawesi region (Roskill, 2019). As the share of proven nickel reserves in Indonesia rose significantly, non-technical risks also increased, reflecting high level of non-technical risks in the country, which stem from poor best practices and weak policy perspectives, according to the Fraser Institute.

In Figure A1(d) platinum exhibits a high NTRP throughout most of the period, with notable spikes, especially in 2016, 2021, and 2022. The best practice premium is largely positive as well, except for 2017 and 2018, which show negative values. The policy perception premium also mostly trends positive, with a significant increase since 2018. In 2018 South Africa, the world's largest platinum producer, which produce more than 70% of the world platinum faced production disruptions due to labor strikes, power outages and operational inefficiencies (Chamber of Mines of South Africa. (2018)).

In Figure A1(e), tin exhibits a consistently positive NTRP throughout the entire period. The values for the NTRP fluctuate, but tend to increase, peaking in 2020, when lockdowns and restrictions in tin-producing countries like Indonesia, Myanmar, and China led to mine closures and reduced production (International Tin Association, 2020). The best practice premium shows generally positive values, with noticeable increases in 2017, 2018, and especially in 2020. The policy perception premium also remains positive throughout, indicating a perception that the policy risk was high over the timeframe with notable peaks in 2018 and 2020.

In Figure A1(f) zinc exhibits a negative NTRP until 2019. From 2020 onwards, the premium becomes positive, suggesting a shift in perception where non-technical factors started adding risk. The best practice premium is mostly negative or neutral until 2016, with positive values emerging more frequently after 2019. The policy perception premium starts negative, but transitions to positive values from 2016 onward, reflecting a decline in satisfaction with the perceived regulatory and policy environment. The increase in NTRP since 2020 is associated with the COVID-19 pandemic in which significant disruptions in production of critical minerals were observed, affecting both supply and downstream industries. Lockdowns and restrictions imposed in major mining regions, such as South Africa, Australia, and South America, led to temporary closures of mines and smelting facilities (International Energy Agency, 2021). Furthermore, logistical challenges, such as port closures, shipping delays and increased transportation costs compounded the supply disruptions (World Bank, 2020). These issues created shortages in raw materials for industries dependent on critical minerals, including electronics, batteries, and clean energy technologies. This in line with increase in geopolitical risk observed over the COVID-19 pandemic in Figure 2.

3.3 Methodology

This section describes our empirical methodology, which consists of a Structural VAR ($SVAR$) model of order p with global macroeconomic uncertainty as to GSCD and the NTRP, which is the specific uncertainty associated with the price volatility of each individual critical mineral:

$$A_0 y_t = B_0 + \sum_{i=1}^{p} A_i y_{t-i} + \varepsilon_t, \tag{13}$$

where $y_t = (GSCD_t, GEU_t, GREA_t, GSCD_t \times NTRP_t, NTRP_t, Volatility_t)$ is a $m \times 1$ $(m = 6)$ vector of endogenous variables consisting of the monthly volatility of the prices of individual critical minerals $Volatility_t$, the monthly GSCD index $GSCD_t$, the GEU index GEU_t, GREA index $GREA_t$, the NTRP index $NTRP_t$ of individual critical minerals, and the interaction of $GSCD_t \times NTRP_t$.

The first block variables in the $SVAR$ Model in Equation (13) are global macroeconomic variables - $GSCD_t$, GEU_t and $GREA_t$ - ordered first and assumed to affect all the second block variables in the individual critical mineral markets including the NTRP, its interaction with global macroeconomic variables and the price volatility of individual critical minerals. Global macroeconomic variables are assumed not respond to the innovations in the variables in the individual critical mineral markets at least within the same month. We set $p = 12$ on the basis that the greatest effect of uncertainty on the economy is generally considered to occur within the first or second year (see Hamilton, 2009; Bloom, 2009; Baumeister & Peersman, 2013).[9] In theory, the empirical results could be sensitive to the order/lag choice of endogenous variables in the $SVAR$ model (see Primeceri (2005) or Koop et al. (2009) for example). In practice, with this dataset and the additional agnostic sign restrictions discussed below, results are similar for different order/lag choices.

The reduced-form VAR model is obtained by multiplying both sides of the $SVAR$ Model in Equation (13) with A_0^{-1}, which has a recursive structure, such that the reduced form error terms e_t are linear combinations of the structural error terms ε_t, where $e_t = A_0^{-1}\varepsilon_t$ and $E_t[e_t e_t'] = \Sigma$ which is a diagonal matrix. We use the least-squares method to estimate the reduced-form VAR model consistently. The resulting estimates are used to construct the $SVAR$ Model in Equation (13).

We impose additional agnostic sign restrictions popularized by Uhlig (2005, 2017) on the impulse responses of the price volatility of critical minerals to the innovations in macroeconomic uncertainty for the identification to construct the $SVAR$ Model in Equation (13). The restrictions are imposed for one period at least. The sign restriction approach allows us to build on a minimalistic handful of uncontroversial signs and zero restrictions on the impulse response functions, $F(\Phi_i)$ where $\Phi_i = (A_0, A_i)$, $i = 1, \ldots, p$, rather than the restrictive assumptions on the entire structural matrix A_0 in the traditional Cholesky approach.

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[9] The long lag of 12 months allows for a potentially long-delay in effects of uncertainty shocks on the critical mineral market and for sufficiently long enough lags to remove potential serial correlation. Sims (1998) and Sims, Stock and Watson (1990) argue that even variables that display no inertia do not necessarily show absence of long lags in regressions on other variables.

Define $e_{j,m}$ the j^{th} column of identity matrix I_m, we implement sign restrictions on the impulse response functions based on $T(\Phi_i) = e'_{1,m}F(\Phi_i)S'_1, \dots, e'_{m,m}F(\Phi_i)S'_m$, where the restriction matrix S_j contains entries of zero and positive/negative signs across both the endogenous variables and the forecast horizons over which the restrictions are imposed. Table 2 summarizes our assumptions underpinning our identifying restrictions on the matrix S_j. We postulate that global supply chain disruptions cause an increase (decrease) in global energy uncertainty and the price volatility of critical minerals (global economic activity). Global energy uncertainty may lower (raise) global economic activity (price volatility of minerals). Shocks to global supply chain disruptions and energy uncertainty raise the non-technical risk premium of individual critical minerals, its interaction with global supply chain disruptions and the price volatility of individual critical minerals. Innovations in unexpected global economic expansion reduce the non-technical risk premium and reduce the price volatility of individual critical minerals. Finally, shocks to the non-technical risk premium and its interaction with global supply chain disruptions cause the increased price volatility of critical minerals.

This set of traditional sign restrictions above is derived from the theoretical predictions in the literature arguing that uncertainty shocks have a significantly negative impact on the economy (e.g., Bloom, 2009; Jurado et al., 2015; Baker et al., 2016). Recent studies show that uncertainty shocks significantly raise the price volatility of commodity (Bakas and Triantafyllou, 2018; Kang et al., 2025). Innovations to global real economic activity that cannot be explained by GSCD and GEU are referred to as shocks to the global demand for industrial commodities including critical minerals (see Kilian, 2009; Kilian and Park, 2009 in the crude oil market). Demand shocks are generally realized to raise prices and lower price volatilities in the commodity market (e.g., Kilian and Park, 2009; Bai and Ríos-Rull, 2015; Kang et al., 2025).

4. Results of the Structural VAR Estimate

4.1.1 Impulse Response Functions of Critical Mineral Price Volatility to GSCD, NTRP and the Magnifying Impact of NTRP on GSCD

Figure 3 presents impulse response functions for the price volatility of individual critical minerals to a one-standard deviation structural shock in the structural VAR Model in Equation (13) over a 24-month forecast horizon with 68% confidence intervals.

Column (1) of Figure 3 shows that an unanticipated shock to the GSCD raises the price volatility of tin in one, four, six, nine and 14 months; platinum in one and two months, aluminium in one, three and nine months; nickel in one, five, eight and 11 months; zinc in one, seven, and 11 months; and copper in one and six months. Column (5) illustrates that an unexpected innovation in the NTRP raises the price volatility of tin in the first month; platinum in one, three, five and seven months; aluminium in one, three and five months; nickel in one and five months; zinc in one – five and 10 months; and copper in one, two, 12 and 20 months. These results confirm that each of NTRP and GSCD have direct positive effects on the price volatility of critical minerals consistent with our first hypothesis. Higher NTRP, driven by policy uncertainty, geopolitical risks and regulatory constraints, discourage investment and expansion in mining projects, leading to constrained supply and higher price volatility. Simultaneously, unanticipated shocks to the GSCD exacerbate supply shortages, amplifying cost-push inflation in critical mineral markets.

Column (4) of Figure 3 shows that an unanticipated shock to the interaction between GSCD and NTRP raises the price volatility of tin, which is positive and statistically significantly in one, two, seven, nine, 10 and 18 months. This shock significantly raises price volatilities in the first three months for platinum and in the first seven months for nickel respectively. An unanticipated shock to the interaction between GSCD and NTRP increases the volatility of aluminium prices in one, two, seven, eight, 10, 14, and 17 months and increases the volatility of zinc prices in the first three months and in a window between seven and eight months marginally. The effects of the interaction shocks are statistically significantly positive on the price volatility of copper in one, seven and 10 months.

In summary, unanticipated shocks to the interaction between GSCD and the NTRP of individual critical minerals cause increases in price volatility as shown in Figure 3, Column 4, consistent with our second hypothesis. As firms face greater exposure to supply chain failures, reduced adaptability due to high NTRP increases the persistence and severity of price volatility shocks. This leads to heightened uncertainty, prompting investors to demand higher returns, further increasing the cost of capital for critical mineral projects.

4.1.2 Historical Decompositions of Critical Minerals Price Volatility to Structural Shocks to the Interaction Between Global Supply Chain Disruption and the Non-technical Risk Premium $(GSCD_t \times NTRP_t)$

The historical episodes of structural shocks are not limited to a one-time shock as shown in the impulse response functions in Figure 3. Figure 4 presents the historical decomposition of the effect of structural shocks to the interaction between global supply chain disruption and the non-technical risk premium $(GSCD_t \times NTRP_t)$, on the price volatility of individual critical minerals during the period of 2012 - 2022.[10] Figure 4 illustrates the cumulative effect of a vector sequence of shocks with different signs and magnitudes at different points in time. Overall, shocks to the interaction between global supply chain disruption and the non-technical risk premium cause long swings in the price volatility of individual critical minerals. Consistent with our third hypothesis, the combined effects of NTRP and GSCD are different on the price volatility of individual critical minerals from one episode to the next, reflecting that the interaction shocks have historically been driven by varying combinations of innovations in NTRP and GSCD at different points in time. Of particular note, the cumulative effect of the interaction innovation significantly contributes to increased price volatility of critical minerals during the COVID-19 pandemic in 2020-2022.

Panel (a) in Figure 4 shows that the non-technical risk premium of tin exhibits generally positive values, tends to increase in 2017, and reaches a peak during the period 2020 to 2022. Panel (b) of Figure 4 illustrates that the culmulative effect of shocks to the interaction term on the price volatility of platinum in the period 2019-2022 was largely due to the increase in the NTRP of platinum. It is a similar story for zinc. As shown in Panel (e) in Figure 4, the higher NTRP for zinc has underpinned the culmulative effect of shocks to the interaction term on the price of zinc since late 2018.

Panel (c) in Figure 4 reports that the non-technical risk premium of aluminium shows consistently positive values since 2013. The buildup in the price volatility of aluminium after 2020 was driven mostly

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[10] We present the 12-month moving average of the historical decomposition for the exposition purpose, because the monthly series is choppy, given that we generate the monthly price volatility using daily prices.

by the cumulative effects of the interaction of the high non-technical risk premium coinciding with global supply chain disruptions over the COVID-19 pandemic period during 2020-2022. Likewise in Panel (f) the cumulative effects of the increased global supply chain disruptions and increased non-technical risk premium for copper contributed to steadily greater price volatility of copper during the years 2021 and 2022. Over the COVID-19 pandemic, major aluminium-producing countries such as China and Australia and major copper-producing countries like Chile, Peru, and Mexico faced temporary mine closures and reduced operations due to lockdowns and concerns about safety measures (Cochilco, 2020).

Panel (d) of Figure 4 shows that the cumulative effects of shocks to the interaction term largely had fluctuating effects on the price volatility of nickel, as the non-technical risk premium flucuates over time. As a result, the effects are relatively smaller over the COVID-19 pandemic period from 2020 to 2022.

4.2.1 Responses of Critical Mineral Prices to Structural Shocks

In this subsection, we present impulse response functions to structural shocks in which we replace price volatility in Equation (13) with the price of individal critical minerals. We assume similar sign restrictions on the response of prices to structural shocks in Table 2, except that innovations in the GEA are expected to raise the price of critical minerals.

The relationship between price and volatility is fundamental to understanding asset risk, a key determinant of the cost of capital. In speculative asset markets, such as commodities, heightened price volatility is often accompanied by sharp price increases, primarily driven by unanticipated geopolitical events and fluctuations in inventory levels. These dynamics contribute to greater uncertainty in asset valuation, potentially elevating the cost of capital. Moreover, prolonged periods of elevated prices exacerbate market instability, particularly in the critical minerals sector, where supply constraints and geopolitical risks further intensify volatility.

Figure 5 reports impulse response functions for the price of each of the six critical minerals to a one-standard deviation structural shock to GSCD, GEU, GREA, the NTRP for each critical mineral and the interaction of GSCD and NTRP over a 24 month forecast horizon, with 68% confidence intervals.

Column (1) in Figure 5 shows the price response to a one-standard deviation GSCD structural shock. An unexpected shock to the GSCD raises the price of tin, which is statistically significant in the first five months and in the 12 – 16 month window. The effects of GSCD shocks are positive and statistically significant for nickel and zinc prices, which are persistent over 24 months. An unexpected shock to GSCD increases prices of platinum and copper for the first three months and marginally raise the price of aluminium in the first month.

Column (5) of Figure 5 reports price reponses to a one-standard deviation structural shock in the NTRP of each critical mineral. Innovations in the NTRP of tin have positive and persistent effects on the price of tin, which are statistically significant in the first three months and in the 15 – 20 month window. The effects of innovations in the NTRP of the prices of the other five critical minerals are positive and statistically significant, but are relatively short-lived. Innovations in NTRP have a postive effect on the price of nickel in the first eight months, copper in the first seven months and zinc, platinum and aluminium for the first five months.

Column (4) in Figure 5 illustrates the impulse reponse of critical mineral prices to a one-deviation structural shock to the interation of GSCD and relevant NTRP of each critical mineral. An unanticipated shock to the interaction between GSCD and NTRP has statistically significantly positive effects on the price of tin, which is persistent over 20 months. The effects of shocks to the interaction for the other five critical minerals on their prices are positive and statistically significant, but relatively short-lived; ie. they are positive for aluminium and zinc in the first eight months, nickel and copper for the first seven months, and platinum for the first five months.

Column (2) in Figure 5 shows the price responses to one-standard deviation shocks to the GEU. This shock causes transitory effects on the prices of critical minerals, an increased price of tin and platimum in the first five months, nickel in the first three months, and for aluminium, zinc and copper in the first month. In contrast as shown in Column (3) of Figure 4, an unanticipated expansion on the GEA, results in increased prices of platinum, nickel, zinc and copper over one year, and increased prices of tin and alumimium in 10 months. Finally in Column (6) of Figure 5, unexpected shocks to individual mineral-market specific prices raise prices, which are transitory within five months for tin, platinum, aluminium, nickel, and copper, and in 10 months for zinc.

In summary, shocks to the NTRP of critical minerals cause their prices to increase as shown in Column (5) of Figure 5. The positive effect is relatively more persistent for critical minerals which exhibit higher NTRP. An example is tin which has the highest NTRP in Figure 2. Additionally, unanticipated innovations in the interaction term between the NTRP and GSCD have statistically significantly positive effects on the prices of critical minerals as shown in Column (4) of Figure 6. The positive effect is relatively more persistent for critical minerals with higher NTRP. For example, for tin, the effect lasts over 20 months as shown in the fourth diagram of the first row of Figure 5. Finally, the effects of unexpected expansion on the GEA are appreciable, whereas the effects of GEU and mineral-market specific price shocks are transitory on the prices of critical minerals.

In Appendix B we present the historical decomposition of the effect of structural shocks on individual critical mineral prices for the period 2012 - 2022. For concreteness we only illustrate the panel of interest (the impact of GSCD, NTRP and the interactions of these two variables on critical mineral prices). The results are similar to those shown in Figure 4 for the historical decomposition of the effect of structural shocks on price volatility. Overall, shocks to GSCD, NTRP and their interaction cause long swings in the price of critical minerals. In particular the cumulative effect of the interaction innovation significantly contributes to the increased price of critical minerals over the COVID-19 pandemic.

These results further confirm that shocks to GSCD, NTRP and their interaction, causing increased price volatility, also generate prolonged increases in the price of critical minerals in the speculative commodity market. The effect likely results in increased uncertainty about valuation that drives the cost of capital up as investors demand higher returns for greater risk. In particular, the GSCD effects of individual critical minerals on price are significantly amplified by innovations in the NTRP throughout the course of the COVID-19 pandemic in 2020 - 2022, consistent with the results for price volatility in Figure 3.

4.2.2 Impulse Response Functions of Critical Mineral Relative Price Volatility to Structural Shocks to the Interaction between Global Supply Chain Disruption and the Non-technical Risk Premium

In this subsection, we replace the price realized volatility ($Volatility_t$) by the relative price volatility ($Volatility_t/Price_t$) in Equation (13) and present the impulse response functions of the relative price volatility for individual critical minerals to structural innovations in the interaction between GSCD and the NTRP to facilitate comparison among the six critical minerals.

Cavallo et al. (2013) show that relative price volatility distorts efficient investment allocation in emerging market economies that are exposed to institutional risks. The relative price volatility of commodities is greater than that of the exchange rate (Bui and Pippenger (1990)) and less than that of manufactured goods (Arezki et al., 2013). The evidence shows that relative price volatility directly influences the firm's cost of capital by affecting both equity and debt financing in speculative commodity markets.

Figure 6 shows that an unanticipated shock to the interaction term ($GSCD_t \times NTRP_t$) causes an increase in relative price volatility in three months for tin in diagram (a) and platinum in diagram (b), two months for aluminium in diagram (c), and in one month for nickel in diagram (d), zinc in diagram (e) and copper in diagram (f), each of which exhibits a relatively lower NTRP (see Figure 2) . The results confirm that innovations in the NTRP of individual minerals, coinciding with a global macroeconomic uncertainty shock of $GSCD_t$, likely raise the cost of capital because of the increased uncertainty associated with valuation in the speculative commodity market.

4.3 Results of Disaggregated NTRPs (Best Practices and Policy Perspective Premiums)

As discussed in Section 3.2, the NTRP consists of the policy perception risk premium and the best practice risk premium. In Appendix C, we estimate Equation (13) for relative price volatility, but replace the NTRP with each of the policy perception risk premium and the best practice risk premium. Overall, the cumulative effects of the interaction between $GSCD$ and the non-technical policy perception risk premiums significantly contribute to the increased relative price volatility of critical mineral over the course of the COVID-19 pandemic in 2020 – 2022. Shocks to the interaction between $GSCD$ and non-technical best practice risk premiums show a relatively more persistent cumulative effect on the relative volatility of critical minerals such as tin, platinum and aluminium since 2018. Innovations in non-technical policy perception risk premiums exhibit either a relatively smaller effect on the relative volatility of tin, platinum and aluminium. The overall cumulative effects of the interaction between $GSCD$ and non-technical policy perception/best practice risk premiums are largely flat on the relative volatility of nickel, zinc, or copper.

5. Effects of Stockpiling on Price Volatility of Critical Minerals

The literature on stockpiling in commodity markets shows that the convenience yield of stockpiles captures the benefit from owning physical inventory of the commodity (e.g., Routledge, et al., 2000; Gospodinov and Ng, 2013). The recent work by Irawan and Okimoto (2021) argues that a favorable strategy for mining firms facing uncertainty is overinvestment that is positively associated with firms' performance. Figure 7 shows that the ratio of spot to future prices in the backwardation market for critical minerals increased during the COVID-19 pandemic in 2020-2022, which indicates that the convenience yield in the critical mineral market was higher.[11] In these circumstances, the benefit of stockpiling outweighs storage and financing costs.

In the spirit of the approach adopted by Den Haan (2000), Den Haan and Summer (2004), and Kilian and Park (2009) for the oil market, in Table 3 we present the conditional covariance of the stockpiles of critical minerals and the cumulative effects of innovations in the interaction of GSCD and NTRP on the price volatility of critical minerals. Table 3 reports the conditional covariance for five of the six critical minerals: aluminium, copper, nickel, tin and zinc. We do not have stockpiling data for platinum. We present the covariance between the 12-month moving average of the cumulative effects because the monthly series is choppy, given that we generate the monthly price volatility using daily prices, and the 12-month moving average of the growth rate of stockpiles of the individual critical minerals. Table 3 shows that the covariances are statistically significantly negative when the cumulative effects of innovations in the interaction of GSCD and NTRP on the volatility of critical minerals are relatively greater; i.e. for tin, aluminum, and nickel as shown in Figure 5. The negative relationship implies that stockpiles likely reduce

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[11] Note that for the exposition purpose of the smooth time series, we present the 24-month moving average of the ratio of spot to future prices of individual critical minerals.

macroeconomic fragility in critical mineral markets by mitigating the effects of shocks to supply chain disruptions and the non-technical risk premium on the price volatility of critical minerals.

6. Conclusions

The macroeconomic fragility mechanism proposed by Acemoglu and Tahbaz-Salehi (2024) applied to critical mineral markets suggest that GSCD and NTRP not only independently weaken supply chain resilience, but also interact to magnify these effects. A high NTRP discourages mining firms from adapting to disruptions by seeking new suppliers or expanding capacity, leading to reduced supply, increased price volatility, and higher costs. Simultaneously, high GSCD heightens reliance on specific suppliers, making production networks more vulnerable to external shocks. Their interaction compounds network rigidity --- firms face greater exposure to supply chain failures, while risk-averse investors demand higher returns due to escalating uncertainty. This dual effect increases the likelihood of supply chain collapse, elevating project development costs and pushing up the cost of capital, further destabilizing critical mineral markets. Using a structural VAR model for six major critical minerals, we show that both effects are economically large and statistically significant, contributing to macroeconomic fragility of critical mineral markets.

Our theoretical extension to the macroeconomic fragility framework (Section 2.1) suggests that stockpiling can moderate the destabilizing interplay between global supply chain disruptions and non-technical risks. Empirical results presented in Section 5 support this hypothesis, revealing a negative relationship between reserve levels and critical mineral price volatility. Specifically, higher stockpiles are associated with reduced output discontinuities and a dampened transmission of fragility-inducing shocks. These findings suggest that strategic stockpiling is an effective mechanism to enhance supply chain resilience, stabilize prices, and mitigate macroeconomic fragility in critical mineral markets.

Although direct empirical evidence specific to critical mineral stockpiling remains, extensive literature on oil markets indicates that national reserves effectively dampen price volatility. Countries have historically maintained strategic petroleum reserves to protect against oil supply disruptions and price shocks, providing a clear blueprint for similar strategic reserves of critical minerals.

Such reserves would allow governments to manage temporary supply shocks in critical minerals, stabilize market expectations and mitigate price volatility, thus enhancing overall economic resilience. This is particularly important for countries transitioning from fossil fuels to clean energy, which relies on these critical minerals.

Our result shows the increased convenience yield of stockpiles that captures the benefit from owning physical inventory during the COVID-19 pandemic in 2020-2022 in the critical mineral market. As the cumulative effects of innovations in GSCD and NTRP on the price volatility of critical minerals are relatively greater, the conditional covariance of stockpiles and the cumulative effects is significantly negative. The negative relationship between the conditional covariance of stockpiles and the cumulative effects implies that stockpiles likely reduce macroeconomic fragility in the critical mineral market by mitigating the effects of shocks to supply chain disruptions and the non-technical risk premium on the price volatility of critical minerals. This conclusion points to the need for further research that identifies more efficient methods of stockpiling critical minerals to reduce price volatility and disruptions in production.

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Table 1. Description of Variables

Name	Description	Source	Period	Frequency
GSCD	Global Supply Chain Pressure Index	Federal Reserve Bank of New York	1998M12 – 2022M10	Monthly
GEU	Global Energy Uncertainty	Dang et al (2023)	1998M12 – 2022M10	Monthly
GREA	Global Economic Activity	Kilian (2009)	1998M12 – 2022M10	Monthly
NTRP	Non-Technical Risk Premium	Vespignani and Smyth (2024) and new data constructed	2012 – 2022	Annual
Futures	Critical Mineral Future Prices	Investing.com	2011M1 – 2022M10	Monthly
Prices	Critical Mineral Spot Prices	World Bank	1998M12 – 2022M10	Monthly
Stockpiles	Critical Mineral Stockpiles	World Bureau of Metal Statistics	2011M1 – 2022M10	Monthly
Volatility	Critical Mineral Prices Volatility	Bloomberg Professional Service	1998M12 – 2022M10	Daily

Table 2. Identification Restrictions on the Signs of the Effect of a Structural Shock

	Supply Chain Disruption	Energy Uncertainty	Economic Activity	Non-Tech Chain Interaction	Non-Tech Risk Premium	Critical Minerals Volatility
GSCD	1	-	-	-	-	-
GEU	1	1	-	-	-	-
GEA	-1	-1	1	-	-	-
NTRP	1	1	-1	1	-	-
NTRPG	1	1	-1	1	1	-
Volatility	1	1	-1	1	1	1

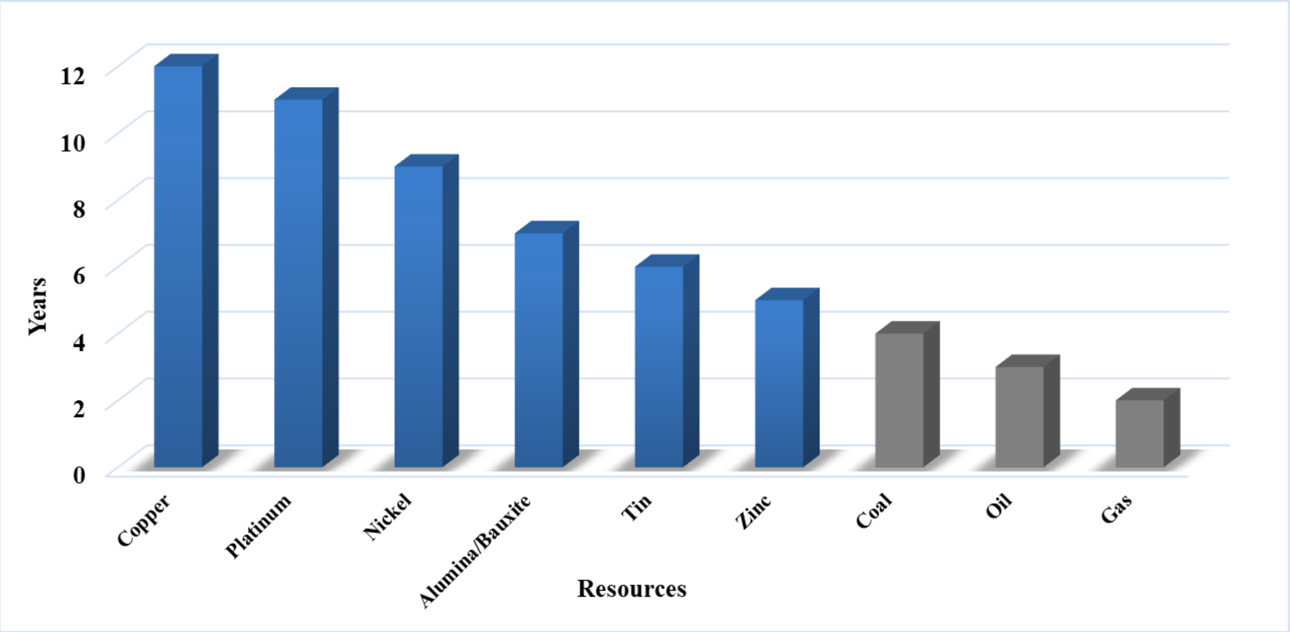
Notes: The table shows the identification restrictions of the signs of the effect of the structural shocks of Non-Technical Risk Premium (NTRP), global supply chain disruption (GSCD), the interaction of NRTP and GSCD (NRPTG), global energy uncertainty (GEU), global economic activity (GEA), and critical minerals price volatility.

Table 3. Covariance of Stockpiles and Effects of the Interaction of GSCD and NTRP

Tin	Aluminium	Nickel	Zinc	Copper
-0.063	-0.017	-0.187	0.099	0.029
(0.018)	(0.007)	(0.060)	(0.032)	(0.027)

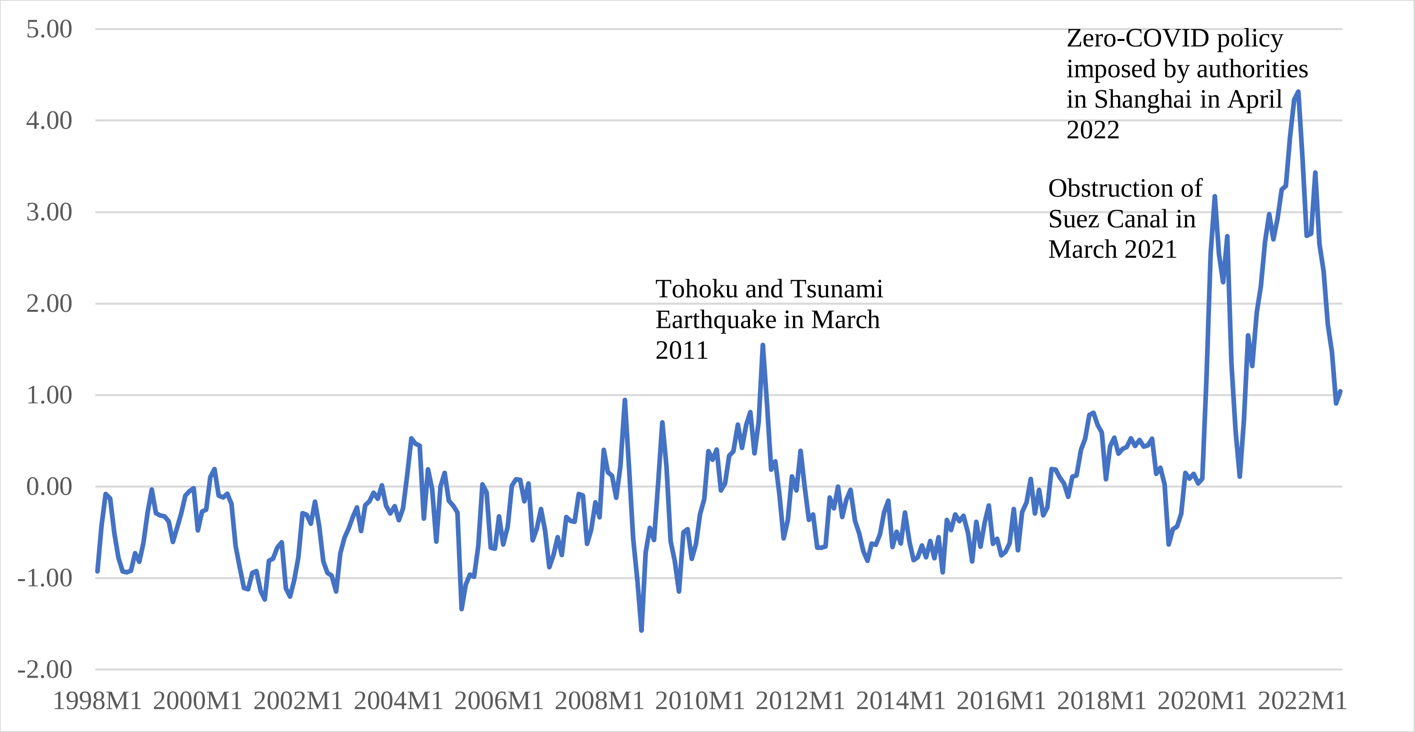
Notes: The table shows the conditional covariance between the stockpiles of individual critical minerals and the cumulative effects of innovations in the interaction of GSCD and NTRP on the price volatility of critical minerals, using the data from 2011M1 – 2022M10. We present the covariance between 12-month moving average of the cumulative effects because the monthly series is choppy, given that we generate the monthly price volatility using daily prices, and the 12-month moving average of the growth rate of stockpiles of individual critical minerals.

Figure 1. The Average Timeline for Project Development, from Exploration to Extraction (Years)



Notes: The data on average development timelines from exploration to extraction for various resources was collected from multiple sources, each focusing on specific minerals for the period 2000-2024. The International Energy Agency (IEA)'s *Global Critical Minerals Outlook 2024* is the main source for cobalt, nickel, and copper. The United Nations Department of Economic and Social Affairs (UN DESA)'s *Harnessing the Potential of Critical Minerals for Sustainable Development (2025)* is the source for aluminium, and platinum. The World Bank Group**'s** *The Growing Role of Minerals and Metals for a Low Carbon Future (2024)* also contains information on cobalt, tin, and zinc. The US Geological Survey (USGS)'s *Mineral Commodity Summaries (2024)* provided historical and current data on coal, gas, oil, zinc and aluminium.

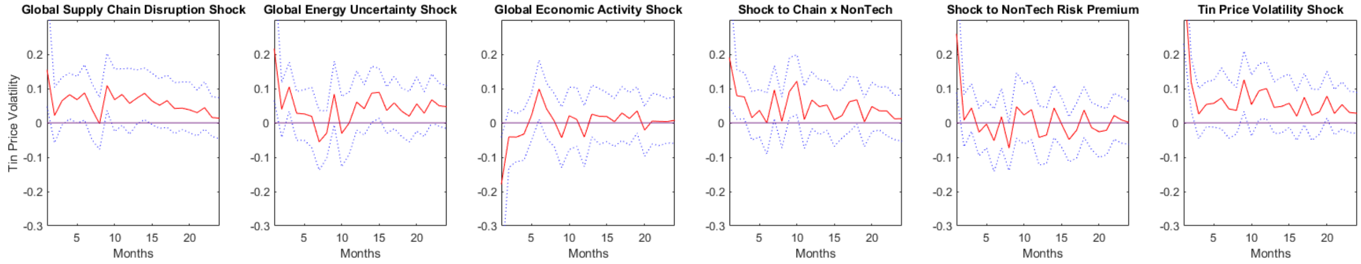
Figure 2. Global Chain Supply Pressure Index



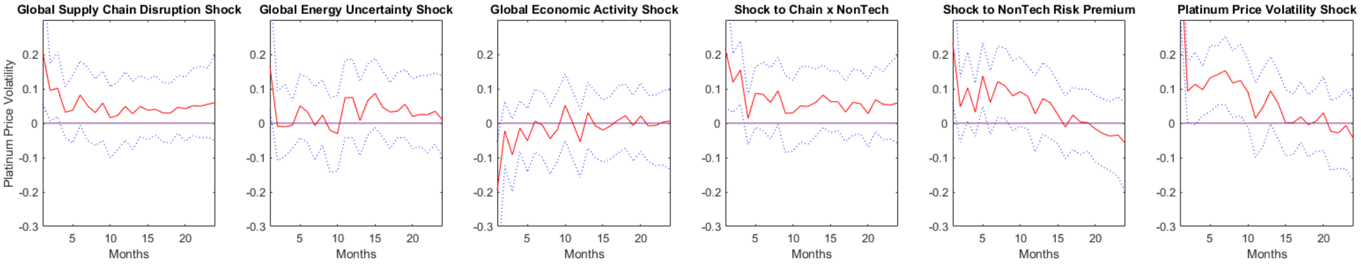
Notes: Data are monthly from 1999M2 to 2022M10. The Global Supply Chain Pressure Index (GSCPI), constructed by the Federal Reserve Bank of New York, integrates transportation cost data and manufacturing indicators to measure the importance of global supply constraints with respect to economic outcomes.

Figure 3. Impulse Response Functions of Critical Mineral Price Volatility to One-Standard Deviation Structural Shocks (Non-technical Risk Premium)

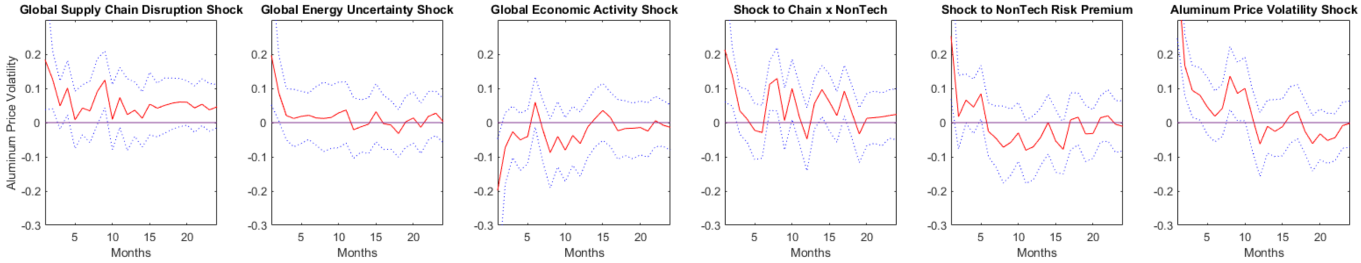
a) Tin Price Volatility



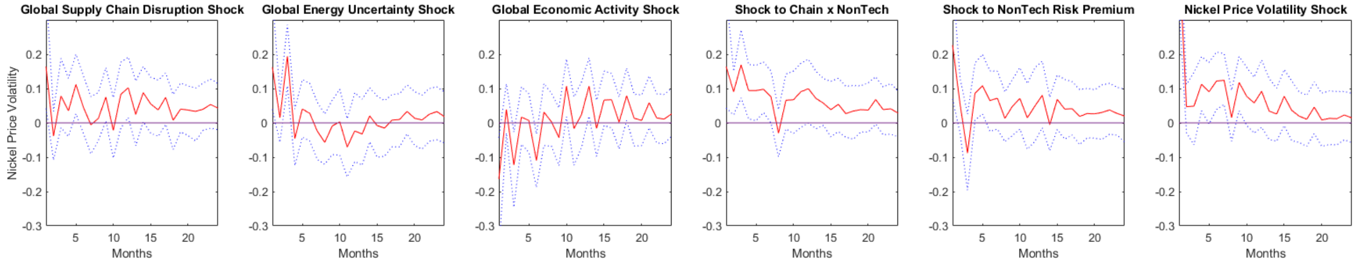
b) Platinum Price Volatility



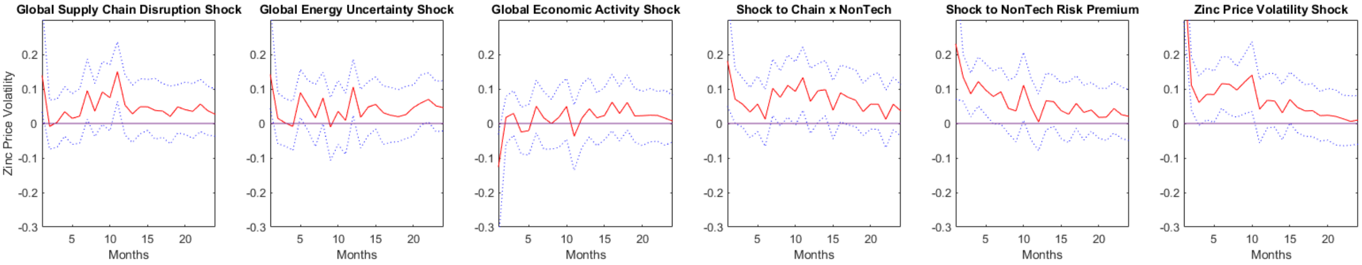
c) Aluminium Price Volatility



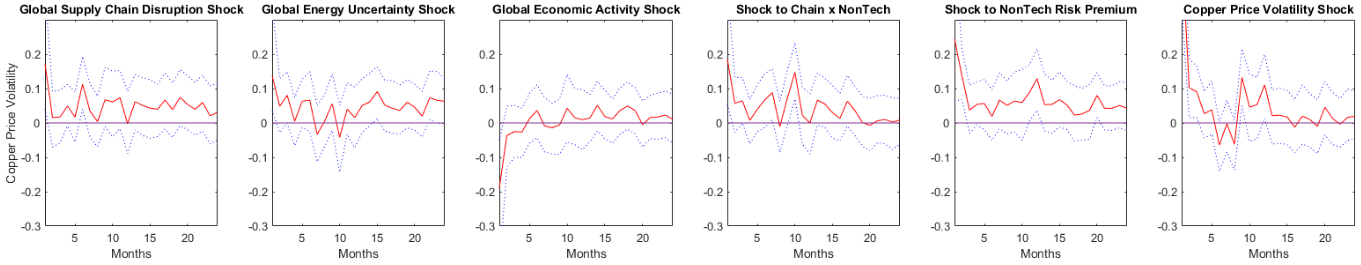
d) Nickel Price Volatility



e) Zinc Price Volatility



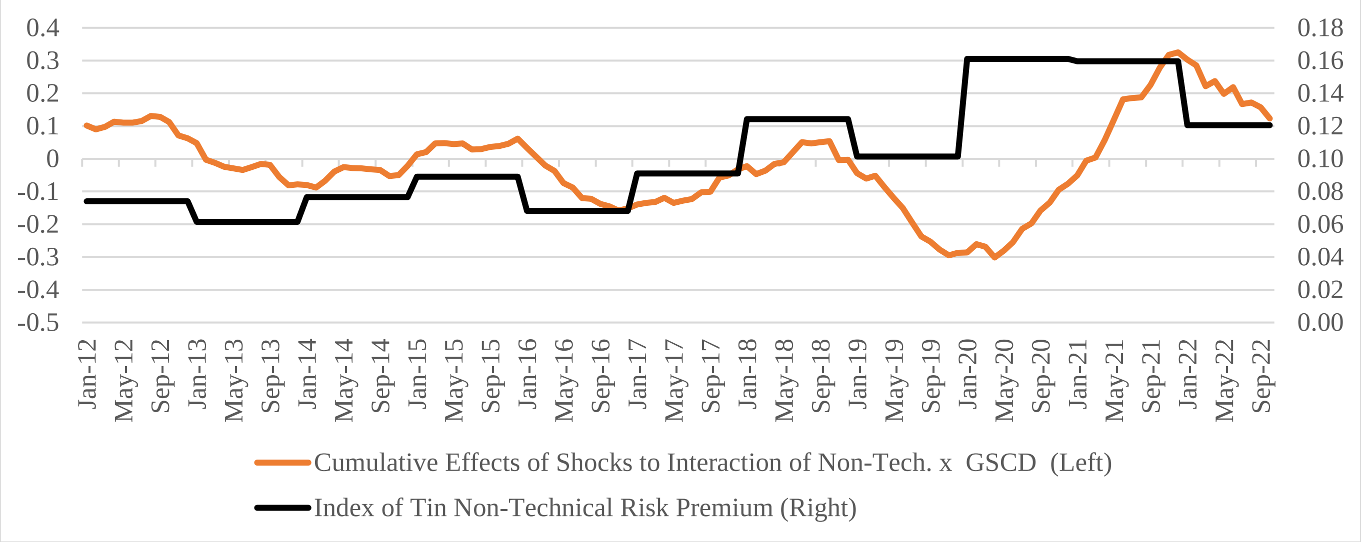
f) Copper Price Volatility



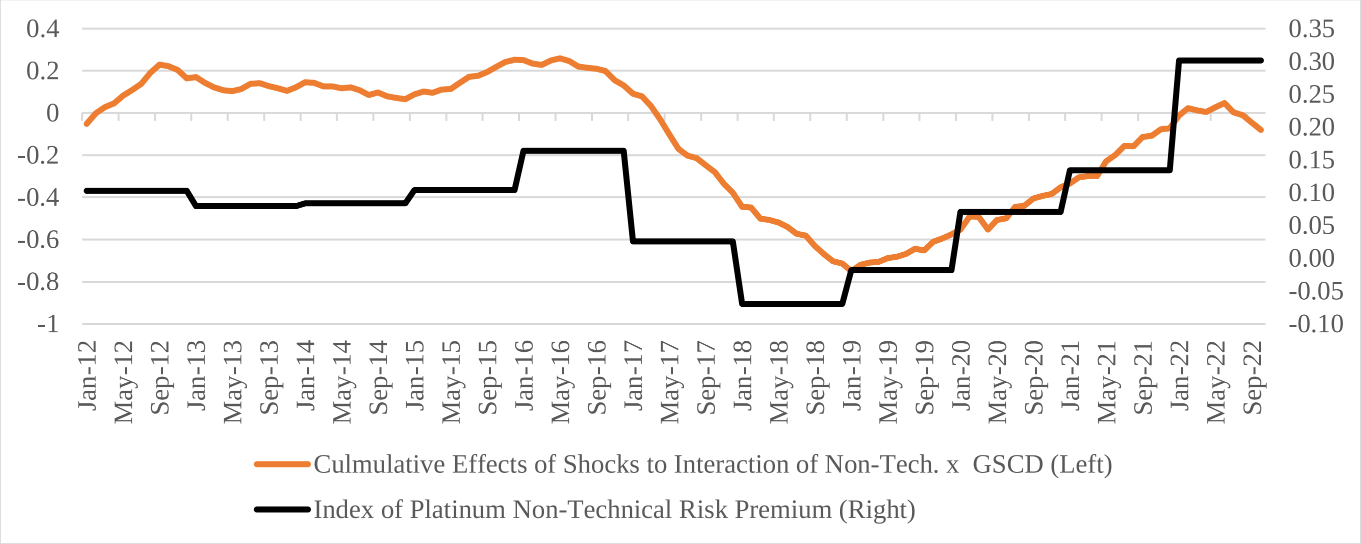
Notes: The figure shows impulse response functions of precious metal price volatility to one-standard deviation structural shocks of global supply chain (GSCD), global energy uncertainty (GEU), global economic activity (GEA), non-technical risk premium (NTRP) and the interaction between GSCD and NTRP (GSCD * NTRP), for individual critical minerals, and critical minerals price volatility, with 68% confidence intervals.

Figure 4. Historical Decompositions of Critical Minerals Price Volatility to Structural Shocks of the Interaction (GSCD × NTRP), 2012 - 2022

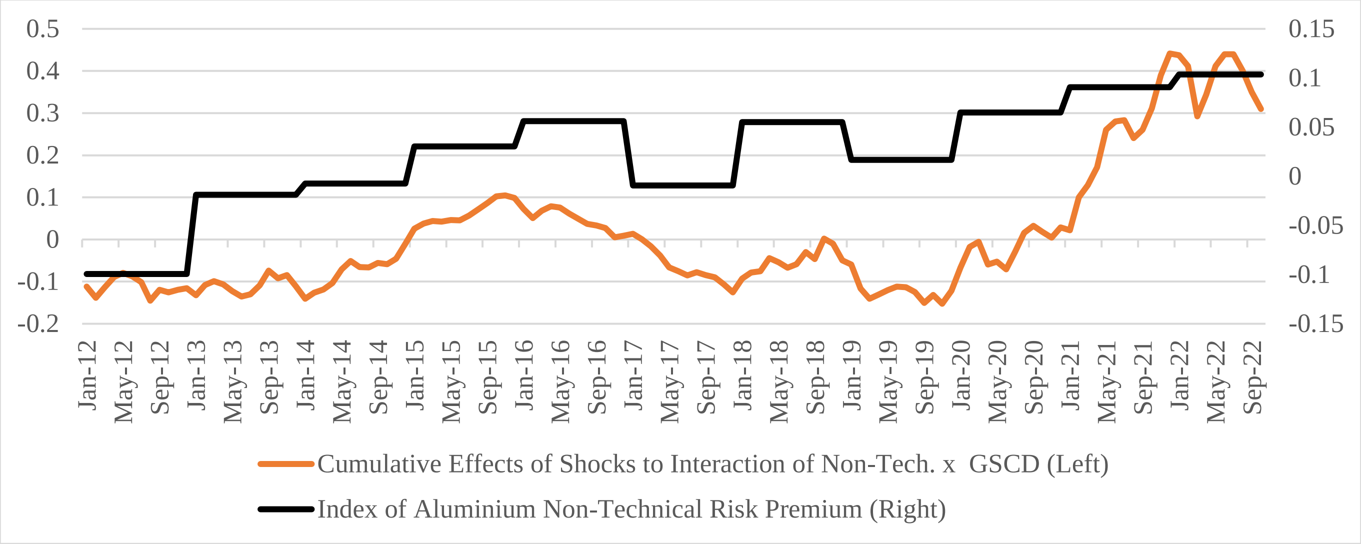
a) Tin Price Volatility



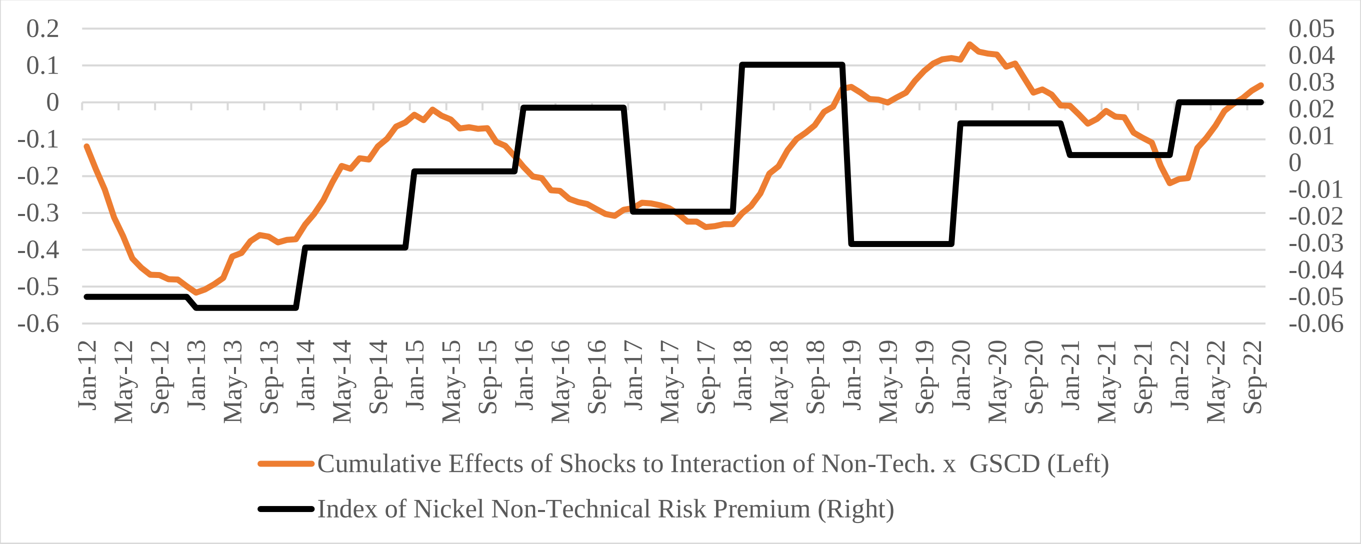
b) Platinum Price Volatility



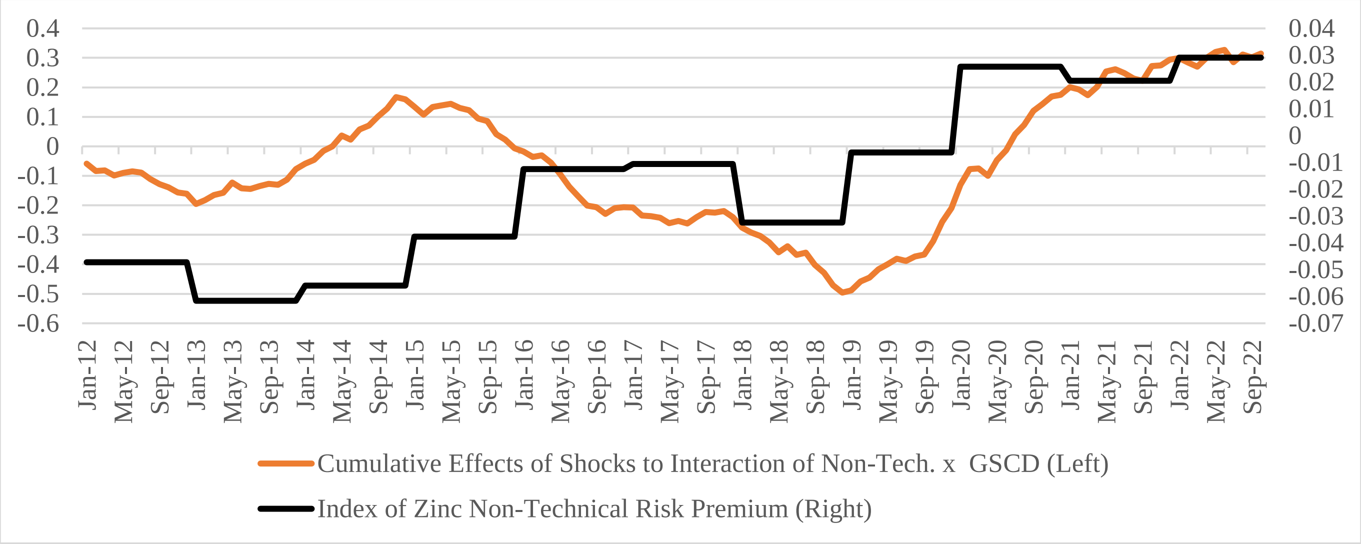
c) Aluminium Price Volatility



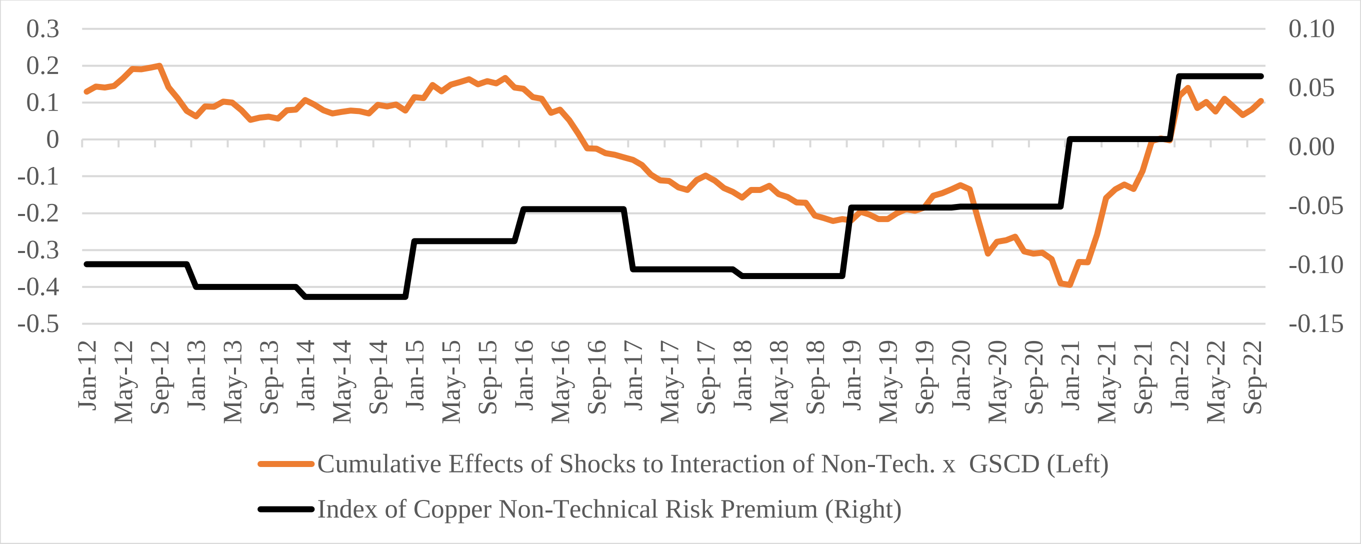
d) Nickel Prices Volatility



e) Zinc Price Volatility



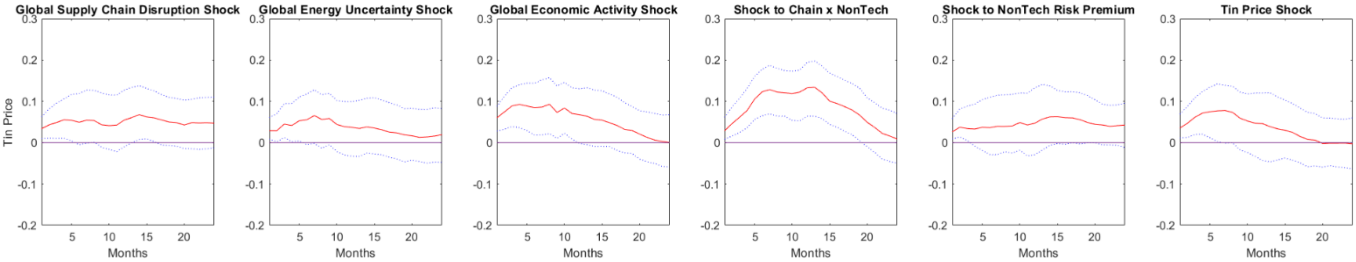
f) Copper Price Volatility



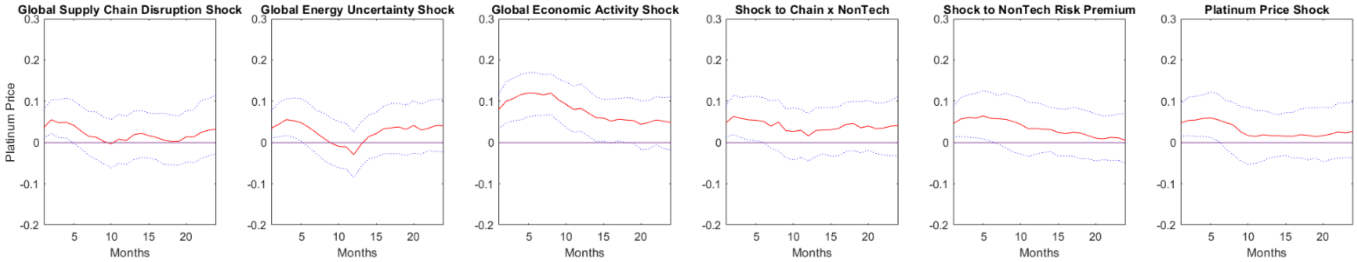
Notes: The figure shows the historical decompositions of critical minerals price volatility to the structure shocks of interaction of GSCD and NTRP. We present the 12-month moving average of the historical decomposition because the monthly series is choppy, given that we generate the monthly price volatility using daily prices.

Figure 5. Impulse Response Functions of Critical Mineral Prices to One-Standard Deviation Structural Shocks (Non-technical Risk Premium)

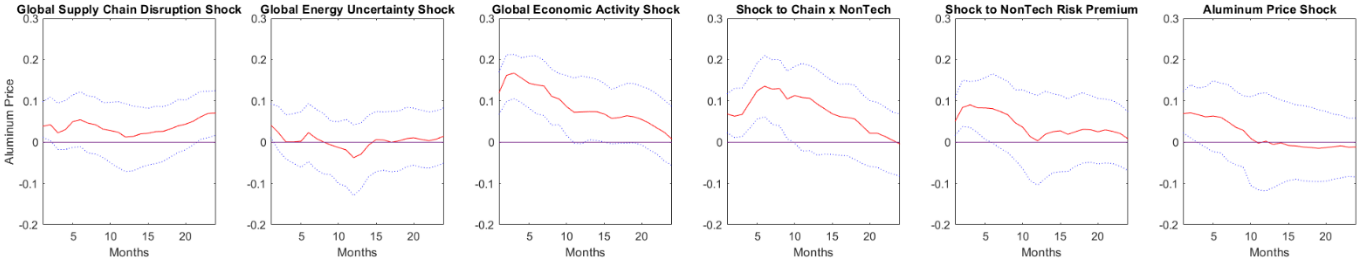
a) Tin Prices



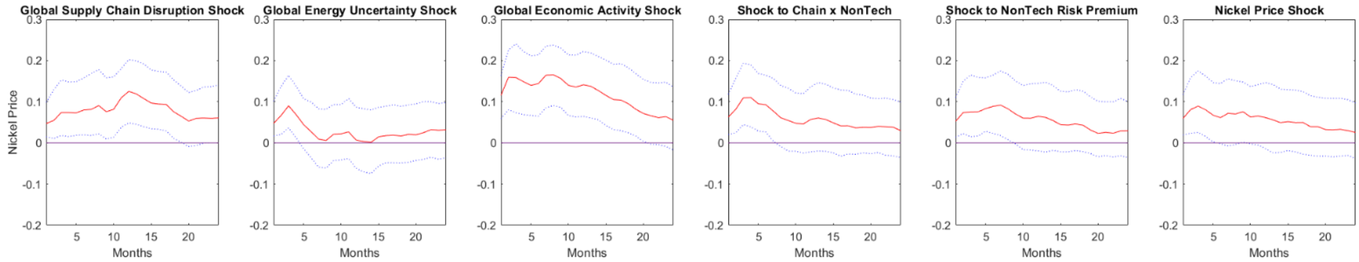
b) Platinum Prices



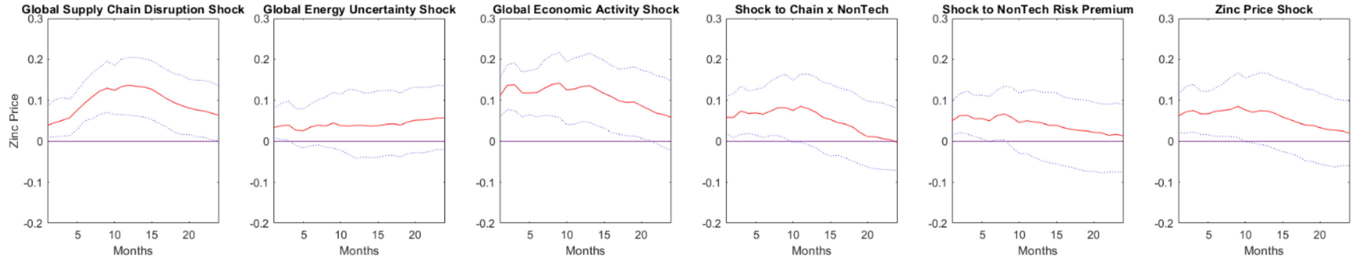
c) Aluminium Prices



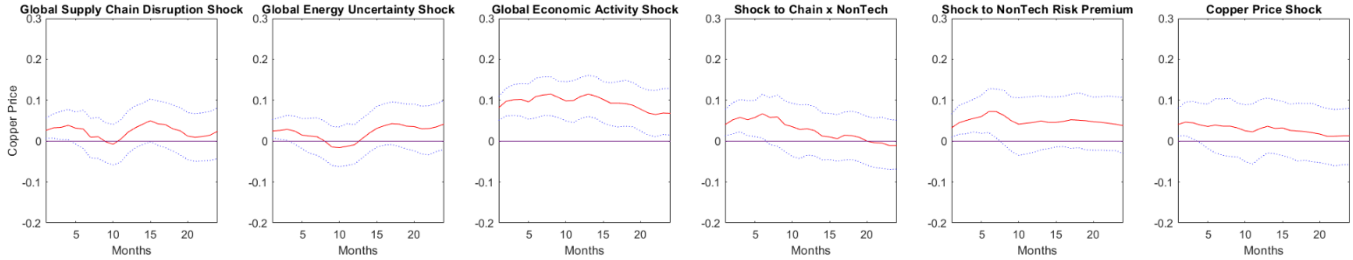
d) Nickel Prices



e) Zinc Prices



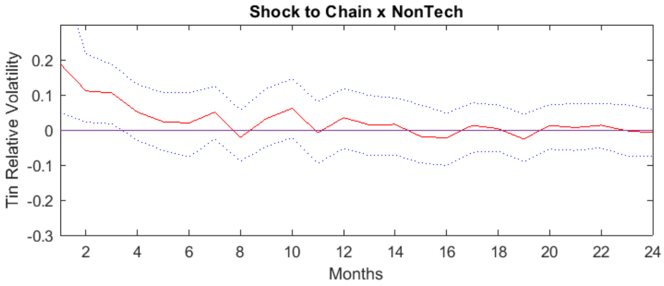
f) Copper Prices



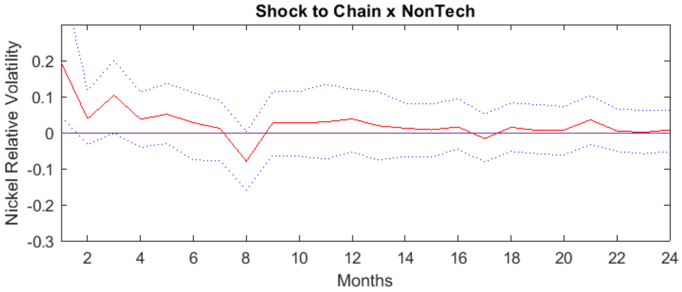
Notes: The figure shows the impulse response functions of precious metal prices to one-standard deviation structural shocks of global supply chain (GSCD), global energy uncertainty (GEU), global economic activity (GEA), interaction (GSCD * NTRP), non-technical risk premium (NTRP) for individual critical minerals, and critical minerals prices, with 68% confidence intervals.

Figure 6. Impulse Response Functions of Critical Mineral Relative Price Volatility to One-Standard Deviation Structural Shocks of the Interaction (GSCD × NTRP)

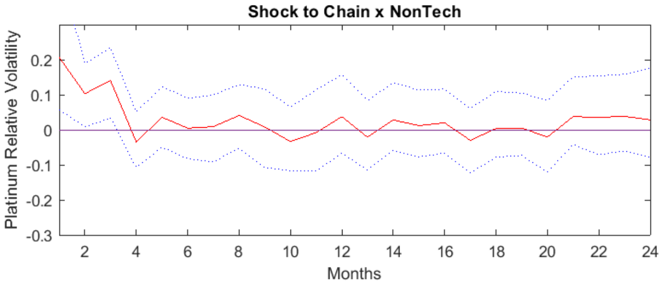
a) Tin Relative Volatility



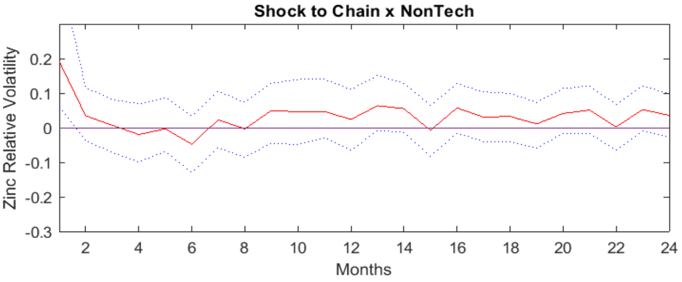
d) Nickel Relative Volatility

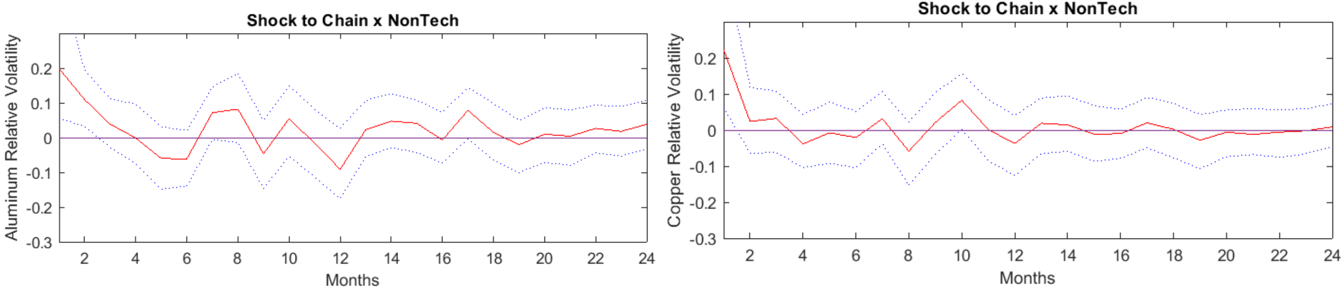


b) Platinum Relative Volatility



e) Zinc Relative Volatility

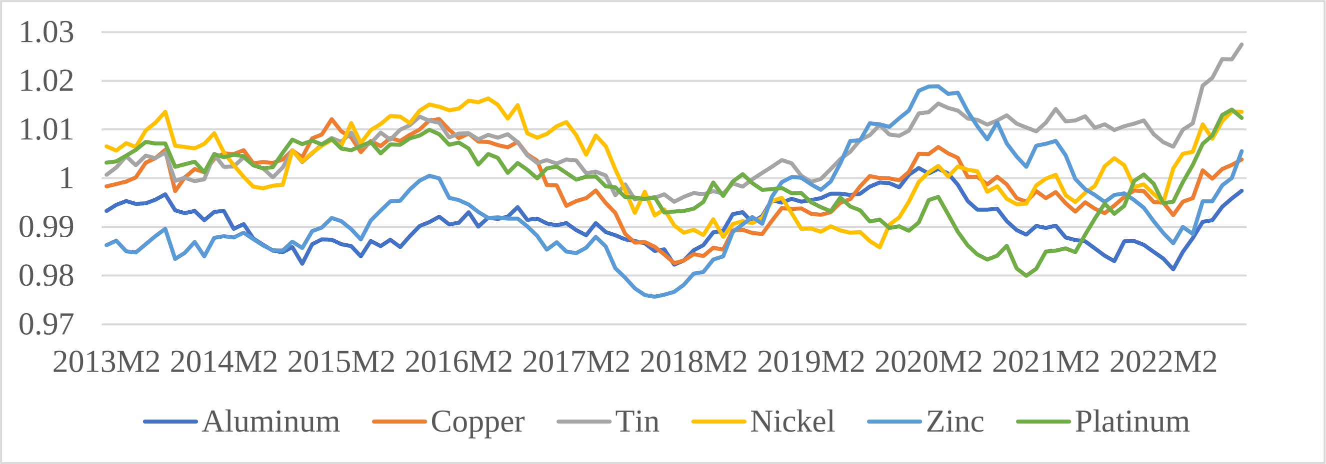



c) Aluminium Relative Volatility

f) Copper Relative Volatility

Notes: The figure shows the medium of impulse response functions of critical minerals relative volatility to one-standard deviation structural shocks of the interaction - global supply chain (GSCD) and non-technical risk premium (NTRP) for individual critical minerals, NTRPG, with the 68% confidence intervals.

Figure 7. Ratio of Spot to Future Prices

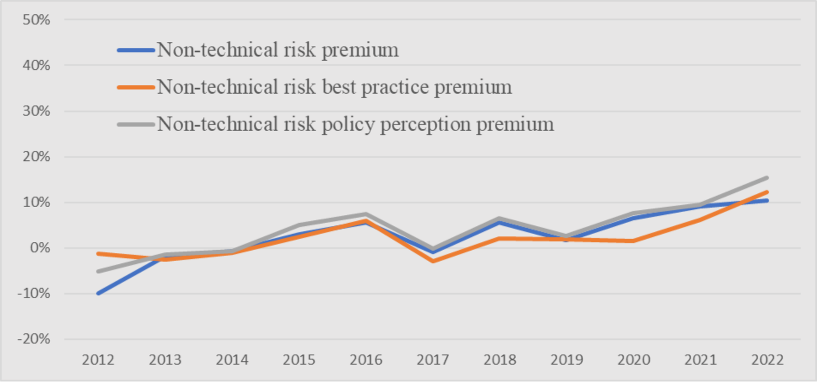


Notes: The figure shows the ratio of spot to future prices of six critical minerals over the period of 2013M2 - 2022M10.

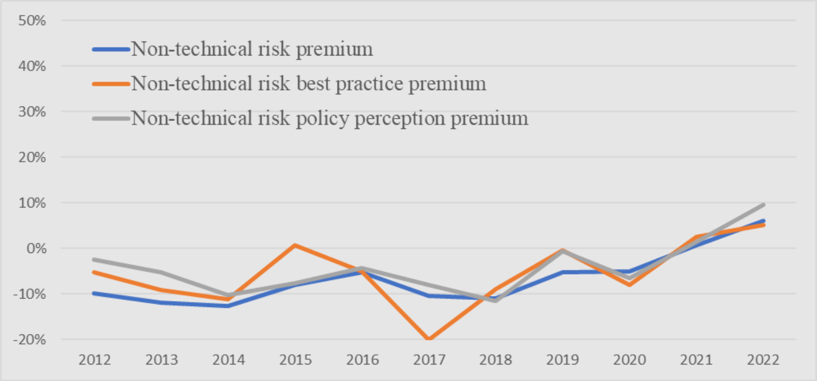
Appendix A: Non-technical Risk Premium (2012-2022)

Figure A1. Non-technical Risk Premiums for Individual Critical Minerals, 2012-2022

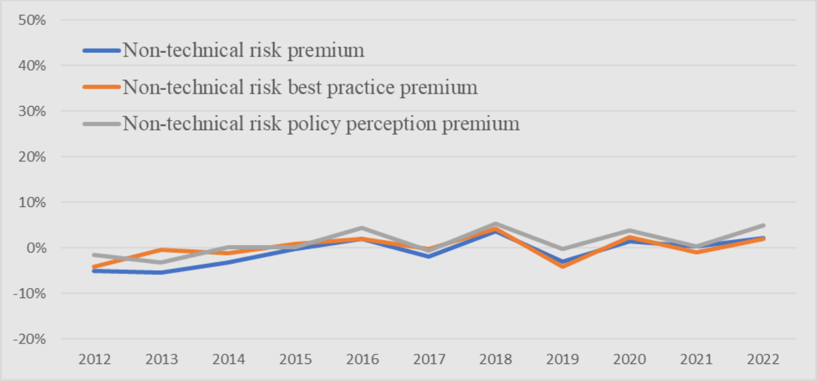
(a) Aluminium



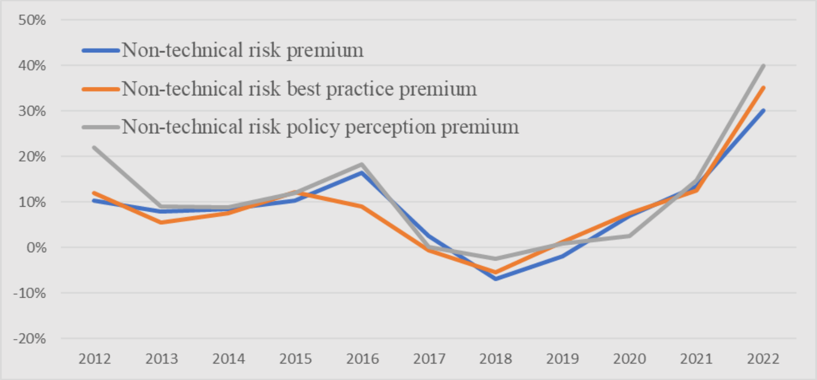
(b) Copper



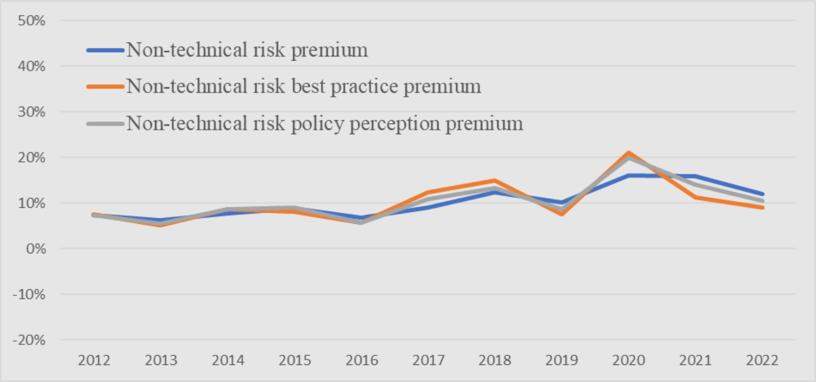
(c) Nickel



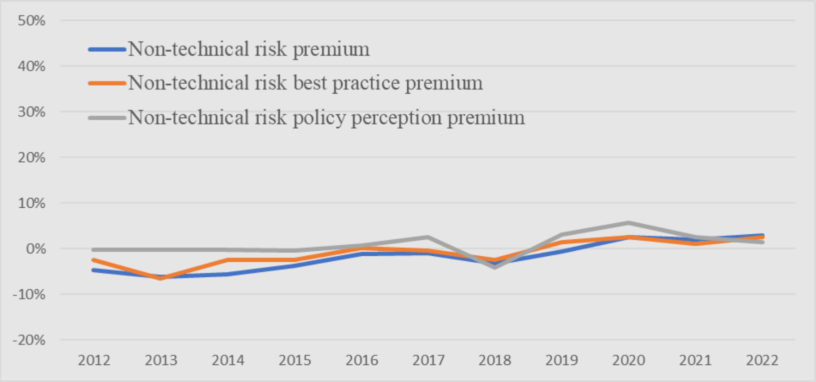
(d) Platinum



(e) Tin



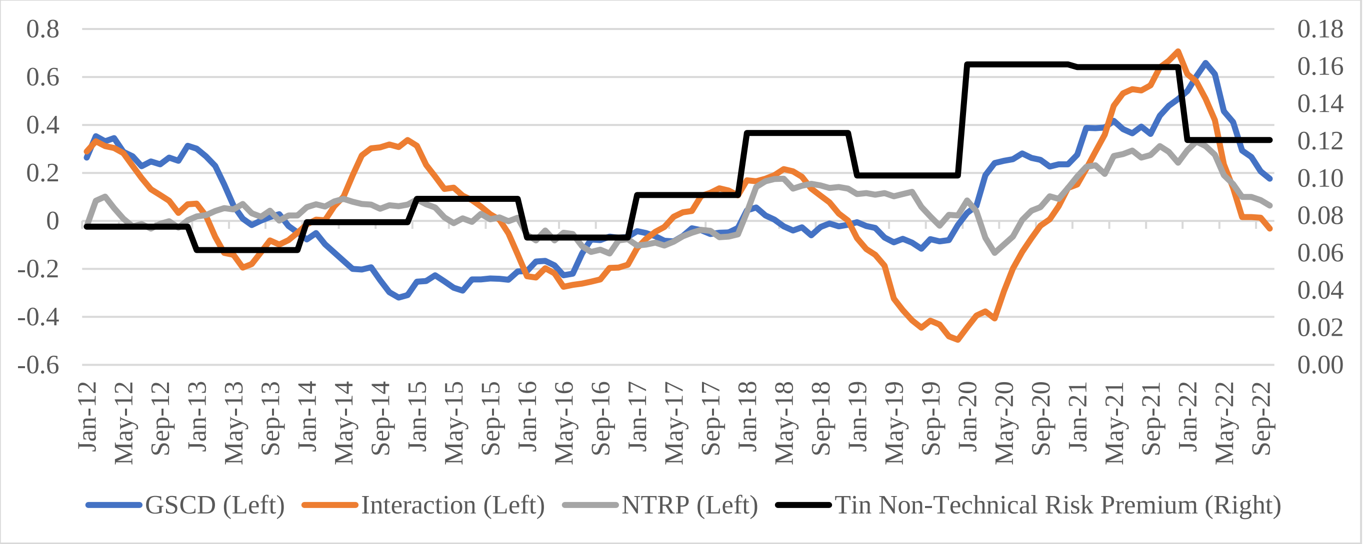
(f) Zinc



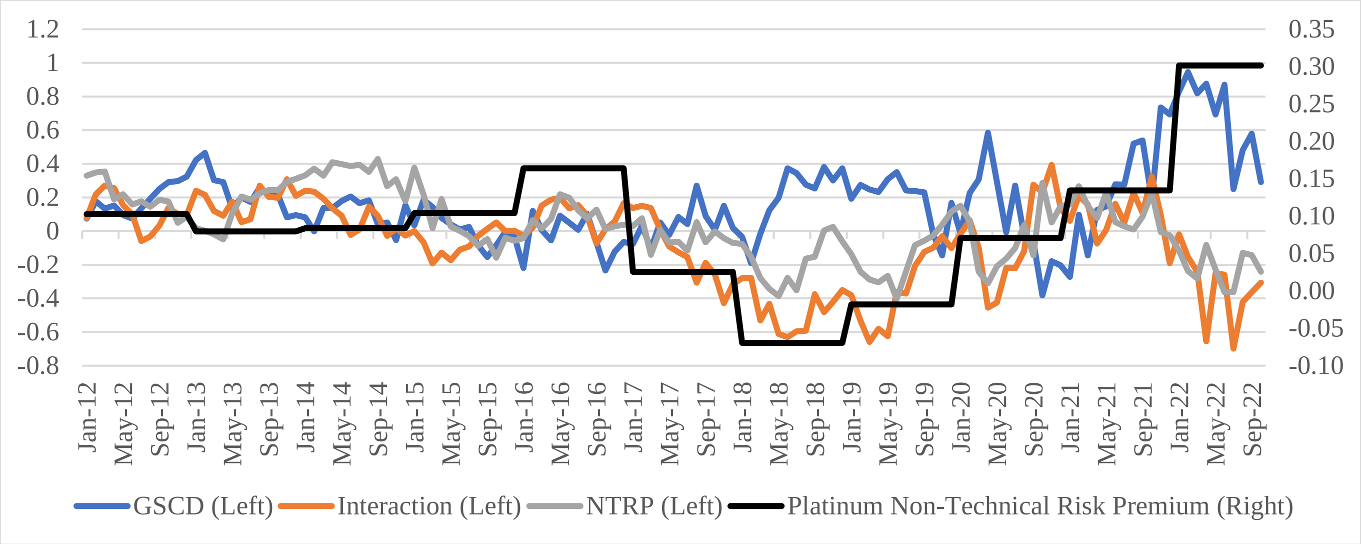
Notes: The figure shows the non-technical risk premiums for the mean of each of the six critical mineral estimates determined by the geographical location of the proven reserves (Vespignani and Smyth (2024)): Aluminium, copper, tin, nickel, zinc, and platinum, from 2012 to 2022. To quantify this premium, Vespignani and Smyth (2024)): construct indexes for 16 major critical minerals by weighting the Investment Attractiveness Index from the Fraser Institute's Annual Survey of Mining Companies with the proven reserves of each mineral in various countries. This approach allows them to assess the non-technical risk premium by comparing the investment attractiveness of critical minerals to that of non-critical, front-ended fossil fuels like coal, oil, and gas.

Appendix B. Historical Decompositions of Critical Minerals Prices to the Structure Shocks of Global Supply Chain ($GSCD$), Interaction of $GSCD$ and $NTRP$ (Interaction), Non-Technical Risk Premium ($NTRP$)

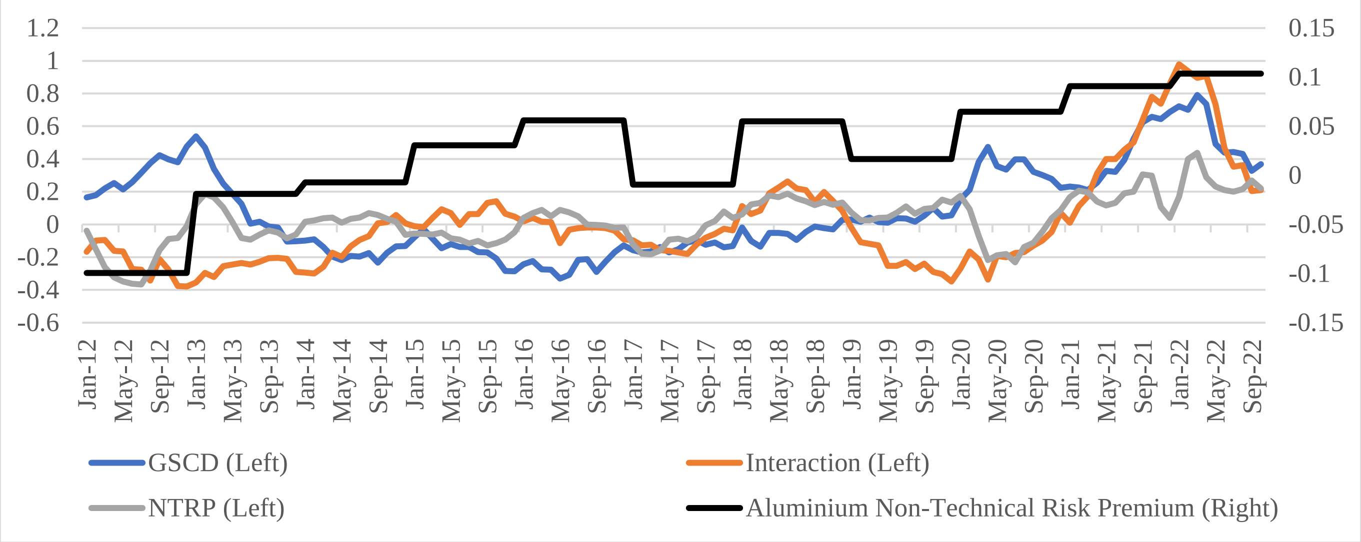
a) Tin Prices



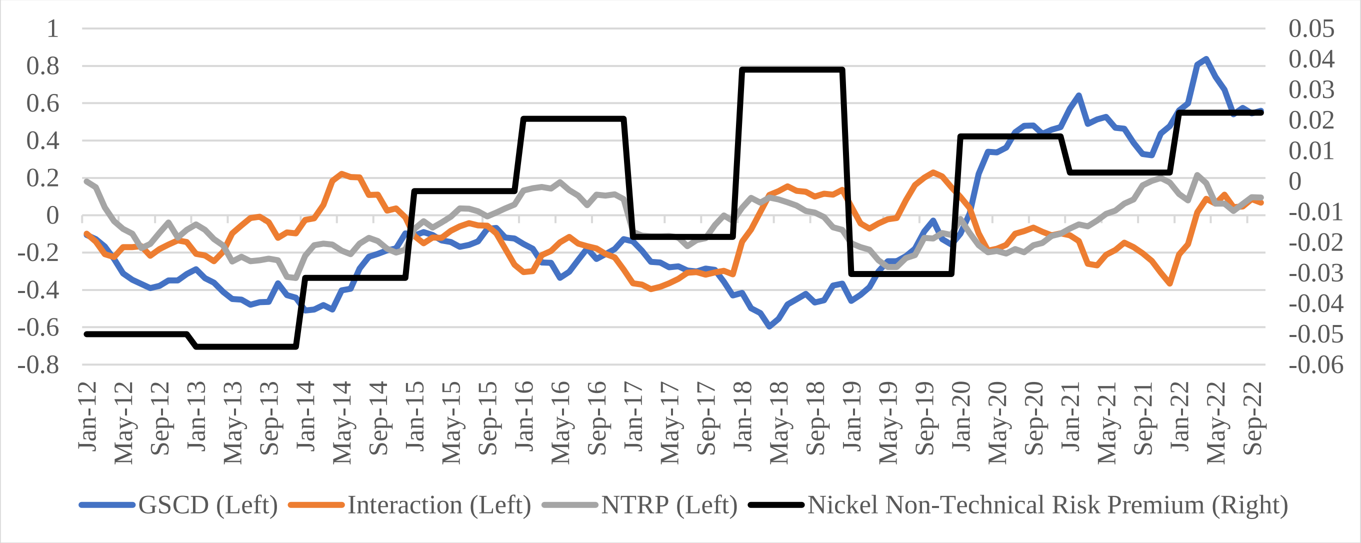
b) Platinum Prices



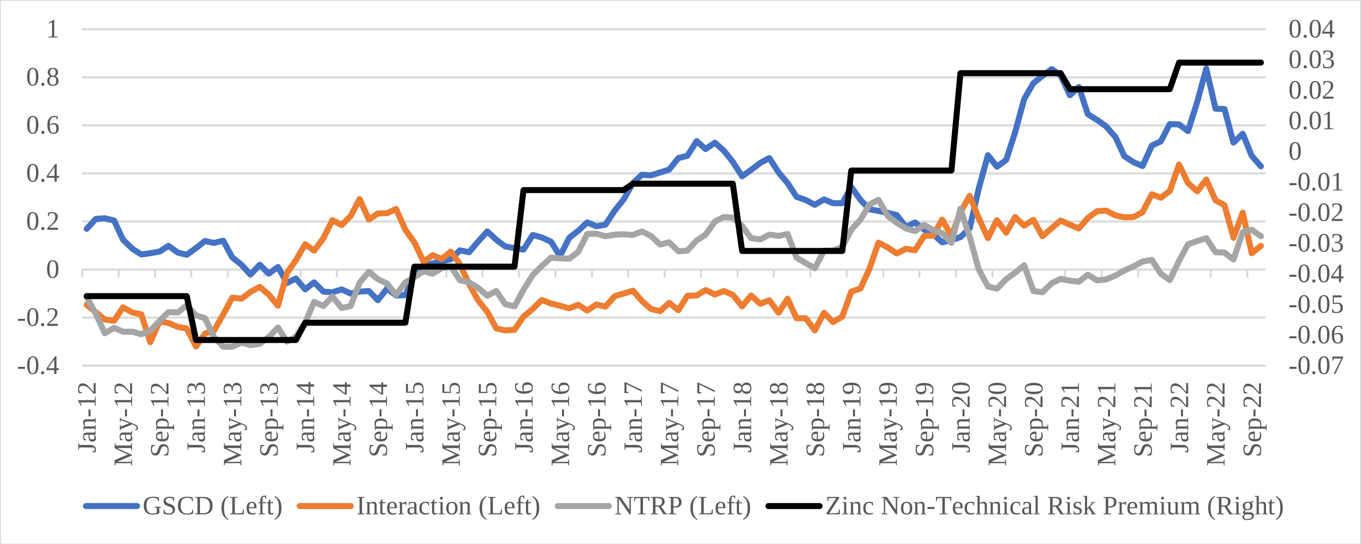
c) Aluminium Prices



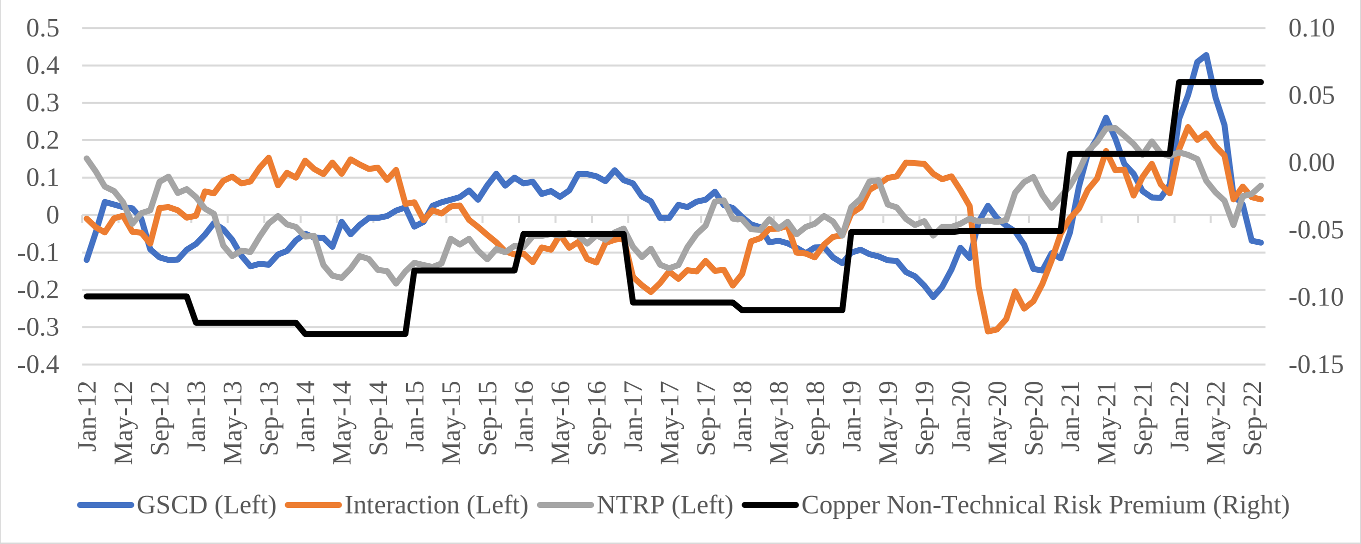
d) Nickel Prices



e) Zinc Prices



f) Copper Prices



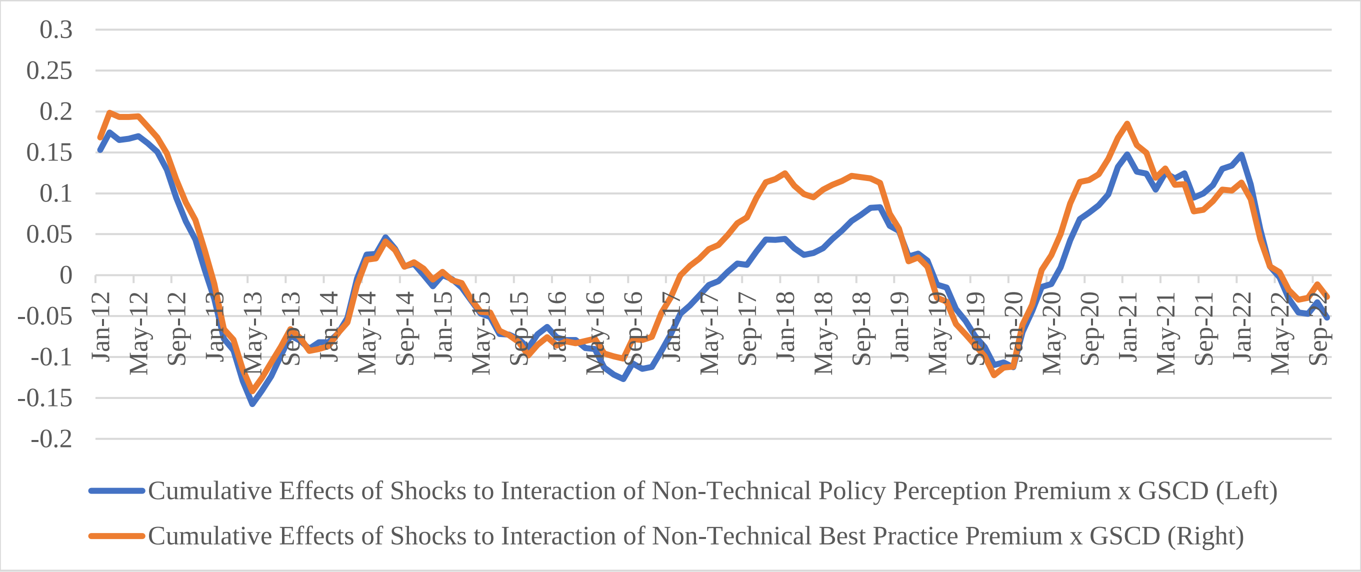
Notes: The figure shows the historical decompositions of critical minerals prices to the structure shocks of global supply chain (GSCD), interaction of GSCD and NTRP (Interaction), Non-Technical Risk Premium for individual critical minerals (NTRP), and the indicator of Non-Technical Risk Premium for individual critical minerals.

Appendix C: Historical Decompositions of Critical Minerals Relative Volatility to the Structure Shocks of the Interaction ($GSCD \times NTRP$ Components - Best Practice Premium and Policy perspective Premium), 2012 - 2022

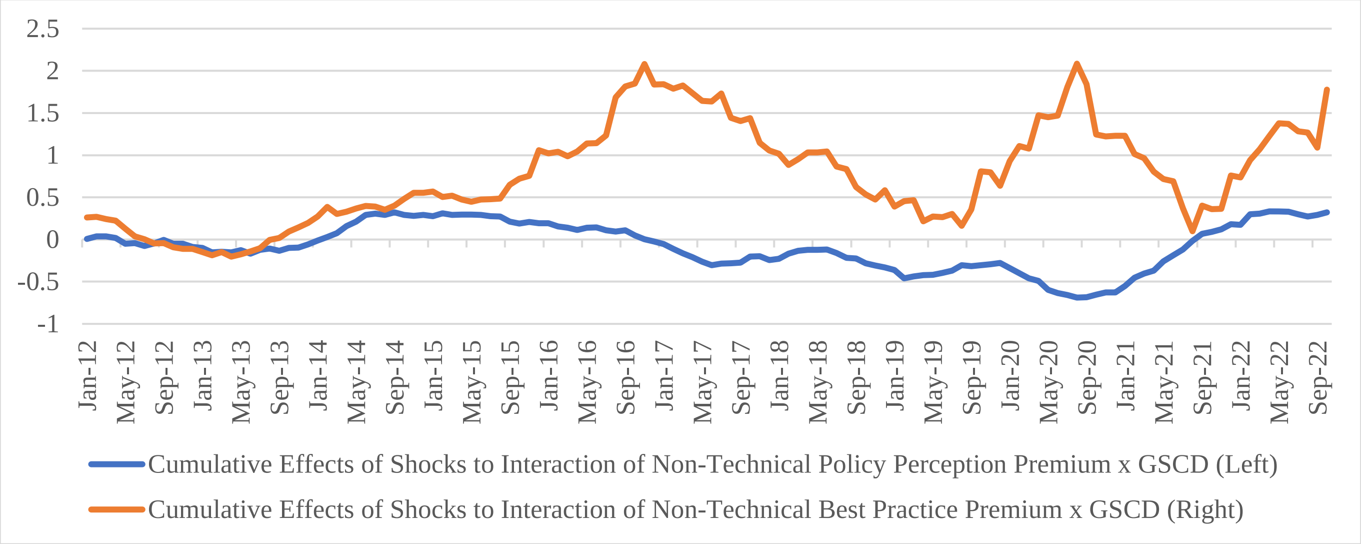
We present figures that show the historical decompositions of relative price volatility of the interaction between GSCD and NTRP ($GSCD \times NTRP$) using the benchmark model by substituting the policy perception risk premiums and best practice risk premiums respectively for NTRP. Overall, the cumulative effects of the interaction between $GSCD$ and non-technical policy perception risk premiums significantly contribute to increased relative volatility of critical mineral prices over the COVID-19 pandemic in 2020 – 2022. Shocks to the interaction between $GSCD$ and non-technical best practice risk premiums show a relatively more persistent cumulative effect on the relative volatility of tin, platinum and aluminium since

2018. Innovations in non-technical policy perception risk premiums exhibit either a relatively short-lived/smaller effect on the relative volatility of \tin, platinum and aluminium. The overall cumulative effects of interaction between $GSCD$ and non-technical policy perception/best practice risk premiums are largely flat on the relative volatility of nickel, zinc, or copper.

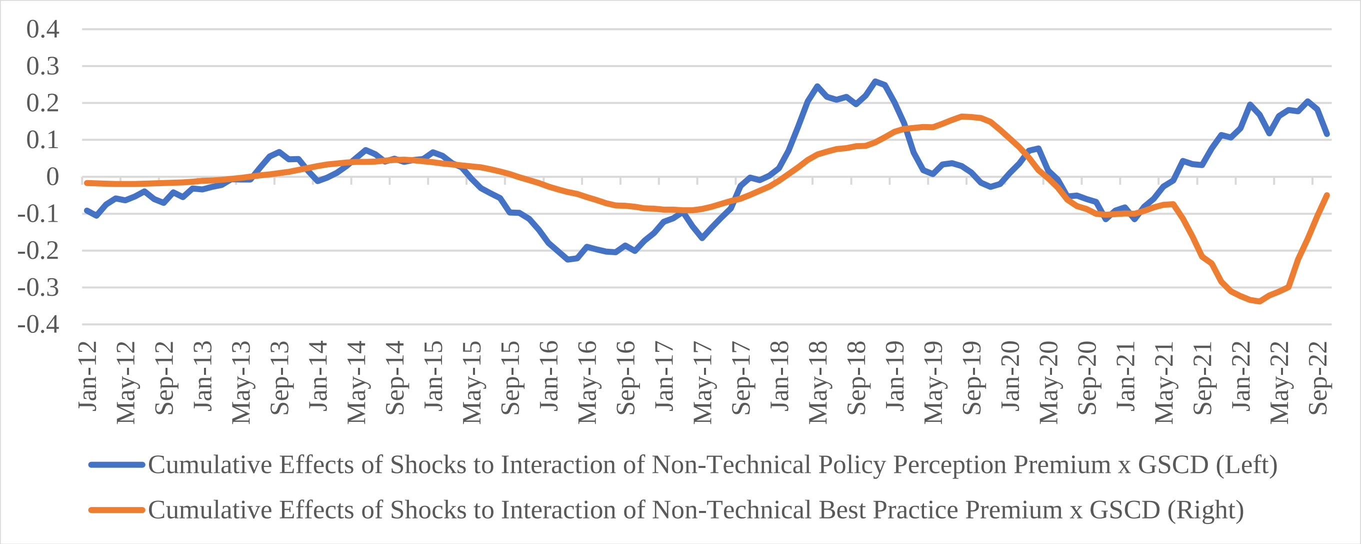
a) Tin Relative Volatility



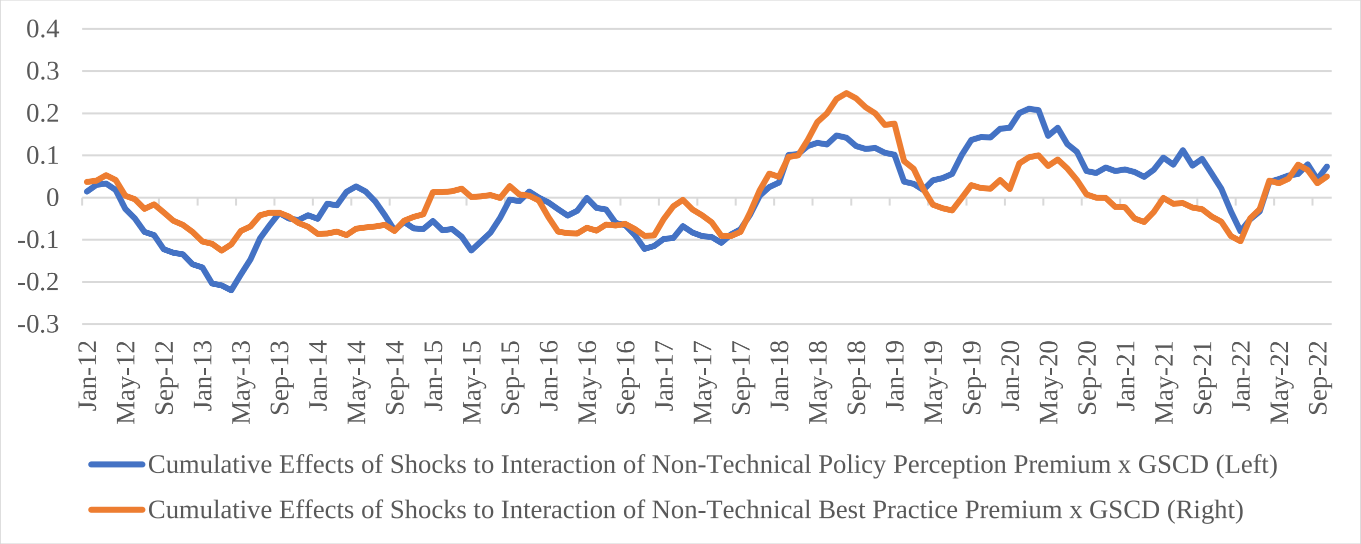
b) Platinum Relative Volatility



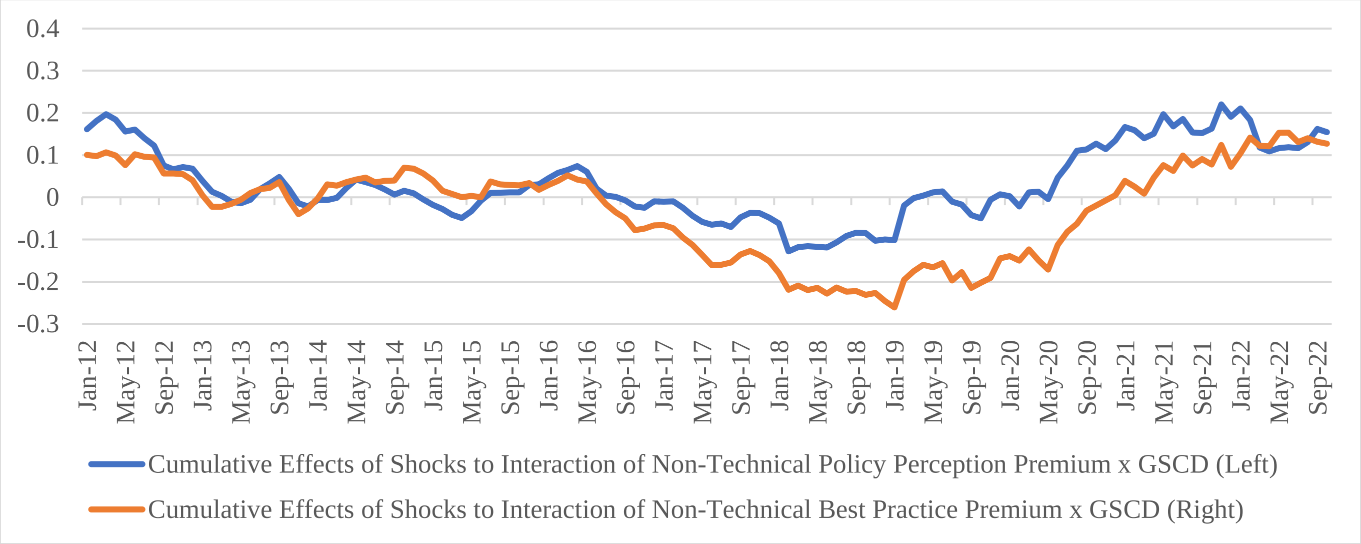
c) Aluminium Relative Volatility



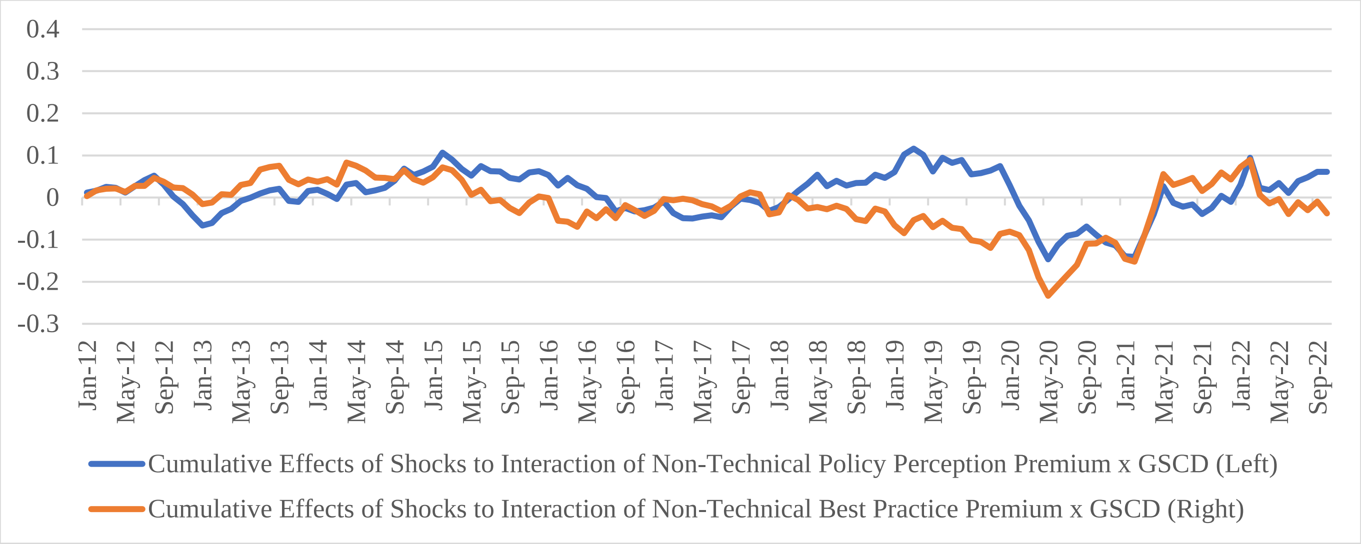
d) Nickel Relative Volatility



e) Zinc Relative Volatility



f) Copper Relative Volatility



Notes: The figure shows the historical decompositions of critical minerals relative volatility to the structure shocks of the interaction of GSCD and NTRP components - best practice premium and policy perspective premium in the year 2012 – 2022.