Monetary Policy Transmission Under Supply Chain Pressure*

Sebastian Laumer† Matthew Schaffer‡

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Abstract

This study examines how global supply chain conditions influence the transmission of US monetary policy during the pre-pandemic period. We find that elevated supply chain pressures amplify the standard effects of monetary policy shocks on macroeconomic outcomes. This amplification arises from an intensification of the credit channel, as financial variables related to the cost of external finance become more sensitive to monetary policy when supply chain conditions are strained. Firm-level estimates of the investment response to monetary policy further support this conclusion. Despite the presence of outliers and other confounding factors, our findings hold when extending the sample beyond 2020.

Keywords: Monetary policy, supply chain disruption, credit channel

JEL Codes: E52, E23, E30

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†University of North Carolina at Greensboro, s_laumer@uncg.edu.

‡Eastern Michigan University, mschaff5@emich.edu.

1 Introduction

Since the beginning of the COVID-19 pandemic in early 2020, the global economy has encountered unprecedented supply chain disruptions. These disruptions have been triggered by a multitude of factors, such as chip shortages[1], the closure of ports[2] and production facilities, backlogs of cargo ships[3], and a lack of truck drivers and shipping containers. At the same time, expansionary fiscal and monetary policy interventions stabilized aggregate demand while households shifted their consumption away from services and towards goods. Both developments put additional pressure on already strained global supply chain systems.

The magnitude of supply chain stress can be observed in Figure 1, which displays Benigno et al. (2022)'s Global Supply Chain Pressure Index (GSCPI). The index measures the common component of several global and country-specific supply chain variables such as cross-border transportation costs, delivery times, backlogs, and inventory. Figure 1 shows that supply chain pressures reached unprecedented heights during the pandemic, and, while peaking in December 2021, nevertheless remained at historically elevated levels until the end of 2022, before normalizing in 2023. Speculation surrounding deglobalization and reshoring, a re-prioritization of robustness over efficiency, and contentious geopolitical developments suggest that global supply chain pressures may remain volatile for years to come. As a result, understanding the macroeconomic implications of supply chain disturbances takes on a new urgency.

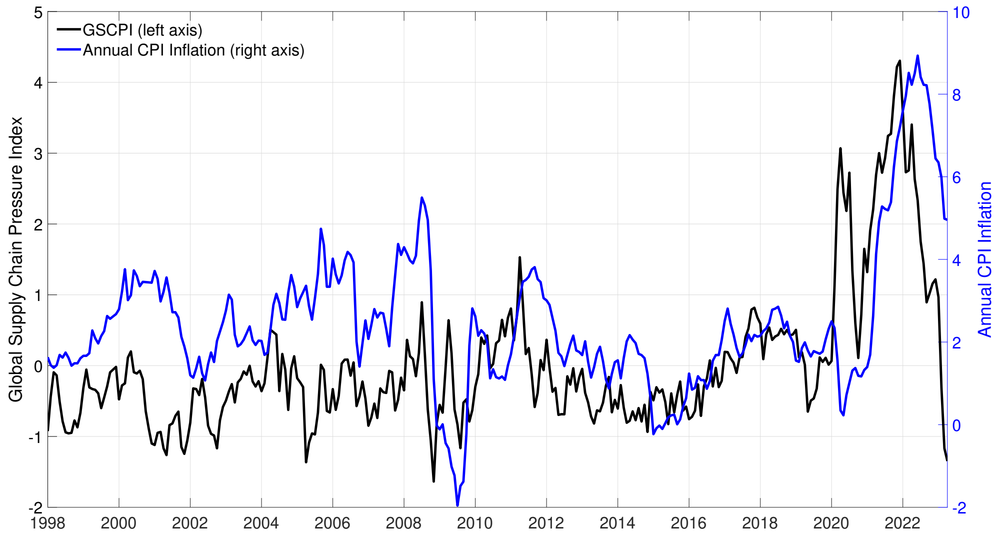
The most recent, pressing challenge for policymakers has been combating decades-high rates of inflation, also shown in Figure 1. Many central banks around the world have sharply increased interest rates in an effort to restore price stability. For example, in 2022 alone, the Federal Reserve raised the federal funds rate by 425 basis points including several rounds of

[1] https://www.latimes.com/business/story/2022-07-01/chip-shortage-keeps-driving-up-auto-prices

[2] https://www.cnn.com/2022/05/06/business/china-lockdowns-global-port-chaos-supply-chains-intl-hnk/index.html

[3] https://www.cnn.com/2021/10/20/business/la-long-beach-port-congestion-problem-national-impact/index.html

Figure 1: Global Supply Chain Pressure Index



Note: The figure shows the Global Supply Chain Pressure Index (GSCPI) developed by Benigno et al. (2022) in black as well as annual rates of CPI inflation in blue. Although global supply chain pressures have reached unprecedented levels since the onset of the pandemic, there have also been notable spikes prior to 2020, e.g., in 2008 during the Great Financial Crisis, in 2011 after the Great East Japan Earthquake, or in 2017/18 following the U.S.-China trade war.

75 basis points hikes. Other central banks such as the Bank of England and the European Central Bank have followed the Fed's example. The economic environment following the COVID-19 pandemic has therefore been characterized by unprecedented levels of supply chain pressure, decades-high rates of inflation and an aggressive tightening of monetary policy. These circumstances motivate the purpose of our study – to better understand how supply chain disruptions influence the transmission of monetary policy.

In this paper, we apply a nonlinear version of the Jordà (2005) local projection (LP) method and use Benigno et al. (2022)'s GSCPI to characterize the state of global supply chain conditions. This approach allows us to examine whether the impact of monetary policy shocks on macroeconomic outcomes varies with the underlying state of supply chain conditions. We uncover that the effects of monetary policy are more pronounced when supply chains face greater disruption. For instance, a contractionary monetary policy shock lowers output and consumer prices in any state, but the decline is more than twice as large for output, and 30% larger for consumer prices, when supply chain pressures are elevated. We report similar amplification effects for other key macroeconomic variables, like retail sales and the unemployment rate.

The amplified response of macroeconomic outcomes during times of supply chain stress can be explained by an intensification of the credit channel of monetary transmission. As argued by, e.g., Bernanke and Gertler (1995), in the presence of financial frictions monetary policy will affect borrowing costs not only through the general level of interest rates, but also through an external finance premium which reflects the fundamentals of a borrower's financial position. We argue that borrower fundamentals become more sensitive to changes in the expected path of interest rates when supply chains face greater disruption. Indeed, in our nonlinear LP framework we show that financial variables related to the cost of external finance become more sensitive to monetary policy when supply chains are strained. A contractionary monetary policy shock results in lower stock prices and higher credit spreads and term premia in any state, but the responses grow significantly in magnitude when supply chain pressures are high. With the external finance premium becoming more sensitive, monetary policy has a larger impact on overall borrowing costs, which, in turn, results in an amplified effect on aggregate demand and outcomes like output and inflation.

We provide additional evidence using micro data from Compustat. Consistent with our baseline results, we find that monetary policy shocks have a larger impact on firm-level investment when supply chain pressures are elevated. Notably, while investment becomes more responsive to monetary policy for all firms, the increased responsiveness in the tight supply chain state is largest for firms that face relatively greater financial constraints. The larger differential response for firms that are most affected by financial frictions provides further support for the hypothesis that supply chain disruptions amplify the macroeconomic impact of monetary policy through an intensification of the credit channel.

As discussed by Ng (2021), many economic time series may have experienced structural breaks in their data generating processes during the pandemic. The pandemic period also introduces a host of factors, like government restrictions on mobility and business openings, that are likely to confound empirical analysis. For these reasons, we restrict our primary focus to a pre-pandemic sample period running from January 1998 to December 2019. Our results remain robust to extending the sample through March 2023, however. Interestingly, while we continue to observe an amplified impact of monetary shocks on macroeconomic outcomes with the extended sample, the dynamics of the impulse responses are altered. Most importantly, there is a longer lag time to the trough/peak of the responses. The longer lag time until peak effect is consistent with the persistence of inflation and resilience of real activity throughout the Fed's aggressive 2022 tightening campaign.

Our results have vital implications for the current policy environment. They suggest that the expansionary policies enacted by the Fed at the onset of the pandemic may have stimulated demand and contributed to inflationary pressures more strongly than expected due to the unprecedented degree of supply chain stress. And, while supply chain pressures have abated since the peak of the pandemic, they nevertheless remained at historically elevated levels during the bulk of the Fed's 2022 tightening cycle. Our results, therefore, imply that the Fed's tightening has a higher likelihood of successfully combating inflation (once appropriate lags have set in) than would be the case under average supply chain conditions. However, they also imply that a meaningful decline in inflation is likely to be accompanied by a relatively weaker real economy due to stronger contractionary effects on output and employment. With supply chain pressures significantly declining in 2023, our results further suggest that any additional tightening by the Fed will likely be less impactful.

Our study is related to several strands of the literature. First, our analysis relates to the literature on the nonlinear effects of monetary policy, see e.g., Weise (1999), Garcia and Schaller (2002), Peersman and Smets (2002), Peersman and Smets (2005) and Tenreyro and Thwaites (2016). These papers analyze how the effect of monetary policy varies with the business cycle. While the earlier studies report a stronger effect of monetary policy during recessions, Tenreyro and Thwaites (2016) find that the effects of monetary policy are "less powerful" during recessions. Our study differs from the pre-existing literature by analyzing the state-dependency of monetary policy with respect to supply chain conditions. Importantly, the GSCPI is purged of demand-side factors related to business cycle fluctuations, which ensures that our results are not driven by co-movement with the business cycle.[4] The findings show that the macroeconomic effect of monetary policy varies significantly with the degree of supply chain pressure in the economy.

Second, our paper is related to the literature that studies production networks, supply chains, and input-output linkages as an amplification mechanism for economic shocks, see e.g., Acemoglu et al. (2016), Barrot and Sauvagnat (2016), Boehm et al. (2019), Acemoglu and Tahbaz-Salehi (2020) and Carvalho et al. (2021). Empirically, Barrot and Sauvagnat (2016) and Boehm et al. (2019) exploit natural disasters as exogenous shocks. They show that the shocks did not only affect firms that were directly hit by the natural disasters, but also the output and sales of their suppliers and customers. Carvalho et al. (2021) estimate the macroeconomic effects of the 2011 Great East Japan Earthquake. They find that the decline in Japan's real GDP growth following the earthquake would have been significantly less severe in the absence of input-output linkages.

A subset of this literature focuses on the amplification of monetary shocks. Theoretical studies such as Carvalho et al. (2021), Pasten et al. (2020), and Nakamura and Steinsson (2010) analyze the role of production networks in enhancing strategic complementarities in price setting and thus increasing short-run money non-neutrality. Ghassibe (2021) provides empirical evidence in favor of this view, finding that the amplification effect of input-output linkages can account for at least 30% of the overall effect of monetary shocks on aggregate consumption. Ozdagli and Weber (2021) find that at least half of the effect of monetary shocks on stock returns can be attributed to indirect production network linkages. The literature has, therefore, identified important ways in which the *existence* of input-output linkages in a production network can amplify the effects of monetary policy. We build upon

[4]According to Benigno et al. (2022), demand-side factors may contaminate the GSCPI to some degree around the Global Financial Crisis, however our baseline results hold even when explicitly controlling for this period.

this pre-existing literature by analyzing how the effect of monetary policy on macroeconomic aggregates varies with the *condition* of global supply chains. Using time series data in a flexible LP framework, we provide novel evidence that elevated supply chain pressure further amplifies the effects of monetary policy.

Third, this study also relates to the credit channel literature that links monetary policy and financial frictions, see e.g., Bernanke and Gertler (1995), Bernanke et al. (1999), Gertler and Karadi (2015), and Ottonello and Winberry (2020). While Smirnyagin and Tsyvinski (2022) report that equity premia increase when individual firms are faced with idiosyncratic supply chain disruptions, we provide novel evidence that the cost of external finance becomes more sensitive to monetary policy in the presence of aggregate supply chain disturbances. Specifically, we show that contractionary monetary policy shocks raise (lower) credit spreads and term premia (stock prices) *more* when supply chain pressures are high, thereby providing an economic explanation for the larger effect of monetary policy on macroeconomic aggregates.

Lastly, our paper is related to the small but growing literature on aggregate supply chain shocks, e.g., Finck and Tillmann (2022); Kuehl et al. (2022); Burriel et al. (2023); Gordon and Clark (2023) and Bernanke and Blanchard (2023). The findings of this literature suggests that shocks to (global) supply chains lead to increases in consumer, producer and import prices. The focus of this study differs from the aforementioned series of papers. We do not study the effects of supply chain shocks, but instead focus on how the effects of US monetary policy shocks are influenced by the state of global supply chain disruptions.

The paper proceeds as follow. Section 2 explains our methodology. Section 3 presents our main results. Section 4 discusses firm-level evidence. Section 5 extends our baseline analysis through the COVID-19 pandemic. Section 6 describes robustness checks. Section 7 discusses and concludes.

2 Methodology

In this section, we describe a number of important details of our econometric methodology. We first generally explain Jordà (2005)'s local projection method that we use to estimate impulse response functions. We then adapt the method to our nonlinear setting. Finally, we outline the Global Supply Chain Pressure Index (GSCPI), developed by Benigno et al. (2022), which is used to capture the degree of supply chain pressure in the economy.

2.1 Local Projection Method

In this study, we use Jordà (2005)'s local projection method to estimate impulse response functions. The following equation represents the linear local projections model:

$$ln(x_{t+h}) = c^h + \sum_{j=1}^{J} \alpha_j^h ln(x_{t-j}) + \sum_{j=0}^{J} \beta_j^h shock_{t-j} + \sum_{j=0}^{J} \Gamma_j^h Z_{t-j} + \epsilon_{t+h},\ h = 0, ..., H, \quad (1)$$

where c is a constant, x is the outcome variable of interest, *shock* is the macroeconomic shock of interest, Z is a vector of control variables, and ϵ is the residual. The local projection method involves a series of regressions for each variable of interest for each of the H impulse response horizons. The key object of interest is the parameter β_0^h. This parameter captures the effect of the macroeconomic shock on the variable of interest h periods after the shock hits the economy. The series of parameters $\{\beta_0^h\}_{h=0}^H$ then gives the impulse response function, i.e., the response of the variable of interest to the shock over time.

Here, we are interested in the macroeconomic effects of a monetary policy shock. To identify a monetary policy shock, we follow the most recent advancements in the literature and rely on high-frequency identification, e.g., following Gürkaynak et al. (2005), Gertler and Karadi (2015) and Nakamura and Steinsson (2018). The idea behind this approach is to isolate the change in a financial variable(s) that captures the stance of monetary policy in a tight window around a central bank policy announcement. As long as no other market moving events occur within the window, the change in the price of the financial variable(s) around the announcement will capture any unanticipated changes in monetary policy. The resulting time series of "surprises" can then be used as a measure of the monetary policy shock.

The monetary shock used in our baseline specification is the daily change in the two-year Treasury zero-coupon yield around FOMC announcements.[5] We focus on changes in the two-year nominal yield for two reasons. First, as argued by Hanson and Stein (2015), it allows us to capture revisions to the expected path of interest rates over a two-year horizon in a straightforward manner – in other words, it accounts for surprise changes in forward guidance in addition to immediate federal funds rate surprises. Second, it allows us to maintain a consistent shock measure across all sample periods, which becomes important when extending our sample in Section 5.

We use two additional monetary shock measures for robustness checks. The first is akin to the "policy news shock" from Nakamura and Steinsson (2018). Specifically, it is constructed using four Eurodollar futures contracts, expiring 1 quarter ahead (ED1) to 4 quarters ahead (ED4). We perform a principal component analysis on the daily changes in the four futures prices around FOMC meetings. The first principal component, which accounts for over 90% of the variation across the four contracts, is then used as the alternative shock measure.[6] We also use the unified monetary shock measure from Bu et al. (2021), which has the advantage of being uncontaminated with potential central bank information effects, as an additional robustness check. For all three measures, a monthly shock series is constructed by summing all high frequency shocks occurring in a given month and setting the series to zero in months without a FOMC meeting. Each measure is normalized so that the impulse response coefficients can be interpreted as the effect of a one standard deviation shock.

Local projections are easily adaptable to nonlinear or state-dependent settings like the

[5]Zero-coupon yields are from Gürkaynak et al. (2007).

[6]Our Eurodollar futures data ends in 2019, hence we are not able to use this shock when extending the sample period to include the pandemic.

one underlying our research question, see e.g., Jordà (2005) or Ramey and Zubairy (2018). For example, Equation (1) can be extended to

$$\begin{aligned} ln(x_{t+h}) = c^h + \sum_{j=1}^{J} \alpha_j^h ln(x_{t-j}) + \sum_{j=0}^{J} \beta_j^h mp_{t-j} + \psi_j^h GSCPI_{t-1} \\ + \sum_{j=0}^{J} \delta_j^h GSCPI_{t-1} mp_{t-j} + \sum_{j=0}^{J} \Gamma_j^h Z_{t-j} + \epsilon_{t+h},\ h = 0, ..., H, \end{aligned} \tag{2}$$

where $GSCPI$ is the Global Supply Chain Pressure Index (GSCPI) which is described in detail in the next subsection, and mp is the high-frequency monetary policy shock. In a nutshell, the GSCPI captures the state of global supply chains and is used here to distinguish between different states of aggregate supply chain conditions. In Equation (2), the main objects of interest are β_0^h and δ_0^h. The GSCPI is normalized so that β_0^h measures the effect of a monetary policy shock on the variable of interest when global supply chain pressures are at their sample average, i.e., when supply chain conditions are "normal". By contrast, δ_0^h captures the *additional* impact of a monetary policy shock when global supply chain pressures are high, i.e., one standard deviation above the sample average. In Section 3, we use $\{\beta_0^h\}_{h=0}^H$ and $\{\beta_0^h + \delta_0^h\}_{h=0}^H$ to study the impulse responses of key economic variables to a monetary policy shock when supply chain pressures are normal and elevated, respectively. Moreover, we use $\{\delta_0^h\}_{h=0}^H$ to test whether the difference in responses across supply chain states is statistically significant. AIC values suggest setting j =2, hence we include two lags of all right hand side variables in our estimation.

Summary statistics for the variables of interest are presented in Table 1. There are 264 monthly observations from January 1998 through December 2019. All macro variables other than the unemployment rate are in log form. For the financial variables, all variables are in percentage points, except the S&P 500 which is in log form. The monetary policy shock is normalized so that a unit change is equivalent to a one standard deviation change. The GSCPI is normalized to have mean zero and unit standard deviation over the 1998-2019 sample period.

Table 1: Summary Statistics (Jan. 1998 - Dec. 2019)

	Mean	Median	Std Dev	Min	Max	Obsv.
Shock						
Monetary policy shock	-0.04	0.00	1.00	-4.17	7.82	264
State Variable						
Global Supply Chain Pressure Index	0.00	-0.09	1.00	-2.59	3.70	264
Macro Variables						
Industrial Production	4.56	4.57	0.06	4.43	4.65	264
Consumer Price Index	5.34	5.37	0.14	5.09	5.55	264
Unemployment Rate	5.74	5.10	1.78	3.50	10.00	264
Retail Sales	12.80	12.80	0.22	12.35	13.17	264
Financial Variables						
S&P 500	7.28	7.19	0.34	6.60	8.08	264
Excess Bond Premium	0.11	-0.11	0.71	-1.09	3.47	264
Two-Year Term Premium	0.17	0.17	0.27	-0.35	0.83	264
Ten-Year Term Premium	0.56	0.55	0.56	-0.74	1.85	264

Note: The table presents summary statistics for variables used in the empirical analysis. Data is monthly over a January 1998 to December 2019 sample period. IP, CPI, retail sales, and the S&P 500 are in log form.

2.2 Global Supply Chain Pressure Index

The nonlinear version of the local projection method requires a variable that captures the underlying state of the economy that the researcher wants to analyze. In this study, we are interested in how the effect of a monetary policy shock may or may not depend on global supply chain conditions. Consequently, we need to employ a variable that captures the state of supply chain pressures during our sample period. Benigno et al. (2022) from the Federal Reserve Bank of New York have developed such a variable, the Global Supply Chain Pressure Index (GSCPI).

To construct the GSCPI, Benigno et al. (2022) collect data on 27 variables. The first six measure cross-border transportation costs: the Baltic Dry Index, which tracks the cost of shipping raw materials; the Harper Index, which tracks container shipping rate changes; and US Bureau of Labor Statistics price indices, which track the cost of air transportation of freight to and from the United States from Asia and Europe. The remaining variables capture country-level manufacturing conditions from Purchase Manager Index (PMI) surveys. Seven countries that play an important role in global supply chain networks, and which have a sufficient history of data available, are included: China, the European Union, Japan, South Korea, Taiwan, the UK and the US. For each country, data on manufacturing delivery times, backlogs, and purchased stocks is incorporated.

The 27 variables are purged of demand side factors by making use of additional information from the PMI surverys. The six cross-border transport costs variables are individually regressed on GDP-weighted averages of the "new orders" and "quantities purchased" PMI subcomponents, where "new orders" proxy for customer demand for firms' products and "quantities purchased" proxies for producers' input demand. The residuals, which can be interpreted as the variation in the transport cost measures attributable to supply factors, are then used as inputs for the construction of the GSCPI. Similarly, the 21 country-specific measures on manufacturing conditions are individually regressed on the contemporaneous value and two lags of that country's "new orders" subcomponent and the residuals are taken as inputs to the GSCPI. After purging the 27 variables of demand-side influence, Benigno et al. (2022) perform a principal component analysis and take the first principal component as the Global Supply Chain Pressures Index.

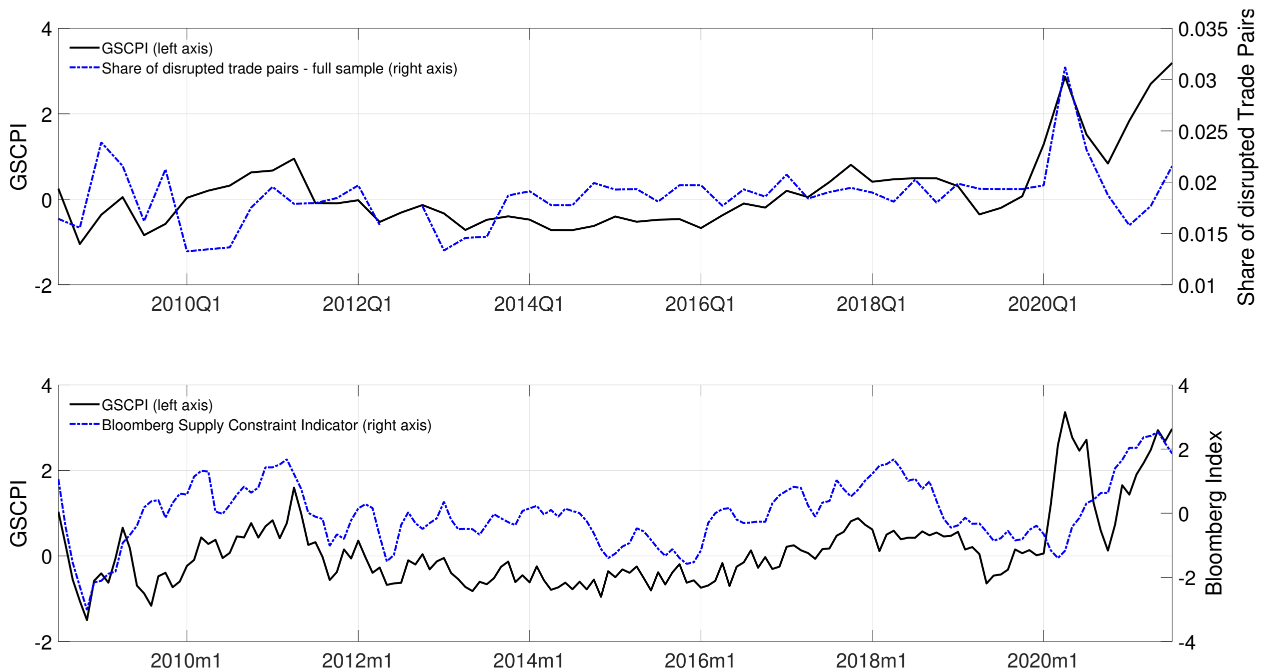
The GSCPI, as displayed in Figure 1 is a monthly index beginning in January 1998. It is normalized so that a value of zero means supply chain pressures are at the sample average.[7] A positive value represents how many standard deviations the index is above average and a negative value represents how many standard deviations the index is below average. In other words, positive values represent elevated supply chain pressures while negative values correspond to a low degree of supply chain pressure.

Apart from a few periods, the GSCPI is negative for the early part of the sample. Hence, supply chain pressures were below average between 1998 and 2008. During the Global Financial Crisis, the GSCPI bounces up and down. In 2011, the GSCPI reaches its pre-

[7]The GSCPI as displayed in Figure 1 is normalized relative to a sample ending in 2022. In our empirical analysis, we re-normalize relative to our 1998-2019 sample period, so that a value of zero represents average pre-pandemic conditions.

COVID-19 peak. This is due to flooding in Thailand and the Tuhoku earthquake in Japan, which led to substantial supply chain disruptions in manufacturing even in the US, see e.g., Barrot and Sauvagnat (2016). Between 2012 and 2017, the GSCPI is negative before it begins to rise in 2017 due to the tariff battle between the US and China (Benigno et al., 2022). Since the outbreak of the COVID-19 pandemic the GSCPI has spiked to previously unseen levels, reaching a peak in late 2021. The GSCPI remained elevated throughout 2022, before declining rapidly in the first half of 2023.

Figure 2: Comparison of the GSCPI with other measures of Supply Chain Disruption



Note: The figure compares the Global Supply Chain Pressure Index (GSCPI) from Benigno et al. (2022) with alternative measures of supply chain disruptions. The left subplot includes the share of disrupted trade pairs from Smirnyagin and Tsyvinski (2022) over their quarterly 2008 to 2021 sample. The right subplot includes the Bloomberg Supply Constraint Indicator over a monthly 2008 to 2021 sample.

Figure 2 compares the GSCPI with two alternative measures of supply chain disruptions. The top panel compares the GSCPI to the share of disrupted trade pairs from Smirnyagin and Tsyvinski (2022). The measures are positively correlated (correlation coefficient: 0.39) and display spikes at similar times, e.g., during the Great Recession 2008/09 and following the Tohuku Earthquake in Japan. The bottom panel shows the GSCPI together with the

Bloomberg Supply Constraint Indicator.[8] The two indexes are also positively correlated (correlation coefficient: 0.53) and exhibit similar behavior around key dates, e.g., both measures are elevated following the 2011 Earthquake in Japan, increase during the US-China tariff dispute, and reach unmatched levels during the COVID-19 pandemic. These alternative measures of supply chain disruptions only become available in 2008, making them ill-suited to be used in our empirical analysis. However, the fact that they are positively correlated with the GSCPI, and share similar dynamics around key events, supports our use of the GSCPI as a gauge of aggregate supply chain conditions.

3 Results

This section presents our main results. We first show the impulse responses of macroeconomic aggregates and then the impulse responses of financial variables related to the cost of external finance. The Appendix provides additional figures and robustness analysis. All responses are normalized to a one standard deviation contractionary monetary policy shock. Point estimates are illustrated by the blue solid line, 68-percent confidence intervals are in dark gray and 90-percent confidence intervals are in light gray with dashed lines.

3.1 Macro Variables

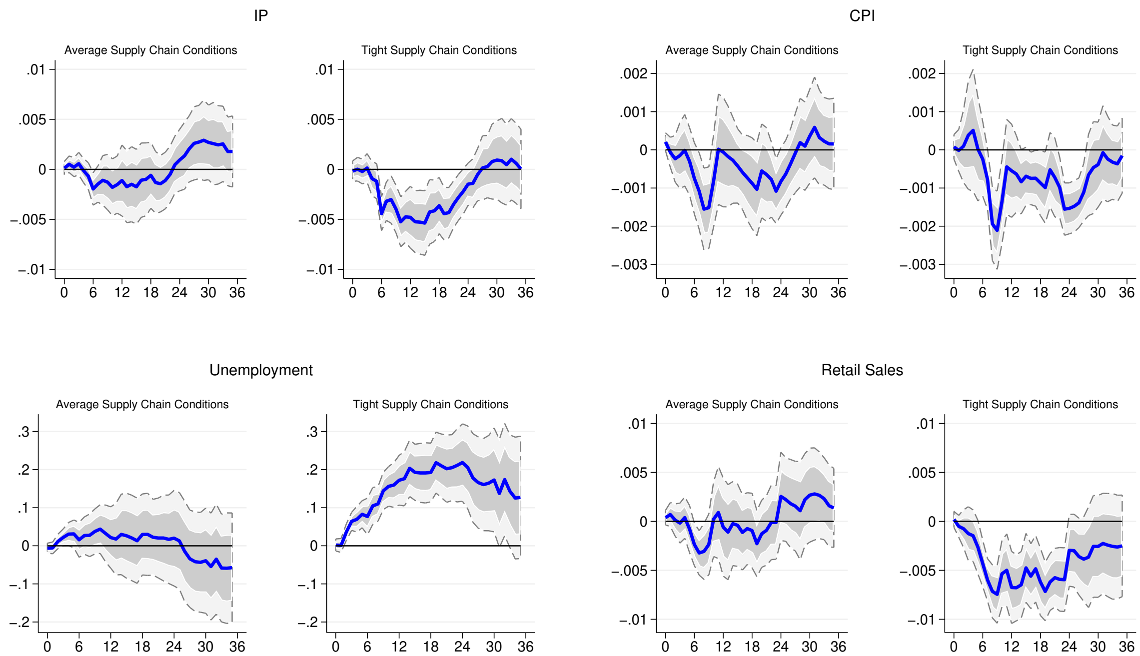
Figure 3 shows the impulse responses of industrial production, the consumer price index, the unemployment rate and retail sales to a contractionary monetary policy shock when supply chain conditions are average (left subplots) and tight (right subplots).[9]

Our baseline results show that heightened supply chain pressures amplify the effects of a monetary policy shock on aggregate macroeconomic outcomes. In the top left panel of Figure 3, a contractionary monetary policy shock leads to a decline in industrial production

[8] `https://www.bloomberg.com/toaster/v2/charts/e0919ea0c2234156901aaafa49203249.html?brand=business&webTheme=light&web=true&hideTitles=true`.

[9] In all figures, "tight supply chain conditions" refers to a state where the GSCPI is one standard deviation above average.

Figure 3: State-dependent impulse responses. Macro variables

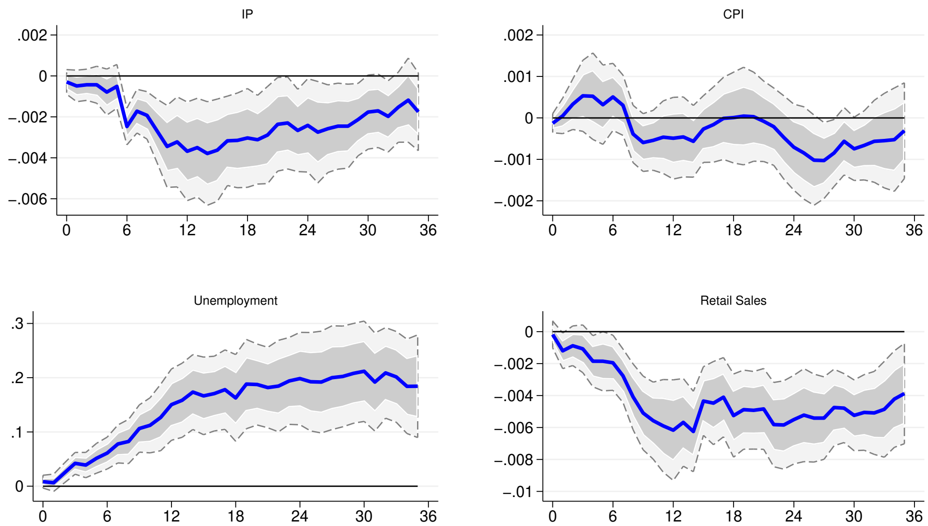


Note: The figure shows the state-dependent impulse response of industrial production, the consumer price index, the unemployment rate and retail sales to a contractionary monetary policy shock. The left panel shows the response (β_0^h) when supply chain pressures are at their sample (1998-2019) average. The right panel shows the response when supply chain pressures are one standard deviation above average ($\beta_0^h + \delta_0^h$). The light grey shaded areas indicate 1.65 standard deviation confidence intervals and the dark grey shaded areas indicate 1 standard deviation confidence intervals constructed from Newey-West standard errors.

with a short delay in both supply chain states.[10] However, the decline is stronger and longer lasting when supply chains are disrupted. Specifically, there is a statistically significant 0.20% decline in IP six months after the shock when supply chain conditions are average. When supply chain pressures are one standard deviation above average the peak effect is more than double in magnitude – a 0.54% decline, fifteen months after the shock. Not only is the peak effect larger in magnitude when supply chain pressures are elevated, but the decline is also significant for a longer period – from roughly three to twenty months following the

[10] Our figures display impulse responses to a positive (contractionary) shock, but it should be noted that the estimates are symmetric, i.e., flipping the sign gives the response to a negative (expansionary) shock. To test for potential asymmetry, we have also conducted the same exercise with i) only expansionary and ii) only contractionary monetary policy shocks and do not find any meaningful differences (results available upon request).

Figure 4: Differential responses. Macro variables



Note: The figure shows the *additional response* (δ_0^h) of industrial production, the consumer price index, the unemployment rate and retail sales to a contractionary monetary policy shock during a period of elevated supply chain pressure, relative to an average period. The light grey shaded areas indicate 1.65 standard deviation confidence intervals and the dark grey shaded areas indicate 1 standard deviation confidence intervals constructed from Newey-West standard errors.

shock.

Figure 3 depicts a similar result for CPI and retail sales. A contractionary shock reduces consumer prices and retail sales by more and for a longer duration when supply chains face greater disruption. The decline in CPI reaches a statistically significant trough after eight months in either state, but the magnitude is nearly 30% larger when supply chain pressures are elevated (-0.21%) compared to when pressures are at their historical average (-0.16%). For retail sales, the peak decline is over twice as large (-0.75% vs -0.32%) when supply chains are disrupted, and the duration of the decline is much longer, lasting from six to twenty-four months after the shock.

Lastly, the unemployment rate increases by a much larger magnitude and for a longer duration following a contractionary shock when supply chain pressures are greater. Indeed, the peak effect when supply chain conditions are average is a marginally significant 0.04 percentage point increase ten months after the shock. In contrast, the peak effect under elevated pressures is a 0.22 percentage point increase after twenty-four months, and the increase remains statistically significant over a twenty-seven month horizon (from three to thirty months after the shock).

Figure 4 illustrates that the responses across states are also statistically different, i.e., the figure shows that the *additional effect* of a contractionary monetary policy shock when supply chains are disrupted, δ_0^h, is statistically different from zero. With a short delay of a few months, we find this to be the case for all four macro variables. The responses of industrial production, retails sales and the unemployment rate remain statistically different for at least twenty-four months. The CPI response is more nuanced and only statistically different at the 68-percent confidence interval between seven and fourteen months as well as between twenty-four and thirty-four months after the shock. Overall, our results indicate that the standard responses of macroeconomic outcomes to a monetary shock, e.g., as shown in Gertler and Karadi (2015), are significantly larger in the face of heightened supply chain pressures.

3.2 Financial Variables

The question that naturally follows is, what explains the larger impact of monetary policy shocks in states of heightened supply chain pressure? We argue that this amplification effect occurs due to an intensification of the credit channel of monetary transmission. Consider a simple illustration of the credit channel from Bean et al. (2002). The interest rate faced by firms, R_t, is equal to the risk-free rate plus an external finance premium:

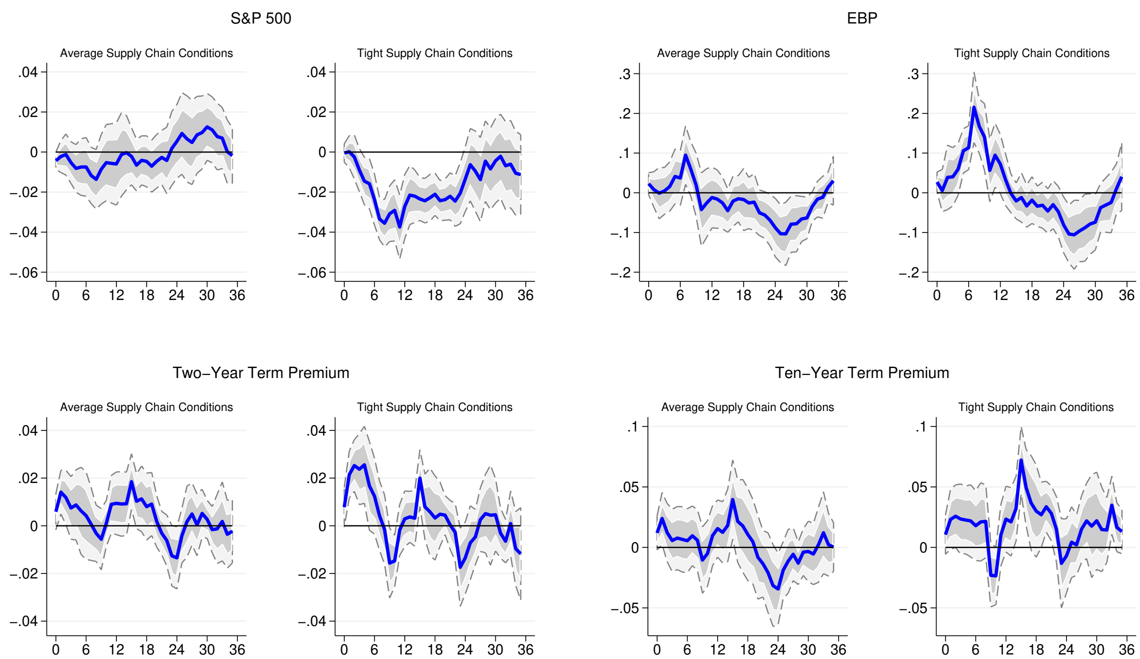
$$R_t = R_t^* + f_t(D_t/E_t) \qquad (f' > 0) \tag{3}$$

where the risk-free rate, R_t^*, is the central bank's policy tool and the external finance premium is a function of the firm's financial position, represented here as a simple debt-to-equity ratio. A long line of literature, including Bernanke and Gertler (1995), has argued that changes to the risk-free rate will directly and indirectly alter a firm's financial position. Since many firms finance inventories and working capital with short-term debt, an increase in interest rates will directly increase borrowing costs ($\uparrow D$). To the extent that higher rates depress demand for a firm's product, there will also be a decline in the expected future cash flows that determine a firm's equity value ($\downarrow E$). A weaker balance sheet, as stylized through a higher debt-to-equity ratio ($\uparrow D/E$), increases the external finance premium ($\uparrow f(D/E)$) and makes it even more costly for firms to access external funds. A policy-induced increase in the risk-free rate will, therefore, increase firm borrowing costs more than one-for-one due to the rise in the external finance premium.

The credit channel of monetary transmission is operative in any state of the world that exhibits information asymmetries, or frictions, in financial markets. However, we postulate that the external finance premium becomes *more* sensitive to changes in the risk-free rate in a state of heightened supply chain pressure. This heightened sensitivity can arise from multiple sources. When supply chains are disrupted, and there is greater uncertainty around the availability of upstream supply or the timing of downstream demand, firms may desire to keep larger stocks of inventories or rely more heavily on working capital. Accordingly, with larger short-term debt requirements, a given increase in interest rates will result in a larger increase in borrowing costs ($\uparrow\uparrow D$). Alternatively, production delays resulting from input scarcity or revenue uncertainty stemming from downstream disruptions, may produce larger downward revisions to expected future cash flows ($\downarrow\downarrow E$) following an increase in rates. It is also possible that investors and lenders place a greater weight on a firm's financial position during times of aggregate supply chain distress ($f'_{tight} > f'_{average}$). Regardless of the precise source, if a strengthening of the credit channel underpins the amplified response of macroeconomic variables documented in Section 3.1, we would expect to observe an increased sensitivity of external financing costs to monetary policy when global supply chain pressures are elevated.

We use the nonlinear LP framework from Equation (2) to examine this hypothesis. Specifically, we replace the four macroeconomic outcome variables with four financial variables related to the cost of obtaining external finance: the S&P 500 stock index, the Gilchrist and Zakrajšek (2012) excess bond premium, and the two-year and ten-year Treasury term premia.[11] The contemporaneous values and two lags of IP, CPI, the unemployment rate, and retail sales are included as controls on the right-hand side, along with two lags of the financial outcome of interest. Once again, the parameters of interest are β_0^h and δ_0^h, where $\{\beta_0^h\}_{h=0}^H$ and $\{\beta_0^h + \delta_0^h\}_{h=0}^H$ are the impulse responses of the financial variables to a monetary policy shock when supply chain pressures are average and tight (one standard deviation above average).

Figure 5: State-dependent impulse responses. Financial variables



Note: The figure shows the state-dependent impulse response of the S&P 500, excess bond premium, and the two and ten-year term premium to a contractionary monetary policy shock. The left panel shows the response (β_0^h) when supply chain pressures are at their sample (1998-2019) average. The right panel shows the response when supply chain pressures are one standard deviation above average ($\beta_0^h + \delta_0^h$). The light grey shaded areas indicate 1.65 standard deviation confidence intervals and the dark grey shaded areas indicate 1 standard deviation confidence intervals constructed from Newey-West standard errors.

[11]The term premia are calculated via the Kim and Wright (2005) methodology.

Figure 5 presents the state-dependent impulse responses. The response of stock prices is largely insignificant when supply chain conditions are average, but there is a highly significant 3-4% decline in the S&P 500 roughly six to twelve months following a contractionary shock when conditions are tight. This indicates equity values becomes much more sensitive to monetary policy when global supply chain pressures are elevated. This result is complementary to Smirnyagin and Tsyvinski (2022), who find that equity premia increase for firms struck by idiosyncratic supply chain disruptions. The top left panel of Figure 6 shows the differential response across states (δ_0^h) and confirms that the greater sensitivity is statistically significant.

Next, we turn our attention to the excess bond premium (EBP). The EBP measures the portion of the interest rate spread between an index of corporate bonds and an equivalent maturity government bond that is not due to default risk. It can therefore be interpreted as the difference in credit costs between otherwise equivalent private and government securities that is purely attributable to the existence of financial frictions. The EBP therefore serves as a direct measure of the external finance premium for large firms.[12]

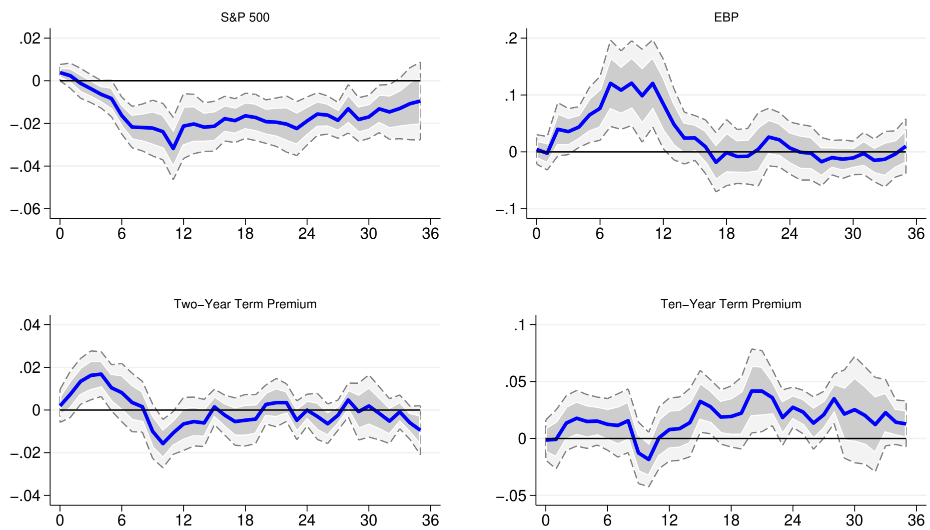
The top right panel of Figure 5 documents a larger response of the EBP when supply chain pressures are elevated. Shortly after the shock, the EBP increases in both supply chain states. However, the increase is more pronounced when supply chain pressures are high. As shown in Figure 6, the effects across states are statistically different between four and twelve months after the shock. In fact, the peak EBP response more than doubles under tight supply chain conditions.[13] Appendix Figure A.1 repeats this exercise for three other measures of credit spreads that do not adjust for default risk. The commercial paper spread responds similarly to the EBP, as there is a significantly larger response around six months after the shock. In addition, the response of the corporate BAA spread is statistically elevated

[12]In addition to its appealing conceptual interpretation, Gilchrist and Zakrajšek (2012) also show that the EBP has the strongest forecasting power for economic activity relative to other financial indicators.

[13]The peak EBP response occurs seven months after the shock. It is 0.09 basis points under average supply chain conditions and 0.22 basis points under tight supply chain conditions. The null that the responses are statistically equivalent is rejected with a p-value of 0.010.

after eighteen months, while the response of the corporate AAA spread is only statistically amplified after eighteen months under the 68-percent confidence interval.[14] All together, the evidence points towards an increased sensitivity of credit spreads to monetary policy under tight supply chain conditions.

Figure 6: Differential responses. Financial variables



Note: The figure shows the *additional response* (δ_0^h) of the S&P 500, the excessive bond premium, and the two and ten-year term premium to a contractionary monetary policy shock during a period of elevated supply chain pressure, relative to an average period. The light grey shaded areas indicate 1.65 standard deviation confidence intervals and the dark grey shaded areas indicate 1 standard deviation confidence intervals constructed from Newey-West standard errors.

The bottom panels of Figure 5 show that the responses of Treasury term premia to a contractionary monetary policy shock also vary with the state of supply chain conditions. The two and ten-year term premia increase following a monetary tightening, but more so when the shock occurs during tight supply chain conditions. As Figure 6 shows, the difference for the two-year is only statistically significant between two and six months following the shock. The difference of the ten-year term premia is significant between twenty and twenty-eight months after the shock, but it remains persistently elevated for up to three years after the shock. Appendix Figure A.2 repeats this exercise for the one- and five-year

[14]The commercial paper, AAA, and BAA spreads are constructed relative to the federal funds rate.

Treasury term premia as well. The differential responses are very similar to the two and ten-year, respectively, as there is an immediate and significantly higher spike in the one-year term premium following the shock and a persistently elevated response in the five-year term premium. As term premia represent the extra return that investors require to take on the risk associated with a longer term maturity, their greater responsiveness offers additional evidence that borrowing costs become more sensitive to monetary policy when supply chains are disrupted.

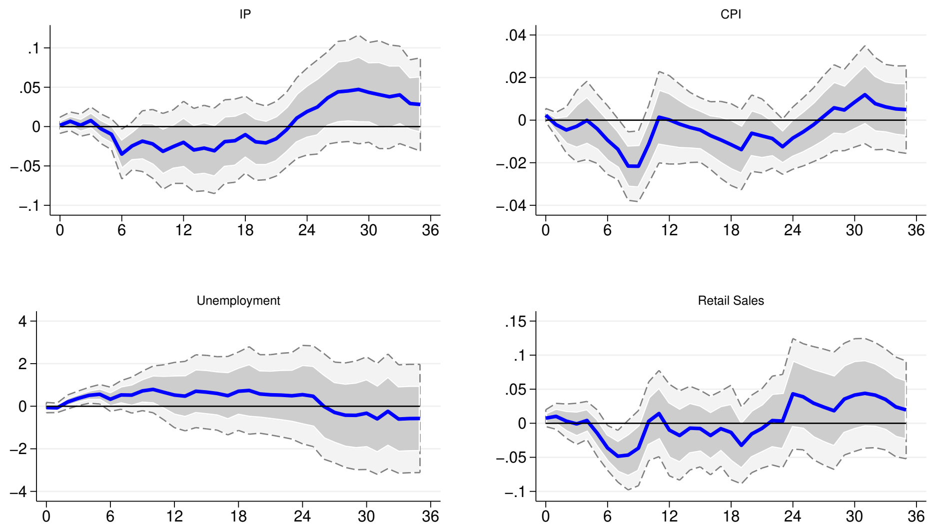
Overall, the larger responses of all four financial variables to monetary shocks when the economy faces greater supply chain pressures is consistent with an intensification of the credit channel. A greater sensitivity of the external finance premium when global supply chains are strained rationalizes the amplified effect of monetary policy on key macroeconomic outcomes documented in Section 3.1.

3.3 Comparison of linear and state-dependency impulse responses

Next, we estimate the linear version of Jordà (2005)'s local projection method, i.e., Equation (1), and compare the resulting impulse responses to their state-dependent counterparts from the previous two subsections. This additional exercise serves two purposes. First, it helps to establish that our LP specification produces results that are comparable to previous studies, e.g., by yielding the expected signs of the impulse responses of key macroeconomic and financial variables. Second, by doing so, we can highlight that the typical effects of contractionary monetary policy shocks on the economy are almost exclusively driven by periods of stressed supply chain conditions. Figures 7 and 8 present results from the linear model.

Figure 7 shows the impulse responses of output, inflation, the unemployment rate, and retail sales. Following a contractionary monetary policy shock, output, inflation and retail sales decrease, while the unemployment rate increases. The point estimates have the expected signs, while the magnitudes are small and confidence intervals often include zero. This

Figure 7: Linear impulse responses. Macro variables

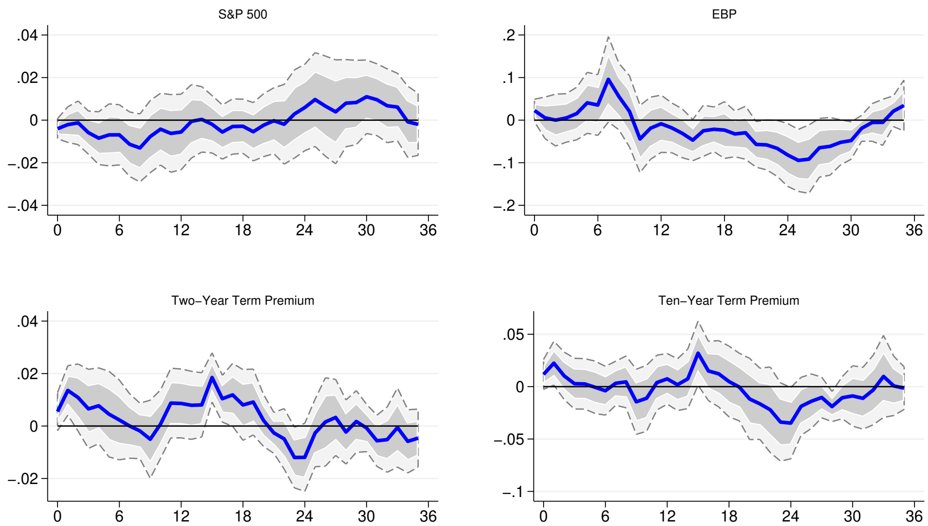


Note: The figure shows the impulse response of industrial production, the consumer price index, the unemployment rate and retail sales to a contractionary monetary policy shock. The light grey shaded areas indicate 1.65 standard deviation confidence intervals and the dark grey shaded areas indicate 1 standard deviation confidence intervals constructed from Newey-West standard errors.

suggests that the effects are weaker and not statistically different from zero for a considerable part of the forecast horizon. Comparing the linear impulse responses to their state-dependent counterparts of Figure 3 suggests that the typical effects of contractionary monetary policy on macroeconomic outcomes are mostly driven by periods of elevated supply chain pressures. Indeed, the estimates from both the linear model and the average supply chain pressure state, are relatively small in magnitude and often not statistically significant. By contrast, during periods of heightened supply chain disruption, a monetary policy tightening leads to sizeable and significant reductions in output, inflation and retail sales, and to a considerable and significant increase in the unemployment rate.

Figure 8 presents impulse responses of the financial variables from the linear model. Similarly to the case of the macroeconomic variables, we find that the responses have the expected signs, e.g., stock prices decline following a contractionary monetary policy shock, but the confidence intervals include zero for a significant portion of the forecast horizon and

Figure 8: Linear impulse responses. Financial variables



Note: The figure shows the impulse response of the S&P 500, excess bond premium, and the two and ten-year term premium to a contractionary monetary policy shock. The light grey shaded areas indicate 1.65 standard deviation confidence intervals and the dark grey shaded areas indicate 1 standard deviation confidence intervals constructed from Newey-West standard errors.

the point estimates have relatively small magnitudes. Again, the comparison of linear and state-dependent impulse responses suggests that the typical effect of monetary policy on financial variables is largely driven by the disrupted supply chain state.

4 Firm-Level Evidence

We provide additional evidence using disaggregated, firm-level data from Compustat. If an intensification of financial frictions explains the amplified effect of monetary policy on macroeconomic variables during times of high supply chain pressure, we would expect that (i) firms, on average, have a larger investment response when supply chain conditions are tight and (ii) firms that are more financially constrained experience a larger increase in responsiveness. To investigate, we estimate the following panel regression:

$$\Delta ln(y_{i,t}) = \alpha_i + \ \beta mp_t + \ \psi GSCPI_{t-1} + \ \delta \ (GSCPI_{t-1} * mp_t) + \ \Gamma Z_{i,t-1} + \epsilon_{i,t} \qquad (4)$$

where $\Delta ln(y_{i,t})$ is the growth rate of firm i's net capital stock, α_i is a firm fixed effect, mp_t is our measure of the monetary policy shock, $GSCPI_{t-1}$ is the Global Supply Chain Pressure Index, and $Z_{i,t-1}$ is a vector of firm-level control variables.[15] Similar to our local projection specification in equation (2), the main objects of interest in Equation (4) are the coefficients on mp_t and $GSCPI_t * mp_t$, here denoted as β and δ. They represent the effect of a contractionary monetary policy shock on firm investment when supply chain pressures are normal and the *additional effect* when pressures are elevated. Summary statistics for the firm-level variables used in the estimation are presented in Appendix Table A.1.

Table 2 shows results from estimating Equation (4). For the full sample (Column 1), we find that firms decrease their investment following a contractionary monetary policy shock by almost 0.6 percentage points. The coefficient is statistically significant at the one-percent level. However, when a monetary policy shock hits the economy during a period of elevated supply chain pressure, firms decrease their investment by an *additional* 1.1 percent points. This coefficient (δ) is statistically significant at the one-percent level and implies the average investment response to a monetary shock nearly triples when supply chain pressures are a standard deviation above average.

The estimates in Column (1) suggest that investment across all firms becomes more sensitive to monetary policy under tight supply chain conditions. However, previous studies such as Gertler and Gilchrist (1994) and Cloyne et al. (2023) have documented an important dimension of firm heterogeneity, namely, that financially constrained firms have a greater sensitivity to monetary policy than firms that are relatively less constrained. If supply chain pressures exacerbate the effects of monetary policy by intensifying existing financial frictions, we would expect to observe a similar differential sensitivity in the tight supply chain state,

[15] As is standard, firm controls are included with a lag to mitigate simultaneity concerns.

Table 2: Firm-level evidence

	(1) All	(2) Young	(3) Old	(4) Small	(5) Large
mp	-0.714***	-0.875***	-0.592***	-0.701***	-0.709***
	[0.079]	[0.148]	[0.090]	[0.132]	[0.062]
GSCPI	1.415***	2.091***	1.048***	1.945***	0.759***
	[0.127]	[0.261]	[0.126]	[0.221]	[0.107]
GSCPI*mp	-1.564***	-1.843***	-1.358***	-1.697***	-1.385***
	[0.131]	[0.252]	[0.143]	[0.213]	[0.116]
Firm controls	Yes	Yes	Yes	Yes	Yes
Firm fixed effects	Yes	Yes	Yes	Yes	Yes
Observations	190,401	72,924	117,286	104,750	85,407
R-squared	0.110	0.146	0.091	0.117	0.127

Note: The table presents results from estimating equation (4). Column (1) reports results for all firms. Columns (2) and (3) split the sample based on the firm age median and report results for firms below and above the median, respectively. Columns (4) and (5) split the sample based on the firm size median and report results for firms below and above the median, respectively. Robust standard errors clustered at the firm-level are in brackets. Coefficients and standard errors on the control variables are omitted to conserve space (but are available upon request). p<0.10; ** p<0.05; *** p<0.01.

i.e., that all firms become more sensitive to a monetary shock, but the increased sensitivity is larger for relatively more constrained firms. To investigate this expected heterogeneity, we require a measure of firm financial constraints. Hadlock and Pierce (2010) show that firm age and size are closely related to the degree to which a firm is financially constrained. Accordingly, we split our sample across these two dimensions and re-estimate Equation (4).

Columns (2) and (3) present results from dividing the sample of firms into two groups: young and old. Young firms are those below the median age in a given quarter and old firms are those above the median. Both sub-samples decrease investment following a contractionary monetary policy shock under average supply chain conditions. Consistent with the prior literature, the coefficient for young firms is more than twice as large as for old firms (0.84 vs 0.39), indicating that financially constrained firms tend to be more sensitive to monetary shocks. Investment decreases *even more* for both groups when supply chain pressures become elevated. Notably, however, the additional decline in investment following a contractionary shock for young firms is 1.66 percentage points compared to only 0.74 percentage points for older firms. There is a much larger increase in responsiveness for relatively constrained firms.

Columns (4) and (5) present results following a similar sample split based on firm size. Small firms are those below the median level of assets in a given quarter and large firms are those above the median. Once again, investment responds significantly to a monetary policy shock under normal supply chain conditions for both sub-samples, but there is a significantly larger response when the GSCPI is elevated. Small firms experience an additional 1.28 percentage point decline in investment following a contractionary shock, whereas investment at larger firms decreases by an additional 0.82 percentage points. Overall, the results in Table 2 indicate that while heightened supply chain pressures increase the sensitivity of firm-level investment to monetary policy in general, the increase is larger for more financially constrained firms.

To confirm that the greater investment sensitivity for relatively constrained firms is statistically meaningful, we can modify Equation (4) to incorporate a triple interaction. That is, rather than splitting the sample by age and size, we now interact age/size with mp_t, $GSCPI_{t-1}$, and $GSCPI_{t-1} * mp_t$:

$$\begin{aligned} \Delta ln(y_{i,t}) =& \alpha_i + \eta_t + \beta\ (GSCPI_{t-1} * Firm_{i,t-1}) + \psi\ (mp_t * Firm_{i,t-1}) \\ &+ \delta\ (GSCPI_{t-1} * mp_t * Firm_{i,t-1}) + \Gamma Z_{i,t-1} + \epsilon_{i,t} \end{aligned} \tag{5}$$

The variable of interest in this case becomes the triple interaction $GSCPI_{t-1}*mp_t*Firm_{i,t-1}$, where $Firm_{i,t-1}$ is firm age or size. If the increased sensitivity of investment to monetary policy under elevated supply chain pressures is weaker for less financially constrained (older and larger) firms, we would expect a positive and statistically significant coefficient on the triple interaction term. The results, presented in Table 3, confirm this is indeed the case: the increased investment sensitivity to monetary policy when supply chains are strained is significantly weaker for older and larger firms.

Table 3: Firm-level evidence. Triple interaction

	(1) Age	(2) Size
mp*Firm	0.014***	0.090**
	[0.005]	[0.045]
GSCPI*Firm	-0.026***	-0.289***
	[0.008]	[0.071]
GSCPI*mp*Firm	0.033***	0.255***
	[0.009]	[0.072]
Firm controls	Yes	Yes
Firm fixed effects	Yes	Yes
Time fixed effects	Yes	Yes
Observations	190,401	190,401
R-squared	0.123	0.123

Note: The table presents results from estimating a modified version of equation (4). In each column, $GSCPI$, mp, and $GSCPI * mp$ are interacted with a firm characteristic ($Firm$) that proxies for the degree to which the firm is financially constrained. The firm characteristic in column (1) is age. The firm characteristic in column (2) is size. Robust standard errors clustered at the firm-level are in brackets. Coefficients and standard errors on the control variables are omitted to conserve space (but are available upon request). p<0.10; ** p<0.05; *** p<0.01.

In the estimation up to this point, our right-hand side variables of interest, mp_t and $GSCPI_{t-1}$, have only varied across time. Note that in this specification however, the variable of interest is a triple interaction term containing cross-sectional variation. This makes it possible to include a time fixed effect, which controls for all potentially confounding time-varying macroeconomic phenomena. The fact that the results in Table 3, which control for all time-varying aggregate conditions, are consistent with our preceding analysis suggests that the prior estimation is unlikely to have been biased by such confounding factors. Nevertheless, we experiment with controlling for a variety of other, potentially relevant time-varying factors in Section 6.

5 Sample Extension Through the COVID-19 Pandemic

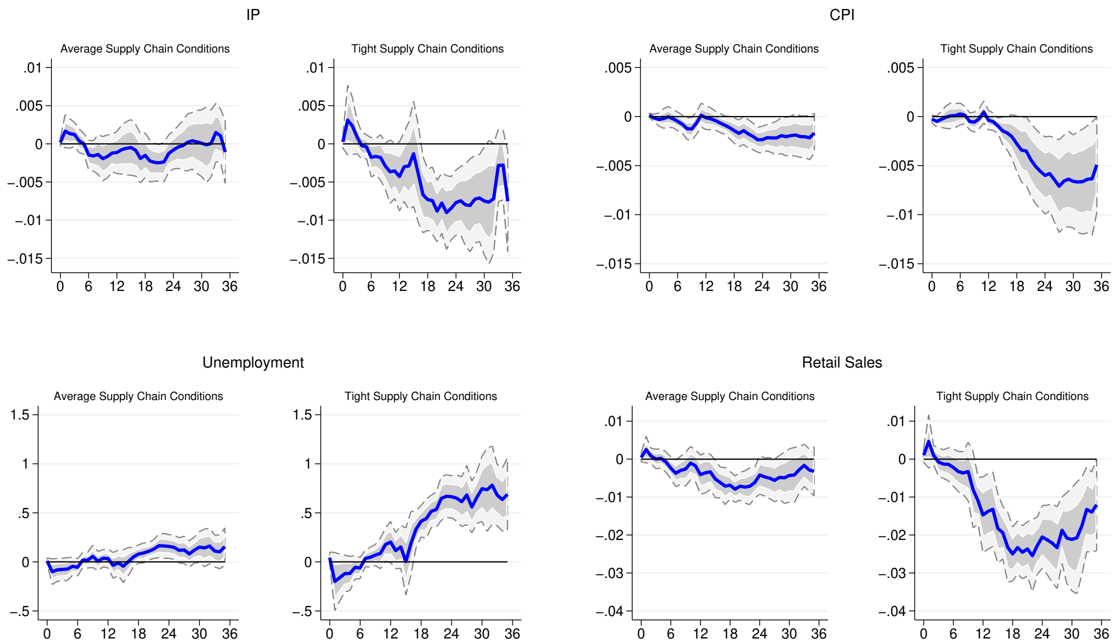
In this section, we extend our sample through the COVID-19 pandemic, up to March 2023. The onset of COVID-19 and resulting pandemic led to significant volatility, outliers, and potential structural breaks in many macroeconomic time series, as can be observed for the GSCPI in Figure 1. Out of an abundance of caution, the focus of our analysis so far has been on the pre-pandemic period where our variables of interest displayed stable dynamics. Nevertheless, it remains an interesting question to explore whether our conclusion, namely, that supply chain distress amplifies the conventional effects of monetary policy, carries through to the post-pandemic period. Such an extension is particularly important from a policy perspective, as the post-pandemic period has seen both unprecedented global supply chain disruptions and dramatic swings in the stance of monetary policy.

The most recent macroeconomic data allows us to extend our baseline local projection estimation through March 2023. Figure 9 shows the responses of industrial production, the consumer price index, unemployment, and retail sales to a contractionary monetary policy shock over the January 1998 to March 2023 sample period. The figure supports our conclusions from Section 3 – industrial production, consumer prices and retails sales decrease following a contractionary monetary policy shock only if the shock hits the economy during elevated supply chain pressure periods. During normal times, the responses are smaller in magnitude and less significant. Appendix Figure A.3 confirms that the amplification effects under tight supply chain conditions remain statistically significant after appropriate lags have kicked in. Comparing the results of Figure 9 with the pre-pandemic evidence from Figure 3 suggests that the effects on macroeconomic variables during periods of elevated supply chain pressures for the extended sample period have larger magnitudes (at the trough or peak) and are longer lasting. On the other hand, the lags until the effects become significant are also longer. For instance, the time before the responses of industrial production, inflation and the unemployment rate become significant for the pre-pandemic period is six, eight and two months, respectively. By contrast, it takes way more than one year before the responses become significant when we include the pandemic years in the sample. Finally, for some variables, e.g., the unemployment rate, the initial responses have the opposite sign.

In addition, Figure 10 displays the responses of the financial variables over the extended sample. The sample once again runs through March 2023, except for the S&P 500, which extends through December 2022 due to data limitations. We once again obtain similar results as Section 3. As with the macro responses, the response of the financial variables during periods of elevated supply chain pressures in Figure 10 have larger magnitudes at the trough or peak relative to Figure 5. Appendix Figure A.4 shows that the difference in the responses between normal and elevated supply chain pressure states is statistically significant for stock prices and term premia, while the difference is somewhat more nuanced for the excess bond premia.

Lastly, following Ng (2021), we include national COVID-19 cases and COVID-19 deaths as controls for potentially altered dynamics in the post-pandemic period. We find that the inclusion of COVID-19 cases and deaths as additional controls makes little difference in our estimation. The differential responses of the macro and financial variables, displayed in Appendix figures A.5 and A.6, are very similar to those shown in Figures A.3 and A.4.

Figure 9: State-dependent impulse responses. Macro variables. Sample extension



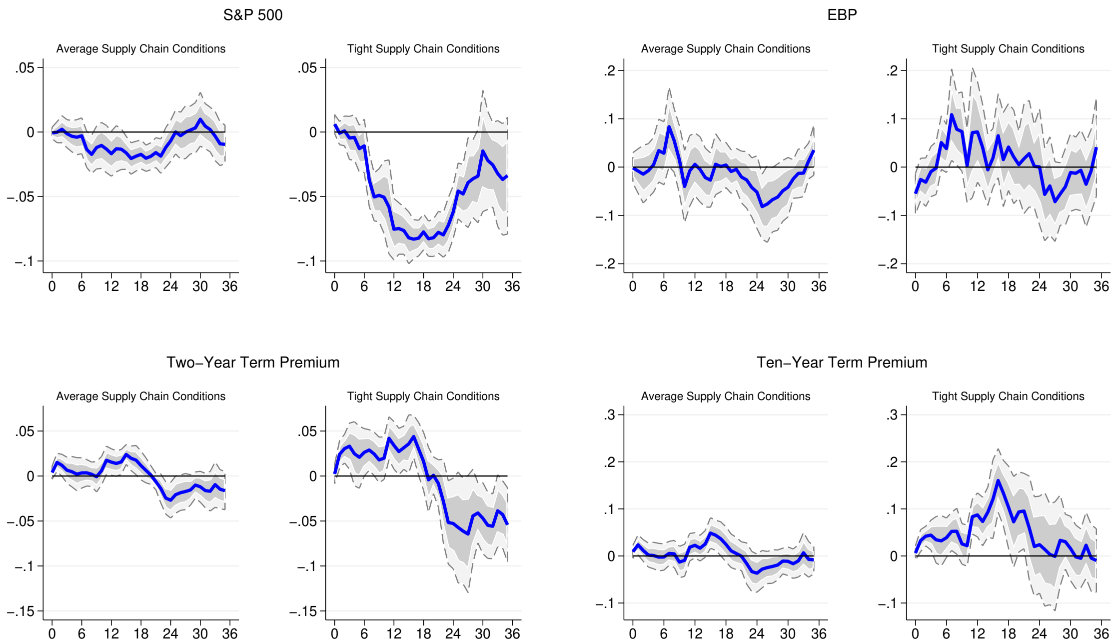
Note: The figure shows the impulse response of industrial production, the consumer price index, the unemployment rate and retail sales to a contractionary monetary policy shock. The sample is extended to run through the COVID-19 pandemic, from January 1998 to March 2023. The left panel shows the response (β_0^h) when supply chain pressures are at their sample average. The right panel shows the response when supply chain pressures are one standard deviation above average ($\beta_0^h + \delta_0^h$). The light grey shaded areas indicate 1.65 standard deviation confidence intervals and the dark grey shaded areas indicate 1 standard deviation confidence intervals constructed from Newey-West standard errors.

Overall, the conclusions from our baseline analysis hold through, and in some respects become even more striking, when we extend the sample beyond the onset of the COVID-19 pandemic. Supply chain disruptions amplify the conventional impact of monetary shocks on macroeconomic variables as the cost of external finance becomes more sensitive to monetary policy.

6 Robustness Analysis

In this section, we provide robustness analysis to our main results. One concern with our empirical approach is that the GSCPI may be contaminated with demand-side factors, in

Figure 10: State-dependent impulse responses. Financial variables. Sample extension



Note: The figure shows the impulse response of the S&P 500, the excess bond premium, and the two and ten-year term premium to a contractionary monetary policy shock. The sample is extended to run through the COVID-19 pandemic, from January 1998 to March 2023. The left panel shows the response (β_0^h) when supply chain pressures are at their sample average. The right panel shows the response when supply chain pressures are one standard deviation above average ($\beta_0^h + \delta_0^h$). The light grey shaded areas indicate 1.65 standard deviation confidence intervals and the dark grey shaded areas indicate 1 standard deviation confidence intervals constructed from Newey-West standard errors.

which case the amplified effects of monetary policy in the high GSCPI state may be due to causes unrelated to the state of global supply chains. Benigno et al. (2022) argue that the index is purged of demand-side influence for the majority of our sample period, with the caveat that its dynamics during the Global Financial Crisis likely capture some demand components. To check for the influence of the period around the crisis, we include in Equation (2) a Great Recession dummy (taking a value of one from Dececember 2007 to June 2009) and its interactions with $GSCPI$, mp, and $GSCPI * mp$. The results in Appendix Figure A.7 shows a similar amplification effect as the baseline results in Figure 4.

It may be the case that the heterogeneous impact of monetary shocks documented in our baseline results is driven by underlying factors other than global supply chain conditions. For instance, Tenreyro and Thwaites (2016) show that the response of the US macroeconomy to monetary policy shocks also varies with the state of the business cycle. Additional studies, including Alpanda et al. (2021), investigate whether the macroeconomic effects of monetary policy vary with the credit cycle and general financial conditions. We already include lags of IP and the EBP as controls in our baseline LP regressions. In Appendix Figures A.8 and A.9, we go one step further and include the interaction of IP and the EBP, respectively, with the monetary policy shock to further control for the state of the business cycle and for aggregate financial conditions. In both cases, the baseline results hold through, as δ_0^h is statistically different from zero with a similar magnitude as in Figure 4.[16]

A similar concern is that the GSCPI may be correlated with omitted global factors, like energy prices. This would imply that the amplification effect documented in Section 3 may not entirely be the result of supply chain pressure but instead might be driven by the state of the global energy market. Appendix Figure A.10 shows the estimates of the interaction term δ_0^h from Equation (2) when we include a global energy price index as an additional control variable, along with its interaction with the monetary policy shock. As the figure displays, the baseline results continue to hold, with δ_0^h remaining statistically different from zero at roughly the same magnitudes as in Figure 4.

To check robustness to alternative constructions of the monetary policy shock, we employ a second measure akin to the "policy news shock" from Nakamura and Steinsson (2018), which is described in detail in Section 2.1. Consistent with the baseline results, Appendix Figure A.11 shows a similarly amplified effect of the alternative shock measure under elevated supply chain pressures. Compared to Figure 4, the interaction term becomes statistically significant for a shorter period for IP, retail sales and the unemployment rate. On the other hand, it also becomes more highly significant for CPI.

One could be concerned that our previous monetary policy shock measures are contaminated with central bank information effects. To check whether information effects, i.e., news

[16]The baseline results, in fact, remain robust to the inclusion of interaction terms of all right-hand side variables with the monetary policy shock.

shocks related to how the Fed views the underlying state of the economy, are influencing our results, we re-estimate Equation (2) with an alternative shock measure from Bu et al. (2021) which cleanses out potential information effects. The impulse responses, shown in Appendix Figure A.12, are once again very similar to our baseline results – the δ_0^h coefficients have the same sign, similar magnitudes, and are, with a short delay, significant over the entire forecast horizon.

In Figure 4, the differential response for CPI is statistically different from zero for only a short duration of the forecast horizon relative to the other variables' responses. To probe the sensitivity of this result, we redo the inflation specification and replace the consumer price index with the personal consumption expenditure index, both with and without food and energy included. Appendix Figure A.13 shows that the amplified impact of monetary shocks on consumer prices does not hinge on the price index used, as the responses of both PCE measures are quite similar to the baseline CPI response.

While the focus of our study is on the US, one might expect that global supply chain conditions influence the macroeconomic effects of monetary policy in a similar manner for other advanced economies. To investigate this point, we redo our main exercise using data from the Euro Area.[17] Appendix Figure A.14 shows the state-dependent impulse response functions for Euro Area industrial production and consumer price index, as well as their corresponding interaction coefficient, δ_0^h. Following a contractionary monetary policy shock, IP and CPI decrease in either state. Consistent with our US results, however, the decrease is larger when supply chain conditions are strained. Comparing these results with those from the US (Figure 3), we can see that the amplification effect occurs at a longer lag of around eighteen months in the Euro Area, and that overall the amplification is somewhat less pronounced than in the US. The general pattern holds nevertheless, suggesting that the state of supply chain conditions may be an important consideration for policymakers globally.

[17] Euro Area monetary shocks are from Jarociński and Karadi (2020).

7 Conclusion

In this paper we investigate how global supply chain conditions impact the transmission of monetary policy to the US macroeconomy using a nonlinear local projection framework and the novel GSCPI (Benigno et al., 2022) for pre-pandemic US data. Our findings show that greater pressure on supply chains amplifies the standard effects of monetary policy on industrial production, consumer prices, unemployment and retail sales. We argue that this is due to an intensification of the credit channel: when supply chain pressure is high, the costs of obtaining credit become more sensitive to monetary policy compared to when supply chain pressures are average. Indeed, our results shows that a contractionary monetary policy shock increases the cost of external finance in any state, but significantly more so in periods with greater supply chain pressure.

Of particular interest, given recent policy challenges, is the result that consumer prices are more responsive to monetary policy when supply chain conditions are strained. This could help explain the initial post-pandemic surge in US inflation, when supply chains were very disrupted and the Fed eased policy significantly. It also suggests that the Fed's 2022 tightening campaign has a higher likelihood of successfully combating inflation, once sufficient lags have kicked in, due to elevated supply chain pressures persisting into early 2023. On the other hand, the increased responsiveness of industrial production and unemployment when supply chains face greater disruption decreases optimism over a "soft landing" scenario. Lastly, the longer estimated monetary policy lags for the extended sample (including the pandemic years) can help to explain the ongoing persistence of US inflation and resilience of the real economy.

More empirical research on how supply chain disruptions influence macroeconomic outcomes is clearly needed. Such research is particularly relevant as the post-pandemic global economy evolves into new supply chain configurations. As more data becomes available, it will be especially interesting to investigate the impact and persistence of the unprecedented supply chain disruptions associated with COVID-19.

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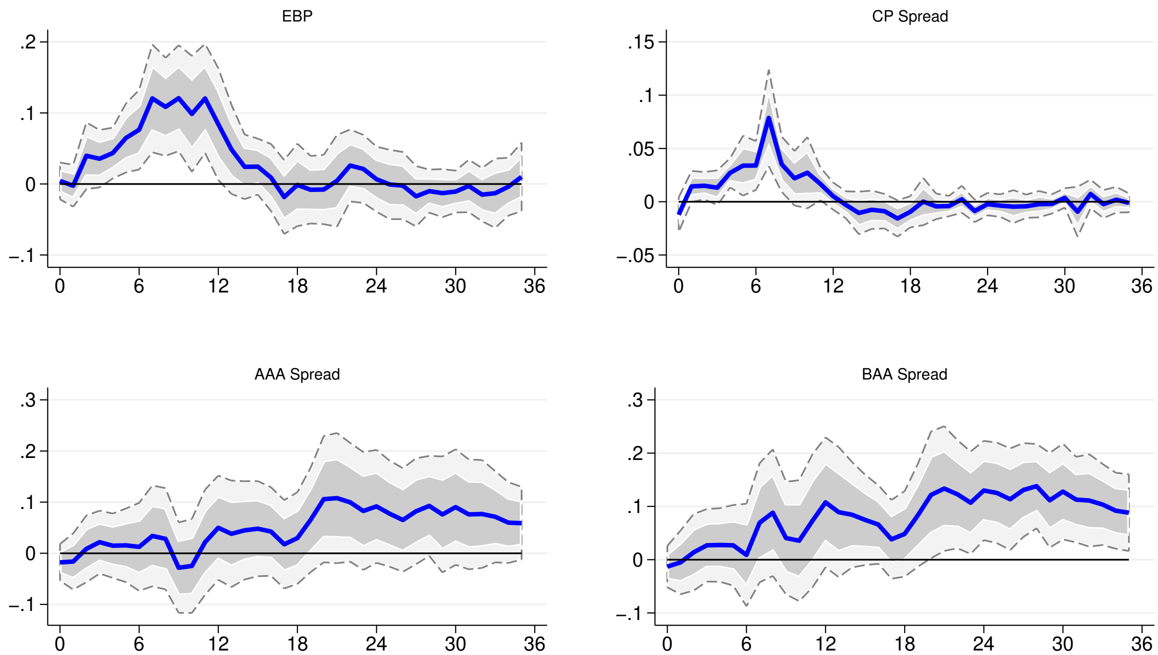
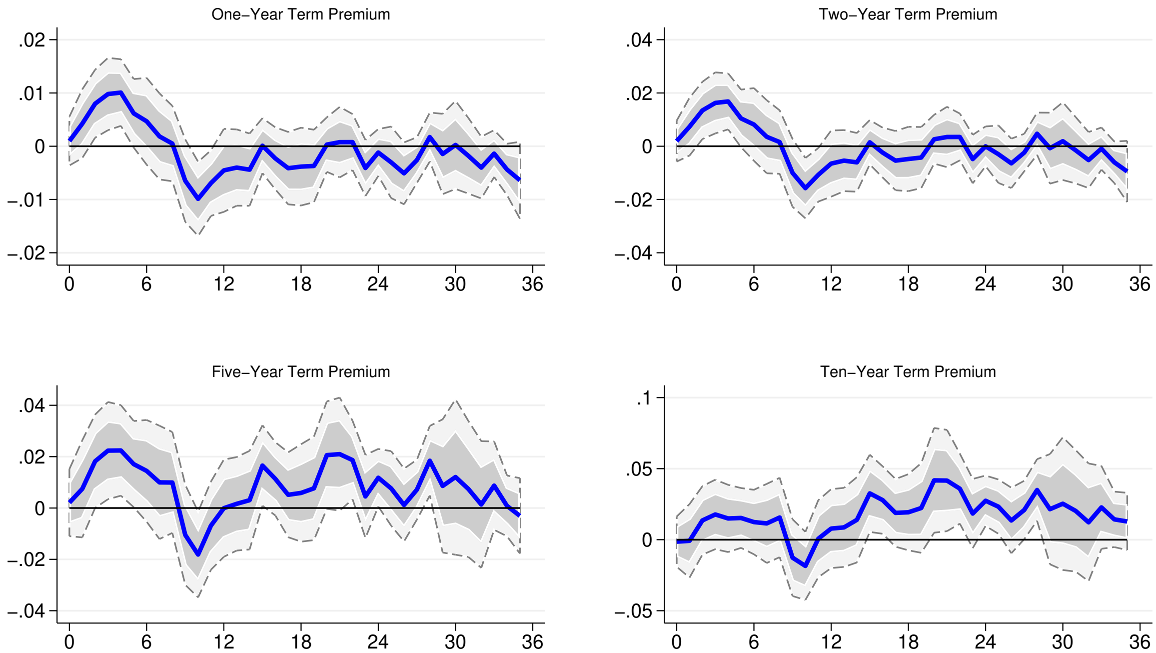
A Appendix

Figure A.1: Differential responses. Credit spreads



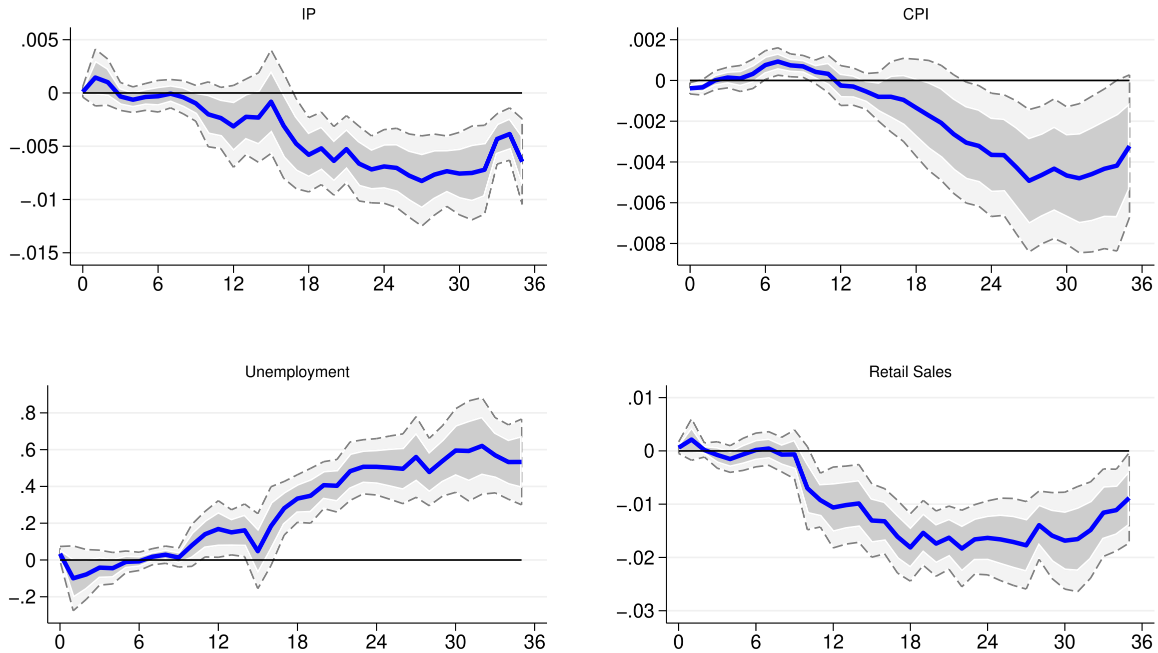
Note: The figure shows the *additional response* (δ_0^h) of four credit spread measures to a contractionary monetary policy shock during a period of elevated supply chain pressure, relative to an average period: the Gilchrist and Zakrajšek (2012) excess bond premium, commercial paper spread over the fed funds rate, Moody's Aaa corporate bond spread over the fed funds rate, and Moody's Baa corporate bond spread over the fed funds rate. The light grey shaded areas indicate 1.65 standard deviation confidence intervals and the dark grey shaded areas indicate 1 standard deviation confidence intervals constructed from Newey-West standard errors.

Figure A.2: Differential responses. Term premia



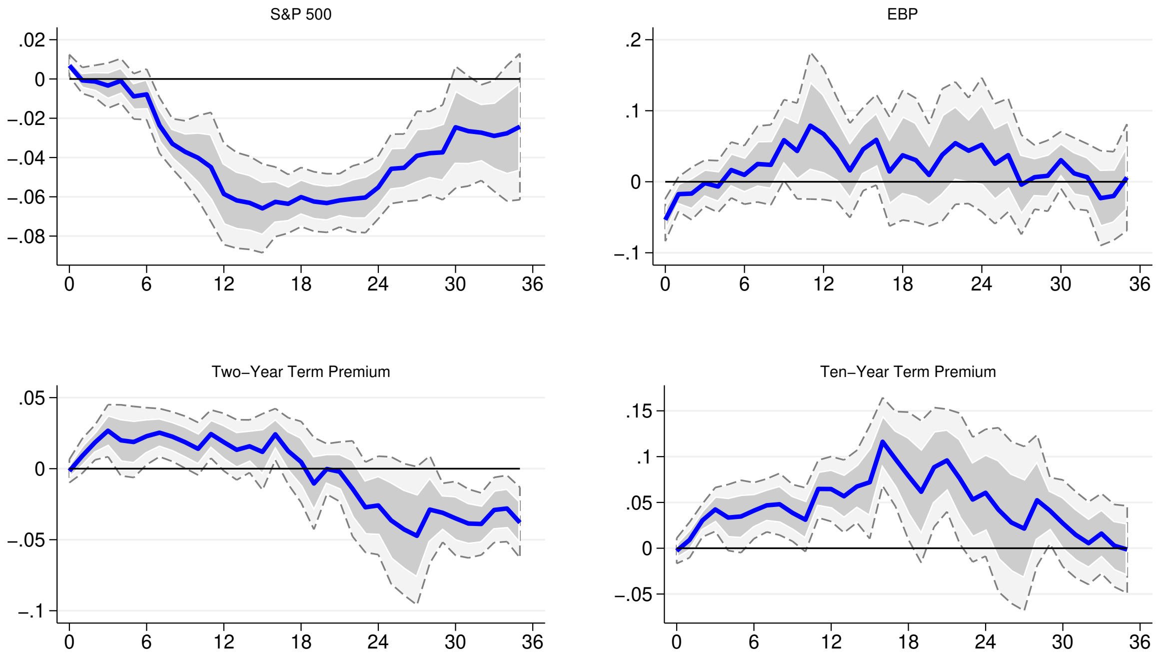
Note: The figure shows the *additional response* (δ_0^h) of term premia on US Treasuries at four different maturities to a contractionary monetary policy shock during a period of elevated supply chain pressure, relative to an average period: the one-year term premium, two-year term premium, five-year term premium, and ten-year term premium. Term premia are calculated through the Kim and Wright (2005) methodology. The light grey shaded areas indicate 1.65 standard deviation confidence intervals and the dark grey shaded areas indicate 1 standard deviation confidence intervals constructed from Newey-West standard errors.

Figure A.3: Differential responses. Macro variables. Sample extension



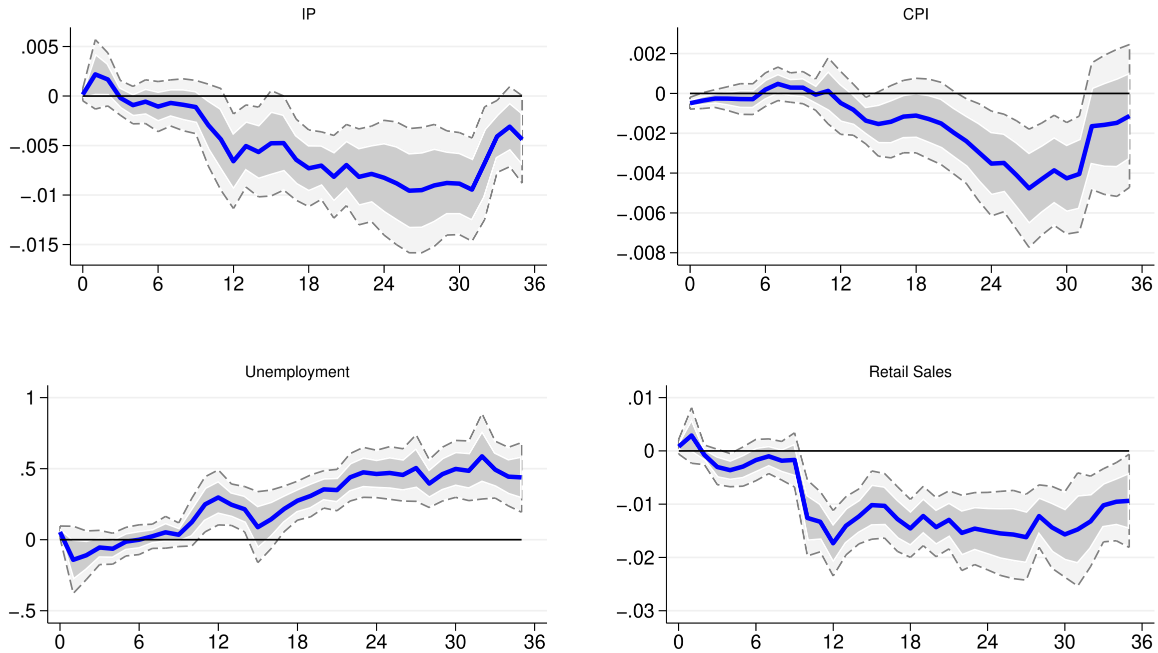
Note: The figure shows the *additional response* (δ_0^h) of industrial production, the consumer price index, the unemployment rate and retail sales to a contractionary monetary policy shock during a period of elevated supply chain pressure, relative to an average period. The sample is extended to run through the COVID-19 pandemic, from January 1998 to March 2023. The light grey shaded areas indicate 1.65 standard deviation confidence intervals and the dark grey shaded areas indicate 1 standard deviation confidence intervals constructed from Newey-West standard errors.

Figure A.4: Differential responses. Financial variables. Sample extension



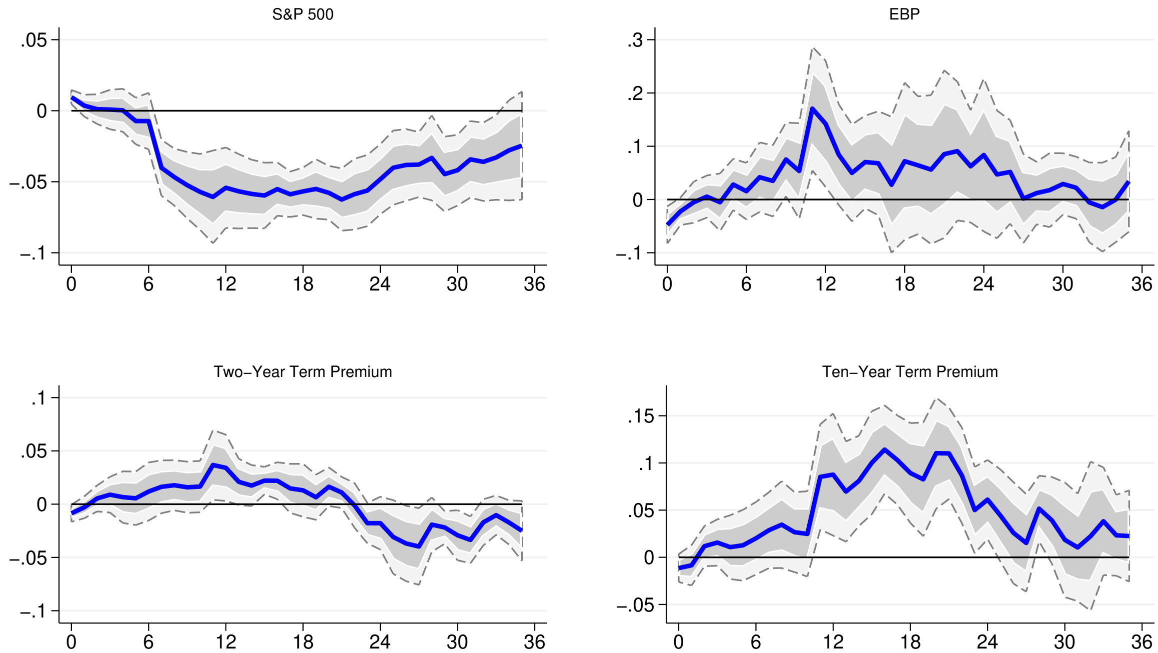
Note: The figure shows the *additional response* (δ_0^h) of the S&P 500, the excessive bond premium, and the two and ten-year term premium to a contractionary monetary policy shock during a period of elevated supply chain pressure, relative to an average period. The sample is extended to run through the COVID-19 pandemic, from January 1998 to March 2023. The light grey shaded areas indicate 1.65 standard deviation confidence intervals and the dark grey shaded areas indicate 1 standard deviation confidence intervals constructed from Newey-West standard errors.

Figure A.5: Differential responses. Macro variables. Sample extension with COVID controls



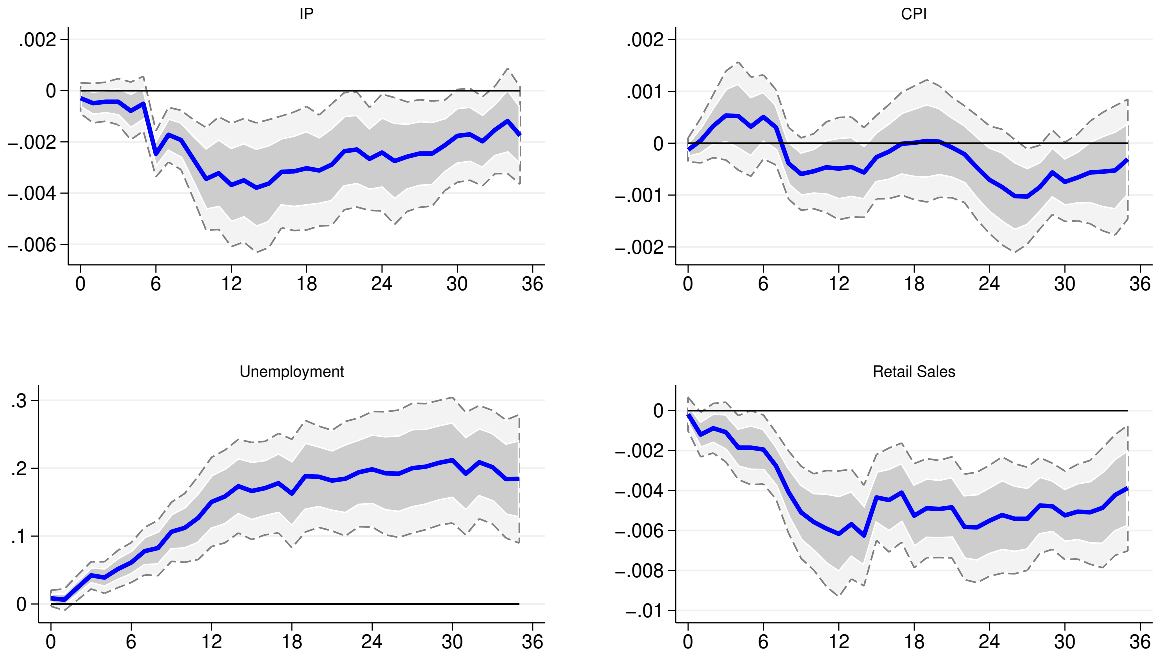
Note: The figure shows the *additional response* (δ_0^h) of industrial production, the consumer price index, the unemployment rate and retail sales to a contractionary monetary policy shock during a period of elevated supply chain pressure, relative to an average period. The sample is extended to run through the COVID-19 pandemic, from January 1998 to March 2023. COVID-19 cases and deaths are included as control variables. The light grey shaded areas indicate 1.65 standard deviation confidence intervals and the dark grey shaded areas indicate 1 standard deviation confidence intervals constructed from Newey-West standard errors.

Figure A.6: Differential responses. Financial variables. Sample extension with COVID controls



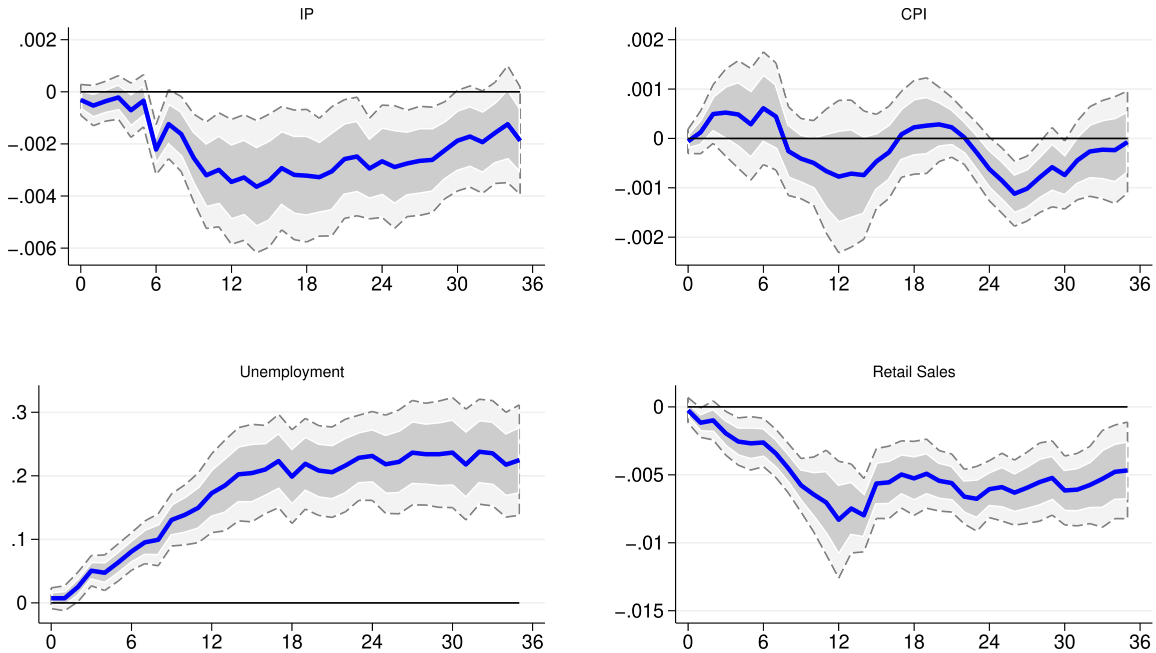
Note: The figure shows the *additional response* (δ_0^h) of the S&P 500, the excessive bond premium, and the two and ten-year term premium to a contractionary monetary policy shock during a period of elevated supply chain pressure, relative to an average period. The sample is extended to run through the COVID-19 pandemic, from January 1998 to March 2023. COVID-19 cases and deaths are included as control variables. The light grey shaded areas indicate 1.65 standard deviation confidence intervals and the dark grey shaded areas indicate 1 standard deviation confidence intervals constructed from Newey-West standard errors.

Figure A.7: Differential responses. Macro variables. Great Recession



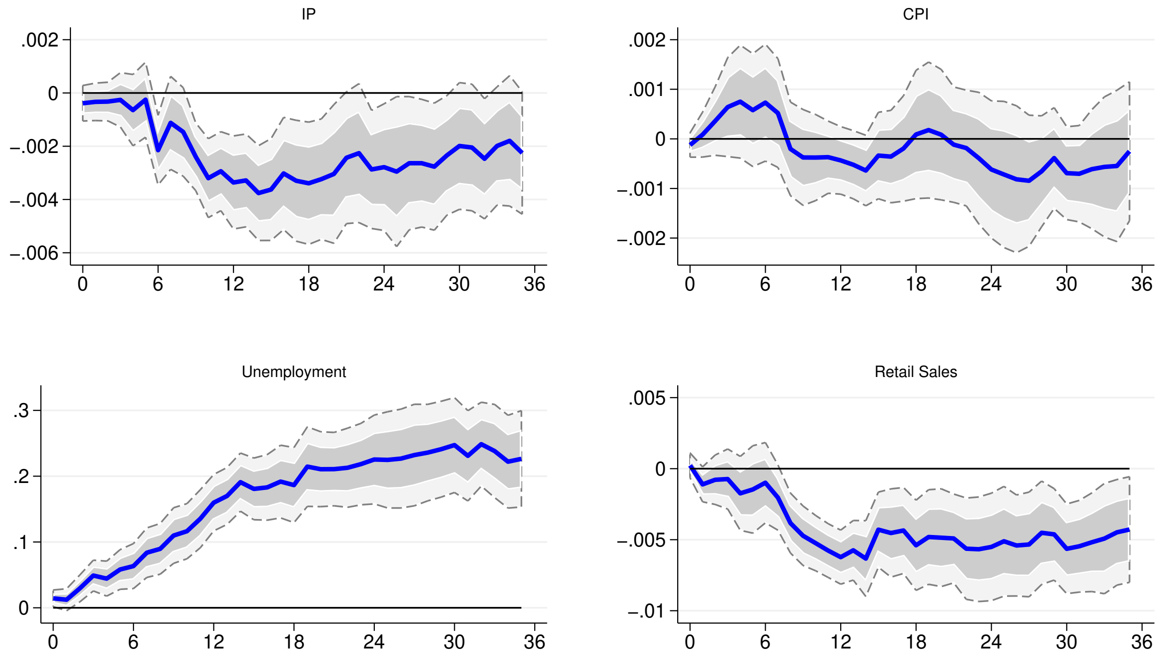
Note: The figure shows the *additional response* (δ_0^h) of industrial production, the consumer price index, the unemployment rate and retail sales to a contractionary monetary policy shock during a period of elevated supply chain pressure, relative to an average period. A Great Recession dummy variable equalling one from December 2007 through June 2009 is included as a control variable, along with its interaction with $GSCPI$, mp, and $GSCPI*mp$. The light grey shaded areas indicate 1.65 standard deviation confidence intervals and the dark grey shaded areas indicate 1 standard deviation confidence intervals constructed from Newey-West standard errors.

Figure A.8: Differential responses. Macro variables. Business cycle



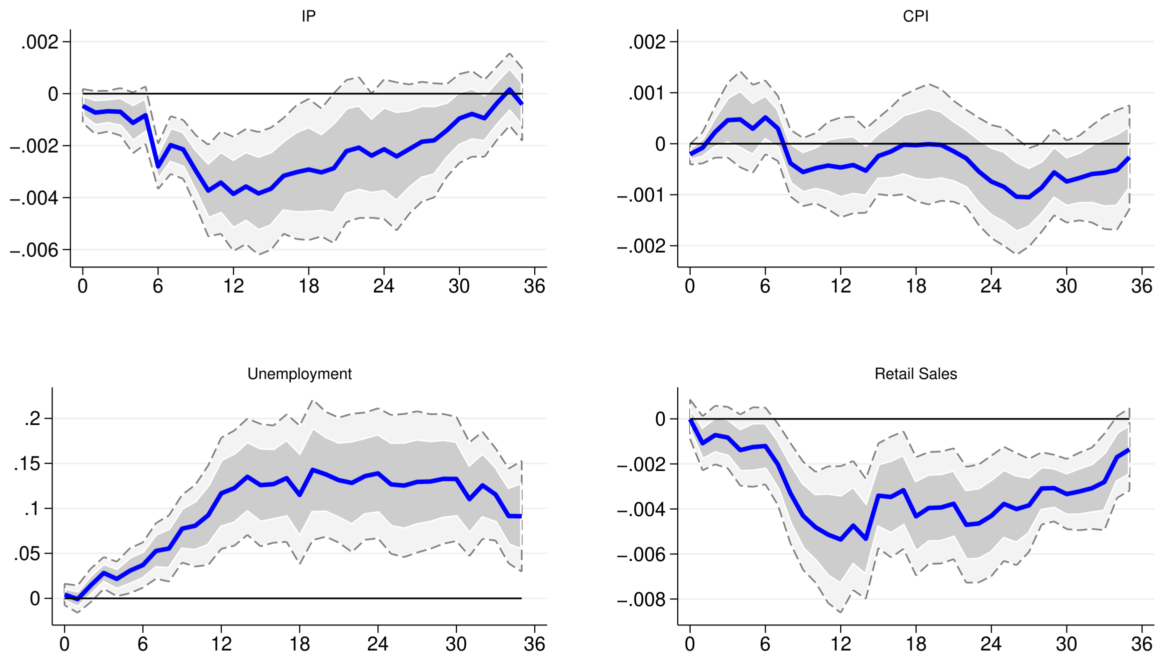
Note: The figure shows the *additional response* (δ_0^h) of industrial production, the consumer price index, the unemployment rate and retail sales to a contractionary monetary policy shock during a period of elevated supply chain pressure, relative to an average period. All lags of industrial production on the right hand side are interacted with *mp* to allow for differential effects of monetary policy over the business cycle. The light grey shaded areas indicate 1.65 standard deviation confidence intervals and the dark grey shaded areas indicate 1 standard deviation confidence intervals constructed from Newey-West standard errors.

Figure A.9: Differential responses. Macro variables. Financial conditions



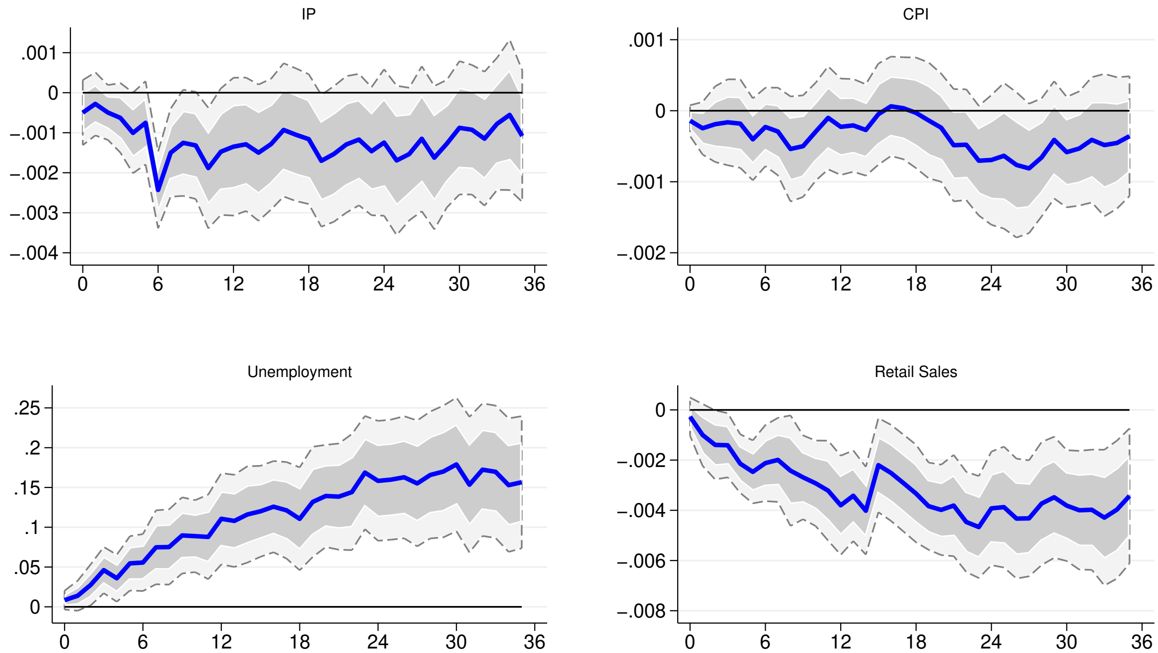
Note: The figure shows the *additional response* (δ_0^h) of industrial production, the consumer price index, the unemployment rate and retail sales to a contractionary monetary policy shock during a period of elevated supply chain pressure, relative to an average period. All lags of the excess bond premium on the right hand side are interacted with mp to allow for differential effects of monetary policy contigent on financial conditions. The light grey shaded areas indicate 1.65 standard deviation confidence intervals and the dark grey shaded areas indicate 1 standard deviation confidence intervals constructed from Newey-West standard errors.

Figure A.10: Differential responses. Macro variables. Energy Prices



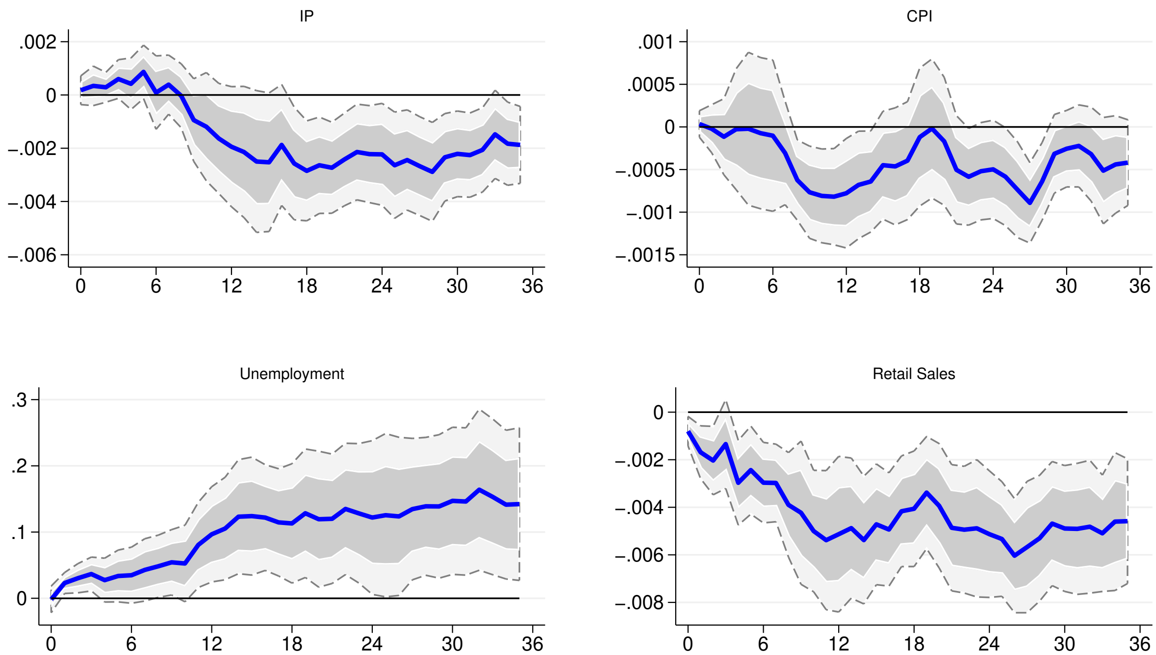
Note: The figure shows the *additional response* (δ_0^h) of industrial production, the consumer price index, the unemployment rate and retail sales to a contractionary monetary policy shock during a period of elevated supply chain pressure, relative to an average period. The global price of energy index is include as an additional control variable. The light grey shaded areas indicate 1.65 standard deviation confidence intervals and the dark grey shaded areas indicate 1 standard deviation confidence intervals constructed from Newey-West standard errors.

Figure A.11: Differential responses. Macro variables. Alternative mp



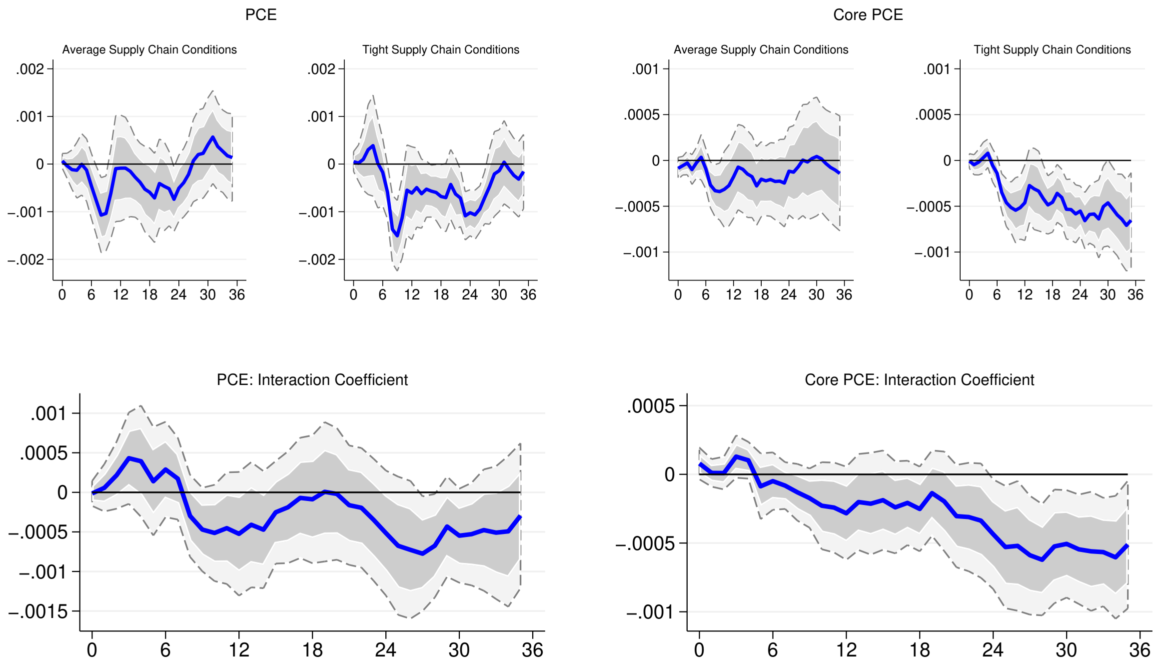
Note: The figure shows the *additional response* (δ_0^h) of industrial production, the consumer price index, the unemployment rate and retail sales to a contractionary monetary policy shock during a period of elevated supply chain pressure, relative to an average period. The monetary policy shock is the first principal component of the daily change in four Eurodollar futures contracts, expiring 1 quarter ahead to 4 quarters ahead, on FOMC announcement days, summed to a monthly frequency. The light grey shaded areas indicate 1.65 standard deviation confidence intervals and the dark grey shaded areas indicate 1 standard deviation confidence intervals constructed from Newey-West standard errors.

Figure A.12: Differential responses. Macro variables. Central bank information effects



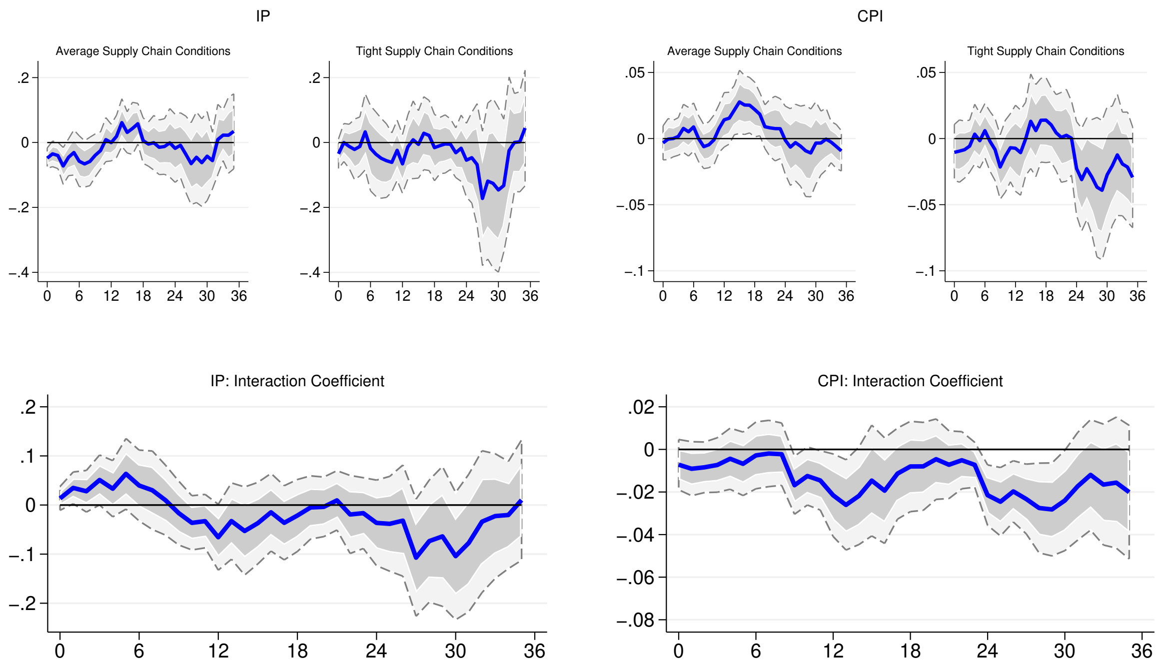
Note: The figure shows the *additional response* (δ_0^h) of industrial production, the consumer price index, the unemployment rate and retail sales to a contractionary monetary policy shock during a period of elevated supply chain pressure, relative to an average period. The monetary policy shock from Bu, Rogers, and Wu (2021) and is stripped of central bank information effects. The light grey shaded areas indicate 1.65 standard deviation confidence intervals and the dark grey shaded areas indicate 1 standard deviation confidence intervals constructed from Newey-West standard errors.

Figure A.13: State-dependent impulse responses. Alternative inflation measures



Note: The top row of the figure shows the state-dependent impulse response of the personal consumption expenditures chain-type price index (PCE) and the personal consumption expenditures excluding food and energy chain-type price index (core) to a contractionary monetary policy shock. The left panel shows the response (β_0^h) when supply chain pressures are at their sample (1998-2019) average. The right panel shows the response when supply chain pressures are one standard deviation above average ($\beta_0^h + \delta_0^h$). The bottom row of the figure shows the *additional response* (δ_0^h) during a period of elevated supply chain pressure, relative to an average period. The light grey shaded areas indicate 1.65 standard deviation confidence intervals and the dark grey shaded areas indicate 1 standard deviation confidence intervals constructed from Newey-West standard errors.

Figure A.14: State-dependent impulse responses. EU Macro variables



Note: The top row of the figure shows the state-dependent impulse response of euro area industrial production and the consumer price index to an ECB contractionary monetary policy shock. The left panel shows the response (β_0^h) when supply chain pressures are at their sample (1998-2019) average. The right panel shows the response when supply chain pressures are one standard deviation above average ($\beta_0^h + \delta_0^h$). The bottom row of the figure shows the *additional response* (δ_0^h) during a period of elevated supply chain pressure, relative to an average period. The monthly ECB monetary policy shock measure is from Jarociński & Karadi (2020). The light grey shaded areas indicate 1.65 standard deviation confidence intervals and the dark grey shaded areas indicate 1 standard deviation confidence intervals constructed from Newey-West standard errors.

Table A.1: Firm-Level Summary Statistics

	Mean	Median	Std Dev	Min	Max	Obsv.
Investment	0.17	-0.19	22.71	-0.46.94	58.98	191,011
Firm age	18.75	16	13.39	1	58	191,011
Firm size	5.68	5.79	2.60	-6.89	13.11	191,011
Current to total assets	0.46	0.45	0.25	0	0.99	191,011
Real sales growth	0.03	0.03	0.56	-1.66	1.77	191,011
Price-to-cost margin	-2.38	0.33	88.19	-19.16	0.92	191,011
Receivables-minus-payables to sales	-1.60	0.20	187.24	-16.82	2.04	191,011
Depreciation to assets	0.01	0.01	0.06	0.001	0.07	191,011
Market capitalization	78.52	29.91	678.86	0.04	699.53	191,011
Leverage	0.38	0.34	0.61	-3.18	3.5	191,011
Liquidity	0.15	0.07	0.19	0	0.86	191,011

Note: The table presents summary statistics for Compustat variables used in the firm-level analysis. Data is quarterly over a 1998Q1 to 2019Q4 sample period.