Endogenous Production Networks and Non-Linear Monetary Transmission

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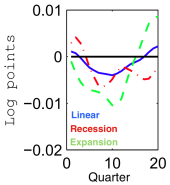
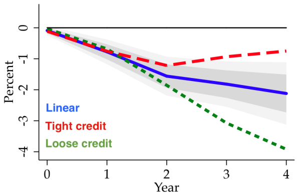
Motivation: non-linear monetary transmission to GDP

Recession vs Expansion



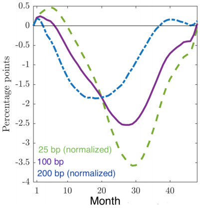
Tenreyro and Thwaites (2016)

Tight vs Loose credit



Jordà et al. (2019)

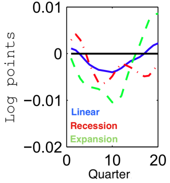
Large vs Small shocks



Ascari and Haber (2019)

Motivation: non-linear monetary transmission to GDP

Recession vs Expansion



Tenreyro and Thwaites (2016)

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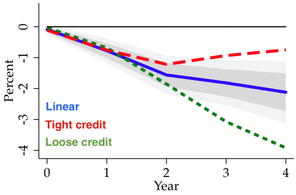

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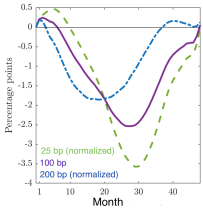
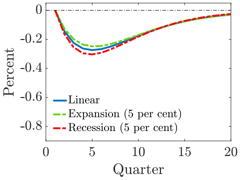
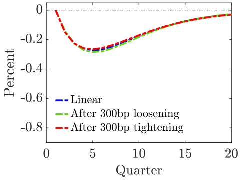
Large vs Small shocks

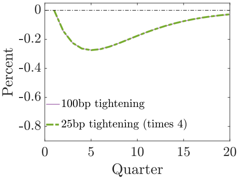


Ascari and Haber (2019)

- 100bp tightening in a fully non-linear medium-scale New Keynesian Model:







This Paper

- A novel tractable framework to rationalize a range of non-linearities in monetary transmission, with the key mechanism supported by evidence using aggregate, sectoral and firm-level data

1. Develop sticky-price New Keynesian model with input-output linkages across sectors that are formed endogenously
    - *Key novel mechanism*: dense network in "good times", sparse network in "bad times" $\rightarrow$ state-dependent strength of complementarities in price setting
2. Jointly rationalize empirically established monetary *non-linearities*:
    - *Cycle dependence*: monetary policy's effect on GDP is *procyclical* (Tenreyro and Thwaites, 2016; Jorda et al., 2019; Alpanda et al., 2019)
    - *Path dependence*: monetary policy's effect on GDP is stronger following *past loose monetary policy* (Jorda et al., 2019)
    - *Size dependence*: large monetary shocks a have disproportionate effect on GDP (Ascari and Haber, 2019)
3. Novel model-free empirical evidence on network responses to shocks

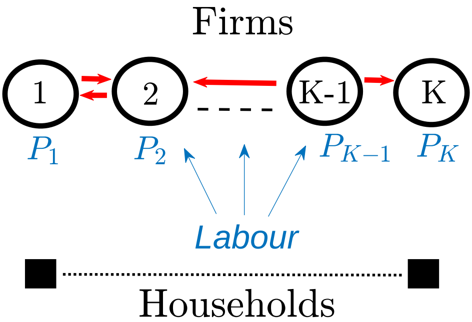
Contribution to the literature

- **Endogenous production networks in macroeconomics**: Carvalho and Voightlaender (2015); Oberfield (2018); Taschereau-Dumouchel (2019); Acemoglu and Azar (2020)
    - *Contribution 1*: first model with endogenous production networks and nominal rigidities
    - *Contribution 2*: model-free econometric evidence on network responses to identified productivity and monetary shocks

- **State dependence in monetary transmission**: Tenreyro and Thwaites (2016); Berger et al. (2018); Jorda et al. (2019); Ascari and Haber (2019); Alpanda et al. (2019); Eichenbaum et al. (2019); McKay and Wieland (2019)
    - *Contribution 3*: first framework to use cyclical variation in the shape of the network to jointly rationalize the observed state dependence in monetary transmission

A TWO-PERIOD MODEL

Model primitives



Firms: production and choice of suppliers

- K sectors, continuum of firms Φ_k in each sector
- *Roundabout Production (for firm j in sector k)*:

$$Y_k(j) = \psi(S, \Omega)\mathcal{A}_k(S_k)N_k(j)^{1-\sum_{r \in S_k} \omega_{kr}} \prod_{r \in S_k} Z_{kr}(j)^{\omega_{kr}}, \quad \forall k, \forall j \in \Phi_k$$

where $S_k \subset \{1, 2, ..., K\}$ is sector k's choice of suppliers, $\mathcal{A}_k(.)$ is the technology mapping, $\omega_{kr} = [\Omega]_{kr}$ are input-output weights

- *Marginal Cost (conditional on supplier choice)*:

$$MC_k = \frac{1}{\mathcal{A}_k(S_k)} W^{1-\sum_{r \in S_{kt}} \omega_{kr}} \prod_{r \in S_k} P_r^{\omega_{kr}}, \qquad \forall k, \forall j \in \Phi_k$$

- *Optimal Network*:

$$S_k^* \in \arg\min_{S_k} MC_k(S, P), \qquad \forall k$$

where $S = [S_1, S_2, ..., S_K]'$ and $P = [P_1, P_2, ..., P_K]'$

Firms: pricing under nominal rigidities

- *Profit maximization*:

$$\max_{P_k^*(j)} \Pi_k(j) = [P_k^*(j) Y_k(j) - (1+\tau_k) MC_k Y_k(j)] \quad \text{s.t.} \quad Y_k(j) \quad = \left(\frac{P_k(j)}{P_k}\right)^{-\theta} Y_k$$

- *Optimal price*:

$$\overline{P}_k = (1+\mu_k) MC_k, \qquad (1+\mu_k) = (1+\tau_k)\frac{\theta}{\theta-1}, \qquad \forall k, \forall j \in \Phi_k$$

- *Calvo lotteries (probability of non-adjustment α_k)*:

$$P_k = \left[\alpha_k P_{k,0}^{1-\theta} + (1-\alpha_k)\left\{\frac{1+\mu_k}{\mathcal{A}_k(S_k)} W \prod_{r \in S_k} \left(\frac{P_r}{W}\right)^{\omega_{kr}}\right\}^{1-\theta}\right]^{\frac{1}{1-\theta}}, \quad \forall k$$

Households and Monetary Policy

- *Flow Utility*: $\mathcal{U} = \log C - N, \quad C \equiv \prod_{k=1}^{K} C_k^{\omega_{ck}}.$

- *Cash-in-Advance Constraint*: $P^c C = \mathcal{M}$

- *Money supply rule*: $\mathcal{M} = \mathcal{M}_0 \exp(\varepsilon^m)$

- *Equilibrium fixed point problem*:

$$P_k = \left[\alpha_k P_{k,0}^{1-\theta} + (1-\alpha_k)\left\{\min_{S_k} \frac{1+\mu_k}{\mathcal{A}_k(S_k)} \mathcal{M} \prod_{r\in S_k} \left(\frac{P_r}{\mathcal{M}}\right)^{\omega_{kr}}\right\}^{1-\theta}\right]^{\frac{1}{1-\theta}}, \quad \forall k$$

Proposition (Equilibrium)

Equilibrium in my economy: (i) exists; (ii) sectoral prices and final consumptions are unique; (iii) supplier choices and remaining quantities are generically unique.

BASELINE ($\varepsilon^m = 0$)

Baseline: a two-sector example

- Two sectors: $\omega_{kk} = 0, \quad \tau_k = -\frac{1}{\theta}, \quad \theta \to 1^+, \quad \forall k = 1, 2$

	Sector 1	Sector 2
$a(.)$	$a_1(\varnothing) = 1, \quad a_1(\{2\}) = \overline{a}$	$a_2(\varnothing) = 1, \quad a_2(\{1\}) = \overline{a}$
Ω	$\omega_{12} = \omega_{c1} = 0.5$	$\omega_{21} = \omega_{c1} = 0.5$
α	$\alpha_1 = 0$	$\alpha_2 = 0.5$

- Real marginal costs: $(mc_{k,0} - m_0) = -a_k(S_{k,0}) + \mathbf{1}_{-k \in S_{k,0}} \frac{1}{2}(p_{-k,0} - m_0)$

- Optimal network choice over (real) marginal costs $(mc_k - m_0)$:

	$S_2 = \varnothing$	$S_2 = \{1\}$
$S_1 = \varnothing$	$(-1, -1)$	$(-1, -\overline{a} - \frac{1}{2})$
$S_1 = \{2\}$	$(-\overline{a} - \frac{1}{4} m_0 - \frac{1}{4}, -1)$	$\left(\frac{2}{7}\left\{-5\overline{a} - m_0\right\}, \frac{2}{7}\left\{-6\overline{a} - 0.5 m_0\right\}\right)$

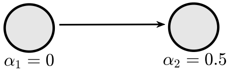
Recession vs Expansion

Recession: $\overline{a} = 0$

	$\varnothing$	$\{1\}$
$\varnothing$	$(-1, -1)$	$(-1, -\frac{1}{2})$
$\{2\}$	$(-0.25, -1)$	$(0, 0)$

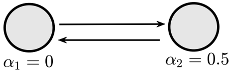
Normal: $\overline{a} = 0.65$

	$\varnothing$	$\{1\}$
$\varnothing$	$(-1, -1)$	$(-1, -1.15)$
$\{2\}$	$(-0.9, -1)$	$(-0.92, -1.11)$



Expansion: $\overline{a} = 0.8$

	$\varnothing$	$\{1\}$
$\varnothing$	$(-1, -1)$	$(-1, -1.30)$
$\{2\}$	$(-1.05, -1)$	$(-1.14, -1.37)$



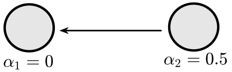
Tight vs Loose money

Tight money: $m_0 = 0$

	$\varnothing$	$\{1\}$
$\varnothing$	$(-1, -1)$	$(-1, -\frac{1}{2})$
$\{2\}$	$(-0.25, -1)$	$(0, 0)$

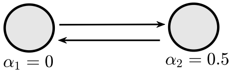
Normal money: $m_0 = 4$

	$\varnothing$	$\{1\}$
$\varnothing$	$(-1, -1)$	$(-1, -\frac{1}{2})$
$\{2\}$	$(-1.25, -1)$	$(-1.14, -0.57)$



Loose money: $m_0 = 8$

	$\varnothing$	$\{1\}$
$\varnothing$	$(-1, -1)$	$(-1, -\frac{1}{2})$
$\{2\}$	$(-2.25, -1)$	$(-2.28, -1.14)$



Baseline: density of the network and activity

Lemma (Baseline supplier choices)

Suppose the marginal cost is quasi-submodular in $(S_k, \mathcal{A}_k(S_k)), \forall k$. *Consider any two baseline pairs* $(\underline{\mathcal{A}}, \underline{\mathcal{M}}_0)$, $(\overline{\mathcal{A}}, \overline{\mathcal{M}}_0)$ *such that either* $\overline{\mathcal{A}} \geq \underline{\mathcal{A}}, \overline{\mathcal{M}}_0 = \underline{\mathcal{M}}_0$ *or* $\overline{\mathcal{A}} = \underline{\mathcal{A}}, \overline{\mathcal{M}}_0 \geq \underline{\mathcal{M}}_0$, *then:*

$$S_k(\overline{\mathcal{A}}, \overline{\mathcal{M}}_0) \supseteq S_k(\underline{\mathcal{A}}, \underline{\mathcal{M}}_0)$$

for all $k = 1, 2, ..., K$.

MONETARY SHOCKS

Comparative Statics: C and S following $\varepsilon^m \neq 0$

Lemma (Comparative statics after a monetary shock)

Suppose the marginal cost is quasi-submodular in $(S_k, \mathcal{A}_k(S_k)), \forall k$. A positive monetary shock $\varepsilon^m > 0$, such that $\mathcal{M} > \mathcal{M}_0$, is (weakly) expansionary and makes the network (weakly) denser:

$$S_k(\mathcal{A}, \mathcal{M}) \supseteq S_k(\mathcal{A}_0, \mathcal{M}_0) \qquad C_k(\mathcal{A}, \mathcal{M}) \geq C_k(\mathcal{A}, \mathcal{M}_0), \quad \forall k$$

The opposite holds for a negative monetary shock $\varepsilon^m < 0$, such that $\mathcal{M} < \mathcal{M}_0$.

Definition (Small monetary shock)

Define a monetary shock ε^m to be **small** with respect to the initial state $(\mathcal{A}, \mathcal{M}_0)$ if and only if it leaves the equilibrium network unchanged relative to the baseline:

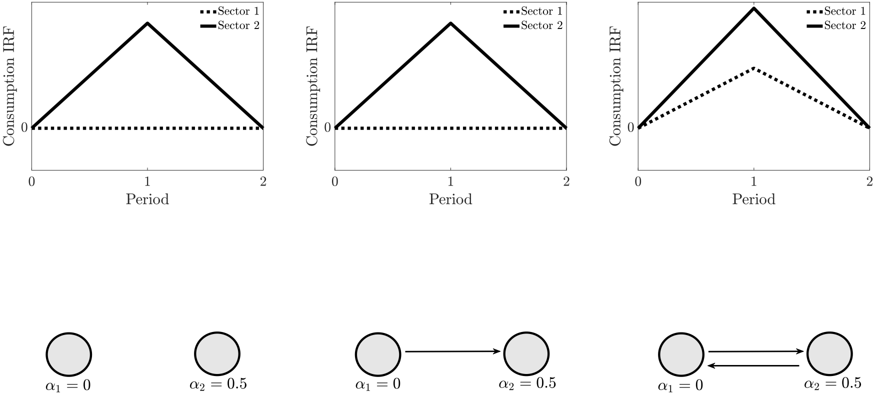
$$S_k(\mathcal{A}, \mathcal{M}) = S_k(\mathcal{A}, \mathcal{M}_0), \quad \forall k$$

Otherwise, define the monetary shock to be **large** with respect to the initial state $(\mathcal{A}, \mathcal{M}_0)$.

Small Monetary Shocks

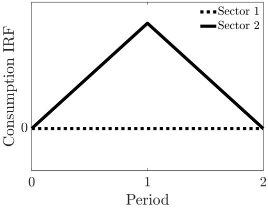
IRFs to a small monetary expansion across the cycle $\overline{a}$

Recession: $\overline{a} = 0$ ***Normal***: $\overline{a} = 0.65$ ***Expansion***: $\overline{a} = 0.8$

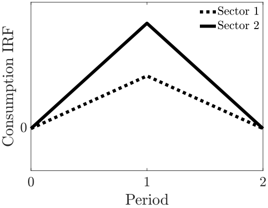


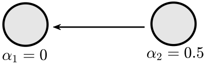
IRFs to a small monetary expansion across initial m_0

Tight money: $m_0 = 0$

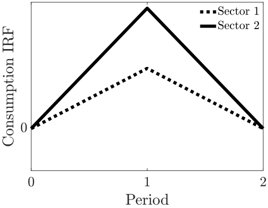


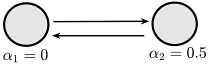
Normal money: $m_0 = 4$





Loose money: $m_0 = 8$





Small shock $\varepsilon^m \neq 0$ across baselines

Proposition (Path dependence)

Let $c_k(\mathcal{A}, \mathcal{M}_0) \equiv \ln C_k(\mathcal{A}, \mathcal{M}) - \ln C_k(\mathcal{A}, \mathcal{M}_0), \forall k$*. Consider any two baseline pairs* $(\underline{\mathcal{A}}, \underline{\mathcal{M}}_0)$, $(\overline{\mathcal{A}}, \overline{\mathcal{M}}_0)$*, and* $\varepsilon^m > 0$ *which is small, and* $P_{k,0} = (1 + \mu_k) g(\mathcal{M}_0) MC_k(\mathcal{A}, \mathcal{M}_0)$*:*

$$\mathbb{c}(\overline{\mathcal{A}}, \overline{\mathcal{M}}_0) - \mathbb{c}(\underline{\mathcal{A}}, \underline{\mathcal{M}}_0) = \left[\mathcal{L}(\overline{\mathcal{A}}, \overline{\mathcal{M}}_0) - \mathcal{L}(\underline{\mathcal{A}}, \underline{\mathcal{M}}_0)\right] \mathcal{E}^m$$

where $\mathbb{c} = [c_1, c_2, ..., c_K]'$, $\mathcal{E}^m = [\varepsilon^m, \varepsilon^m, ..., \varepsilon^m]'$ *and* $\mathcal{L}$ *is a Leontief inverse given by:*

$$\mathcal{L}(\mathcal{A}, \mathcal{M}_0) = [I - (I - A)\Gamma(\mathcal{M}_0)\Omega(\mathcal{A}, \mathcal{M}_0)]^{-1} [I - (I - A)\Gamma(\mathcal{M}_0)]$$

where $A = diag(\alpha_1, ..., \alpha_K)$, $\Gamma(\mathcal{M}_0) = diag(\gamma_1(\mathcal{M}_0), ..., \gamma_K(\mathcal{M}_0))$, $\gamma_k = \frac{1}{\alpha_k (g(\mathcal{M}_0))^{1-\theta} + 1 - \alpha_k}$ *and* $[\Omega(\mathcal{A}, \mathcal{M}_0)]_{kr} = \omega_{kr}$ *if* $r \in S_k$ *and 0 otherwise.*

Cycle Dependence of the effect of a small $\varepsilon^m \neq 0$

Proposition (Cycle dependence)

Let $c_k(\mathcal{A}, \mathcal{M}_0) \equiv \ln C_k(\mathcal{A}, \mathcal{M}) - \ln C_k(\mathcal{A}, \mathcal{M}_0), \forall k$. *Consider any two baseline pairs* $(\underline{\mathcal{A}}, \underline{\mathcal{M}}_0)$, $(\overline{\mathcal{A}}, \overline{\mathcal{M}}_0)$, *and* $\varepsilon^m > 0$ *which is small, and* $P_{k,0} = (1 + \mu_k) g(\mathcal{M}_0) MC_k(\mathcal{A}, \mathcal{M}_0)$, *and* $\overline{\mathcal{A}} \geq \underline{\mathcal{A}}$*:*

$$\mathbb{c}(\overline{\mathcal{A}}, \overline{\mathcal{M}}_0) - \mathbb{c}(\underline{\mathcal{A}}, \underline{\mathcal{M}}_0) = \left[\mathcal{L}(\overline{\mathcal{A}}, \overline{\mathcal{M}}_0) - \mathcal{L}(\underline{\mathcal{A}}, \underline{\mathcal{M}}_0)\right] \mathcal{E}^m$$

where $\mathbb{c} = [c_1, c_2, ..., c_K]'$, $\mathcal{E}^m = [\varepsilon^m, \varepsilon^m, ..., \varepsilon^m]'$ *and* $\mathcal{L}$ *is a Leontief inverse given by:*

$$\mathcal{L}(\mathcal{A}, \mathcal{M}_0) = [I - (I - A)\Gamma(\mathcal{M}_0)\Omega(\mathcal{A}, \mathcal{M}_0)]^{-1} [I - (I - A)\Gamma(\mathcal{M}_0)]$$

where $A = diag(\alpha_1, ..., \alpha_K)$, $\Gamma(\mathcal{M}_0) = diag(\gamma_1(\mathcal{M}_0), ..., \gamma_K(\mathcal{M}_0))$, $\gamma_k = \frac{1}{\alpha_k (g(\mathcal{M}_0))^{1-\theta} + 1 - \alpha_k}$ *and* $[\Omega(\mathcal{A}, \mathcal{M}_0)]_{kr} = \omega_{kr}$ *if* $r \in S_k$ *and 0 otherwise.*

Path Dependence of the effect of a small $\varepsilon^m \neq 0$

Proposition (Path dependence)

Let $c_k(\mathcal{A}, \mathcal{M}_0) \equiv \ln C_k(\mathcal{A}, \mathcal{M}) - \ln C_k(\mathcal{A}, \mathcal{M}_0), \forall k$. *Consider any two baseline pairs* $(\underline{\mathcal{A}}, \underline{\mathcal{M}}_0)$, $(\overline{\mathcal{A}}, \overline{\mathcal{M}}_0)$, *and* $\varepsilon^m > 0$ *which is small, and* $P_{k,0} = (1+\mu_k)g(\mathcal{M}_0)MC_k(\mathcal{A}, \mathcal{M}_0)$, *and* $\overline{\mathcal{M}}_0 \geq \underline{\mathcal{M}}_0$:

$$\mathbb{c}(\overline{\mathcal{A}}, \overline{\mathcal{M}}_0) - \mathbb{c}(\underline{\mathcal{A}}, \underline{\mathcal{M}}_0) = \left[\mathcal{L}(\overline{\mathcal{A}}, \overline{\mathcal{M}}_0) - \mathcal{L}(\underline{\mathcal{A}}, \underline{\mathcal{M}}_0)\right] \mathcal{E}^m$$

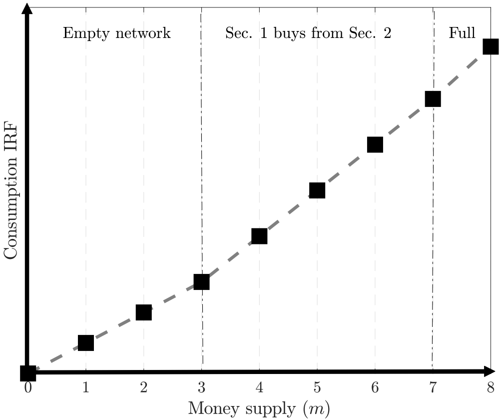
where $\mathbb{c} = [c_1, c_2, ..., c_K]'$, $\mathcal{E}^m = [\varepsilon^m, \varepsilon^m, ..., \varepsilon^m]'$ *and* $\mathcal{L}$ *is a Leontief inverse given by:*

$$\mathcal{L}(\mathcal{A}, \mathcal{M}_0) = [I - (I - A)\Gamma(\mathcal{M}_0)\Omega(\mathcal{A}, \mathcal{M}_0)]^{-1} [I - (I - A)\Gamma(\mathcal{M}_0)]$$

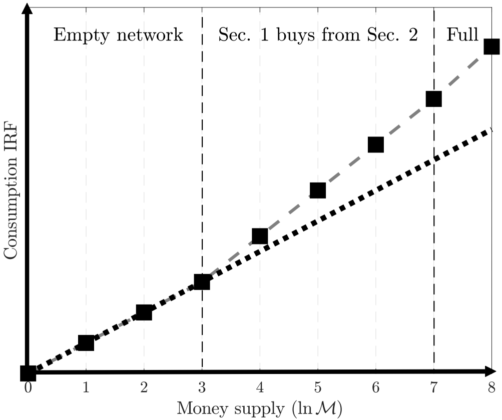
where $A = diag(\alpha_1, ..., \alpha_K)$, $\Gamma(\mathcal{M}_0) = diag(\gamma_1(\mathcal{M}_0), ..., \gamma_K(\mathcal{M}_0))$, $\gamma_k = \frac{1}{\alpha_k(g(\mathcal{M}_0))^{1-\theta}+1-\alpha_k}$ *and* $[\Omega(\mathcal{A}, \mathcal{M}_0)]_{kr} = \omega_{kr}$ *if* $r \in S_k$ *and 0 otherwise.*

Large Monetary Shocks

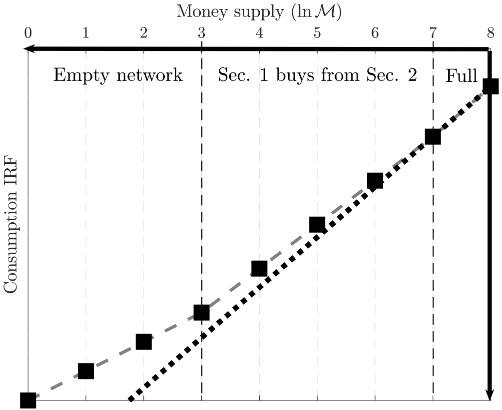
Large monetary expansions



Large monetary expansions



Large monetary contractions



Time Dependent pricing, **Size Dependent** effects

Proposition (Large monetary expansion)

Let $E_+^m > 0$ be a large expansionary monetary shock, and $\varepsilon_+^m > 0$ be a small expansionary monetary shock, both with respect to $(\mathcal{A}, \mathcal{M}_0)$; further, denote $S_{E_+} \equiv S^* \left(\mathcal{A}, \mathcal{M}_0 \exp(E_+^M)\right)$, then:

$$\mathcal{L}(S_0)A(\mathbb{E}_+^m - \varepsilon_+^m) \leq \mathbb{c}(\mathcal{A}, \mathcal{M}_0; E_+^m) - \mathbb{c}(\mathcal{A}, \mathcal{M}_0; \varepsilon_+^m) \leq \mathcal{L}(S_{E_+})\, A(\mathbb{E}_+^m - \varepsilon_+^m)$$
$$+ h.o.t. \qquad\qquad + h.o.t.$$

Hence, large monetary expansions have a ***more than proportional effect on GDP*** *than small monetary expansions.*

Time Dependent pricing, **Size Dependent** effects

Proposition (Large monetary contraction)

Let $E^m_- < 0$ be a large contractionary monetary shock, and $\varepsilon^m_- > 0$ be a small contractionary monetary shock, both with respect to $(\mathcal{A}, \mathcal{M}_0)$; further, denote $S_{E_-} \equiv S^* \left(\mathcal{A}, \mathcal{M}_0 \exp(E^M_-)\right)$, then:

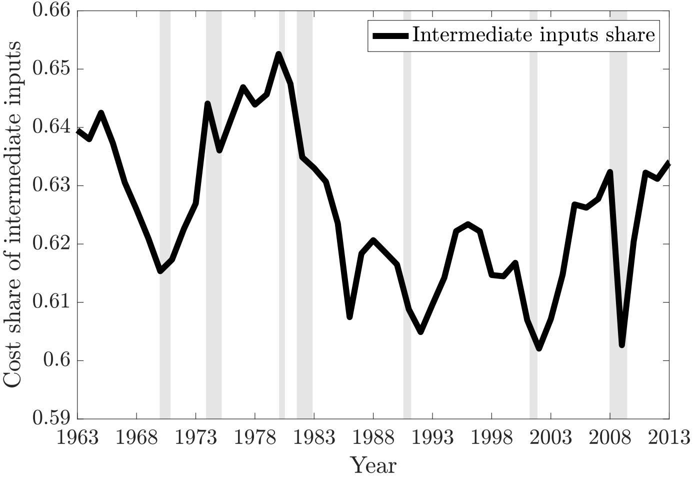
$$\mathcal{L}(S_0)A(\mathbb{E}^m_- - \varepsilon^m_-) \geq \mathbb{c}(\mathcal{A}, \mathcal{M}_0; E^m_-) - \mathbb{c}(\mathcal{A}, \mathcal{M}_0; \varepsilon^m_-) \geq \mathcal{L}(S_{E_-})A(\mathbb{E}^m_- - \varepsilon^m_-) \\ + h.o.t. \qquad\qquad + h.o.t.$$

*Hence, large monetary contractions have a **more less proportional effect on GDP** than small monetary contractions.*

EMPIRICAL EVIDENCE

Sectoral Data

Cost share of intermediate inputs (BEA, US)



Cyclical fluctuations in intermediates intensity

- Use BEA annual sectoral accounts (KLEMS) to construct sectoral measures of intermediates intensity between 1987-2017 for 65 sectors (Summary level):

$$\delta_{kt} = \frac{\text{Expenditure on Intermediates}_{kt}}{\text{Expenditure on Intermediates}_{kt} + \text{Compensation of Employees}_{kt}}$$

  which exactly matches to $\sum_{r \in S_{kt}} \omega_{kr}, \forall k$, in our theoretical framework

- Linear local projection:

$$\delta_{k,t+H} = \alpha_{k,H} + \beta_H s_t + \gamma_H x_{k,t-1} + \varepsilon_{k,t+H}$$

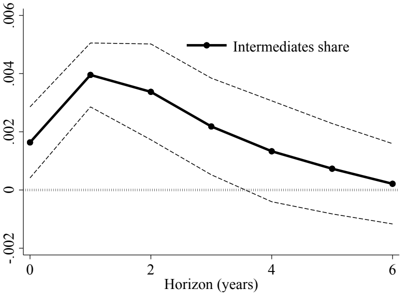
- Non-linear local projection:

$$\delta_{k,t+H} = \alpha_{k,H} + \beta_H^{lin} s_t + \beta_H^{sign} s_t \times \mathbf{1}\{s_t > 0\} + \beta_H^{size} s_t \times |s_t| + \gamma_H x_{k,t-1} + \varepsilon_{k,t+H},$$

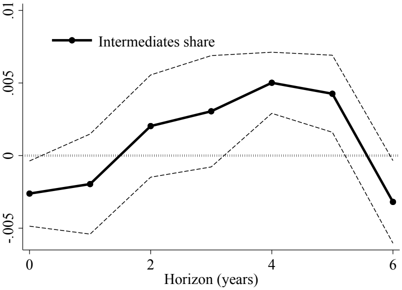
- Use Fernald's TFP shocks and Romer-Romer monetary shocks

Intermediates intensity response: linear local projection

Effect of +1% productivity expansion

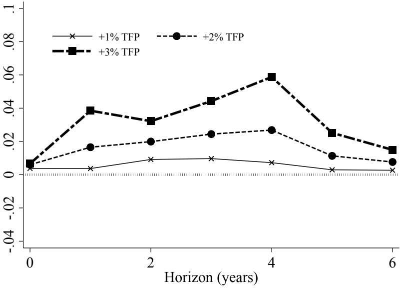


Effect of -100bp monetary easing

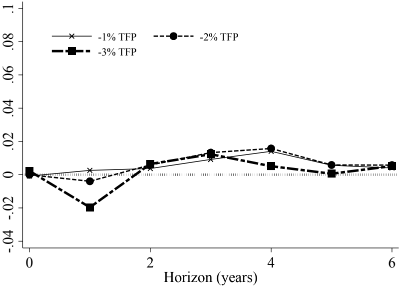


Productivity shocks: non-linear local projection

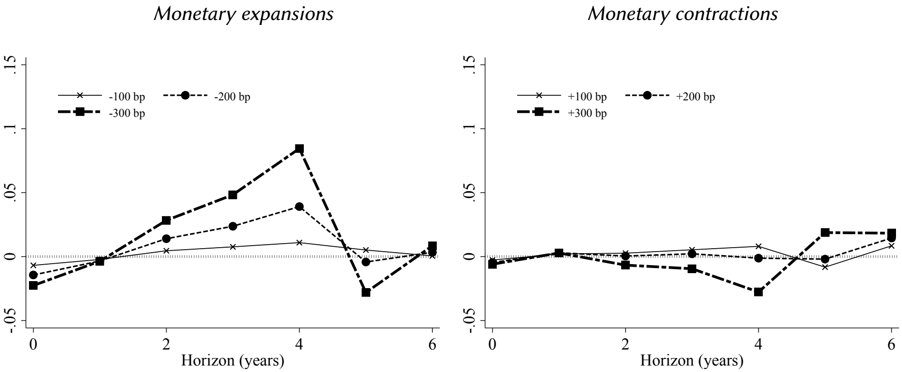
Productivity expansions



Productivity contractions



Monetary shocks: non-linear local projection



Firm-level Data

Cyclical fluctuations in the number of suppliers

- Measure the number of suppliers at firm level, using data on ”in-degree” computed by Atalay et al. (2011) for US publicly listed firms available in Compustat

- Linear local projection:

$$indeg_{k,t+H} = \alpha_{k,H} + \beta_H s_t + \gamma_H x_{k,t-1} + \varepsilon_{k,t+H}$$

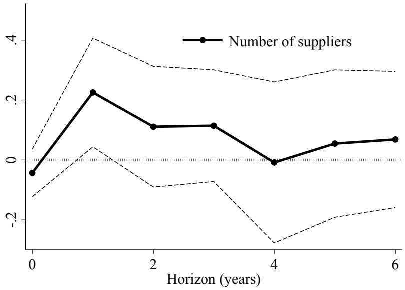
- Non-linear local projection:

$$indeg_{j,t+H} = \alpha_{j,H} + \beta_H^{lin} s_t + \beta_H^{sign} s_t \times \mathbf{1}\{s_t > 0\} + \beta_H^{size} s_t \times |s_t| + \gamma_H x_{j,t-1} + \varepsilon_{j,t+H},$$

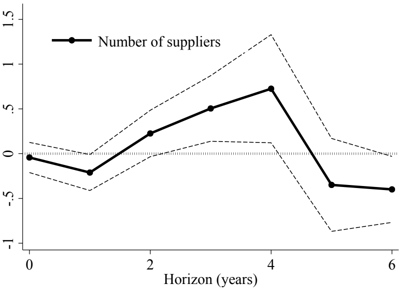
- Use Fernald’s TFP shocks and Romer-Romer monetary shocks

Number of suppliers response: linear local projection

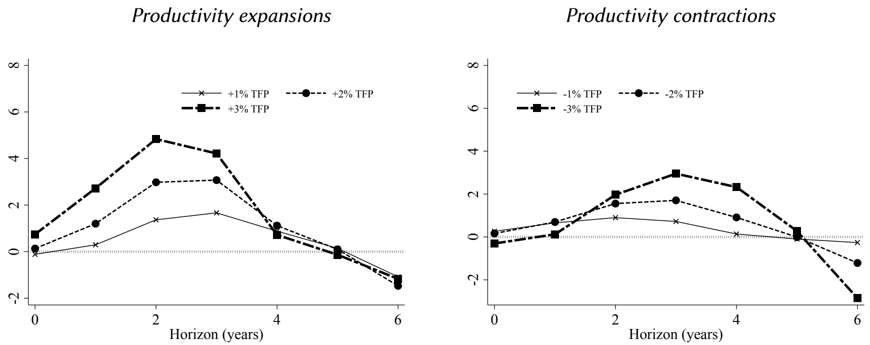
Effect of +1% productivity expansion



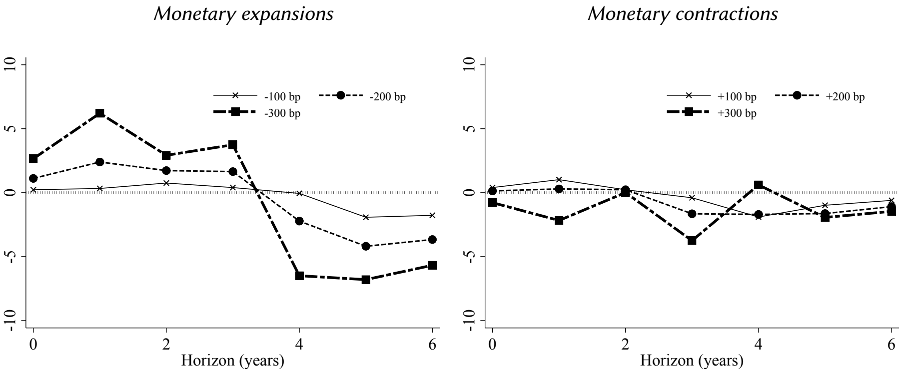
Effect of -100bp monetary easing



Productivity shocks: non-linear local projection



Monetary shocks: non-linear local projection



Conclusion

- Develop a sticky-price New Keynesian model with endogenous input-output linkages across sectors
- Results rationalize observed non-linearities associated with monetary transmission: cycle dependence, path dependence and size dependence (without using state-dependent pricing)
- Novel empirical evidence in support of the mechanism
- Quantify the mechanisms in a calibrated multi-sector setting
- Future work: endogenous networks across countries, monetary transmission under varying ”openness”

APPENDIX