

# Inflation Dynamics During the Financial Crisis

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## Abstract

Using confidential product-level price data underlying the U.S. Producer Price Index (PPI), this paper analyzes the effect of changes in firms' financial conditions on their price-setting behavior during the "Great Recession" that surrounds the financial crisis. The evidence indicates that during the height of the crisis in late 2008, firms with "weak" balance sheets increased prices significantly relative to industry averages, whereas firms with "strong" balance sheets lowered prices, a response consistent with an adverse demand shock. These stark differences in price-setting behavior are consistent with the notion that financial frictions may significantly influence the response of aggregate inflation to macroeconomic shocks. We explore the implications of these empirical findings within a general equilibrium framework that allows for customer markets and departures from the frictionless financial markets. In the model, firms have an incentive to set a low price to invest in market share, though when financial distortions are severe, firms forgo these investment opportunities and maintain high prices in an effort to preserve their balance-sheet capacity. Consistent with our empirical findings, the model with financial distortions—relative to the baseline model without such distortions—implies a substantial attenuation of price dynamics in response to contractionary demand shocks.

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# 1 Introduction

In spite of substantial and persistent economic slack—as well as a significant tightening of financial conditions—the U.S. economy experienced only a mild disinflation during the “Great Recession” and its aftermath. The absence of significant deflationary pressures during this period is at odds with the canonical New Keynesian framework, which rationalizes the puzzling behavior of inflation by appealing to large unobservable shocks to the markup of price over marginal cost. In this paper, by contrast, we analyze inflation dynamics during the 2007–09 financial crisis through the lenses of customer-markets theory, while allowing for departures from the Modigliani–Miller paradigm of frictionless financial markets.

As formalized by Bilal (1989), the key idea behind customer markets is that pricing decisions are a form of investment that builds the future customer base. In the presence of financial market frictions, however, firms experiencing a deterioration in the quality of their balance sheets may find it optimal to increase prices—relative to financially healthy firms—and sacrifice future sales in order to boost current cash flows; see, for example, Gottfries (1991); Bucht, Gottfries, and Lundin (2002) and Chevalier and Scharfstein (1996). This suggests that changes in financial conditions may have a direct effect on aggregate inflation dynamics, especially in periods of acute financial distress. Importantly, the interaction of financial factors and the price-setting behavior of firms may limit the deflationary pressures that are often associated with the boom-bust nature of credit-driven cyclical fluctuations, which are typically characterized by a significant deterioration in the quality of borrowers’ balance sheet conditions and large increases in the cost of external finance.

As a first step in our analysis, we construct a novel data set by merging a subset of monthly *product-level* prices from the U.S. Producer Price Index (PPI), constructed and published by the Bureau of Labor Statistics (BLS), with the respondents’ quarterly income and balance sheet data from Compustat. The micro-level aspect of our data allows us to analyze how changes in financial conditions of these large publicly-traded firms affect their price-setting behavior during the 2005–12 period. Our results indicate that at the peak of the crisis in late 2008—after the collapse of Lehman Brothers—financially vulnerable firms, on average, dramatically increased prices relative to their industry average, whereas their financially healthy counterparts lowered prices in response to the ensuing collapse in aggregate demand. During this period, the price increases by firms with “weak” balance sheets generate a differential of 10 percentage points in the monthly producer price inflation relative to firms with “strong” balance sheets. The resulting differential in relative prices of financially weak and strong firms is highly persistent over time.

Formal regression analysis also indicates that financially weak firms were significantly more likely to increase prices during the height of the financial crisis. At the same time, these firms were less likely to lower prices before the crisis and in its aftermath. These results strongly suggest that firms with weak balance sheets actively manage their prices to maintain cash flows in the face of declining demand, and argues against the possibility that price differentials arise because firms

with weak balance sheets are less well managed and hence less responsive to changes in economic conditions.<sup>1</sup>

To explore the macroeconomic and policy consequences of financial distortions in a customer-markets framework, we build a general equilibrium model, the essential feature of which is that firms face costly price adjustment, while setting prices to actively manage current versus future expected demand. We do so in the context of the “deep habits” framework formulated by Ravn, Schmitt-Grohe, and Uribe (2006a), which is augmented with a tractable model of costly external finance. As in Gourio and Rudanko (2011), customer base in our model is a form of investment. The investment literature has long emphasized the notion that financial distortions may create a debt-overhang problem, which leads firms to pass up otherwise positive net present value projects (Myers (1977)).<sup>2</sup> The presence of financial distortions may similarly influence the incentive to invest into customers via price reductions, implying a sensitivity of price-setting decisions to changes in balance sheet conditions—when cash flow is low or external finance is very costly, firms will “disinvest” by maintaining high prices. In this sense, our framework echoes the theoretical insights of Chevalier and Scharfstein (1996) regarding the role of financial market frictions on the cyclical variation in the markup but generalizes their results to a fully dynamic general equilibrium setting. More generally, the framework presented in this paper can be viewed as a special application of liquidity-based asset pricing (Holmstrom and Tirole (2001)) to the New Keynesian pricing theory.

Relative to the baseline model with frictionless financial markets, our model implies a significant attenuation of the response of prices to contractionary demand shocks. Moreover, in a calibration where external finance is extremely costly—as was likely the case at the nadir of the 2007–09 financial crisis—our model implies that inflation rises rather than falls in response to a contractionary demand shock. These theoretical results are consistent with the apparent lack of significant deflationary pressures during the recent recession, and they also suggest that financial factors may help explain sluggish price responses more generally.

One of the defining features of the recent macroeconomic experience is the fact that since the end of 2008, the federal funds rate has been stuck at its effective lower bound. The implications of our model for macroeconomic outcomes at the zero lower bound (ZLB) are striking. In a model with financial distortions, the attenuation of deflationary pressures implies that the ZLB is both harder to achieve, and when achieved, the economy is likely to exit the ZLB environment sooner.

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<sup>1</sup>Christiano, Eichenbaum, and Evans (2005), Christiano, Gust, and Roldos (2004), and the empirical work of Barth and Ramey (2002) all emphasize a “cost channel,” whereby firms borrow to finance inputs to production. To the extent that firms with weak balance sheets face higher borrowing costs, which during the crisis increase more sharply than those for firm with strong balance sheet, financially vulnerable firms may pass those cost increases on to their customers in the form of higher prices. As we discuss below, the cost channel naturally arises in the context of our model but is not the primary mechanism through which financial frictions influence price-setting in the customer-markets framework.

<sup>2</sup>See Fazzari, Hubbard, and Petersen (1988), Chirinko (1993), and Gilchrist and Himmelberg (1995) for related empirical evidence and discussion.

In other words, the sharp contractionary nature of a deflationary spiral at the zero lower bound is surprisingly mitigated to a great extent by the presence of financial distortions, a result suggesting that in a customer-markets model, financial frictions may paradoxically improve overall economic outcomes in an environment where the zero lower bound is binding. This echoes recent findings of Denes, Eggertsson, and Gilbukh (2013) and Eggertsson (2011), who argue that certain forms of taxation may improve economic outcomes in situations where short-term interest rates are stuck at their effective lower bound.

We also consider an extension of our benchmark model that allows for heterogeneity in fixed operating costs across firms. The resulting differences in operating efficiency translate directly into differences in financial conditions: A firm with low operating efficiency (i.e., high fixed operating costs) is in a much more precarious financial position because, on average, it will have a more difficult time meeting its liquidity needs using internally-generated funds and, therefore, will face a higher external finance premium. In such context, an adverse financial shock causes financially healthy firms to aggressively cut prices in an effort to gain a market share, whereas their financially constrained counterparts find it optimal to increase prices to avoid relying on costly external finance. The resulting “price war” induces countercyclical dispersion in firm-level inflation rates—as well as in output and employment—a pattern consistent with that reported by Vavra (2011). However, it is important to emphasize that in our framework the countercyclical dispersion in inflation rates (and other variables) arises endogenously in response to differences in financial conditions across firms, whereas Vavra (2011) generates the countercyclical dispersion in inflation rates using an exogenous countercyclical second-moment shock.

The theoretical mechanism that we study has broader implications for the conduct of monetary policy. The standard New Keynesian framework analyzes optimal policy from the perspective of the welfare losses induced by output fluctuations and price dispersion owing to nominal rigidities. In the standard framework, demand shocks imply the so-called divine coincidence, the fact that countercyclical monetary policy achieves the joint stabilization of output and inflation. The trade-off between inflation and output stabilization only arises in circumstances where the “cost-push” shocks move inflation and output in opposite directions. In our model, demand shocks may also lead to opposing movements in inflation and output. However, when firms face varying costs of external finance, demand shocks also lead to increased dispersion in prices, even in the absence of large swings in aggregate inflation. These results suggest that customer-markets models with financial distortions may have starkly different implications for the inflation-output tradeoff—and therefore for the conduct of monetary policy—especially at times of significant distortions in financial markets.

## 2 Data Sources and Methods

To understand the interaction between price-setting behavior of firms and the condition of their balance sheets, we construct a new firm-level data set using two sources: (1) *product-level* price data underlying the Producer Price Index published by the Bureau of Labor Statistics; and (2) *firm-level* income and balance sheet data from Compustat.

### 2.1 Producer Price Data

The confidential PPI micro-level price data from the BLS form the cornerstone of our analysis for two reasons.<sup>3</sup> First, they allow us to construct firm-level inflation rates, thereby overcoming the limitations of working with aggregate price indexes. And second, they allow us to analyze firm-level price dynamics directly in conjunction with the respondents' corresponding financial data. Both of these features represent an important advance over any analysis that employs aggregate price series—even if narrowly defined—because price dynamics at the product and firm levels are subject to large idiosyncratic shocks (cf. Nakamura and Steinsson (2008); Bils and Klenow (2004); and Gopinath and Itskhoki (2011)). Moreover, prices at the level of individual products contain potentially important information to understand the economics of price adjustment at the firm level.

From a practical perspective, we focus on the PPI data because they yield a much broader match with the data set of publicly-traded Compustat firms. Economic considerations also point to studying producer prices as they most directly reflect the response of production unit to changes in the underlying economic fundamentals. The CPI data, in contrast, reflect the pricing behavior of non-producing retailers—the so-called outlets—which are subject to price responses by the entire distribution network and therefore may exhibit quite different price-setting behavior. Moreover, the PPI data exclude prices of imported goods, which are an important part of the CPI, but for which data on financial conditions of the underlying production units are not readily available. All told, our sample contains about 100,000 monthly producer price quotes collected by the BLS from 28,300 production units. The time-series range of our data runs from January 2005 through September 2012 and thus fully includes the 2007-09 financial crisis and its aftermath.

Our measure of firm-level inflation—denoted by  $\pi_{j,k,t}$ —is given by the weighted monthly average price changes of goods produced by each firm, after filtering out monthly industry-level (2-digit

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<sup>3</sup>The PPI data are described at length for example in Nakamura and Steinsson (2008), Bhattarai and Schoenle (2010) and Goldberg and Hellerstein (2009). The data are representative of the entire U.S. production structure and have the important quality that they are carefully and consistently sampled. In particular, goods within a firm are uniquely identified according to several consistent criteria: their “price-determining” characteristics such as the type of buyer, the type of market transaction, the method of shipment, the size and units of shipment, the freight type, and the day of the month of the transaction. Once a good is identified, prices are consistently collected each month for that very same good and the same customer. Such consistent sampling avoids the problem of having to compute unit prices as is given with many micro data sets. All prices are transaction prices, not list prices as critiqued by Stigler and Kindahl (1970).

NAICS) inflation rates (denoted by  $\pi_{k,t}$ ). Formally,

$$\pi_{j,k,t} = \frac{1}{n_j} \sum_{i=1}^{n_j} w_{i,j,k,t} (\Delta p_{i,j,k,t} - \pi_{k,t}), \quad (1)$$

where  $\Delta p_{i,j,k,t}$  denotes monthly log price changes for each good  $i$  produced by firm  $j$  that operates in an industry  $k$ , and  $n_j$  the number of goods produced by that firm.<sup>4</sup> Importantly, we use *quality-adjusted* prices when constructing these inflation rates. For each item, the quality-adjusted price in month  $t$  is defined as the ratio of the recorded price  $p_{i,j,k,t}^*$  to the base price  $p_{i,j,k,t}^b$ , where the latter takes into account changes in the item’s quality over time:  $p_{i,j,k,t} = \frac{p_{i,j,k,t}^*}{p_{i,j,k,t}^b}$ . The fraction of firm-level price changes is constructed analogously using a quarterly price change indicator variable instead of the monthly log price difference but without filtering.

We construct weights very carefully based on the relative importance weights used by the BLS and firm-level value of shipments data recorded by the BLS for computation of the aggregate PPI. We define the within-firm good-level weight  $w_{i,j,k,t}$  as follows:

$$w_{i,j,k,t} = \bar{w}_{i,j,k,t} \times \omega_{j',t}, \quad (2)$$

where  $\bar{w}_{i,j,k,t}$  denotes the relative weight for good  $i$  in the production structure of firm  $j$ , according to the BLS definition. The second term in the expression is an adjustment factor that takes into account the fact that in our merge with Compustat data more than one BLS respondent may fall within the Compustat firm definition  $j$ . The adjustment factor is therefore defined as the relative value of shipments weight of one BLS firm with respect to all other BLS firms within the same Compustat firm unit.

## 2.2 Indicators of Financial and Product Market Frictions

We use quarterly Compustat data to characterize the firms’ financial conditions and product market characteristics. Our primary measure of financial conditions is the liquid-asset ratio, defined as

$$LIQUIDITY_{j,t} = \frac{\text{Cash and other Liquid Assets}_{j,t}}{\text{Total Assets}_{j,t}}, \quad (3)$$

where cash (and other liquid assets) and total assets are measured at the end of month  $t$  corresponding to the firm’s fiscal quarter, which is properly aligned with the calendar month and thus each monthly inflation rate.<sup>5</sup> As a robustness check, we also consider two alternative financial

<sup>4</sup>Note that taking out “industry inflation” does not take into account the weight assigned to each industry for a firm if the firm operates across multiple industries. This is not a problem for our data. The reason is the the BLS defines firms as price-setting units in one production unit, which is usually unique to a NAICS code, especially at 2-digit level of filtering. We drop the handful of cases where a firm operates across multiple industries.

<sup>5</sup> Other widely used indicators to measure the degree of financial frictions faced by firms include the dividend payout status (Carpenter, Fazzari, and Petersen (1994)); firm size (Gertler and Gilchrist (1994) and

indicators: cash-flow ratio and interest coverage. We define the cash-flow ratio as:

$$CASH-FLOW_{j,t} = \frac{Operating\ Income_{j,t}}{Total\ Assets_{j,t-1}}; \quad (4)$$

and the interest coverage ratio as:

$$INTEREST-COVERAGE_{j,t} = \frac{Interest\ Expense_{j,t}}{Total\ Sales_{j,t}}. \quad (5)$$

To measure product-market characteristics motivated by the customer-markets theory, which emphasizes the idea that price setting is a form of investment that builds the future customer base, we include into our analysis sales and general administrative expenses (SG&A), a commonly-used indicator of frictions in product markets. We normalize SG&A expenditures by sales:

$$SGAXR_{j,t} = \frac{SGAX_t}{Total\ Sales_{j,t}}. \quad (6)$$

It is important to emphasize that the intensity of SG&A spending can have opposite implications for pricing decisions. On the one hand, for a firm with a relatively high SG&A ratio—an indication that the firm is likely operating in a customer market environment (e.g., Gourio and Rudanko (2011))—one would expect a stronger incentive to lower prices today in order to expand market share tomorrow. On the other hand, due to the quasi-fixed nature of SG&A expenses, a high ratio of SG&A to sales may be associated with low operating efficiency. In turn, this would force firms to set higher prices today to boost current cash flow, a dynamic that would be exacerbated during periods of financial stress when external financing is very costly. In the empirical analysis, we let the data speak for themselves to see which force dominates the pricing dynamics during the financial crisis.

### 2.3 Matched Compustat-PPI Sample

To link the BLS micro-level research database with the firm-level Compustat, we use the matching algorithm developed by Schoenle (2010). The algorithm works by running a fuzzy match of the names of firms in the PPI and Compustat databases.<sup>6</sup> After sorting all nonperfect matches in

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Carpenter, Fazzari, and Petersen (1998)); the reliance of trade credit (Nilsen (2002)); the presence (or absence) of an external credit rating (Gilchrist and Himmelberg (1995)); the length and/or number of banking relationships Petersen and Rajan (1994); and industrial effects arising from factor intensity differentials (Rajan and Zingales (1998)).

<sup>6</sup>The steps of the algorithm can be summarized as follows: First, firm names in the PPI and Compustat data are assimilated through a series of string manipulations by means of capitalization, punctuation removal, standardization of terms, and removal of generic terms. Second, a modified string similarity algorithm computes a measure of similarity between base and target firm names. It summarizes the quality of matches using Dice's coefficient  $s = 2c/(x_1 + x_2)$  where  $c$  is the number of common bigrams,  $x_1$  the number of bigrams in the first string and  $x_2$  the number of bigrams in the second string. Note that when  $s = 1$ , we have a perfect match.

decreasing order of similarity, we then manually select “good” matches in addition to perfect matches.

After applying the algorithm to the two data sets over the 2005-12 period, we successfully matched 780 Compustat firms, on average, per quarter. Given that we have information on almost 5,000 Compustat firms in an average quarter, this implies a matching rate of 16 percent. In terms of basic characteristics, the firms in the matched sample tend to be larger, a result that is not at all surprising because large firms are more likely to be sampled by the BLS. In terms of their price-setting behavior, we find that there are no significant differences between average monthly inflation rates in the full PPI data set and the matched subsample. At the same time, the frequency of price changes in the matched sample is somewhat higher than in the full sample (see Table 1).

Figure 1 plots the aggregate inflation rates for the full and matched sample of firms. The two series are highly correlated, an indication that our matched sample is broadly representative of the economy as a whole. And lastly, as indicated in Table 2, our matched sample of firms exhibits somewhat lower liquidity, SG&A and interest expense ratios, on average, compared with the sample of all U.S. publicly-traded nonfinancial corporations.

### 3 Inflation Dynamics and Financial Conditions

To analyze the role of financial distortions in determining inflation dynamics, we first compute industry-adjusted firm-level inflation rates as described above. Then for each month  $t$ , we sort firms into financially “weak” and “strong” categories based on whether a specified financial indicator in month  $t - 1$  (i.e., liquid asset ratio, cash flow ratio, or interest coverage ratio) is below/above the median of its distribution in that period. To minimize the switching of firms between the two categories, we use a rolling 12-month backward moving average of financial ratios when sorting firms into financially weak and strong categories. We use the same method to identify firms with a high (low) intensity of SG&A spending. Finally, we compute average weighted monthly inflation for each category using firms sales as weights.

The top panel of Figure 2 shows the industry-adjusted inflation rates for firms with weak balance sheets, while the bottom panel depicts the the same information for firms in a strong financial position. Regardless of the financial indicator used to sort firm into financially weak and strong categories, a strikingly similar picture emerges: At the peak of the crisis in the fourth quarter of 2008, firms with weak balance sheets significantly increased—relative to their industry trend—prices, whereas their financially healthy counterparts substantially lowered prices, a response consistent with the sharp drop in demand that was occurring at that time. Note that such differences in price-setting behavior in response to a contractionary demand shock will lead to a persistent and long-lasting dispersion in prices.

Our next empirical exercise focuses on firms with different product-market characteristics. The top panel of Figure 3 shows the industry-adjusted inflation rates for firms with different intensities



of SG&A spending. The bottom panel focuses on a subset of SG&A expenses, namely advertising expense, a narrower indicator of whether a firm is operating in a customer-markets environment. According to both panels, firms that likely operate in the customer-markets environment significantly increased prices in the latter part of 2008. In contrast, firms that likely operate in competitive markets lowered their prices significantly, a response consistent with the concomitant drop in demand. These results suggest that a substantial part of the SG&A expenditures reflects overhead costs and that this ratio may not be indicative of whether a firm is operating in a customer-markets environment.

The results in Figures 2 and 3 are difficult to reconcile with the standard price-adjustment mechanism emphasized by the New Keynesian literature, a paradigm where firms' financial conditions play no role in determining their price-setting behavior. In general, we would expect that firms hit by an adverse demand shock—the kind the U.S. economy experienced in the latter part of 2008—should induce firms to lower prices. Moreover, if the proxies used to measure the strength of firms' balance sheets were also indicative of the weakness in demand, we would expect financially vulnerable firms to lower prices even more relative to financially strong firms. However, we observe exactly the opposite reaction in the data.

As emphasized by [Bils, Klenow, and Malin \(2012\)](#), disinflationary pressures during the “Great Recession” were most pronounced in nondurable goods industries. The top panel of Figure 4 shows inflation rates of financially strong and weak firms within the durable and nondurable goods sectors, while the bottom panel contains inflation rates for firms with varying intensity of SG&A spending, again within the durable and nondurable goods sectors. According to both panels, the deflationary pressures during the recent financial crisis were concentrated primarily in the nondurable goods sector, a result consistent with that reported by [Bils, Klenow, and Malin \(2012\)](#).

However, within the nondurable goods sector, price deflation reflects solely the massive price cut by financially healthy firms or firms that are unlikely to operate within the customer-markets environment. In contrast, nondurable goods producers with weak balance sheets or those with a high SG&A expense ratio significantly increased prices during the height of the crisis. The fact that inflation dynamics in nondurable goods industries during the financial crisis appear to be shaped significantly by financial conditions and SG&A expenditures is consistent with the notion that nondurable goods are typically frequently-purchased items, subject to habits and past experience, factors at the center of the customer-markets theory. In contrast, we expect customers to be less loyal to past purchase habits when buying large-item durable goods that are purchased relatively infrequently.

### **3.1 Extensive Margin of Price Adjustment**

In this section, we provide new evidence on the importance of the strength of firm balance sheets and the intensity of SG&A spending for price adjustment at the extensive margin—that is, the

frequency of price adjustment. As Bhattarai and Schoenle (2010), we estimate a multinomial logit of the form:

$$\Pr(Y_{i,j,t+1} = \{-1, 0, 1\} | X_{i,j,t} = x) = \Lambda(\beta'_t X_{i,j,t}), \quad (7)$$

where  $Y_{i,j,t+1}$  is an indicator variable for price changes at time  $t + 1$  of good  $i$  produced by firm  $j$ :  $-1$  = price decrease;  $0$  = no change (base category); and  $1$  = price increase. The set of firm-level explanatory variables  $X_{i,j,t}$  includes the liquidity ratio, the SG&A-to-sales ratio, and sales growth at time  $t$ . In addition, the specification includes time and (3-digit NAICS) industry fixed effects.

To allow for time-series variation in the response coefficients  $\beta_t$ , we estimate the multinomial logit specification using a four-quarter rolling window. The resulting (time-varying) estimates are used to compute the elasticity of the response variable—that is, the percent change in the probability of a price adjustment for a given percent change in a variable of interest, evaluated at the sample mean of the explanatory variables.

The top panel of Figure 5 depicts the time-varying elasticity estimates of price adjustment with respect to financial conditions, as measured by the liquid-asset ratio; the left panel depicts the elasticity of downward price adjustment, while the right panel depicts the elasticity of upward price adjustment. According to these estimates, firms with weak balance sheets became significantly more likely to increase prices during the financial crisis, as evidenced by the fact that the estimated elasticity of upward price adjustment with respect to liquidity ratio (right panel) dropped noticeably into the negative territory in the latter half of 2008; conversely, financial healthy firms were less likely to increase prices during that period.

In economic terms, an increase in the liquidity ratio of one percentage points in the second half of 2008 is estimated to lower—*ceteris paribus*—the probability of upward price adjustment 16 basis points relative to no price change. At the same time, the results in the left panel indicate that a high liquidity ratio is consistently associated with a greater likelihood of downward price adjustment. In sum, these results suggest that financially strong firms face lower downward price rigidity—at least at the extensive margin—compared with their weaker counterparts.

The bottom panel of Figure 5 presents the elasticities of price adjustment with respect to the SG&A ratio. The fact that both directional elasticities are consistently negative indicates that firms with a high intensity of SG&A spending are less likely to change their prices—either up or down—relative to no price change. Moreover, there is little evidence to suggest that this pattern has changed appreciably during the financial crisis; at the same time, there is a sizable drop—at least in economic terms—in the elasticity of downward price adjustment during the crisis, an indication that firms with higher SG&A-to-sales ratio were less likely to lower their prices during that period.

## 4 Model

In this section, we develop a general equilibrium model that is qualitatively able to match the salient facts about inflation dynamics during the nadir of the 2007–09 financial crisis. The model’s key feature are monopolistically-competitive firms that set prices in a customer-markets environment, whereby the firms’ current pricing decisions influence their future market shares. We show that in the presence of financial market distortions, firms have an incentive to raise prices in response to adverse demand shocks. This counterintuitive result reflects the firms’ reaction to preserve internal liquidity and avoid tapping costly external finance, factors that significantly strengthen the usual countercyclical behavior of markups implied by New Keynesian models. We show that through a standard financial accelerator mechanism, this behavior creates an aggregate demand externality, which has quantitatively important feedback effects on the macroeconomy.

To motivate the competition for market shares implied by the customer-markets hypothesis, we consider household preferences that allow for the formation of a *customer base*—that is, “low” prices today are a form of investment in a future market share (see Rotemberg and Woodford, 1991).<sup>7</sup> Specifically, we adopt the good-specific habit model of Ravn, Schmitt-Grohe, and Uribe (2006b), which we augment with nominal rigidities in the form of quadratic adjustment costs faced by firms when changing nominal prices. Because our empirical analysis indicates that financial factors primarily affect the price-setting behavior of firms in the nondurable goods sector, we consider only perishable goods in our model formulation. To explore the influence of financial frictions on the firms’ price-setting behavior, our framework also includes a stylized but tractable model of costly external finance.

To highlight the essential mechanism at work in our model, we first consider a case of homogeneous firms. We then extend the basic model to a case of heterogeneous firms and study the extent to which financially weak firms—in response to a fall in aggregate demand—may increase prices relative to those of their financially strong counterparts, a behavior documented for the peak of the crisis in latter part of 2008. Allowing for firm heterogeneity significantly amplifies the adverse feedback loop between financial conditions and the real economy because firms with relatively strong balance sheet—and thus relatively easy access to external finance—exploit the weak financial position of their competitors by lowering prices and stealing their market share.

### 4.1 Preferences and Technology

The model contains a continuum of households indexed by  $j \in [0, 1]$ . Each household consumes a variety of consumption goods indexed by  $i \in [0, 1]$ . The preferences of households are defined over

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<sup>7</sup>Switching cost models of the type surveyed by Klemperer (1995) would serve the same purpose. We chose the good-specific habit model because of its tractability in a dynamic general equilibrium setting.

a habit-adjusted consumption bundle  $x_t^j$  and labor  $h_t^j$  as follows:

$$\mathbb{E}_t \sum_{s=0}^{\infty} \beta^s U(x_{t+s}^j - \psi_{t+s}, h_{t+s}^j), \quad (8)$$

where the AR(1) demand shock  $\psi_t$  affects the final demand by altering the current marginal utility of consumption.

The consumption/habit aggregator is defined as

$$x_t^j \equiv \left[ \int_0^1 \left( \frac{c_{it}^j}{s_{i,t-1}^\theta} \right)^{1-\frac{1}{\eta}} di \right]^{\frac{1}{1-\frac{1}{\eta}}}; \quad \theta < 0 \text{ and } \eta > 0, \quad (9)$$

where  $c_{it}^j$  denotes the amount of a good of variety  $i$  consumed by household  $j$  and  $s_{it}$  is the habit stock associated with good  $i$ . The good-specific habit stock is assumed to be external and thus taken as given by consumers. Specifically, we assume that the external habit evolves according to

$$s_{it} = \rho s_{i,t-1} + c_{it}; \quad 0 < \rho < 1, \quad (10)$$

where  $1 - \rho$  is the rate of depreciation of the current habit stock.

The dual problem of cost minimization gives rise to a good-specific demand:

$$c_{it}^j = \left( \frac{p_{it}}{\tilde{p}_t} \right)^{-\eta} s_{i,t-1}^{\theta(1-\eta)} x_t^j, \quad (11)$$

where  $p_{it} = P_{it}/P_t$  is the relative price of variety  $i$  in terms of  $P_t = \left[ \int_0^1 P_{it}^{1-\eta} di \right]^{1/(1-\eta)}$ , and the externality-adjusted composite price index  $\tilde{p}_t$  is given by

$$\tilde{p}_t = \left[ \int_0^1 (p_{it} s_{i,t-1}^\theta)^{1-\eta} di \right]^{\frac{1}{1-\eta}}. \quad (12)$$

The supply side of the economy is characterized by a continuum of monopolistically-competitive firms producing a differentiated variety of goods indexed by  $i \in [0, 1]$ . The production technology is given by

$$y_{it} = \left( \frac{A_t}{a_{it}} h_{it} \right)^\alpha - \phi; \quad 0 < \alpha \leq 1, \quad (13)$$

where  $A_t$  is an aggregate productivity shock that follows an AR(1) process, and  $a_{it}$  is an idiosyncratic (i.i.d.) productivity shock distributed as  $\log a_{it} \sim N(-0.5\sigma^2, \sigma^2)$ ; note that we allow the production technology to exhibit either decreasing or constant returns to scale. In addition, we assume that production is subject to fixed operating costs—denoted by  $\phi$ —which makes it possible for firms to incur negative income, thereby creating a liquidity squeeze if external financing is costly.

Although we do not explicitly model the balance sheet of the firm, implicitly, these fixed costs can include “long-term debt payments,” a coupon payment to perpetual bond holders. Thus broadly speaking, the presence of fixed operating costs captures the possibility of a debt overhang.

## 4.2 Pricing Frictions and Financial Distortions

To allow for nominal rigidities, we follow Rotemberg (1982) and assume that firms face quadratic adjustment costs when changing nominal prices:

$$\frac{\gamma_p}{2} \left( \frac{P_{it}}{P_{i,t-1}} - \bar{\pi} \right)^2 c_t = \frac{\gamma_p}{2} \left( \pi_t \frac{p_{it}}{p_{i,t-1}} - \bar{\pi} \right)^2 c_t; \quad \gamma_p > 0.$$

It is worthwhile to note that staggered pricing models such as those of Calvo (1983) would not change the main conclusions of our paper. Rather, the convex adjustment costs are adopted for the sake of mathematical tractability.<sup>8</sup>

Firms make pricing and production decisions to maximize the present value of discounted dividends. Our timing assumptions imply that firms must commit to pricing decisions—and hence production—based on all aggregate information available within the period, but prior to the realization of their idiosyncratic productivity shock. Based on this aggregate information, firms post prices, take orders from customers, and plan production based on expected marginal costs. Firms then realize actual marginal cost and hire labor to meet the demand. Labor must be paid within the period and in the presence of fixed operating costs, the firm’s ex post profits may be too low to cover the total cost of production. In that case, the firm must raise external funds.

To introduce a wedge between the cost of internal and external finance in a tractable manner, we focus on equity as the sole source of external finance. That is, firms can obtain external funds only by issuing new equity, a process that involves dilution costs reflecting agency problems in financial markets.<sup>9</sup> Formally, we assume that equity finance involves a constant per-unit dilution cost  $\varphi \in (0, 1)$  per dollar of equity issued. To keep the model tractable, we abstract from firm savings decisions by assuming that all dividends are paid out within the period.<sup>10</sup> This formulation of costly external finance allows us to highlight the basic mechanism within a framework that deviates only slightly from the standard good-specific habit model. In particular, in our model, all firms are identical ex ante, and as a result, only firms with an idiosyncratic productivity shock below an endogenous threshold incur negative profits and are forced to issue new equity.

<sup>8</sup>In the numerical implementation of the model, we also assume convex adjustment costs for nominal wages—parametrized by  $\gamma_w$ —by introducing market power associated with differentiated labor. For expositional purposes, we omit those details.

<sup>9</sup>As shown by Gomes (2001) and Stein (2003), other forms of costly external finance reflecting departures from the Modigliani–Miller paradigm of perfect capital markets can be replicated by properly parametrized equity dilution costs.

<sup>10</sup>An interesting extension would involve incorporating precautionary demand for liquid assets in the model. Allowing for costly equity financing and liquidity hoarding, however, would make the *distribution* of firms’ liquid asset holdings a state variable of the model. We leave this nontrivial extension for future research.

### 4.3 Profit Maximization

The firm's problem is to maximize the present value of a dividend flow,  $\mathbb{E}_0[\sum_{t=0}^{\infty} m_{0,t} d_{it}]$ , where  $d_{it}$  denotes the (real) dividend payout when positive and equity issuance when negative and  $m_{0,t}$  is the stochastic discount factor. Note that the presence of equity dilution costs implies that when a firm issues a notional amount of equity  $d_{it} < 0$ , actual cash intake from the issuance is reduced to  $-(1 - \varphi)d_{it}$ .

The firm's problem is subject to the flow-of-funds constraint:

$$0 = p_{it}c_{it} - w_t h_{it} - \frac{\gamma_p}{2} \left( \pi_t \frac{p_{it}}{p_{i,t-1}} - \bar{\pi} \right)^2 c_t - d_{it} + \varphi \min \{0, d_{it}\}; \quad (14)$$

and given the monopolistically-competitive product markets, the demand constraint specified in equation (11). Formally, letting  $\lambda_{it}$ ,  $\nu_{it}$ ,  $\kappa_{it}$ , and  $\xi_{it}$  denote the Lagrange multipliers associated with equations (10), (11), (13), and (14), respectively, the Lagrangian associated with the firm's problem is given by

$$\begin{aligned} \mathcal{L} = & \mathbb{E}_0 \sum_{t=0}^{\infty} m_{0,t} \left\{ d_{it} + \kappa_{it} \left[ \left( \frac{A_t}{a_{it}} h_{it} \right)^\alpha - \phi - c_{it} \right] \right. \\ & + \xi_{it} \left[ p_{it}c_{it} - w_t h_{it} - \frac{\gamma_p}{2} \left( \pi_t \frac{p_{it}}{p_{i,t-1}} - \bar{\pi} \right)^2 c_t - d_{it} + \varphi \min \{0, d_{it}\} \right] \\ & \left. + \nu_{it} \left[ \left( \frac{p_{it}}{\tilde{p}_t} \right)^{-\eta} s_{it-1}^{\theta(1-\eta)} x_t - c_{it} \right] + \lambda_{it} [\rho s_{i,t-1} + (1 - \rho)c_{it} - s_{it}] \right\}. \end{aligned} \quad (15)$$

The firm's optimal choices of its decision variables are summarized by the following first-order conditions:<sup>11</sup>

$$\text{Dividend payout } d_{it} : \quad \xi_{it} = \begin{cases} 1 & \text{if } d_{it} \geq 0 \\ 1/(1 - \varphi) & \text{if } d_{it} < 0; \end{cases} \quad (16)$$

$$\text{Labor input } h_{it} : \quad \kappa_{it} = \xi_{it} a_{it} \left( \frac{w_t}{\alpha A_t} \right) (c_{it} + \phi)^{\frac{1-\alpha}{\alpha}}; \quad (17)$$

$$\text{Production scale } c_{it} : \quad \nu_{it} = \mathbb{E}_t^a [\xi_{it}] p_{it} - \mathbb{E}_t^a [\kappa_{it}] + (1 - \rho)\lambda_{it}; \quad (18)$$

$$\text{Habit stock } s_{it} : \quad \lambda_{it} = \rho \mathbb{E}_t [m_{t,t+1} \lambda_{i,t+1}] \theta (1 - \eta) \mathbb{E}_t \left[ m_{t,t+1} \nu_{i,t+1} \left( \frac{c_{i,t+1}}{s_{it}} \right) \right]; \quad (19)$$

$$\begin{aligned} \text{Relative price } p_{it} : \quad 0 = & \mathbb{E}_t^a [\xi_{it}] c_{it} - \eta \frac{\nu_{it}}{p_{it}} c_{it} - \gamma_p \frac{\pi_t}{p_{i,t-1}} \left( \pi_t \frac{p_{it}}{p_{i,t-1}} - \bar{\pi} \right) c_t \\ & + \gamma_p \mathbb{E}_t \left[ m_{t,t+1} \mathbb{E}_{t+1}^a [\xi_{it}] \pi_{t+1} \frac{p_{i,t+1}}{p_{it}^2} \left( \pi_{t+1} \frac{p_{i,t+1}}{p_{it}} - \bar{\pi} \right) c_{t+1} \right]. \end{aligned} \quad (20)$$

<sup>11</sup>Note that in equation (17), we replace  $h_{it}$  by the conditional labor demand  $h_{it} = (c_{it} + \phi)^{\frac{1}{\alpha}} \left( \frac{a_{it}}{A_t} \right)$  after we derive the associated first-order condition.

Implicit in the last three conditions is the assumption that the firm makes pricing and production decisions prior to the realization of the idiosyncratic productivity shock  $a_{it}$ . Accordingly, these first-order conditions involve the expected value of internal funds  $\mathbb{E}_t^a[\xi_{it}] \equiv \int_0^\infty \xi_{it} dF(a)$ , where the expectations are formed using all aggregate information up to time  $t$ , except, of course, the realization of the idiosyncratic shock. In contrast, the realized values  $\xi_{it}$  and  $a_{it}$  enter the efficiency conditions (16) and (17) without the expectations operator because dividend payouts (or new equity issuance) and labor hiring decisions are made after the realization of the idiosyncratic productivity shock.<sup>12</sup>

Under risk-neutrality and with i.i.d. idiosyncratic productivity shocks, the timing convention adopted above implies that firms are identical ex ante. Hence, we focus on a symmetric equilibrium, in which all monopolistically-competitive firms choose identical relative price ( $p_{it} = 1$ ), production scale ( $c_{it} = c_t$ ), and habit stock ( $s_{it} = s_t$ ). However, the distributions of labor inputs ( $h_{it}$ ) and dividend payouts ( $d_{it}$ ) are non-degenerate and depend on the realization of the idiosyncratic productivity shock.

#### 4.4 Value of Internal Funds and the Customer Base

Define the equity issuance trigger  $a_t^E$  as the level of idiosyncratic productivity that satisfies the flow-of-funds constraint (14) when dividends are exactly zero:

$$a_t^E = \frac{c_t}{(c_t + \phi)^{\frac{1}{\alpha}}} \frac{A_t}{w_t} \left[ 1 - \frac{\gamma_p}{2} (\pi_t - \bar{\pi})^2 \right]. \quad (21)$$

The first-order condition for dividends (16) implies that because of costly external financing, the realized shadow value of internal funds increases from 1 to  $1/(1 - \varphi) > 1$ , when the realization of the idiosyncratic productivity shock is greater than the threshold value  $a_t^E$ :

$$\xi(a_{it}) = \begin{cases} 1 & \text{if } a_{it} \leq a_t^E \\ 1/(1 - \varphi) & \text{if } a_{it} > a_t^E. \end{cases} \quad (22)$$

Let  $z_t^E$  denote the standardized value of  $a_t^E$ ; that is,  $z_t^E = \sigma^{-1}(\log a_t^E + 0.5\sigma^2)$ . The expected shadow value of internal funds can then be expressed as

$$\mathbb{E}_t^a[\xi_{it}] = \int_0^{a_t^E} dF(a) + \int_{a_t^E}^\infty \frac{1}{1 - \varphi} dF(a) = 1 + \left[ \frac{\varphi}{1 - \varphi} \right] [1 - \Phi(z_t^E)] \geq 1, \quad (23)$$

where  $\Phi(\cdot)$  denotes the standard normal CDF.

The expected shadow value of internal funds is strictly greater than unity as long as equity issuance is costly ( $\varphi > 0$ ) and the firm faces idiosyncratic liquidity risk ( $\sigma > 0$ ). This makes the

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<sup>12</sup>A similar timing convention has been used by Kiley and Sim (2012) in the context of financial intermediation.

firm de facto risk averse when making its pricing decision. Setting the price too low and taking an imprudently large number of orders exposes the firm to the risk of incurring negative operating income, which must be financed through costly equity issuance.<sup>13</sup>

After imposing the symmetric equilibrium condition, the first-order condition (18) implies that the value of marginal sales is given by

$$\frac{\nu_t}{\mathbb{E}_t^a[\xi_{it}]} = 1 - \frac{\mathbb{E}_t^a[\kappa_{it}]}{\mathbb{E}_t^a[\xi_{it}]} + (1 - \rho) \frac{\lambda_t}{\mathbb{E}_t^a[\xi_{it}]}, \quad (24)$$

where the first term represents current profits, and the second term captures the value of the customer base. The first-order condition (17) implies that the value of current profits is equal to

$$1 - \frac{\mathbb{E}_t^a[\kappa_{it}]}{\mathbb{E}_t^a[\xi_{it}]} = \frac{\tilde{\mu}(A_t, c_t, w_t, \pi_t) - 1}{\tilde{\mu}(A_t, c_t, w_t, \pi_t)},$$

where

$$\tilde{\mu}(A_t, c_t, w_t, \pi_t) \equiv \frac{\mathbb{E}_t^a[\xi_{it}]}{\mathbb{E}_t^a[\xi_{it}a_{it}]} \alpha \left( \frac{A_t}{w_t} \right) (c_t + \phi)^{\frac{\alpha-1}{\alpha}} \quad (25)$$

denotes the gross markup inclusive of expected financing costs.<sup>14</sup>

With frictionless financial markets,  $\mathbb{E}_t^a[\xi_{it}] = \mathbb{E}_t^a[\xi_{it}a_{it}] = 1$ , and we obtain the standard result that the markup is the inverse of the marginal cost of production. The adjustment to the standard markup in equation (25) reflects the fact that financial distortions raise the internal value of marginal revenue—the term  $\mathbb{E}_t^a[\xi_{it}]$ —while also increasing the expected marginal cost net of financing through the term  $\mathbb{E}_t^a[\xi_{it}a_{it}]$ . It is straightforward to show that

$$\frac{\mathbb{E}_t^a[\xi_{it}]}{\mathbb{E}_t^a[\xi_{it}a_{it}]} = \frac{1 - \varphi\Phi(z_t^E)}{1 - \varphi\Phi(z_t^E - \sigma)} < 1, \quad (26)$$

so that an increase in the expected marginal cost outstrips the value of additional revenue and thereby reduces the firm's profitability.<sup>15</sup> This mechanism introduces a form of the cost channel

<sup>13</sup>Equation (21) imposes the symmetric equilibrium. From the firm's perspective, raising prices increases profits and hence reduces the cost of external finance if  $\frac{p_{it}c_{it}}{w_t h_{it}}$  is increasing in the price charged. Given the production function (13), this is true if  $1 - \eta \left(1 - \frac{1}{\alpha} \frac{c_t}{c_t + \varphi}\right) > 0$ , where  $\eta$  is the short-run demand elasticity. Because the term in parentheses is close to zero, this condition is satisfied in any reasonable calibration of the model.

<sup>14</sup>Note that the markup depends directly on  $A_t$ ,  $w_t$ , and  $c_t$  through their effect on the marginal production costs and indirectly through their effect on external financing costs as determined by the cutoff value  $a_t^E$  given by equation (21); this cutoff value also depends on aggregate inflation  $\pi_t$ .

<sup>15</sup>Using properties of a log-normal distribution (see Kotz, Johnson, and Balakrishnan, 2000), the interaction term can be expressed as

$$\mathbb{E}_t^a[\xi_{it}a_{it}] = \int_0^{a_t^E} a dF(a) + \int_{a_t^E}^{\infty} \frac{a}{1 - \varphi} dF(a) = 1 + \frac{\varphi}{1 - \varphi} [1 - \Phi(z_t^E - \sigma)] \geq 1.$$



into the model, through which financial frictions raise marginal costs and reduce markups.

Let  $g_t \equiv c_t/s_{t-1} = (s_t/s_{t-1} - \rho)/(1 - \rho)$  and define the growth-adjusted discount factor  $\tilde{\beta}_{t,s+1}$  as

$$\tilde{\beta}_{t,s+1} \equiv m_{s,s+1} g_{s+1} \times \prod_{j=1}^{s-t} [\rho + \theta(1 - \eta)(1 - \rho)g_{t+j}] m_{t+j-1,t+j}.$$

By iterating equation (19) forward, one can solve for the marginal value of an increase in the customer base—the term  $\lambda_t/\mathbb{E}_t^a[\xi_{it}]$ —as the growth-adjusted present value of marginal profits. Substituting the resulting expression into equation (24) then yields the value of marginal sales:

$$\frac{\nu_t}{\mathbb{E}_t^a[\xi_{it}]} = \frac{\tilde{\mu}_t - 1}{\tilde{\mu}_t} + \chi \mathbb{E}_t \left[ \sum_{s=t+1}^{\infty} \tilde{\beta}_{t,s} \frac{\mathbb{E}_s^a[\xi_{is}]}{\mathbb{E}_t^a[\xi_{it}]} \left( \frac{\tilde{\mu}_s - 1}{\tilde{\mu}_s} \right) \right], \quad (27)$$

where  $\chi = (1 - \rho)\theta(1 - \eta) > 0$  if  $\theta < 0$  and  $\eta > 1$ .

In this context, the liquidity condition of the firm—as summarized by the sequence of  $\mathbb{E}_s^a[\xi_{is}]$ ,  $s = t, \dots, \infty$ —determines the weight that the firm places on current versus future profits when determining the expected price trajectory. If today's liquidity premium outweighs the future liquidity premia, the firm places a greater weight on current profits relative to future profits and, as a result, chooses a higher price trajectory.

#### 4.5 The Phillips Curve

Imposing the symmetric equilibrium ( $p_{it} = 1$  and  $c_{it} = c_t$ ) and dividing equation (21) through by  $\mathbb{E}_t^a[\xi_{it}]c_{it}$  yields the following Phillips curve:

$$1 = \gamma_p \pi_t (\pi_t - \bar{\pi}) - \gamma_p \mathbb{E}_t \left[ m_{t,t+1} \frac{\mathbb{E}_{t+1}^a[\xi_{i,t+1}]}{\mathbb{E}_t^a[\xi_{it}]} \pi_{t+1} (\pi_{t+1} - \bar{\pi}) \frac{c_{t+1}}{c_t} \right] + \eta \frac{\nu_t}{\mathbb{E}_t^a[\xi_{it}]}.$$
 (28)

The local dynamics of inflation can be assessed by log-linearizing equation (28), which yields

$$\hat{\pi}_t = \frac{1}{\gamma_p} (\hat{\xi}_t - \hat{\nu}_t) + \beta \mathbb{E}_t [\hat{\pi}_{t+1}], \quad (29)$$

where  $\hat{\xi}_t$  and  $\hat{\nu}_t$  denote the log-deviations of  $\mathbb{E}_t^a[\xi_{it}]$  and  $\nu_t$ , respectively (see section ?? of the model appendix for details). Equation (29) clearly shows that given inflation expectations, the current inflation rate depends crucially on the tradeoff between the value of internal funds ( $\mathbb{E}_t^a[\xi_{it}]$ ) and the value of marginal sales ( $\nu_{it}$ ).

To highlight the relationship between the model's structural parameters and inflation dynamics, we can log-linearize equation (27) and substitute the result in equation (29). These steps yield the

following expression for the Phillips curve:

$$\begin{aligned} \hat{\pi}_t = & -\frac{\omega(\eta-1)}{\gamma_p} \left[ \hat{\mu}_t + \mathbb{E}_t \sum_{s=t}^{\infty} \chi \tilde{\delta}^{s-t+1} \hat{\mu}_{s+1} \right] + \beta \mathbb{E}_t [\hat{\pi}_{t+1}] \\ & + \frac{1}{\gamma_p} [\eta - \omega(\eta-1)] \mathbb{E}_t \sum_{s=t}^{\infty} \chi \tilde{\delta}^{s-t+1} \left[ (\hat{\xi}_t - \hat{\xi}_{s+1}) - \hat{\beta}_{t,s+1} \right], \end{aligned} \quad (30)$$

where  $\omega = 1 - \beta\theta(1 - \rho)/(1 - \rho\beta)$ ,  $\tilde{\delta} = \beta[\rho + \theta(1 - \eta)(1 - \rho)]$ , and  $\hat{\beta}_{t,s+1}$  is the log-deviation of the growth-adjusted discount factor  $\tilde{\beta}_{t,s+1}$ . Note that in the absence of external habit ( $\theta = 0$ ),  $\omega = 1$  and  $\chi = 0$ , and we obtain the standard New Keynesian Phillips curve,  $\hat{\pi}_t = -\hat{\mu}_t + \beta \mathbb{E}_t [\hat{\pi}_{t+1}]$ , in which case current inflation equals a present discounted value of expected future marginal cost (i.e., the inverse of the markup).

With external habit but no financial distortions, ( $\theta < 0$  and  $\varphi = 0$ ), all terms involving  $\hat{\xi}_t - \hat{\xi}_{s+1}$  in the second line of equation (30) drop out. However, with customer habits,  $\chi > 0$ , and there are two offsetting effects of demand-driven movements in output on current inflation conditional on future inflation. First, the present value of future markups directly enters the Phillips curve and implies that current inflation responds to future marginal cost, conditional on the next period's expected inflation. This term increases the sensitivity of current inflation to future fluctuations in output. Second, the term  $\hat{\beta}_{t,s+1}$  captures the capitalized growth rate of the customer base and thus measures the present value of the marginal benefit from expanding the customer base today. According to equation (30), when the firm expects a greater benefit from the future customer base, it is more willing to lower the current price in order to build its customer base. This term thus reduces the sensitivity of current inflation to future output movements. Because these two effects offset each other, customer markets may lead to more or less responsiveness of inflation to output fluctuations.

Frictions in financial markets also have two effects on inflation dynamics. First, the markup must be adjusted for the financial distortions that create a cost channel. Under reasonable calibrations, this adjustment reduces the countercyclicality of the markup and attenuates the response of inflation to output fluctuations—this adjustment occurs regardless of whether we allow for customer habits. Second, customer habits imply that the firm takes into account the future customer base when setting its current price. In this case, financial distortions influence the effective discount factor captured by the shadow value of dividends today relative to the future—the term  $\hat{\xi}_t - \hat{\xi}_{s+1}$ . In practice, however, the effect of the cost channel is small, and the primary mechanism through which financial market frictions affect inflation is by altering the discount factor associated with how the firm values the benefits of the future customer base.

Faced with both a sticky customer base and costly external finance, firms are confronted with a fundamental tradeoff between current profit maximization and the long-run maximization of their market share, which is reflected in the term  $(\hat{\xi}_t - \hat{\xi}_{s+1}) - \hat{\beta}_{t,s+1}$ . Maximizing their market share

requires firms to lower current prices. However, firms may be forced to deviate from this strategy, provided that their current liquidity position—as summarized by  $\hat{\xi}_t$ —is sufficiently weak relative to their future liquidity position  $\hat{\xi}_{s+1}$ . In that case, firms may raise their current prices in response to an adverse demand shock in order to avoid costly external financing, a pricing strategy that resembles a myopic optimization of current profits.<sup>16</sup>

## 4.6 Closing the Model

We assume that equity issuance costs are paid out to households and hence do not affect the aggregate resource constraint. Costs incurred when firms change nominal prices are similarly returned to households in a lump-sum manner. As detailed in section ?? of the model appendix, the household’s optimal consumption-savings decision then implies that the stochastic discount factor  $m_{t,t+1}$  satisfies

$$m_{t,t+1} = \beta \frac{U_x(x_{t+1} - \psi_{t+1}, h_{t+1}) s_{t-1}^\theta}{U_x(x_t - \psi_t, h_t) s_t^\theta}. \quad (31)$$

Letting  $r_t$  denote the ex ante nominal interest rate, then the Fisher equation may be expressed as

$$1 = \mathbb{E}_t \left[ m_{t,t+1} \left( \frac{1 + r_t}{1 + \pi_{t+1}} \right) \right].$$

The efficiency condition governing the household’s consumption-leisure choice is given by:

$$\frac{w_t}{\tilde{p}_t} = - \frac{U_h(x_t - \psi_t, h_t)}{U_x(x_t - \psi_t, h_t)}. \quad (32)$$

The endogenous aggregate state variable  $s_t$  evolves according to  $s_t = \rho s_{t-1} + c_t$ , where, from the demand curve, the aggregate consumption index  $x_t = c_t s_t^{\theta(1-\eta)}$ .

The supply side of the model is then summarized by the markup equation (25), equation (27) governing the valuation of marginal sales, and the Phillips curve (28), along with the production function that determines labor demand, according to

$$h_t = \left[ \frac{c_t + \phi}{\exp [0.5\alpha(1 + \alpha)\sigma^2]} \right]^{\frac{1}{\alpha}}, \quad (33)$$

where the term in the denominator follows from the integration over the distribution of idiosyncratic technology shocks.<sup>17</sup>

<sup>16</sup>The fundamental tradeoff between current cash flows and future market shares relies on the parameter restriction  $\eta - \omega(\eta - 1) > 0$ . Otherwise firms in strong financial condition may *increase* their current prices in order to *increase* their long-run market shares. As long as  $\theta$ ,  $\rho$  and  $\eta$  are chosen such that the steady-state marginal profit is strictly positive, we can exclude such pathological cases.

<sup>17</sup>The adjusted markup  $\tilde{\mu}_t$  and the expected external financing cost  $\mathbb{E}_t^a [\xi_{it}]$  are static functions of aggregate variables. After substituting out for these variables, the model adds two dynamic equations—a backward-looking equation for the endogenous stock of habit  $s_t$  and the forward-looking valuation equation for  $\nu_t / \mathbb{E}_t^a [\xi_{it}]$ —to the

Lastly, we assume that the monetary authority sets the nominal interest rate  $r_t$  using a Taylor-type rule that responds to the inflation and output gaps:

$$r_t = \max \left\{ 0, (1 + r_{t-1})^{\rho_r} \left[ (1 + \bar{r}) \left( \frac{\pi_t}{\pi^*} \right)^{\rho_\pi} \left( \frac{y_t}{y_t^*} \right)^{\rho_y} \right]^{1-\rho_r} - 1 \right\}. \quad (34)$$

The rule also allows for policy inertia, as reflected in letting  $\rho_r \in (0, 1)$ . In our baseline calibration of the model, we set  $\rho_y = 0$ , implying that monetary authorities respond only to inflation. We also bound the policy rate below by zero, which allows us to explore the role of financial distortions at the zero lower bound, a topic of particular relevance during the 2007–09 financial crisis and its aftermath.<sup>18</sup>

## 5 Calibration

A period in the model equals one quarter. Accordingly, the time discounting factor is set to 0.99. Following Ravn, Schmitt-Grohe, and Uribe (2006b), we set the deep habit parameter  $\theta$  equal to  $-0.8$ . To highlight the firms' incentive to compete for market share, we also choose a fairly persistent habit formation process by assuming that only 5 percent of the habit stock is depreciated in a quarter (i.e.,  $\rho$  in equation (10) is 0.95).<sup>19</sup> The CRRA parameter in the household's utility function is then set equal to 1, given that the deep habit specification provides a strong motive to smooth consumption. We set the elasticity of labor supply equal to 5.

The elasticity of substitution across varieties of differentiated goods is a key parameter in the customer-markets model—smaller the degree of substitutability, greater is the firm's market power, and greater is its incentive to invest in customer base. Broda and Weinstein (2006) provide a set of estimates for the elasticity of substitution for the U.S. economy. Their estimates lie in the range between 2.1 and 4.8, depending on the characteristics of products (commodities vs. differentiated goods) and subsamples (before 1990 vs. after 1990). Using the post-1990 data, Broda and Weinstein (2006) estimate the median value of the elasticity of substitution for differentiated goods at 2.1. Because this is a product category that is most relevant for the deep habits model, we set  $\eta = 2$ .<sup>20</sup>

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otherwise standard three-equation log-linearized New Keynesian model.

<sup>18</sup>When analyzing the dynamics of the economy when the policy rate is constrained by the zero lower bound, we use the deterministic simulation routine of Adjemian, Bastani, Juillard, Mihoubi, Perendia, Ratto, and Villemot (2011) to allow for a fully nonlinear solution after replacing the max operator in equation (34) with a smooth approximation, namely,  $\max\{x, 0\} \approx 0.5 \times (\sqrt{x^2 + \epsilon^2} + x)$  (in our simulations, we set  $\epsilon = .0001$ ). The use of a nonlinear solution method is important in this case because the shocks that push the policy rate to the zero lower bound are typically large and thus place the economy in the region where local dynamics in the neighborhood of a nonstochastic steady state may not adequately approximate the nonlinear response of macroeconomic aggregates to such shocks. In all other cases, however, impulse response functions are based on the first-order Taylor expansion around the deterministic steady state.

<sup>19</sup>Our calibration of the external habit process is only marginally more persistent than that of Ravn, Schmitt-Grohe, and Uribe (2006b).

<sup>20</sup>This value is also in line with a point estimate of 2.48 obtained by Ravn, Schmitt-Grohe, Uribe, and Uuskula

Another important parameter is the fixed operating cost  $\phi$ . This parameter is determined jointly with the returns-to-scale parameter  $\alpha$ . Specifically, we set  $\alpha$  first and then choose  $\phi$  so that the dividend payout ratio (relative to income) hits the post-WWII mean value of 2.5 percent. It is worth noting that in our model, decreasing returns to scale enhance the link between financial frictions and the firms' pricing decisions. In our baseline calibration  $\alpha = 0.8$ .<sup>21</sup> Given the values of  $\alpha$ ,  $\phi$ , and  $\eta$ , the average gross markup is equal to 1.19.

Following Cooley and Quadrini (2001), we calibrate the degree of financial market frictions—the equity dilution costs—by setting  $\varphi = 0.30$ . When analyzing the macroeconomic implications of financial disturbances—which we model as exogenous shocks to equity dilution costs—we set the persistence of the financial shock to 0.90. To abstract from the differences in the persistence of different aggregate disturbances, the AR(1) parameters of the processes for the aggregate technology shock ( $A_t$ ) and the demand shock ( $\psi_t$ ) are both set equal to 0.9.<sup>22</sup> We calibrate the volatility of the aggregate technology shock at the conventional value of 0.01 (4 percent at an annual rate). The volatility of the demand shock is set to 0.33 percent (1.3 percent at an annual rate). In the absence of financial disturbances, this calibration implies an equal contribution of technology and demand shocks to the variance of aggregate output.

The volatility of the idiosyncratic technology shock ( $a_{it}$ ) is calibrated at 0.05 (20 percent at an annual rate), which implies a moderate amount of idiosyncratic uncertainty. With the fixed operating cost calibrated as described above, the combination of  $\sigma = 0.05$  and  $\varphi = 0.30$  yields an annualized expected premium on external funds of about 13 percent (i.e.,  $\mathbb{E}^a[\xi_i] = 1.127$ ). In our crisis experiment, a simulation exercise that imposes an extreme degree of financial distortions, we let  $\varphi = 0.50$ , in which case the premium on external funds increases to 20 percent.

For the parameters related to nominal rigidities, we set the adjustment costs of nominal prices  $\gamma_p = 10.0$  and wages  $\gamma_w = 30.0$ . These values are within the range of point estimates of 14.5 and 41.0 in Ravn, Schmitt-Grohe, and Uribe (2006b), who show that deep habits substantially enhance the persistence of inflation, without the reliance on an implausibly large amount of stickiness in nominal prices. Finally, we set the inertial coefficient  $\rho_r$  in the policy rule (34) at a conventional level of 0.75, and  $\rho_\pi$ , the coefficient on the inflation gap, at 1.5, values in line with those used in the New Keynesian literature. (Recall that in our baseline calibration, we let monetary authorities respond only to inflation—that is,  $\rho_y = 0$ .)

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(2010) using a structural estimation method.

<sup>21</sup>This degree of returns to scale is common in the empirical investment literature that relies on firm-level data; see, for example, Hennessy and Whited (2007). It is also worth noting that the model's dynamics are not substantially affected by varying the  $\alpha$  between 0.8 and 1.

<sup>22</sup>The persistence of the aggregate technology shock is somewhat lower than that employed in the real business cycle literature; this choice reflects the fact our model has a number of elements that generate persistent dynamics of the endogenous quantities.

## 6 Model Simulations: Homogeneous Firms

The goal in developing the above model is to gain an insight as to why the substantial and persistent slack in the productive capacity of the U.S. economy during the Great Recession and its aftermath did not result in significant disinflation, let alone an outright deflationary spiral that was of much concern to both academics and policymakers. To study the dynamics of inflation and other endogenous variables during a financial crisis, this section reports results from two experiments. First, we consider a financial crisis situation. One of the salient features of the 2007–09 crisis was the near-breakdown of the credit intermediation process in response to the extraordinary financial strains in the latter part of 2008. We capture this facet of the crisis by calibrating the degree of financial market frictions to a level that severely curtails the ability of firms to obtain external finance. Although raising external equity is not impossible in our crisis situation, it is extremely costly, and the firms finance themselves predominantly through internal funds. In the second experiment, we consider an economy with a “normal” degree of financial distortions that experiences a temporary bout of financial turmoil, which is captured by a short-term increase in the cost of external finance.

### 6.1 Financial Crisis and Inflation Dynamics

To implement a financial crisis in the model, we set  $\varphi = 0.50$ , which implies an external finance premium of 20 percent (annualized). Such a high expected cost of external funds strikes us as plausible at the nadir of the 2007–09 crisis, a period during which the commercial paper market froze, corporate bond credit spreads blew out, equity prices tanked, asset price volatility skyrocketed, and virtually no firm could contemplate raising outside equity to finance its operating costs and investment. With this calibration, we analyze the impact of both financial and demand shocks on the pricing decisions of firms in our model.

Figure 6 compares the macroeconomic impact of an adverse demand shock across two model economies: a baseline economy with frictionless financial markets (dotted lines) and an economy with financial distortions calibrated to a crisis situation (solid lines). In the absence of financial market frictions, the negative demand shock leads a sizable drop in real output (panel (a)) and a decline in inflation (panel (b)). The comparison of responses in panel (a) reveals that financial distortions amplify the response of output to a demand shock, a result consistent with the standard financial accelerator mechanism.

Although differences in output dynamics are fairly modest, the initial response of inflation differs substantially across the two models. In particular, in the model with financial market frictions, inflation rises rather than falls. The explanation for this difference can be found in panels (e)–(f). Our timing assumptions imply that firms are aware that the economy has been hit by an adverse demand shock before making their pricing decisions. In the presence of financial distortions, this

reduces the firms' expected internal cashflows and increases the probability that they will require costly external finance. As a result, the shadow value of internal funds jumps almost 200 basis points upon the impact of the shock (panel (f)). To protect themselves against the idiosyncratic tail event in which the ex post cashflows are negative and they must raise costly external finance, firms significantly boost their markups relative to the model without financial distortions (panel (e)).

In a crisis situation, the severity of financial market frictions causes the value of internal cashflows and the value of marginal sales to move in tandem (panels (f) and (g)). Because cashflows are discounted using internal valuations, financial distortions create a direct link between the two valuations, which does not exist in an economy with frictionless financial markets. Note that in both models, the negative demand shock leads to a sharp initial increase in the markup (panel (e)). Financial frictions, however, substantially amplify the countercyclical behavior of markups—the increase in the markup in the model with financial distortions is double that implied by the model without such distortions. Moreover, in an economy with financial frictions, the markup remains elevated for quite some time after the initial impact of the shock, while in the frictionless case, the high initial markup is offset by low future markups. As highlighted in panels (f) and (g), the driving force behind the strong countercyclical nature of markups in the presence of financial distortions is the deterioration in the firms' liquidity positions, which causes firms to increase markups in an effort to stabilize near-term profits in the face of falling demand.

Figure 7 considers the same experiment, but in an environment without nominal (price and wage) rigidities. The negative demand shock again causes a drop in output and hours worked and, in the model with financial frictions, an increase in the value of internal funds. In the absence of financial distortions, the markup is not affected by the demand shock upon impact but then declines gradually and remains persistently below steady state. Thus, in the absence of nominal rigidities and financial distortions, the markup is strongly procyclical in response to demand shocks in this version of the deep habits model. Adding sticky prices alone to the model imparts at best only a modest degree of countercyclicity to the markup. However, with the addition of financial frictions, the markup becomes strongly countercyclical, as firms seek to increase current profits to overcome the liquidity squeeze.

In the standard model of monopolistic competition, the markup provides a summary measure of the distortion to the aggregate labor input—and hence to output—owing to the limited competition in product markets. In New Keynesian models, sticky prices provide the sole source of variation in the markup. With deep habits, however, the markup does not completely reflect the “labor wedge,” as defined by the gap between the marginal product of labor and the household's marginal rate of substitution between consumption and leisure. This difference is highlighted in Figure 8, which shows the dynamics of the labor wedge in response to an adverse demand shock for the four distinct models considered above.

In the model with neither financial frictions nor nominal rigidities, the monopolistically-

competitive product market structure implies a modest increase in the labor wedge—about 15 basis points upon impact—in response to the contractionary demand shock. In the model with financial frictions and nominal rigidities, by contrast, the response of the labor wedge doubles to 30 basis points. Most of this increase can be attributed to the distortions in financial markets rather than to nominal rigidities. In this sense, the real economic effects implied by this model depend very little on the degree of price stickiness, rather, they are heavily influenced by changes in financial conditions.

## 6.2 Financial Shocks and Inflation Dynamics

This section analyzes the macroeconomic implications of financial shocks. That is, rather than considering a crisis situation in which it is extremely costly to raise outside equity, we introduce financial distress in the model by considering a disturbance that temporarily boosts the cost of external funds. Formally, we implement this idea by assuming that the equity issuance cost parameter  $\varphi$  follows an AR(1) process of the form:

$$\varphi_t = \bar{\varphi} f_t; \quad \log f_t = 0.90 \log f_{t-1} + \epsilon_{t,f}.$$

Using this framework, we then analyze the macroeconomic effects of a one standard deviation shock  $\epsilon_{t,f}$ , a financial disturbance that increases equity dilution costs 25 percent from their steady-state level upon impact. The equity issuance cost parameter then converges back to its normal level, following the autoregressive dynamics specified above.

Under our baseline calibration ( $\bar{\varphi} = 0.3$ ), this financial shock boosts the level of equity dilution costs from 0.3 to 0.375 upon impact, a degree of financial distortions that is significantly below that assumed in the crisis situation. In addition to the financial shock, we also subject this economy to a one standard deviation negative demand shock, the same as in the financial crisis experiment. The solid lines in Figure 9 depict the results of this simulation. For comparison purposes, the dashed lines show the corresponding impulse responses from Figure 6, an experiment in which the economy facing a severe—but constant—degree of financial distortions is hit solely by an adverse demand shock.

According to panels (a) and (b), the temporary increase in external financing costs has large additional effects on economic activity: The immediate decline in both output and hours worked in response to a contractionary demand shock when the economy is concurrently also experiencing an adverse financial shock is about one-third greater than in the case when the economy—though subject to much more distorted financial markets—is hit only by a negative demand shock. The response of inflation is also amplified substantially when both shocks hit the economy. In effect, a temporary deterioration in the firms’ liquidity positions shrinks the financial capacity of the economy, which then directly shifts the Phillips curve upward.



Panels (e), (f), and (g) show the essential mechanism at work. When the economy is hit by both types of shocks, the markup, the shadow value of internal funds, and the value of marginal sales all increase sharply relative to the case when the economy is perturbed only by a demand shock. Note that a significant portion of the increase in the shadow value of internal funds reflects the economy’s endogenous response to the temporary increase in financial distortions, as the additional deterioration in economic outlook brought about by the financial shock increases the probability that firms will require costly external finance. This causes the shadow value of internal funds to increase substantially more than in the case when the economy experiences only an adverse demand shock, even though in this latter case, firms face significantly greater (in absolute terms) degree of financial market distortions. This within-period financial multiplier amplifies the effect of the initial shock and plays a key role in enhancing the propagation of shocks in our model.

### 6.3 Monetary Policy Implications

In the customer markets model with financial market imperfections, output falls while inflation rises in response to a contractionary demand shock or an adverse financial disturbance. These results stand in sharp contrast to those implied by either standard New Keynesian models or financial accelerator models that work through investment demand (see Bernanke, Gertler, and Gilchrist, 1999), where output and inflation exhibit strong positive comovement in response to demand and financial shocks. This positive comovement is at the heart of the so-called divine coincidence of monetary policy, whereby monetary authorities—by lowering nominal interest rates—can simultaneously stabilize both output and inflation and thus eliminate any concern of an active tradeoff for monetary policy.

To explore this issue further, we re-consider our canonical crisis experiment shown in Figure 6 by allowing monetary authorities to respond to inflation and output. Figure 10 reports the results of this simulation for the output gap coefficient  $\rho_y$  equal to 0.125 and 0.25; for comparison purposes, the figure also shows the responses from the original exercise in which  $\rho_y = 0$ , that is, the central bank is concerned only about inflation.<sup>23</sup> As evidenced by the differences in the impulse responses, increasing the coefficient on the output gap successfully stabilizes output but comes at the very obvious cost of destabilizing inflation. Thus in our model, there exists a meaningful tradeoff between output and inflation stabilization in response to demand and financial shocks. Although beyond the scope of the current paper, it is of obvious interest for future research to consider optimal monetary policy in a model with customer markets and financial market frictions.

A distinct feature of the 2007–09 financial crisis is the fact that the Federal Reserve, in an effort to short-circuit the adverse feedback loop between financial conditions and the macroeconomy that emerged in the aftermath of the Lehman collapse, lowered the policy rate to its effective zero

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<sup>23</sup>In all three of these cases, the coefficient on the inflation gap in the policy rule  $\rho_\pi = 1.5$ , while the degree of interest rate smoothing  $\rho_r = 0.75$ .

lower bound (ZLB) by the end of 2008. It is therefore of considerable interest to understand the interaction of customer markets and financial distortions in the ZLB environment. We explore this interaction by considering the “paradox of thrift” experiment, a scenario in which the agents’ time discounting factor increases exogenously for a certain number of periods before returning back to its normal level. Specifically, we assume that

$$\beta_t = \bar{\beta}u_t; \quad \log u_t = 0.90 \log u_{t-1} + \epsilon_{t,u},$$

where the discount rate shock  $\epsilon_{t,u} = 0.009$  for  $t = 1, \dots, 4$  and  $\epsilon_{t,u} = 0.0$  for  $t = 5, \dots, \infty$ . This sequence of shocks causes the time discount factor  $\beta_t$  to peak at 1.016—an environment of “hyper patience”—and then return gradually to its normal level ( $\bar{\beta} = 0.99$ ).

The solid lines in Figure 11 show the macroeconomic implications of such a sequence of discount rate shocks for an economy subject to a severe degree of financial market frictions ( $\varphi = 0.5$ ), while the dashed lines depict the corresponding responses for an economy with frictionless financial markets. In a ZLB environment, firms in the model with financial distortions are much more reluctant—compared with their counterparts facing perfect capital markets—to cut their prices in order to support their current and near-term cashflows. While firms in the economy without financial distortions take a very aggressive stance in response to the onset of “hyper patience” among consumers and slash prices more than 15 percent (at an annual rate), the cut in prices implied by the model with financial distortions is only about 5 percent.

With the ZLB impinging on the short-term nominal interest rate (panel (h)), the massive price cut in the economy with frictionless financial markets translates into a significant increase in the real interest rate, which, in turn, leads to a substantial contraction in output and a drop in hours worked. These simulations suggest that once the economy is at the ZLB, the incentive of firms to slash prices in order to maintain their market shares can be a highly destabilizing force for the macroeconomy. The prohibitive cost of external finance due to the severity of financial distortions in a crisis, however, significantly damps the acute deflationary pressure brought about the competition for market shares because of the firms’ need to support current cashflows in the face of a liquidity crunch.<sup>24</sup>

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<sup>24</sup>We also performed an experiment in which the economy is hit by the same sequence of discount rate shocks, except the degree of nominal rigidities (both nominal price and wage adjustment costs) was five times as large as in our baseline calibration. In the model without financial distortions, this degree of nominal rigidities makes it difficult for firms to cut prices as aggressively as in Figure 11. As a result, the deflationary pressures are much weaker than those reported above, a result consistent with Christiano, Eichenbaum, and Rebelo (2011), who document that increased price flexibility exacerbates a deflationary spiral. In the model with financial distortions, in contrast, it makes quantitatively very little difference whether firms face mild or severe degree of price and wage stickiness.

## 7 Model Simulations: Heterogeneous Firms

In the above simulations, we exploited the notion of symmetric equilibrium, according to which all firms in the model chose the same price. We now extend the model to generate a nondegenerate equilibrium distribution of prices across firms in the economy. This extension highlights an important aspect of the interaction between customer markets and financial market frictions in periods of financial distress. In a crisis situation, financially strong firms—in response to an adverse demand shock—attempt to drive out their weaker competitors by undercutting their prices. This “price war” creates an aggregate demand externality, whereby significant heterogeneity in financial conditions across firms may lead to a greater contraction in output relative to a situation in which firms are uniformly constrained in their access to external finance.

### 7.1 Heterogeneous Operating Costs

To introduce a meaningful degree of heterogeneity in the model, we modify the production technology in equation (13), according to

$$y_{it} = \left( \frac{A_t}{a_{it}} h_{it} \right)^\alpha - \phi_i, \quad (35)$$

where  $\phi_i$  denotes fixed operating costs of firm  $i$ . These costs can take on one of  $N$ -values from a set  $\{\phi_1, \dots, \phi_N\}$ , where  $0 \leq \phi_1 < \dots < \phi_N$ . The measure of firms at the level of operating efficiency  $\phi_k$  is denoted by  $\Xi_k$ , where  $\sum_{k=1}^N \Xi_k = 1$ . Lastly, we also assume that all firms face the same distribution of the idiosyncratic technology shock  $a_{it}$  (i.e.,  $\log a_{it} \sim N(-0.5\sigma^2, \sigma^2)$ ).

As shown in section ?? of the model appendix, the introduction of heterogeneous operating costs implies that the external financing trigger is specific to each sector  $k$ , with  $d\mathbb{E}_t^a[\xi_{it}|\phi_k]/d\phi_k > 0$ . Thus, the lower the level of operating efficiency, the greater is the likelihood that the firm will have difficulties meeting its liquidity needs using only internally generated funds. In other words, all firms in a sector characterized by low operating efficiency face higher expected external financing costs and thus are considered to be financially “weak.”

Within this framework, we again consider a symmetric equilibrium, in which all firms with a given level of operating efficiency choose the same price and production scale. The derivation of firm-specific prices, financing costs, labor inputs, and output decisions is analogous to the homogeneous model. In particular, firm-specific inflation rates evolve according to a sector-specific Phillips curve. Note that although all firms with the same  $\phi_k$  choose the same price level, sectoral heterogeneity in fixed operating costs generates the dispersion of prices across firms. Aggregate quantities are then obtained in a standard manner. Specifically, the aggregate inflation rate can be expressed as

a weighted average of sectoral inflation rates:

$$\pi_t = \left[ \sum_{k=1}^N \Xi_k (p_{k,t-1} \pi_{kt})^{1-\eta} \right]^{\frac{1}{1-\eta}}, \quad (36)$$

where  $\pi_{kt} \equiv P_{kt}/P_{k,t-1}$  is the inflation rate in sector  $k$  and  $p_{kt} \equiv P_{kt}/P_t$  is the sector-specific relative price.

## 7.2 Countercyclical Dispersion of Inflation Rates

For maximum intuition, we consider only two sectors in our numerical simulations. The first sector consists of financially “strong” firms, which are characterized by having  $\phi_1 = 0$ . The second sector is made up of financially “weak” firms, distinguished by having  $\phi_2 = 0.3$ , the value used in our baseline calibration. For simplicity, we assume that the two sectors are of equal sizes—that is,  $\Xi_1 = \Xi_2 = 0.5$ . Within this setup, we seek to answer the following question: In periods of financial turmoil, do financially strong firms slash their prices to drive out their weaker competitors? To answer this question, we perturb the model economy with a financial shock, which, as in subsection 6.2, corresponds to a temporary increase in equity dilution costs from their normal level ( $\varphi = 0.3$ ).<sup>25</sup>

The solid line in panel (a) of Figure 12 shows the response of relative prices ( $p_{kt} = P_{kt}/P_t$ ) for financially weak firms, whereas the dashed line depicts the corresponding response of their financially weak counterparts. In response to an adverse financial shock, financially healthy firms cut their prices—behavior consistent with the concurrent decline in aggregate demand—while the financially vulnerable firms actually increase their prices in an effort to avoid costly external financing. Panel (b) translates this difference in the price-setting behavior into the sector-specific inflation rates ( $\pi_{kt} = P_{kt}/P_{k,t-1}$ ). Clearly evident is the countercyclical behavior of the dispersion in inflation rates, a result consistent with that documented by Vavra (2013). What is different in our case is that the countercyclical dispersion in inflation rates arises endogenously in response to the differences in financial conditions across firms, whereas Vavra (2013) relies on an exogenous second-moment (i.e., uncertainty) shock that is calibrated countercyclically.

Panel (c) shows the dynamics of output. As a result of “winning” the price war, financially strong firms gradually expand output in order to satisfy the growing demand engendered by the relative price cut. Financially weak firms, by contrast, slash production, a move that causes the aggregate output and hour worked to decline moderately. Again, the dispersion in output and labor input at the micro level is generated endogenously by the distortions in financial markets.

The dynamics of the relative market shares of the two sectors are shown in panel (e). Consistent with their aggressive pricing behavior, financially healthy firms significantly expand their market share during the economic downturn. Because of the deep-habit preferences, the customer base of

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<sup>25</sup>Unlike the experiment reported in Figure 9, this exercise for simplicity abstracts from the simultaneous impact of the demand shock.

financially strong firms expands only gradually, though the expansion is quite persistent. Moreover, the customers that switched products during the downturn form a loyal group, as a substantial part of them stays with the new products, even after the relative prices of the goods produced in the two sectors return to their respective steady-state levels. For example, after 20 quarters, the relative prices charged by financially strong firms are for all practical purposes back to their normal level, but their relative market share remains elevated, which highlights the primary reason why undercutting competitors' prices can be such a profitable investment.

### 7.3 The Paradox of Financial Strength

The last exercise considered is termed the “paradox of financial strength.” The idea behind this exercise is to see whether firms with ample financial capacity can slash their prices so aggressively that they drive out the financially weaker firms to such an extent so as to generate a sizable drop in aggregate output. Such a scenario can be implemented in several different ways. One way is to make the contribution of the habit to the final demand more important and more persistent by choosing higher values for  $\theta$  and  $\rho$ . Alternatively, we can reduce the price elasticity of demand by lowering  $\eta$ . In our simulation, we follow the first approach and set  $\theta = -0.85$  (the baseline value is  $-0.8$ ) and  $\rho = 0.985$  (the baseline value is  $0.9$ ).

Using this new calibration, we consider two model specifications, distinguished only by the degree of firm heterogeneity. In the first specification (Case I), we assume that  $\phi_1 = 0.8\phi_2$ , with  $\phi_2 = 0.3$ ; the second specification (Case II) has  $\phi_1 = 0$  and  $\phi_2 = 0.3$ . In both cases, the two sectors are of the same size. Note that although the first model features a greater proportion of financially weak firms compared with the second model, there is considerably less heterogeneity in financial conditions across firms in that case. The dynamics of relative prices and output in response to our standard financial shock are depicted Figure 13.

The paradox of financial strength can be seen from the fact that a financially more fragile economy (Case I) experiences a noticeably less severe decline in aggregate output in response to an adverse financial shock, compared with the economy that overall has greater financial capacity but more pronounced heterogeneity in the relative strength of the firms' balance sheets (Case II). As shown in the top two panels, the reason for this difference reflects the inability of financially strong firms in the first model to slash prices as aggressively as their counterparts in the second model: The price cut by financially strong firms in the first case is less than one-half of that masterminded by the financially strong firms in the second case.

According to the bottom two panels, the aggressive pricing strategy of financially healthy firms in the second case is a Pyrrhic victory because it drives down the output of financially weak firms to such an extent that the economy experiences a significantly more severe economic slump than in the first case. Thus from a policy perspective, the presence of this negative aggregate demand externality suggests that macroeconomic stabilization policies aimed at providing liquidity support

to financially vulnerable firms during periods of financial distress may offer policymakers an effective tool to avoid a potentially catastrophic economic outcomes associated with deflationary spirals.

## 8 Conclusion

In this paper, we have investigated the effect of financial conditions on price-setting behavior during the “Great Recession.” We did through the lenses of customer-market theory, which emphasizes the idea that price-setting is a form of investment that builds the future customer base.

To motivate our analysis, we used confidential, individual producer prices from the BLS and Compustat to compare pricing behavior across firms with weak balance sheets relative to firms with strong balance sheets. We find strong evidence that at the peak of the crisis firms with relatively weak balance sheets increased prices, while firms with strong balance sheets lowered their prices. Similarly, firms that likely have high fixed operating costs—as evidenced by a high intensity of their SG&A spending—increased their prices, while firms with presumably better operating efficiency lowered prices. Regression analysis shows that liquidity positions and operating efficiency significantly influence the firms’ price-setting behavior during the height of the 2007–09 financial crisis.

We explored the implications of these empirical findings within the context of a New Keynesian framework that allows for customer markets and departures from the Modigliani-Miller paradigm of frictionless financial markets. In our model, firms have an incentive to set a low price to invest in market share. When financial distortions are severe, firms forgo these investment opportunities and maintain high prices. The model implies a substantial attenuation of price dynamics relative to the baseline model without financial distortions in response to contractionary demand shocks. This implies that in the context of the zero lower bound, financial frictions can paradoxically improve overall economic outcomes.

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Table 1: Summary Statistics, PPI and Matched Sample

		Full PPI	Matched PPI Sample
Monthly Inflation	Trimmed Mean	0.170%	0.147%
	Std. Dev.	0.147%	0.216%
	Median	0.180%	0.164%
Monthly Standard Deviation	Trimmed Mean	0.727%	1.053%
	Std. Dev.	0.084%	0.223%
	Median	0.707%	1.013%
Monthly Inflation, Weighted	Trimmed Mean	0.095%	0.120%
	Std. Dev.	0.517%	0.564%
	Median	0.158%	0.170%
Monthly Frequency of Price Changes	Trimmed Mean	13.80%	17.12%
	Std. Dev.	1.11%	1.55%
	Median	13.88%	17.28%
Monthly Frequency of Price Changes, Weighted	Trimmed Mean	41.28%	52.39%
	Std. Dev.	5.27%	9.00%
	Median	42.48%	52.11%
Number of Firms	Trimmed Mean	23628	769
	Std. Dev.	1515	109
	Median	23369	780

NOTE: We compute the above statistics using the micro price data underlying the PPI (full sample) and our sample matched to Compustat. The time period is from January 2005 through December 2012. First, we compute monthly inflation rates and the frequency of price changes at the level of the firm as the (weighted) means of log price changes and the price change indicators using within-firm importance weights. Second, we take (sales-weighted) means in each monthly cross section of firms. Finally, we report trimmed means, medians, and standard deviations of these means, as well as of the average monthly number of firms in the data.

Table 2: Summary Statistics, COMPUSTAT and Matched Sample

		Full Sample	Matched Sample
Liquidity Ratio	Trimmed Mean	0.217	0.149
	Std. Dev.	0.136	0.088
	Median	0.134	0.097
Operating Income Ratio	Trimmed Mean	0.005	0.030
	Std. Dev.	0.032	0.019
	Median	0.024	0.032
Interest Expense Ratio	Trimmed Mean	0.068	0.023
	Std. Dev.	0.021	0.011
	Median	0.017	0.013
SG&A Ratio	Trimmed Mean	0.495	0.272
	Std. Dev.	0.227	0.147
	Median	0.281	0.220
Sales Growth	Trimmed Mean	1.08%	0.52%
	Std. Dev.	3.91%	2.22%
	Median	1.03%	0.62%
Sales	Trimmed Mean	833.120	1538.576
	Std. Dev.	92.874	360.267
	Median	67.613	313.119
Number of Unique Firms		6326	584

NOTE: We compute the above statistics using the full Compustat database for 2005 through 2012 and our matched sample. First, we compute at the firm level and quarterly frequency the ratio of cash and other liquid assets to total assets, the ratio of operating income to total assets, the ratio of interest expenses to total assets, and the ratio of sales and administrative expenses to total assets. Second, we compute time-series averages for each firm of these ratios, sales growth, and total sales. Finally, we report trimmed means, medians, and standard deviations of these means, as well as the number of unique firms in the data.

Table 3: Baseline Calibration

Description	Calibration
Preferences and production	
Time discounting factor, $\beta$	0.99
Constant relative risk aversion, $\gamma_x$	1.00
Deep habit, $\theta$	-0.80
Persistence of deep habit, $\rho$	0.95
Elasticity of labor supply, $1/\gamma_h$	5.00
Elasticity of substitution, $\eta$	2.00
Persistence of technology shock, $\rho_A$	0.90
returns to scale, $\alpha$	0.80
Fixed operation cost, $\phi$	0.26
Nominal rigidity and monetary policy	
Price adjustment cost, $\gamma_p$	10.0
Wage adjustment cost, $\gamma_w$	30.0
Monetary policy inertia, $\rho^r$	0.75
Taylor rule coefficient for inflation gap, $\rho^\pi$	1.50
Financial Frictions	
Equity issuance cost, $\varphi$	0.30, 0.50
Idiosyncratic volatility (a.r.), $\sigma$	0.20
Persistence of financial shock, $\rho_\varphi$	0.90

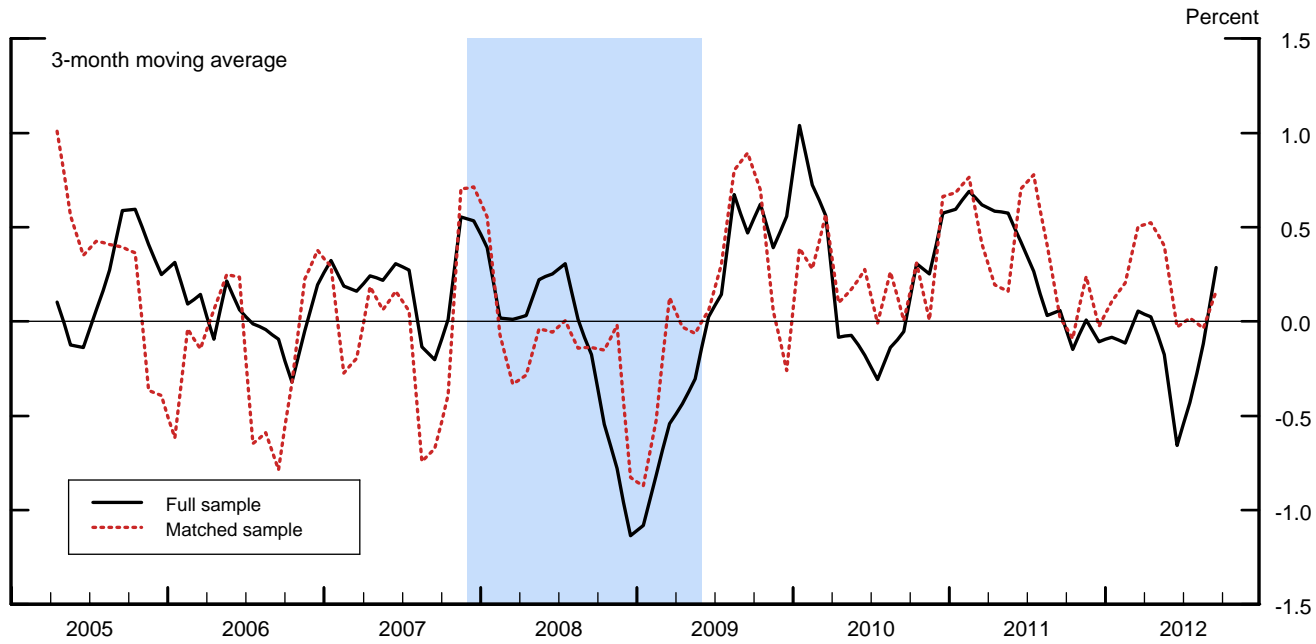
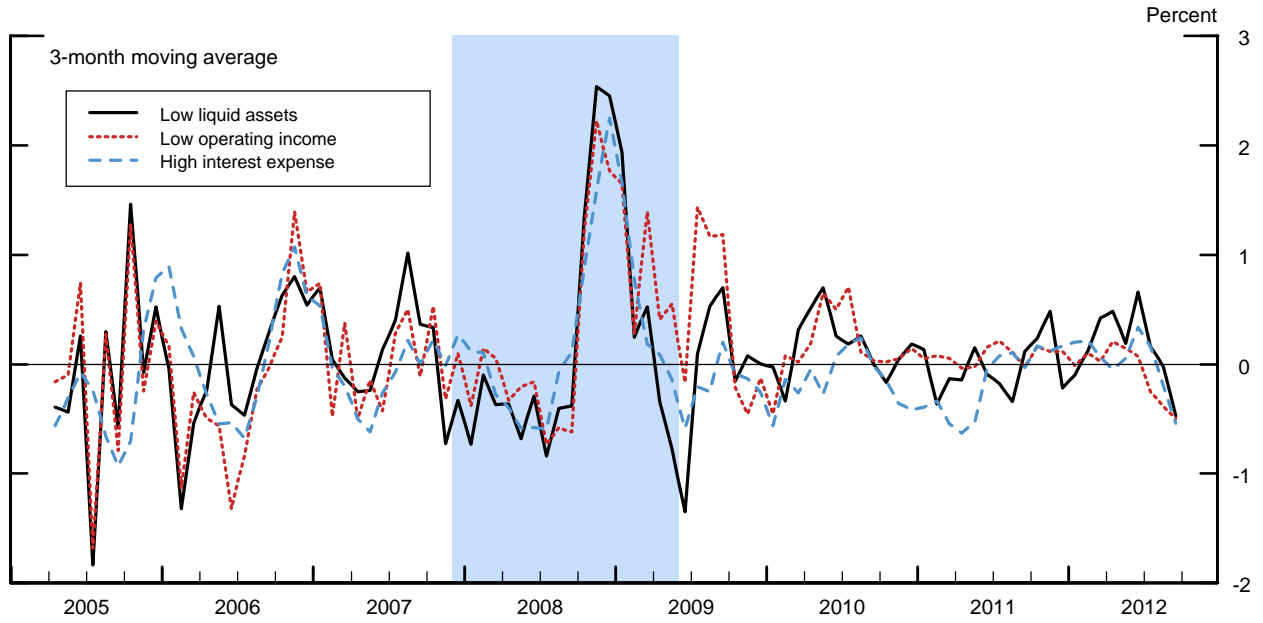
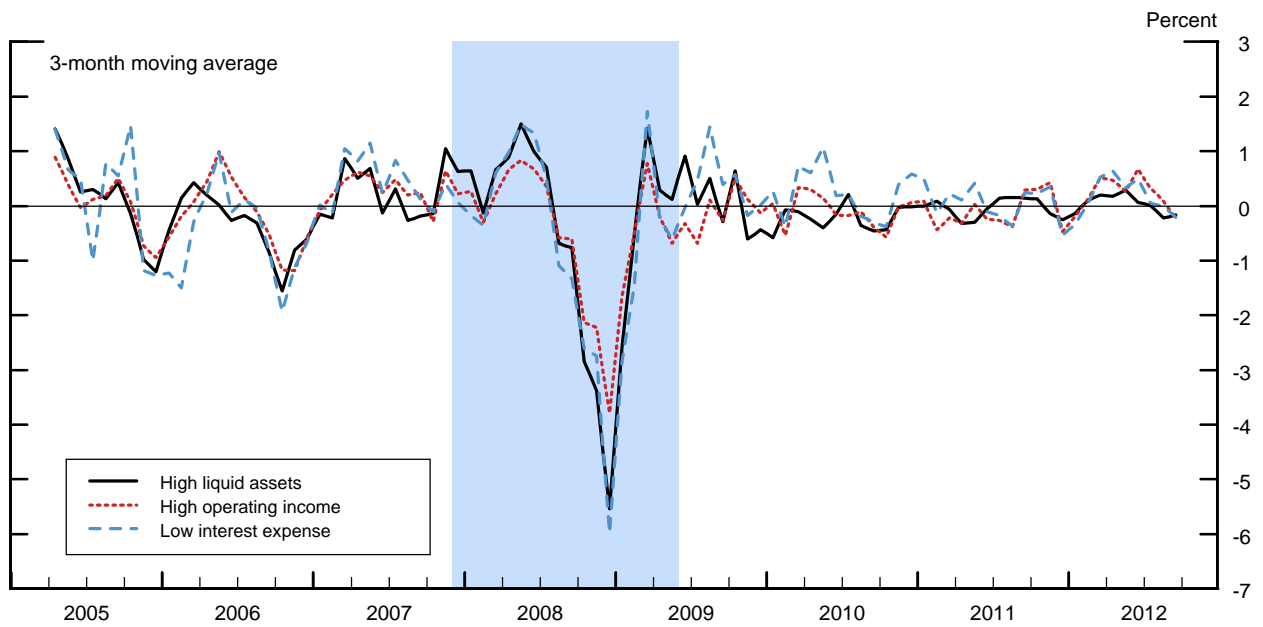


Figure 1: Producer Price Inflation, Full vs. Matched PPI Sample

NOTE: The solid line depicts the 3-month moving average of monthly inflation calculated using the full PPI sample, while the dotted line depicts the corresponding inflation calculated using the subsample of Compustat firms.



(a) Financially Weak Firms



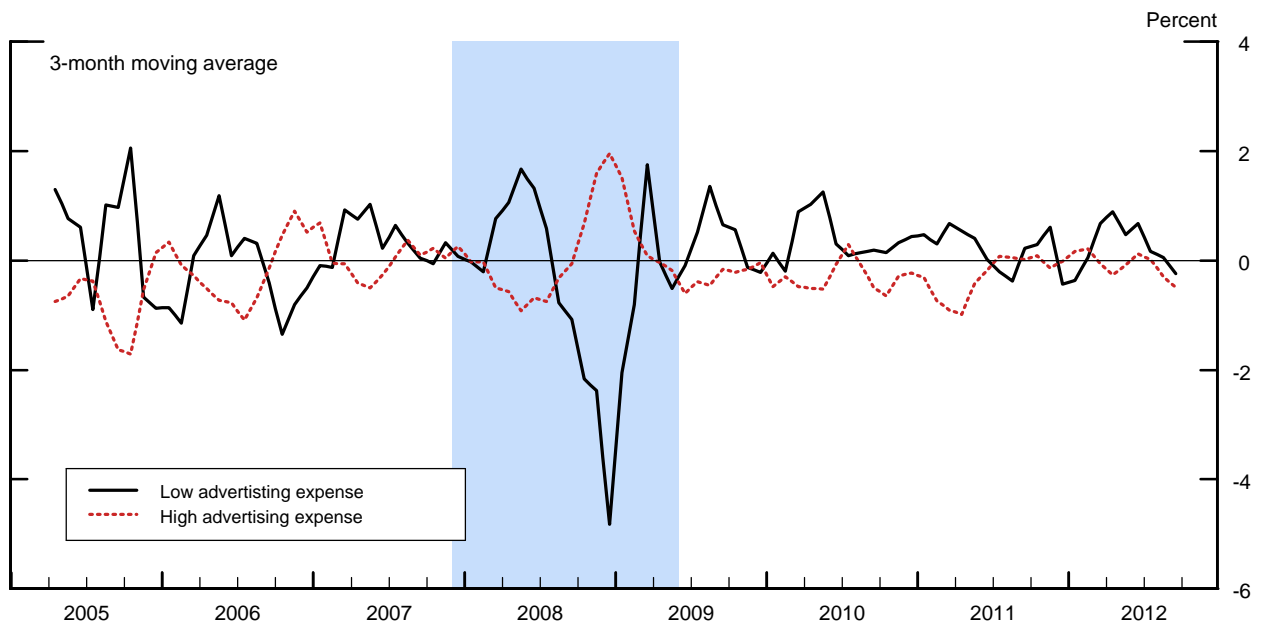
(b) Financially Strong Firms

Figure 2: Producer Price Inflation by Selected Financial Characteristics

NOTE: The top panel shows the industry-adjusted 3-month moving average of monthly inflation rates for financially weak firms, while the bottom panel shows the corresponding inflation rates for financially strong firms; see text for details.



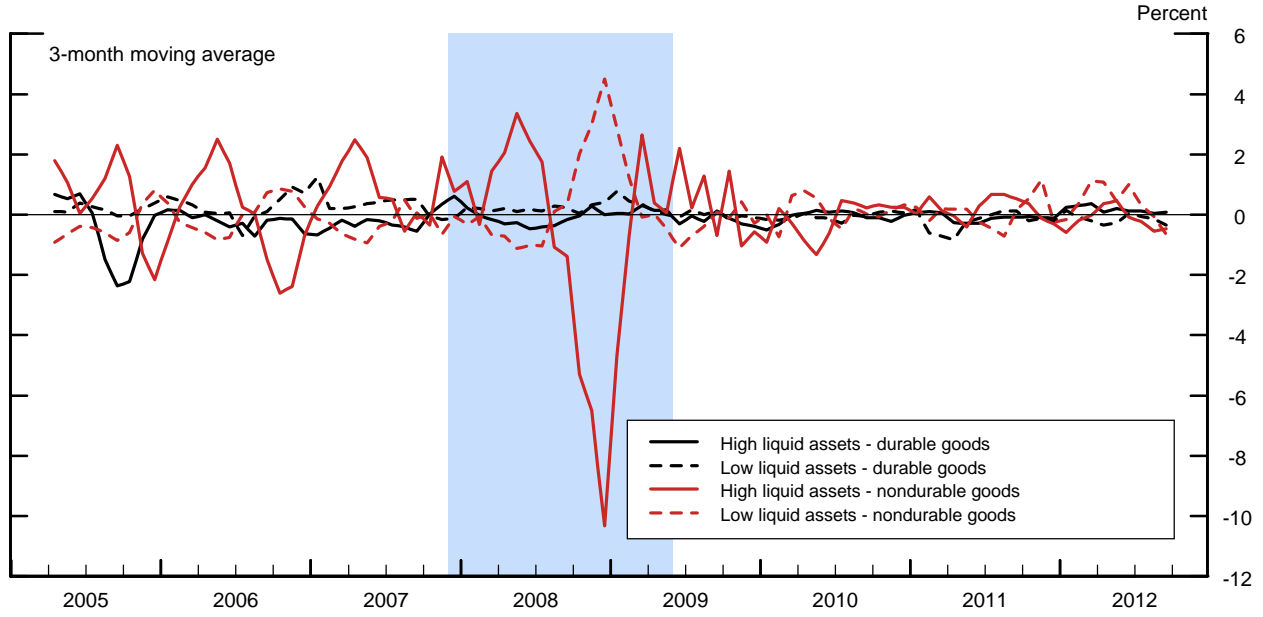
(a) By SG&A Expense Ratio



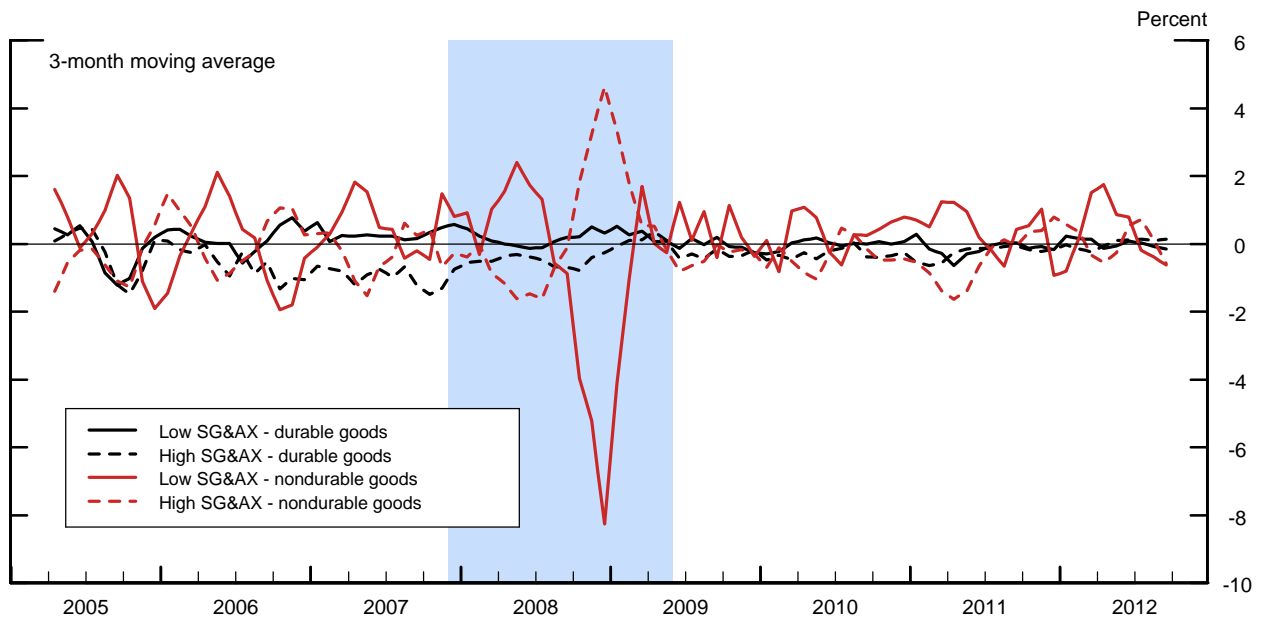
(b) By Advertising Expense Ratio

Figure 3: Producer Price Inflation by Selected Product-Market Characteristics

NOTE: The top panel shows the industry-adjusted 3-month moving average of monthly inflation rates for firms with different product-market characteristics; see text for details.



(a) By Durable vs. Nondurable Goods Sector and Liquidity Ratio



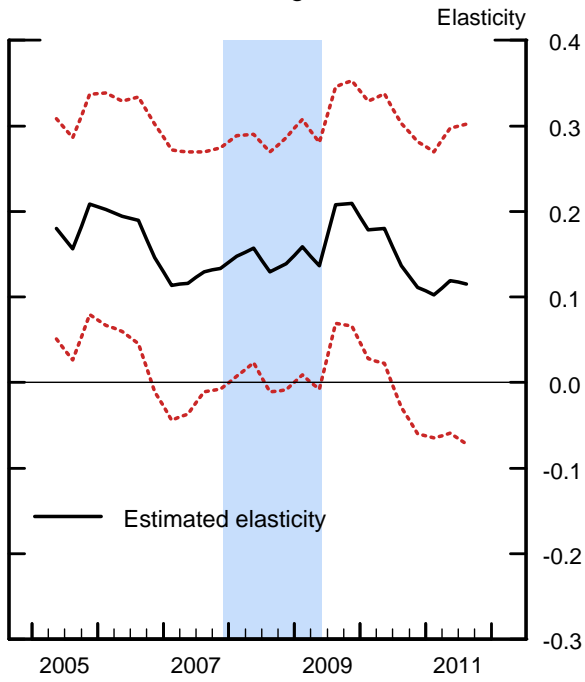
(b) By Durable vs. Nondurable Goods Sector and SG&A Ratio

Figure 4: Producer Price Inflation by Selected Firm Characteristics and Production Sector

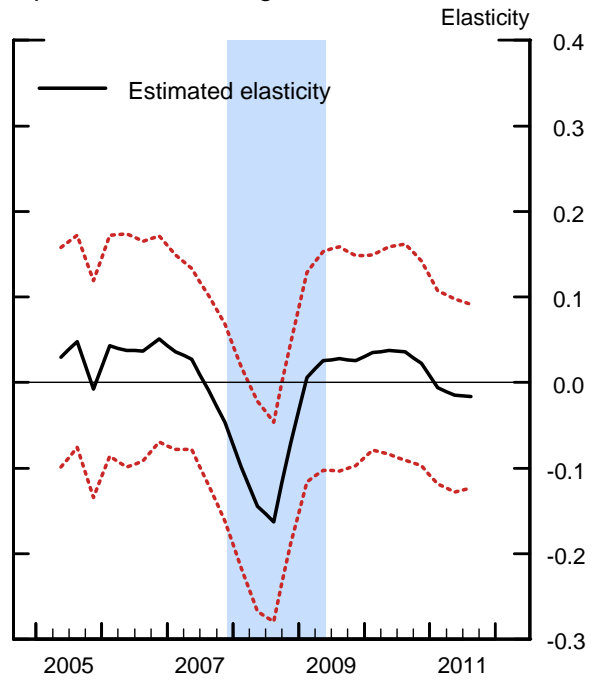
NOTE: The top panel shows the 3-month moving average of monthly inflation rates for firms in different financial positions within the durable and nondurable goods sector. The bottom panel shows the 3-month moving average of monthly inflation rates for firms with different product-market characteristics within the durable and nondurable goods sectors; see text for details.



Downward Price Changes

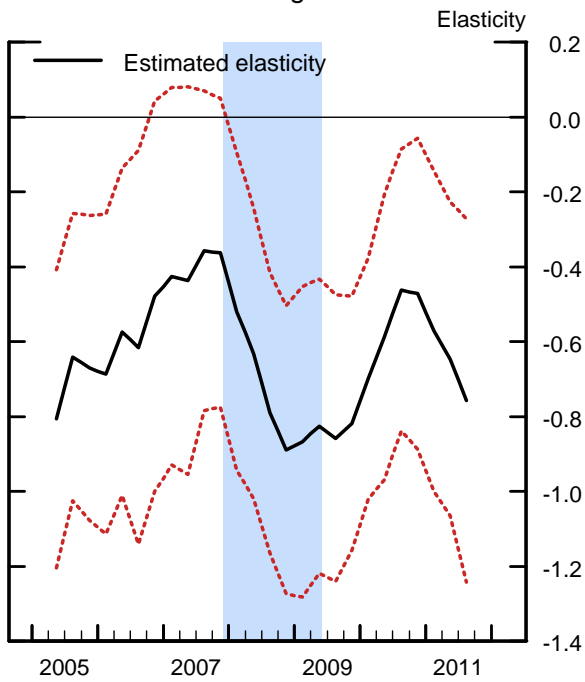


Upward Price Changes

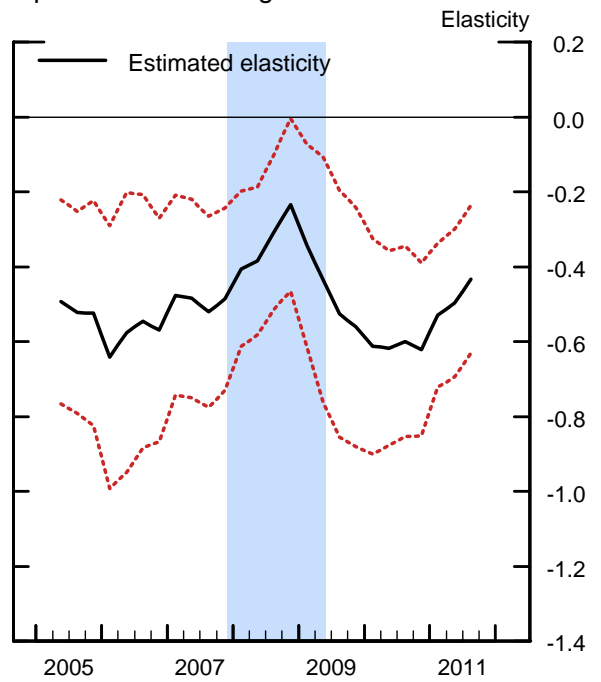


(a) With Respect to Liquidity Ratio

Downward Price Changes



Upward Price Changes

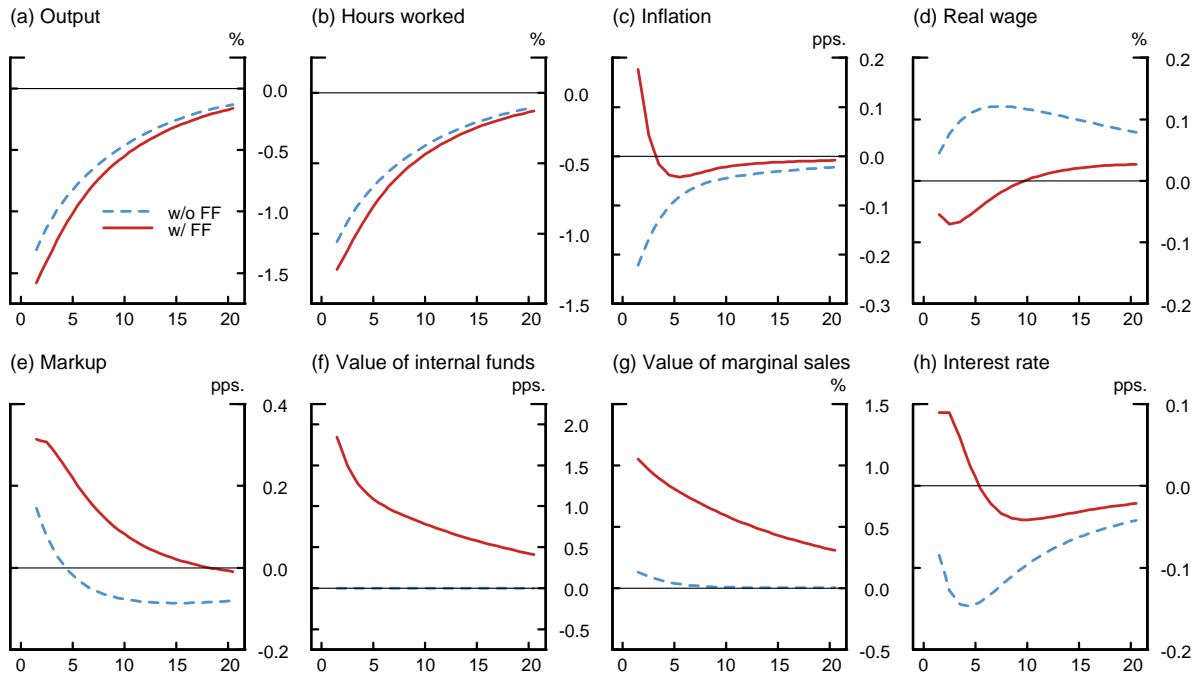


(b) With Respect to SG&A Ratio

Figure 5: Elasticities of Directional Price Changes

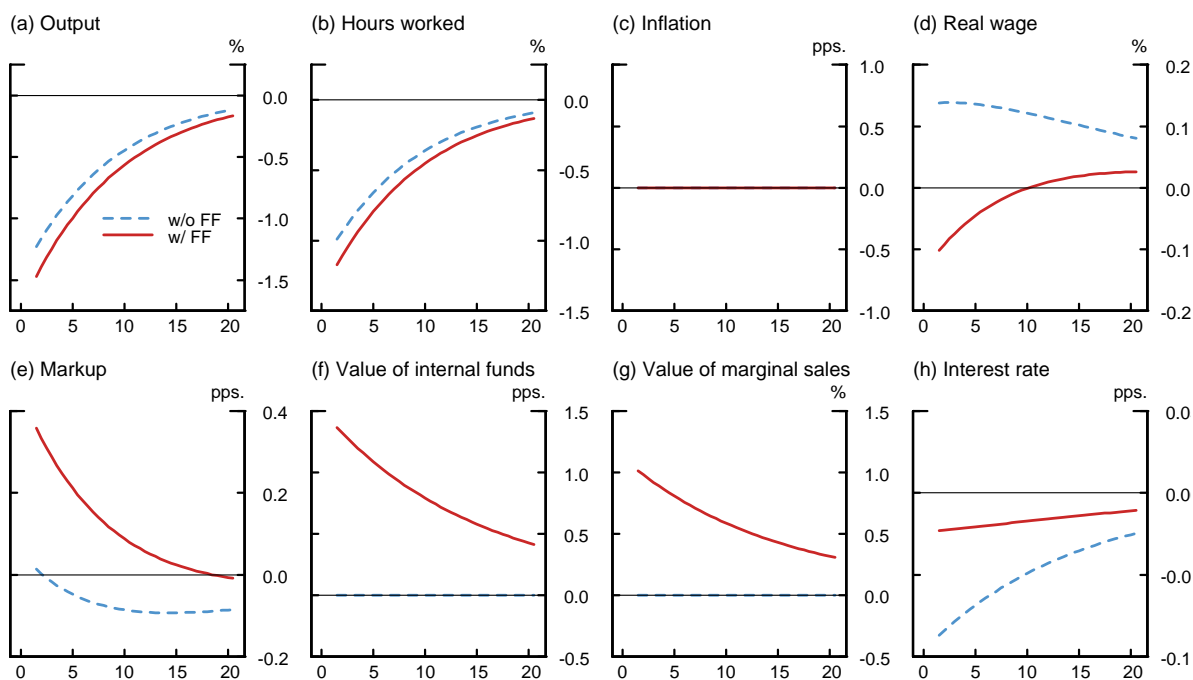
NOTE: The solid line in each panel depicts the estimated time-varying elasticity of the decision to adjust prices upwards or downwards—relative to a base category of no change—based on a multinomial logit specification; see text for details. Dotted lines denote robust 95% confidence intervals.

Figure 6: Impact of a Demand Shock During Financial Crisis  
(With Nominal Rigidities)



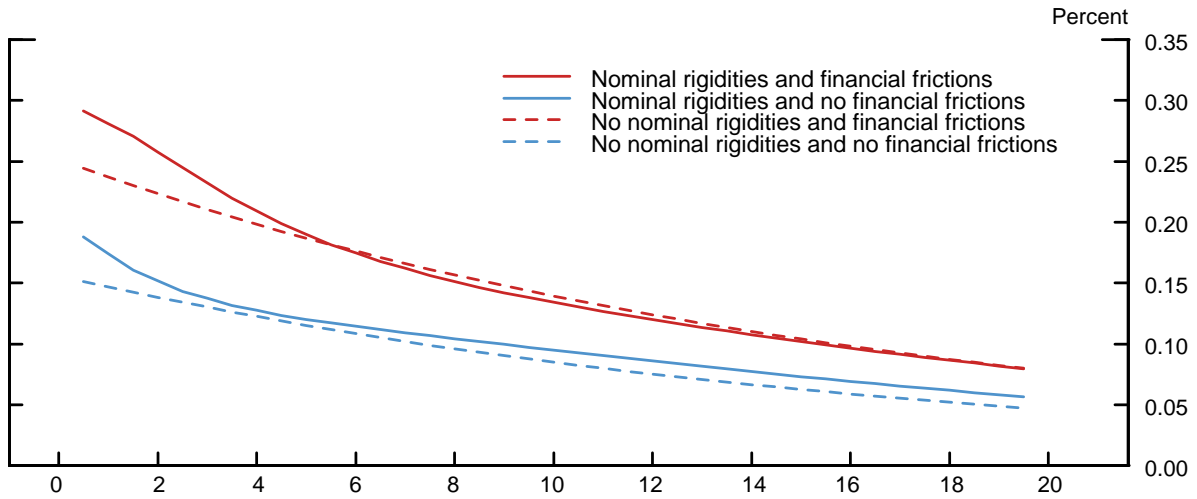
NOTE: The panels of the figure depict the model-implied responses of selected variables to a negative demand shock of 1 standard deviation: w/o FF = responses implied by a model without financial frictions ( $\varphi = 0$ ); and w/ FF = responses implied by a model with financial frictions, with the degree of financial frictions calibrated to a crisis situation ( $\varphi = 0.5$ ). All variables are in deviations from their respective (deterministic) steady-state values (see the text for details).

Figure 7: Impact of a Demand Shock During Financial Crisis  
*(Without Nominal Rigidities)*



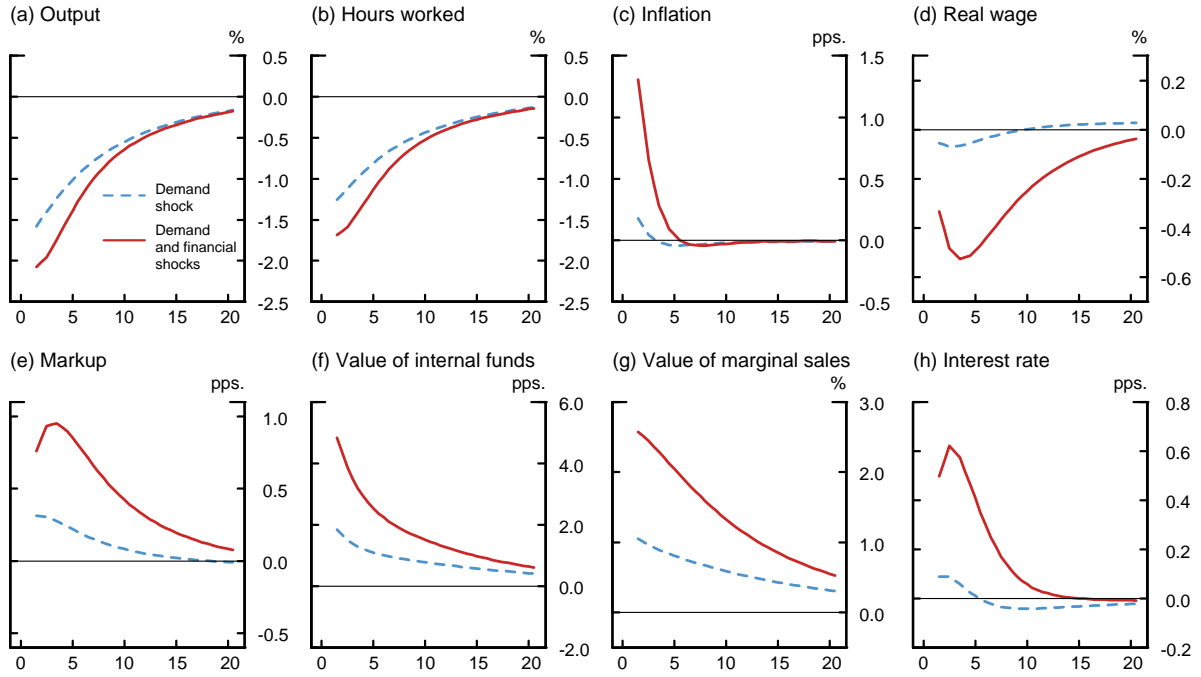
NOTE: The panels of the figure depict the model-implied responses of selected variables to a negative demand shock of 1 standard deviation: w/o FF = responses implied by a model without financial frictions ( $\varphi = 0$ ); and w/ FF = responses implied by a model with financial frictions, with the degree of financial frictions calibrated to a crisis situation ( $\varphi = 0.5$ ). All variables are in deviations from their respective (deterministic) steady-state values (see the text for details).

Figure 8: Demand Shocks and the Labor Wedge  
*(A Financial Crisis Experiment)*



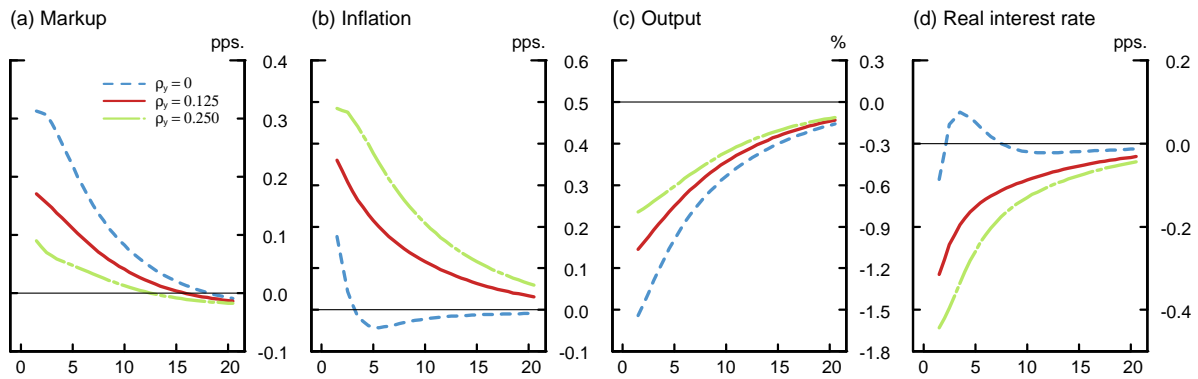
NOTE: The figure depicts the responses of the labor wedge—for different model specifications—to a negative demand shock of 1 standard deviation. The labor wedge is defined as the difference between the marginal product of labor and the household’s marginal rate of substitution between consumption and leisure. For models with financial frictions, the degree of financial frictions is calibrated to a crisis situations ( $\varphi = 0.5$ ); models with no nominal rigidities feature perfectly flexible prices and wages. All labor wedges are in deviations from their respective (deterministic) steady-state values (see the text for details).

Figure 9: Impact of Financial and Demand Shocks  
(With Nominal Rigidities)



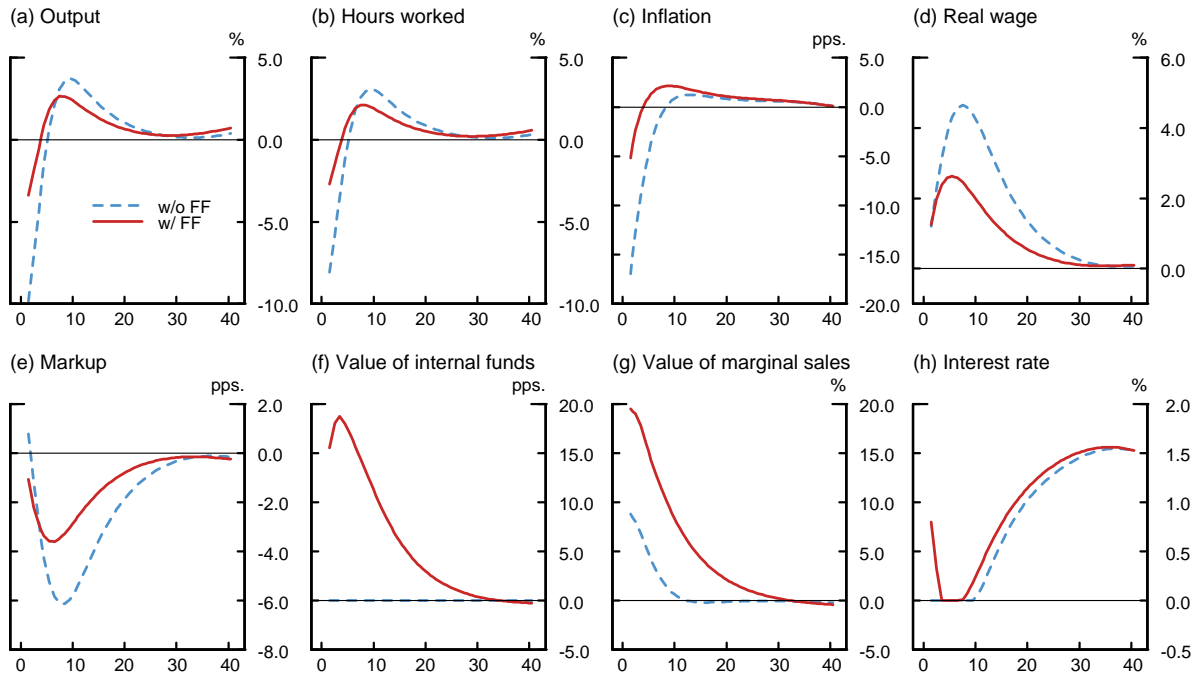
NOTE: The solid lines depict the model-implied responses of selected variables to a combined impact of a 1 standard deviation negative demand shock and a 1 standard deviation negative financial shock, where the latter is defined as a temporary increase in equity dilution costs from a normal level ( $\varphi = 0.3$ ). The dashed lines are responses implied by a negative demand shock of the same magnitude for an economy with a time-invariant level of financial frictions calibrated to a crisis situations ( $\varphi = 0.5$ ). All variables are in deviations from their respective (deterministic) steady-state values (see the text for details).

Figure 10: Impact of a Demand Shock During Financial Crisis  
*(Alternative Monetary Policy Rules)*



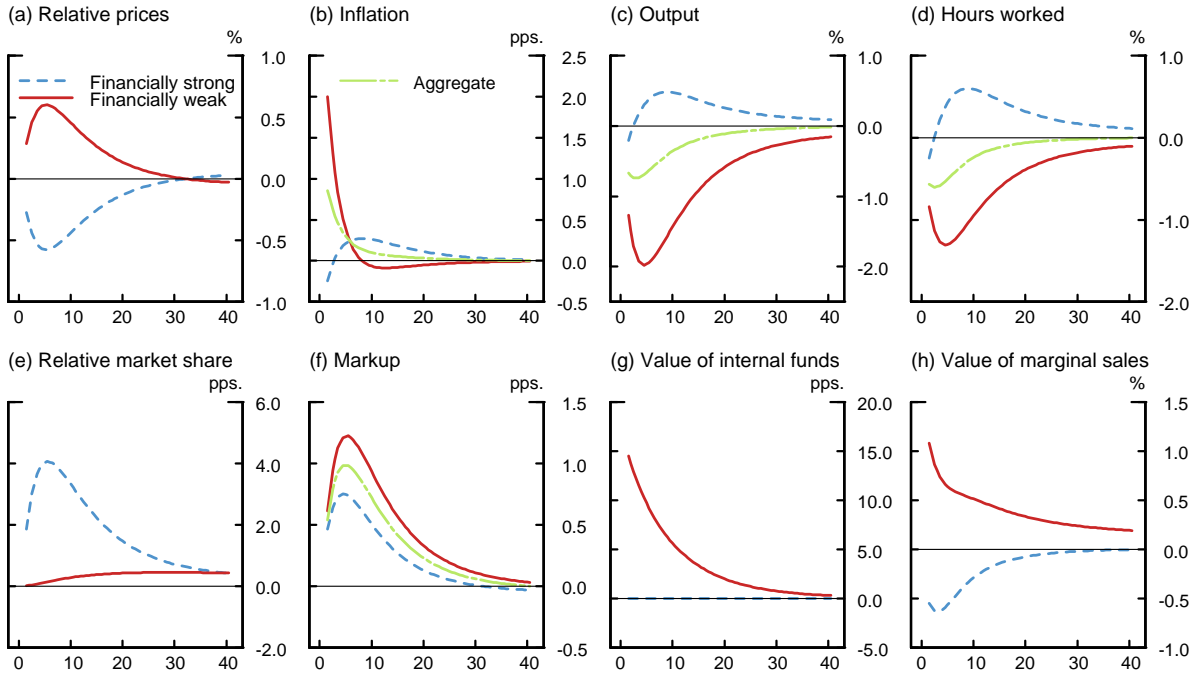
NOTE: The panels of the figure depict the model-implied responses of selected variables to a negative demand shock of 1 standard deviation for different values of an output gap coefficient  $\rho_y$  in the monetary policy (see equation 34). All responses are based on the model featuring nominal rigidities and financial frictions, with the level of financial frictions calibrated to a crisis situations ( $\varphi = 0.5$ ). All variables are in deviations from their respective (deterministic) steady-state values (see the text for details).

Figure 11: Impact of Discount Rate Shocks During Financial Crisis  
*(Binding ZLB Constraint on Nominal Interest Rates)*



NOTE: The panels of the figure depict the model-implied responses of selected variables to a sequence of discount rate shocks that push the economy to the ZLB: w/o FF = responses implied by a model without financial frictions ( $\varphi = 0$ ); and w/ FF = responses implied by a model with financial frictions, with the degree of financial frictions calibrated to a crisis situation ( $\varphi = 0.5$ ). Both model feature the same degree of nominal rigidities. All variables are in deviations from their respective (deterministic) steady-state values (see the text for details).

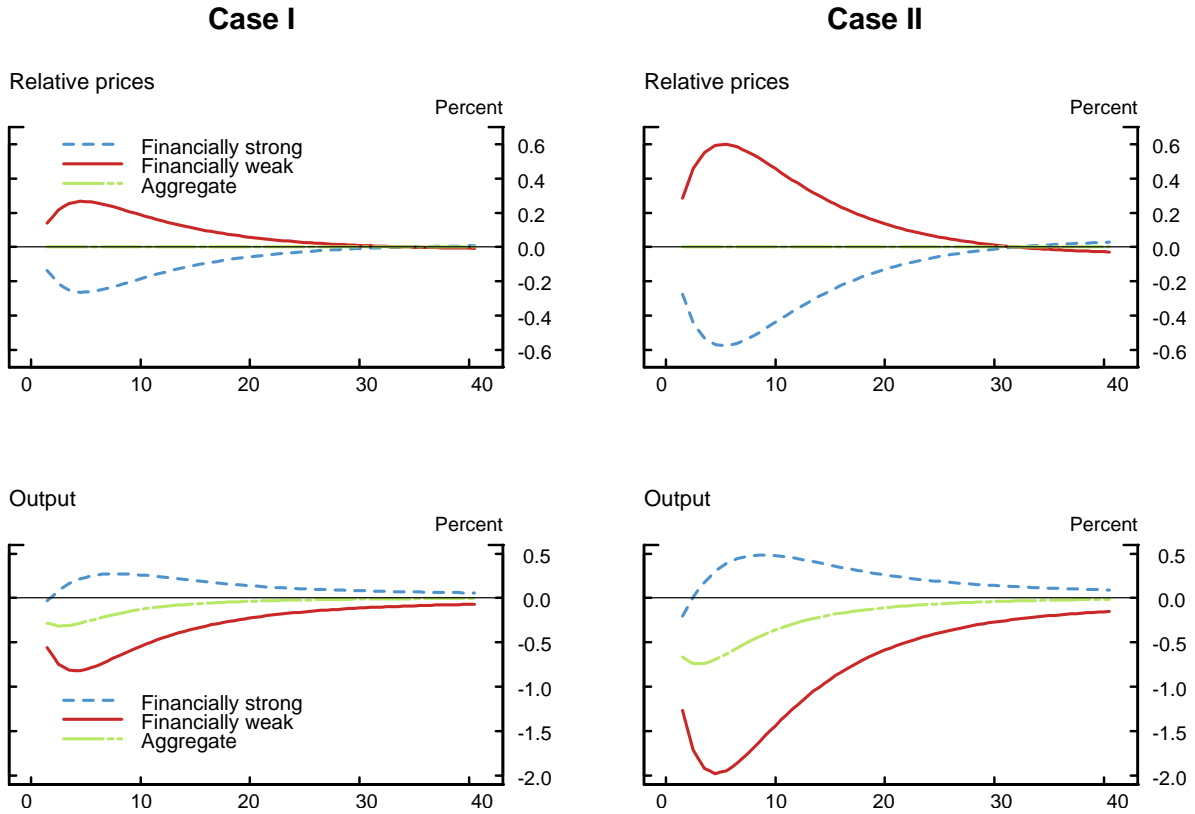
Figure 12: Impact of a Financial Shock  
(*Heterogeneous Firms*)



NOTE: The panels of the figure depict the model-implied impulse responses of selected variables to a negative financial shock of 1 standard deviation, defined as a temporary increase in equity dilution costs from a normal level ( $\varphi = 0.3$ ). The sector consisting of financially strong firms is defined by the operating efficiency level  $\phi_1 = 0$ , whereas the sector consisting of financially weak firms has the operating efficiency level  $\phi_2 = 0.3$ . The aggregate responses are computed under the assumption that the two sectors are of equal sizes. All variables are in deviations from their respective (deterministic) steady-state values (see the text for details).



Figure 13: Paradox of Financial Strength  
(*Heterogeneous Firms*)



NOTE: The panels of the figure depict the model-implied impulse responses of selected variables to a negative financial shock of 1 standard deviation, defined as a temporary increase in equity dilution costs from a normal level ( $\varphi = 0.3$ ). Case I: model specification with  $\phi_1 = 0.8\phi_2$ , with  $\phi_2 = 0.3$ ; and Case II: model specification with  $\phi_1 = 0$  and  $\phi_2 = 0.3$ . In both cases, financially strong firms are in sector 1, which is characterized by the operating efficiency level  $\phi_1$ ; financially weak firms, in contrast, operate in sector 2 with the efficiency level  $\phi_2$ . The aggregate responses are computed under the assumption that the two sectors are of equal sizes. All variables are in deviations from their respective (deterministic) steady-state values (see the text for details).

# Appendices

## A Log-linearization of Phillips Curve

From (??), we derive the steady state relationship between the value of internal funds and the value of marginal sales as

$$\frac{\mathbb{E}^a[\nu_i]}{\mathbb{E}^a[\xi_i]} = \eta. \quad (\text{A-1})$$

(??) in the steady state implies

$$\mathbb{E}^a[\nu_i] = \mathbb{E}^a[\xi_i] - \mathbb{E}_t^a[\kappa_i] + (1 - \rho)\lambda$$

Dividing this expression through by  $\mathbb{E}^a[\nu_i]$  yields

$$1 = 1/\eta - \frac{\mathbb{E}_t^a[\kappa_i]}{\mathbb{E}^a[\nu_i]} + (1 - \rho)\frac{\lambda}{\mathbb{E}^a[\nu_i]} \quad (\text{A-2})$$

Since the ratio between the marginal value of customer base and the marginal value of sales is determined by (??) as

$$\frac{\lambda}{\mathbb{E}^a[\nu_i]} = \frac{\beta\theta(1 - \rho)}{(1 - \rho\beta)}, \quad (\text{A-3})$$

combining (A-2) and (A-3) yields

$$\frac{\mathbb{E}_t^a[\kappa_i]}{\mathbb{E}^a[\nu_i]} = 1/\eta - 1 - (\eta - 1)\frac{\beta\theta(1 - \rho)}{(1 - \rho\beta)}$$

Subtracting the above expression from the inverse of (A-1) yields

$$\begin{aligned} \frac{\mathbb{E}^a[\xi_i]}{\mathbb{E}^a[\nu_i]} - \frac{\mathbb{E}^a[\kappa_i]}{\mathbb{E}^a[\nu_i]} &= \frac{\mathbb{E}^a[\xi_i]}{\mathbb{E}^a[\nu_i]} \cdot \left[ 1 - \frac{\mathbb{E}^a[\kappa_i]}{\mathbb{E}^a[\xi_i]} \right] \\ &= 1 + (\eta - 1)\frac{\beta\theta(1 - \rho)}{(1 - \rho\beta)} = \eta - \omega(\eta - 1) \end{aligned}$$

where  $\omega \equiv 1 - \frac{\beta\theta(1 - \rho)}{1 - \rho\beta}$ . Hence, requiring  $\eta - \omega(\eta - 1) > 0$  is equivalent to a strictly positive marginal profit in the steady state.

## B Equilibrium Dispersion of Prices in the Steady State

In the steady state, the Phillips curve implies

$$p_k = \eta \frac{\mathbb{E}^a[\nu_i|\phi_k]}{\mathbb{E}^a[\xi_i|\phi_k]}. \quad (\text{B-1})$$

From the FOC for  $s$ , we have

$$\frac{\lambda_k}{\mathbb{E}^a[\xi_i|\phi_k]} = \frac{\theta(1 - \eta)\beta}{1 - \rho\beta} \frac{\mathbb{E}^a[\nu_i|\phi_k]}{\mathbb{E}^a[\xi_i|\phi_k]}. \quad (\text{B-2})$$

Combining the two yields

$$\frac{\lambda_k}{\mathbb{E}^a[\xi_i|\phi_k]} = p_k \frac{\theta(1-\eta)\beta}{\eta(1-\rho\beta)}. \quad (\text{B-3})$$

The FOC for  $c$  and  $h$  in the steady state imply

$$\frac{\mathbb{E}^a[\nu_i|\phi_k]}{\mathbb{E}^a[\xi_i|\phi_k]} = -\frac{\mathbb{E}^a[\xi_i a_i|\phi_k]}{\mathbb{E}^a[\xi_i|\phi_k]} \frac{w}{\alpha A} (c_k + \phi_k)^{\frac{1-\alpha}{\alpha}} + p_k + (1-\rho) \frac{\lambda_k}{\mathbb{E}^a[\xi_i|\phi_k]}. \quad (\text{B-4})$$

Substituting (B-1) and (B-3) in (B-4) yields

$$p_k = \frac{\eta(1-\rho\beta)}{(\eta-1)[(1-\rho\beta) - \theta\beta(1-\rho)]} \frac{\mathbb{E}^a[\xi_i a_i|\phi_k]}{\mathbb{E}^a[\xi_i|\phi_k]} \frac{w}{\alpha A} (c_k + \phi_k)^{\frac{1-\alpha}{\alpha}}. \quad (\text{B-5})$$

The external financing triggers in the steady state are given by

$$a_k^E = \frac{p_k c_k}{(c_k + \phi_k)^{1/\alpha}} \frac{A}{w}. \quad (\text{B-6})$$

The consumption aggregators in the steady state imply

$$\frac{c_k}{c_l} = \left( \frac{p_k}{p_l} \right)^{-\eta} \frac{s_k^{\theta(1-\eta)}}{s_l^{\theta(1-\eta)}} \quad (\text{B-7})$$

and

$$x = \left[ \sum_{m=1}^N \omega_m (c_m^{1-\theta})^{1-1/\eta} \right]^{1/(1-1/\eta)}. \quad (\text{B-8})$$

Equilibrium consistency requires

$$1 = \left[ \sum_{m=1}^N \omega_m p_m^{1-\eta} \right]^{1/(1-\eta)}, \quad (\text{B-9})$$

which is the steady state version of (??) with  $\pi = \pi_k = 1$ . Finally labor market and goods market clearing conditions imply

$$\frac{w}{\tilde{p}} x^{-\gamma_x} = \zeta h^{\gamma_h} \quad (\text{B-10})$$

and

$$c = \left[ \sum_{m=1}^N \omega_m [\exp(0.5\alpha(1+\alpha)\sigma^2) h_m^\alpha - \phi_m]^{1-1/\eta} \right]^{1/(1-1/\eta)} \quad (\text{B-11})$$

where the type conditional labor demand satisfies

$$h_k = \left[ \frac{c_k + \phi_k}{\exp(0.5\alpha(1+\alpha)\sigma^2)} \right]^{1/\alpha} \quad (\text{B-12})$$

and

$$h = \sum_{m=1}^N h_m \quad (\text{B-13})$$

Deep-habit adjusted price index in the steady state satisfies

$$\tilde{p} = \left[ \sum_{m=1}^N \omega_m p_m^{1-\eta} c_m^{\theta(1-\eta)} \right]^{1/(1-\eta)}. \quad (\text{B-14})$$

which is the steady state version of (??). (B-5)~(B-14) can then be solved for  $4N + 5$  variables:  $p_k, c_k, a_k^E, h_k$  for  $k = 1, \dots, N$  and  $x, w, \tilde{p}, h$  and  $c$ .