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Phillips Curve and Price-Change Distribution under Declining Trend Inflation*

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Abstract

The relationship between the price-setting behaviors at the micro level and the inflation dynamics at the macro level is an underexplored research area. In this paper, we first document that (i) a remarkable shift in cross-sectional price-change distributions at the micro level and (ii) a flattening of Phillips curve at the macro level were simultaneously observed in Japan, from the high-inflation periods until the mid-1990s to the low-inflation periods afterward. We, then, empirically show that the menu-cost hypothesis fits the price-setting behavior in Japan and construct a multi-sector general equilibrium model with a higher menu cost in the services sector based on our empirical findings. The quantitative exercise using the model indicates that the above observations at the micro and macro level in Japan can be consistently replicated within a unified model under the declining average inflation and the increasing share of services in output.

JEL classification: E31, E32, E52

Keywords: Phillips curve, Price-change distribution, Menu cost, Service price rigidity, Deflation, Trend inflation.

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1. Introduction

While recent studies using micro data for prices give some insights on price-setting behaviors per se, the relation between the price-setting behaviors at the micro level and the inflation dynamics at the macro level is still an underexplored and growing research area.[1] In particular, amid rising deflationary pressure in many developed countries, much attention has been paid to how declining trend inflation affects price-setting behaviors at the micro level, and how the changes in price-setting behaviors, in turn, affect the inflation dynamics at the macro level.

To understand the relation between the micro and macro price dynamics under the declining trend inflation, the Japanese experience from the high-inflation periods (1982–1994 FY) to the low-inflation periods (1995–2012 FY) gives the following thought-provoking stylized-facts. First, at the micro level, a remarkable shift in cross-sectional price-change distributions has been observed. Specifically, along with the decline in average inflation, the price-change distributions in the services sector have been weighted more heavily around 0% and its dispersion has narrowed, while the distributions in the goods sector only shifted leftward. Second, at the macro level, the Phillips curve—the relation between inflation and macroeconomic demand-supply balance—has flattened in both goods and services sectors. That is, as average inflation has declined, price sensitivity to business cycles has also declined in both sectors. In contrast to the sectoral differences in the micro-level price-setting behaviors, the flattening of the Phillips curve has been observed not only in the services sector but also in the goods sector.

The purpose of this paper is to provide a consistent explanation for the stylized-facts observed at the micro and macro levels in Japan and deepen our understanding of the relationship between firms' price-setting behaviors and their macroeconomic consequences. Specifically, we show that the menu-cost hypothesis can explain both the flattening of the Phillips curve and the shifts in the price-change distributions in a

[1] As empirical studies using micro data for prices, see Bils and Klenow (2004), Klenow and Kryvtsov (2008), Nakamura and Steinsson (2008, 2013) for the U.S., Higo and Saita (2007), Kurachi *et al*. (2016) for Japan, and Dhyne *et al*. (2006) for the Euro area.

consistent way. To consider the validity of the menu-cost hypothesis, we carry out both empirical and theoretical studies.

In the empirical part, we set up an empirical model with price rigidities in the vicinity of a 0% inflation rate to test the menu-cost hypothesis. Specifically, we employ a panel data analysis using a limited dependent variable model with two-sided thresholds, which is used by the recent study of Honoré *et al*. (2012). Employing the empirical model, we estimate parameters regarding the menu-cost hypothesis based on individual item data of Consumer Price Index (CPI). In order to adequately identify menu-cost parameters, we extract common factors such as demand and supply shocks from the large macroeconomic dataset using a principal component approach as in Boivin *et al*. (2009). We then use these factors as explanatory variables to control for macroeconomic factors driving price fluctuations. Our empirical study indicates higher menu cost in the services sector than in the goods sector, which is consistent with our empirical findings regarding price-change distributions and other empirical studies such as Nakamura and Steinsson (2010) for U.S. or Dhyne *et al.* (2006) for the Euro area.

In the theoretical part, we examine whether the menu-cost hypothesis can consistently explain the observed shift in price-change distributions by sector as well as the flattening of the Phillips curve under shifting trend inflation within a unified model. For this purpose, we construct a multisector dynamic general equilibrium model with heterogeneous firms and assume that the services sector bears higher menu cost than the goods sector, following our findings in the empirical part. We then calibrate the model parameters to replicate some moments regarding the observed cross-sectional distributions of price changes in both goods and services sectors. Using the calibrated model, we explore how shifts in trend inflation as well as the share of services in total output affect the slope of the Phillips curve through changes in price-change distributions. Our quantitative results of the comparative statics with respect to the shift in trend inflation as well as the share of services in total output lead to the following two findings. First, the multisector menu-cost model can adequately replicate the change in price-change distributions in both goods and services sectors. Second, the model can also replicate almost the same degree of flattening of the Phillips curves as observed during the deflationary period in Japan in both sectors. These findings imply that the menu-cost hypothesis can consistently account for the change in firms' price-setting behaviors during the deflationary period in Japan and its macroeconomic consequences.

The relationship between the Phillips curve and the menu cost is a classical topic discussed by, for example, Ball *et al*. (1988). They imply that, based on the menu-cost hypothesis, a decline in trend inflation rates increases price rigidities and makes the Phillips curve flatter.[2] Recently, a number of studies have shed new light on this topic on the basis of a general equilibrium model with a menu-cost element (e.g., Golosov and Lucas, 2007; Midrigan, 2011; Vavra, 2014; Kehoe and Midrigan, 2015; Watanabe and Watanabe, 2017). In particular, the most closely related studies to the current paper are Enomoto (2007) and Nakamura and Steinsson (2010), which examine a price-setting behavior and monetary neutrality using a multisector general equilibrium model with a menu cost.[3] The current paper belongs to this line of research, by assessing whether a multi-sector general equilibrium model with a menu cost adequately explains the observed shift in price-change distributions by sector as well as the flattening of the Phillips curve, both of which were observed during the deflationary period in Japan.

The remainder of the paper proceeds as follow. Section 2 shows empirical findings about shifting price-change distributions and the changing slope of the Phillips curve during the deflationary period in Japan. Section 3 describes the menu-cost hypothesis and an empirical procedure to test the plausibility of the menu-cost hypothesis. In Section 4, we construct a multisector general equilibrium model with the heterogeneous menu-cost structure across sectors. Section 5 shows quantitative analyses based on the theoretical model. Section 6 presents the conclusion.

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[2] Following Ball *et al*. (1988), there is another line of research investigating time-varying price stickiness by endogenizing the degree of nominal rigidities in a Calvo-style sticky price models (see Romer, 1990; Kiley, 2000; Devereux and Yetman, 2002; Levin and Yun, 2007; Kimura and Kurozumi, 2010; Kurozumi, 2016).

[3] In terms of methodology and motivation, while those two papers use a classic monetary model with money supply shocks and focus on monetary neutrality, the current paper uses a model with an interest rate feedback rule by central banks and focus on business cycles driven by demand shocks in line with the recent quantitative monetary economics literature.

2. Price-Change Distributions and the Phillips Curve

In this section, we first describe the micro-level price dataset we use in this paper and explain the filtering method which we apply to the price data. We then examine price-change distributions, the frequency of price adjustments, and the slope of the Phillips curve during the period of declining average inflation in Japan since the late 1980s.

2.1 Price-Change Distribution

Our dataset covers the 588 price indices of individual items composing the CPI.[4] Before analyses, we removed temporary price changes from each price series. Recent works such as Bils and Klenow (2004) show that micro-level price series fluctuate much more frequently than the aggregate ones. To give consistent explanations for price-setting behaviors at both the macro and micro levels, Kehoe and Midrigan (2015) emphasize the need to distinguish temporary and regular price changes in the micro-level price series. They also show that temporary price changes in the micro-level price data do not affect the aggregate price rigidity, based on the theoretical analysis.

Therefore, to derive implications for the aggregate price rigidity from the micro-level price-change distributions, we need to remove temporary price changes from the original price series. We adopt a simplified method developed by Kehoe and Midrigan (2015) to remove temporary price changes. Specifically, the five-month centered running mode of the original price series is computed.[5] This type of algorithm is employed by, for example, Eichenbaum *et al*. (2011) and Sudo *et al*. (2014).

After the above filtering, we examine developments of price-change distributions during both the inflationary and deflationary periods in Japan. First, we examine the

[4] Recently, there are some studies using scanner data for investigating micro price dynamics in Japan (see Abe and Tonogi, 2010; Sudo *et al*., 2014). However, they focus only on goods prices because the most of the scanner data includes few service prices. In this paper, we use CPI individual data including 141 individual service prices for investigating both goods and services price dynamics.

[5] We define the most frequent price over five months as the regular price and identify the difference between the actual and regular prices as the temporary price change.

dispersion of distributions by focusing on weighted quantile points.[6] Figure 1 shows developments of first/second (i.e., median)/third weighted quantile points from a high-inflation period (1982–1994 FY) to a low-inflation period (1995–2012 FY) by sector. According to Figure 1 (1) for CPI (all items, less fresh food and imputed rent), the weighted median remained in the vicinity of 0% and the range from first to third quantiles became narrower from the high to low-inflation period.[7] However, there is large heterogeneity across goods and services. For goods prices, Figure 1 (2) shows that each quantile point moved smoothly and the range from first to third quantiles was approximately constant in both the high- and low-inflation periods. Meanwhile, Figure 1 (3) for service prices shows that the range from first to third quantiles became quite narrower during the same period and the weighted median remained in the vicinity of 0%. These facts imply that from the high to low-inflation period, price rigidity dramatically increased in the services sector, whereas it was nearly stable in the goods sector.

The increase of price rigidity in the services sector can be also confirmed by the frequency of price adjustments. Figure 2 provides the frequency of price adjustments.[8] While the frequency of price adjustments had increased moderately for goods, it had significantly decreased since the late 1990s for services.[9] This implies that only service price rigidity had increased along with the decline in average inflation.

Finally, Figure 3 displays price-change distributions in the high- and low-inflation period. In the goods sector, the price-change distribution only shifted leftward, with the weight in the vicinity of 0% almost unchanged. In the services sector, however, the shape of distribution changed dramatically from the high to the low-inflation period; (i) the

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[6] Weighted quantile is calculated from weighted distribution based on the CPI weight (2010 year basis) of each individual item. As a robustness check, we confirm that our main results do not change with alternative weights in the years 2000 and 2005.

[7] We exclude the price of imputed rent from the data because it does not reflect macroeconomic demand-supply balance directly. As a robustness check, we confirm that our main results do not change with the data including imputed rent.

[8] "Price change" is defined as a quarterly change more than ±0.1% in the item level.

[9] This observation is consistent with Higo and Saita (2007) and Kurachi *et al.* (2016).

distribution had more weight in the vicinity of 0%, (ii) the dispersion became narrower, and (iii) the positive skewness observed in the high inflation period disappeared.

2.2 Phillips Curves

In this section, we examine changes in the slope of the Phillips curve. The slope of the Phillips curve indicates the degree of output-inflation tradeoff. In other words, it is a parameter that links nominal and real economic activities. In that sense, identifying the slope of the Phillips curve is important for central banks to achieve their price stability target.

Many previous studies investigating the Phillips curve in Japan provide evidence for flattening of the Phillips curve during the deflationary period. For example, De Veirman (2009) and Kaihatsu and Nakajima (2015) estimate the slope of the Phillips curve and report that the Phillips curve had flattened in the 1990s. Figure 4 displays the slope of the Phillips curve for CPI inflation rate (all items, goods, and services) in both the high- and low-inflation periods.[10] We find that the Phillips curve had significantly flattened from the high-inflation periods to the low-inflation periods in both goods and services sectors.

2.3 Implications of the Menu-Cost Hypothesis

The observed shift in price-change distributions and the changing slope of the Phillips curve are potentially explained by the menu-cost hypothesis in a consistent manner. With the menu cost, firms must pay fixed costs in order to change their prices. If trend inflation declines in this situation, firms' incentive to change prices decreases because relative prices change only moderately. Consequently, the frequency of price adjustments decreases and the price-change distribution is likely to have more weight in the vicinity of 0% and narrower dispersion. From the macroeconomic point of view, the Phillips curve becomes flatter because a decreased frequency of price adjustments reduces the sensitivity to shocks from the real economy (Ball *et al.*, 1988).

[10] Note that the degree of flattening of Phillips curve depends on the data used for estimation.

There may be another explanation for the observed shift in price-change distributions and the changing slope of the Phillips curve during a deflationary period: the downward nominal rigidity of wages (see Akerlof *et al*., 1996). We do not deny the influence of downward wage rigidity, since it does not necessarily contradict the menu-cost hypothesis. However, it would not be empirically supported that the increasing price rigidity during the deflationary period is accounted for only by downward nominal rigidity in wages. Figure 5 shows the development of quantile points in a firm-level wage cost distribution per head. The figure indicates that quantile points move smoothly even in the deflationary period in Japan after mid-1990s, which implies that workers started to accept nominal wage cuts in Japan (see also Kuroda and Yamamoto, 2003).[11]

Another issue is how we can reconcile the flattening Phillips curve in goods sector with the micro evidence that goods-price rigidity has been almost unchanged. There are several consistent explanations for this issue. For example, increasing competitiveness by deregulation or globalization (see Gaiotti, 2010), or strengthening commitment for anchoring inflation expectations by monetary authorities (see Boivin *et al*., 2010), could make the Phillips curve flatter. In particular, globalization could affect the goods sector more strongly than the services sector because goods are tradable. Another possible explanation is the influence of interaction between the goods and services sectors via general equilibrium effects. In this regard, increasing price rigidity in the services sector could somehow affect the goods-price rigidity. We will take up this point later by constructing the general equilibrium model.

3. Empirical Analysis of the Menu-Cost Model

In this section, to assess the validity of the menu-cost hypothesis, we estimate a limited dependent variable model with two-sided thresholds, following Sekine and Tachibana (2004) and Honoré *et al*. (2012).

[11] Although some downward rigidity was observed in regular wages, Japanese firms flexibly adjusted nominal wages by changing bonuses, comprising a large fraction of total wages in Japan.

3.1 Empirical Specification

Our empirical model is closely related to that in Honoré *et al.* (2012), which specifies a reduced form of the menu-cost model; firms would change their prices only if the optimal level of inflation rate (the latent inflation rate, hereafter) is significantly different from zero. Here, the latent inflation rate is an unobservable variable, which is supposed to reflect exogenous conditions, including various factors such as demand and supply shocks. The threshold for firms beyond which they change their prices is determined by the menu cost that firms must pay for changing their prices.

As a simplified specification of this idea, we estimate a limited dependent variable model with two-sided thresholds.[12] Inflation rate π_{it} for an item i at time t is determined by

$$\pi_{it} = \begin{cases} \pi_{it}^{*} - \theta^{+} & if\ \pi_{it}^{*} \geq \theta^{+} \\ 0 & if\ -\theta^{-} < \pi_{it}^{*} < \theta^{+} \\ \pi_{it}^{*} + \theta^{-} & if\ \pi_{it}^{*} \leq -\theta^{-} \end{cases} \tag{1}$$

where π_{it}^{*} represents the latent inflation rate, which is characterized in detail later, and $\theta^{-}, \theta^{+} > 0$ are parameters to determine threshold values for price changes. Here, we assume that the threshold values differ depending on directions of price changes: the first line in Equation (1) represents the friction for price increases, whereas the third line represents the friction for price decreases. Figure 6 describes the shape of Equation (1). The figure implies that if the latent inflation rate π_{it}^{*} lies between $-\theta^{-}$ and θ^{+}, we will observe a 0% inflation rate. Also, the figure indicates that when the latent inflation rate π_{it}^{*} is outside of the interval $[-\theta^{-}, \theta^{+}]$, the actual inflation π_{it} does not jump to the latent inflation π_{it}^{*} but gradually changes in proportion to π_{it}^{*}. This gradual change is supposed to capture the feature that the firm tries to avoid drastic price changes by considering the possibility of taking back the price change in future. If the estimated distance of interval $[-\theta^{-}, \theta^{+}]$ is significantly different from zero in this specification, i.e., sign restrictions for these variables are valid, it is implied that there exists price rigidity in the vicinity of 0%. In other words, the menu-cost hypothesis is likely to be relevant in

[12] This estimation model is also called "friction model." See Rosett (1959) in detail.

firms' price-setting behaviors.

The issue in empirical estimation of the model is how to specify the latent inflation rate, π^*_{it}. This is because the latent inflation rate is the unobservable variable that is determined to reflect various factors such as demand and supply shocks. In this paper, we specify this unobservable variable based on the ideas of Boivin *et al*. (2010) and Honoré *et al*. (2012). These studies show that price fluctuations of individual items are mainly driven by sectoral inflations; hence, we use them as a proxy for the change in the latent inflation rate. Specifically, we assume that the latent inflation rate depends on both sectoral inflation trend and sector-specific deviations from its trend.[13] Following Honoré *et al*. (2012), the empirical specification reads

$$\pi^*_{it} = \beta_1 \bar{\pi}_{jt} + \beta_2 \hat{\pi}_{jt} + \varepsilon_{it}\ , \tag{2}$$

where $\bar{\pi}_{jt}$ denotes sectoral inflation trend, $\hat{\pi}_{jt}$ denotes sector-specific shocks in sector j that an individual item i belongs to, and ε_{it} denotes an idiosyncratic error following IIN(0, σ^2) process. Each sector is classified as one of the following five sectors based on classification provided by the Statistic Bureau: durable goods, semi-durable goods, non-durable goods, public services, and private services.

To specify sectoral inflation trend $\bar{\pi}_{jt}$ and sector-specific shocks $\hat{\pi}_{jt}$, we estimated the following model. Let π_{jt} denote the actual inflation rate in sector j, $\mathbf{C}_t$ denotes a vector of common macroeconomic shocks, and $\boldsymbol{\lambda}_j$ denotes the estimates of the corresponding factor loadings for each variable. We assume that each actual inflation rate π_{jt} can be decomposed into a sectoral inflation average $\bar{\pi}_j$, common component on each sector $\boldsymbol{\lambda}_j \mathbf{C}_t$, and an idiosyncratic component (e_{jt}):

$$\pi_{jt} = \underbrace{\bar{\pi}_j + \boldsymbol{\lambda}_j \mathbf{C}_t}_{\bar{\pi}_{jt}} + \underbrace{e_{jt}}_{\hat{\pi}_{jt}} \tag{3}$$

To identify the vector of common macroeconomic shocks $\mathbf{C}_t$, we use a principal component approach. We construct large macroeconomic dataset including input price, production, and consumption of goods or services and extract four principal component

[13] Boivin *et al*. (2010) showed that the sector-specific shocks account on average for 85 percent of monthly fluctuations in disaggregated prices.

factors from the dataset. See Table 1 for the detail of series including the dataset. Estimating Equation (3) enables us to obtain $\bar{\pi}_j$, $\boldsymbol{\lambda}_j\mathbf{C}_t$, and e_{jt}. Then, we substitute $\bar{\pi}_{jt} = \bar{\pi}_j + \boldsymbol{\lambda}_j\mathbf{C}_t$ and $\hat{\pi}_{jt} = e_{jt}$ for Equation (2). Finally, we estimate a limited dependent variable model with two-sided thresholds. Specifically, we estimate Equations (1) and (2) simultaneously by the maximum likelihood method to obtain the latent inflation rates.[14]

3.2 Estimation Results

We estimate the model using data from February 1988 to December 2015. In the estimation, we take a weighted maximum likelihood approach by using the CPI weight using 2010 as a baseline. In addition, we control for consumption tax changes in the estimation.[15] We exclude the price data which changes over $\pm$50% as outliers.

Table 2 reports that the estimates of θ^- and θ^+ are significantly different from zero in both goods and services sectors, which implies that the interval $[-\theta^-, \theta^+]$ is significantly positive. Moreover, a value of θ^- is estimated to be higher in the services sector than in the goods sector. In other words, there exists higher menu cost in services sector and particularly in the case of negative price changes. This means that firms in services sector tend to refrain from decreasing their prices even under the deflationary pressure. This contrasts with firms in goods sector, which are likely to decrease their prices in a relatively smooth way.

3.3 Robustness Check

In our empirical framework, the degree of aggregation could bias the estimates of parameters regarding the menu-cost structure. A highly aggregated price index tends to be more flexible than a less aggregated one if the price-change probability of disaggregated prices is identical in both cases. In CPI, the degree of aggregation differs among price indices of individual items. In general, the degree of aggregation of price

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[14] The simulated maximum likelihood method is used for the estimation, following Train (2003), Sekine and Tachibana (2004).

[15] During the estimation period in Japan, consumption tax was raised three times (1989 FY: 0→3%, 1997 FY: 3→5%, 2014 FY: 5→8%). To control for these tax rate increases in the estimation for dutiable goods, we add an explanatory variable which takes the values of consumption tax hike in each fiscal year.

indices in the services sector tends to be lower than that in the goods sector because the number of samples in the services sector is generally smaller than that in the goods sector due to difficulty in data collection. Therefore, the result of the previous section that the services sector bears a higher menu cost than the goods sector could be biased by the lower degree of aggregation in the services sector.

As a robustness check, we carry out the same estimation procedure for the Retail Price Survey (RPS) instead of the CPI data. RPS, which is conducted by the Statistics Bureau, is used as basic data for calculating CPI. In this sense, RPS is more disaggregated price data than CPI, although a certain number of items, such as a car and a mobile phone, are not covered by RPS. Furthermore, it is worth noting that RPS is not perfectly disaggregated data; the price series of RPS is released as an average of prices collected in each city. The number of collected prices is different among cities and ranges from 1 to 42 according to city size. To avoid the influence of aggregation issues, we restrict our dataset to RPS data series that consist of only 1 price data.

Figure 7 displays the price-change distribution based on RPS. In goods and services sectors, the proportion of 0% inflation is higher in RPS than in CPI (Figure 3). This implies that the aggregation process might affect the observed price rigidity in both sectors. In Table 3, however, the estimation result shows that the distance of interval $[-\theta^{-}, \theta^{+}]$ is significantly positive in both sectors, implying that price rigidities in the vicinity of 0% exist. In addition, the estimate θ^{-} is higher in the services sector than in the goods sector. These results are consistent with those obtained by the estimation based on the CPI data, as shown in the previous subsection. On the whole, this robustness check confirms the menu-cost hypothesis based on more disaggregated price data. Furthermore, both θ^{-} and θ^{+} are higher than those based on the CPI data. This result implies that the data aggregation tend to make it difficult to observe price rigidity, compared with the case of disaggregated price data.

4. Multisector Menu-Cost Model

In this section, we investigate the macroeconomic implications of each firm's price-setting behavior by constructing a multisector menu-cost model. In particular, we focus on the relationship of flattening of the Phillips curve with a decline in trend inflation and with a rise in the share of services in Japan. We examine whether such a relationship can be explained consistently with the microeconomic price-setting behavior described in the previous sections.

The model in this section is a multisector version of a general equilibrium menu-cost model with heterogeneous firms, such as the one given in Midrigan (2011). One sector with a lower menu cost corresponds to a goods sector, while the other sector with higher menu cost corresponds to the services sector.

The private sector of the economy consists of a representative household, consumption-good firms, and intermediate-good firms. The intermediate-good firms in each sector are heterogeneous with respect to their productivity and maximize their profits by choosing their prices under both a state-dependent and time-dependent nominal friction. The central bank conducts monetary policy using the nominal interest rate as a policy tool. Each agent's behavior is described in turn.

4.1 Household

The representative household supplies a labor force to obtain wage income, $W_t L_t$, where W_t denotes the nominal wage and L_t denotes hours worked. In addition, because the household owns all firms in the economy as a stockholder, it also obtains a nominal dividend, D_t, as another source of income. The household allocates its income to a consumption basket, C_t, and savings as a form of nominal one-period bond, B_t. The household faces the budget constraint

$$P_t C_t + B_t = R_{t-1} B_{t-1} + W_t L_t + P_t D_t \tag{4}$$

where P_t is the price level and R_t is the gross nominal interest rate. The consumption basket consists of goods, denoted by g, and services, denoted by s, with the weight χ,

$$C_t = \left(\chi C_{g,t}^{\frac{\eta-1}{\eta}} + (1-\chi) C_{s,t}^{\frac{\eta-1}{\eta}} \right)^{\frac{\eta}{\eta-1}},$$

where η is a parameter for elasticity between goods and services. The price level of the consumption basket P_t is defined by $P_t C_t = P_{g,t} C_{g,t} + P_{s,t} C_{s,t}$ as usual. Given those conditions, the household maximizes its expected lifetime utility by choosing consumption and labor supplies

$$\max_{C_{g,t},C_{s,t},C_t,L_t} E_0 \sum_{t=0}^{\infty} \frac{\beta^t}{A_t}[\log C_t - \omega L_t],$$

subject to the budget constraint (4). $\beta \in (0,1)$ is a constant discount factor, A_t is a shock to the discount factor, and ω is the disutility of labor.

The optimal allocation between goods and services gives the price indicator

$$P_t = \left[\chi P_{g,t}^{1-\eta} + (1-\chi)P_{s,t}^{1-\eta}\right]^{\frac{1}{1-\eta}}, \tag{5}$$

as well as the demand function for consumption in each sector

$$C_{g,t} = q_{g,t}^{-\eta} C_t \text{ and } C_{s,t} = q_{s,t}^{-\eta} C_t, \tag{6}$$

where $q_{j,t} \equiv P_{j,t} / P_t$ is a relative price in sector $j \in \{g, s\}$. Also, the first order conditions for $C_t, B_t,$ and L_t give the Euler equation

$$1 = E_t\left[\frac{R_t}{\pi_{t+1}} \frac{\beta C_t}{a_{t+1} C_{t+1}}\right], \tag{7}$$

where $\pi_{t+1} = P_{t+1} / P_t$ and $a_{t+1} = A_{t+1} / A_t$, as well as the labor supply function

$$\frac{w_t}{C_t} = \omega, \tag{8}$$

where $w_t = W_t / P_t$ is a real wage rate. Finally, the stochastic discount factor is defined as

$$Q_{t+1}(C_t, C_{t+1}, a_{t+1}) \equiv \frac{\beta C_t}{a_{t+1} C_{t+1}}. \tag{9}$$

As is shown later, firms maximize the sequence of profits discounted by this stochastic discount factor.

4.2 Central Bank

The central bank sets the nominal interest rate according to a type of Taylor rule responding only to inflation rates,

$$R_t = R_{ss}\left(\frac{\pi_t}{\pi^*}\right)^{\phi_\pi}, \tag{10}$$

where π^* is the target inflation rate, which is identical to trend inflation in steady state, and $R_{ss} = \pi^* / \beta$ is the nominal interest rate at the steady state. We assume $\phi_\pi > 1$ so that the Taylor principle holds.

4.3 Firm

The consumption-good firm in sector $j \in \{g, s\}$ produces the final good, $Y_{j,t}$, using the intermediate goods, $y_{i,j,t}$, produced by firm i in sector j using the following CES aggregator, $Y_{j,t} = \left(\int_0^1 y_{i,j,t}{}^{\frac{\theta-1}{\theta}} di\right)^{\frac{1}{\theta-1}}$, where $\theta > 1$ is the elasticity of substitution. Let $p_{i,j,t}$ be the price of each intermediate good. The price index, $P_{j,t}$, is then defined as

$$P_{j,t} = \left(\int_0^1 p_{i,j,t}{}^{1-\theta} di\right)^{\frac{1}{1-\theta}}, \tag{11}$$

and the demand for each intermediate good is derived as a result of profit maximization of the representative consumption-good firm,

$$y_{i,j,t} = q_{i,j,t}^{-\theta} Y_{j,t}, \tag{12}$$

where $q_{i,j,t} \equiv p_{i,j,t} / P_{j,t}$ is a relative price of the differentiated goods produced by firm i.

A continuum of intermediate-good firms produces differentiated intermediate goods using labor, $l_{i,j,t}$, according to the following linear technology,

$$y_{i,j,t} = z_{i,j,t} l_{i,j,t}, \tag{13}$$

where $z_{i,j,t}$ is an idiosyncratic productivity for firm i in sector j at period t. The profit for firm i in sector j before subtracting the menu cost, $\varphi(q_{i,j,t}, z_{i,j,t};\ Y_{j,t})$, is

$$\begin{aligned}\varphi(q_{i,j,t}, z_{i,j,t};\ Y_{j,t}) &= \frac{p_{i,j,t}}{P_{j,t}} y_{i,j,t} - w_t l_{i,j,t} \\ &= \left(q_{i,j,t} - \frac{\omega Y_t}{z_{i,j,t}}\right) q_{i,j,t}^{-\theta} Y_{j,t}.\end{aligned} \tag{14}$$

The last equation comes from (8), (12), (13), and the market clearing condition $Y_t = C_t$. Under monopolistic competition, the intermediate-good firm i in sector j sets the price of its differentiated products and maximizes the sequence of profits, $\varphi(q_{i,j,t}, z_{i,j,t};\ Y_{j,t})$, discounted by the stochastic discount factor, $Q_{t+1}(Y_t, Y_{t+1}, a_{t+1})$, subject to the sequence of aggregate state variables, $Y_t, Y_{g,t}, Y_{s,t}, \pi_t, P_{g,t}, P_{s,t}$, and a_t.

4.4 Characterization of Equilibrium

First, the stochastic processes for structural shocks are specified. In this model, we assume one aggregate shock, a_t, and one idiosyncratic shock, $z_{i,t}$. The growth rate of discount rate shock is assumed to follow the AR(1) process,

$$\log a_t = \rho_a \log a_{t-1} + \varepsilon_{a,t}, \tag{15}$$

where $\varepsilon_{a,t}$ follows $N(0, \sigma_a)$. The idiosyncratic productivity shock for firm i in sector j is also assumed to follow the AR(1) process, but the shock to the idiosyncratic productivity arrives only with probability μ,

$$z_{i,j,t} = \begin{cases} z_{i,j,t-1}^{\rho_z} \exp\left(\varepsilon_{z_{i,j},t}\right) & \textit{with prob. } \mu \\ z_{i,j,t-1} & \textit{with prob. } 1-\mu, \end{cases} \tag{16}$$

where $\varepsilon_{z_{i,j},t}$ follows $N\left(0, \sigma_{j,z}\right)$. The assumption of infrequent shocks is incorporated to account for the fat-tailed distribution of price changes observed in data.[16] Note also that the volatility of idiosyncratic productivity shocks $\sigma_{j,z}$ could be different in each sector. In a quantitative analysis, we discretize the state space for $z_{i,j,t}$ and a_t, and approximate the AR(1) process by a first order Markov process with different value of volatility by sector.

In order to solve the model, we need to calculate aggregate state variables by aggregating each firm-specific variable. Computing aggregate state variables is, however, not trivial in this model because of heterogeneity in firm's productivity. Therefore, we make some assumptions to make the model computationally tractable. First, we assume that the elasticity between goods and services is equal to that between intermediate goods in each sector, i.e., $\eta = \theta$. Under this assumption, the demand functions (6) and (12) imply

$$y_{i,j,t} = q_{i,t}^{-\theta} Y_t, \tag{17}$$

[16] While this assumption improves the model fit, it does not affect main results in this paper including the skewness of price change distribution.

where $q_{i,t} \equiv p_{i,j,t} / P_t$. Since the demand for intermediate-good firm i is now a function of the aggregate demand and the relative price to the aggregate price, Y_t and $q_{i,t}$, the demand and the relative price in each sector, $Y_{j,t}$ and $q_{j,t}$, are not relevant for each firm's optimization and consequently can be dropped from the aggregate state variables. Second, according to Krusell and Smith (1998) and its application to a menu-cost model such as Midrigan (2011) and Vavra (2014), the law of motion for a key macroeconomic state variable is approximated by a linear function. In particular, we assume that the aggregate demand follows the AR(1) process with variable constant terms with respect to a_t and a_{t+1} after log-transformation,

$$\log Y_{t+1} = \beta_{0,a_t} + \beta_{1,a_{t+1}} + \beta_2 \log Y_t, \tag{18}$$

where β_{0,a_t}, $\beta_{1,a_{t+1}}$, and β_2 are constant terms (i.e., fixed effects) corresponding to each grid of a_t and a_{t+1}.

Given the law of motion for Y_t approximated by (18), the inflation rate π_t can be expressed as a function of Y_t and a_t. By plugging nominal interest rates by the Taylor rule (10) into the Euler equation (7), we have the following forward equation for inflation,

$$\pi_t = \pi^* E_t \left[\left(\frac{Y_{t+1}}{Y_t} a_{t+1} \right)^{\frac{1}{\phi_\pi}} \times \left(\frac{Y_{t+2}}{Y_{t+1}} a_{t+2} \right)^{\frac{1}{\phi_\pi^2}} \times \left(\frac{Y_{t+3}}{Y_{t+2}} a_{t+3} \right)^{\frac{1}{\phi_\pi^3}} \times \left(\frac{Y_{t+4}}{Y_{t+3}} a_{t+4} \right)^{\frac{1}{\phi_\pi^4}} \times \cdots \right].$$

Since we assume that a_{t+1} follows the AR(1) process and that Y_{t+1} is a function of Y_t, a_t, and a_{t+1} as described in (18), the right hand side of the equation can be computed one by one. Furthermore, as long as $\phi_\pi > 1$, each term in the right hand side converges to zero. In a quantitative analysis, we stop the calculation at twenty terms,

$$\pi_t \approx \pi^* E_t \left[\prod_{k=1}^{20} \left(\frac{Y_{t+k}}{Y_{t+k-1}} a_{t+k} \right)^{\left(\frac{1}{\phi_\pi}\right)^k} \right], \tag{19}$$

because the value of inflation does not change significantly even if the number of terms for calculation is increased to more than twenty.

When the intermediate-good firm chooses its relative prices, $q_{i,t}$, it is faced with the following state-dependent and time-dependent nominal frictions. First, the firm obtains the opportunity for price changes with probability $\xi \in [0, 1]$ in every period, exactly as in the Calvo model. Second, upon obtaining the opportunity for price changes, the firm faces the menu cost γ_j with probability $\nu \in [0,1]$. Therefore, while the firm faces zero menu cost and must change its prices with probability $1-\nu$, the firm faces a positive menu cost and solves the discrete choice problem between changing its prices and not changing them with probability ν. This assumption of zero menu cost with a small probability is incorporated to account for the small price changes observed in data and is used in other studies including Vavra (2014). In the discrete choice problem for price setting, we assume that each firm stochastically makes their decisions. That is, the fraction of firms who change prices is denoted by $\Gamma(\cdot) \in [0,1]$ and expressed as a function of state variables as in a generalized Ss-model in Caballero and Engel (2007).

Finally, each firm's optimization problem is characterized recursively. The value function for the intermediate-good firm i in sector j, which is denoted by $V_j(q_i, z_{i,j}; Y, a)$, has two individual state variables, q_i and $z_{i,j}$, as well as two aggregate state variables, Y and a, and consists of three value functions. Given the constraints (9), (14), (15), (16), (18), and (19), the optimization problem for each intermediate-good firm i in sector j is formulated by the value function,

$$V_j(q_i', z_{i,j}; Y, a) = E_{a'} Q(Y, Y', a') E_{z_{i,j}'} \left\{ \begin{array}{l} \xi\left[\nu V_j^C(q_i', z_{i,j}'; Y', a') + (1-\nu) V_j^A(z_{i,j}'; Y', a')\right] \\ +(1-\xi) V_j^N(q_i', z_{i,j}'; Y', a') \end{array} \right\}$$

where V_j^C, V_j^A, and V_j^N are the value function for the discrete choice problem, the value function for changing prices and the value function for not changing prices, respectively. Also, $Q(\cdot,\cdot,\cdot)$ is a stochastic discount factor defined in (9). The value function for the discrete choice problem, $V_j^C(q_i, z_{i,j}; Y, a)$, is formulated as

$$\begin{aligned} V_j^C(q_i, z_{i,j}; Y, a) &= \Gamma(q_i, z_{i,j}; Y, a) \times \left[V_j^A(z_{i,j}; Y, a) - \gamma_j\right] \\ &\quad + \left(1 - \Gamma(q_i, z_{i,j}; Y, a)\right) \times V_j^N(q_i, z_{i,j}; Y, a). \end{aligned}$$

Note that the firms have to pay the menu cost γ_j when they change prices and obtain V_j^A. The fraction of firms who change prices, $\Gamma(q_i, z_{i,j}; Y, a)$, is defined as

$$\Gamma(q_i, z_{i,j}; Y, a) = G\left(\left[V_j^A(z_{i,j}; Y, a) - \gamma_j\right] - V_j^N(q_i, z_{i,j}; Y, a), k_{1,j}, k_{2,j}\right),$$

where $G(\cdot, k_{1,j}, k_{2,j})$ is a cumulative distribution function of a Gamma distribution with parameter $k_{1,j}$ and $k_{2,j}$. Since $G(\cdot, k_{1,j}, k_{2,j})$ is an increasing function in $[0, 1]$, the above definition of $\Gamma(\cdot)$ implies that the fraction of firms who change prices approaches one (zero) as the net benefit of changing prices increases (decreases). Finally, the value function for changing prices, $V_j^A(z_{i,j}; Y, a)$, and that for not changing prices, $V_j^N(q_i, z_{i,j}; Y, a)$, are formulated as

$$V_j^A(z_{i,j}; Y, a) = \max_{q_i'}[\varphi(q_i', z_{i,j}; Y) + V_j(q_i', z_{i,j}; Y, a)],$$

and

$$V_j^N(q_i, z_{i,j}; Y, a) = \varphi\left(\frac{q_i}{\pi}, z_{i,j}; Y\right) + V_j\left(\frac{q_i}{\pi}, z_{i,j}; Y, a\right).$$

Those two value functions show that when the firm i changes prices, it can choose an optimal level of relative price q_i', and the current profit and future value are computed based on the optimal q_i'. When the firm i does not change prices, the relative price for the firm's products is deflated by inflation rate $\pi(= \pi_t)$, and the current profit and future value are evaluated based on the deflated relative price, q_i / π. By solving the optimization problem for each sector j, we have the following two policy functions: the optimal choice of relative prices if the firm changes the price, $q_j^*(q_i, z_{i,j}; Y, a)$ and the optimal probability to change the price, $\Gamma_j^*(q_i, z_{i,j}; Y, a)$.

The procedure to compute a recursive competitive equilibrium is as follows. First, given an initial guess for the coefficients β_{0,a_t}, $\beta_{1,a_{t+1}}$, and β_2 in the conjectured law of motion (18), we solve the optimization problem for firm i, which is recursively formulated by value functions. Once the optimal policy function for price setting q_i is obtained, we construct a simulated path of aggregate demand Y_t under the artificially generated sequence of a_t and the optimal policy function of q_i. In order to construct the simulated path of aggregate demand, we search for Y_t that satisfies the consistency of aggregate price (i.e., the market clearing condition),

$$\chi \sum_{z_i} \sum_{q_i} q_g^*(q_i, z_i; Y_t, a_t)^{1-\theta} \Upsilon_{g,t}(q_i, z_i)$$
$$+ (1-\chi) \sum_{z_i} \sum_{q_i} q_s^*(q_i, z_i; Y_t, a_t)^{1-\theta} \Upsilon_{s,t}(q_i, z_i) = 1,$$

in each period of time. Here, $Y_{j,t}(q_i, z_i)$ is the mass of firms in sector j for each individual state, (q_i, z_i). Note that the mass of firms for each state changes in every period depending on macroeconomic conditions. Upon constructing the simulated path of Y_t, we estimate the law of motion (18) by ordinary least squares regression using the simulated path. We then update $\beta_{0,a_t}, \beta_{1,a_{t+1}}$, and β_2 if needed, and repeat the procedure until the law of motion (18) is converged upon.

5. Quantitative Analysis

In this section, we conduct a quantitative analysis to investigate the macroeconomic implications of each firm's price-setting behavior using the multisector menu-cost model described in the previous section. In particular, we focus on the relationship between a flattening of the Phillips curve and macroeconomic changes such as a decline in trend inflation or a rise in the share of services in Japan. We then examine whether such relationships can be explained consistently with the microeconomic price-setting behavior described in Section 2. In the quantitative analysis, we first calibrate parameters so that the price-change distribution in the model is consistent with that in Japanese data for both goods and services sectors and simulate dynamics of aggregate inflation and output. Then we estimate a Phillips curve based on those simulated variables to investigate the relationship between the slope of the Phillips curve and the trend inflation, or the share of services, through comparative statics.

5.1 Calibration and Distribution of Price Changes

First, we calibrate some parameters at a standard value. Table 4 summarizes our parameter values. One period in the model corresponds to a quarter, so the discount rate is set to $\beta = 0.98^{\frac{1}{4}}$. The elasticity of substitution between goods, θ, and the responsiveness of nominal interest rates to inflation, ϕ_π, are set to 6.0 and 1.5, both of which are conventional values. The disutility of labor supply, ω, is set to one just as a normalization.

Then, some of parameters are chosen so that macro moments are consistent with Japanese data. As described in the previous section, we have the simulated path of Y_t and a_t computed by the model. Thus, the AR(1) parameter and the standard deviation of the discount rate shock, ρ_a and σ_a, are chosen so that the autocorrelation and the standard deviation of simulated path of Y_t are consistent with those of the Hodrick-Prescott-filtered output in Japan. Furthermore, since we can compute the simulated path of inflation, π_t, by (19) using the simulated path of Y_t and a_t, the slope of the Phillips curve in the model can be obtained by regressing the simulated path of π_t on that of Y_t. While the slope of the Phillips curve is influenced by many parameter values, one of key determinants is the probability to get chances for price changes, ξ. Therefore, we choose the value of $\xi = 0.6$ so that the slopes of the Phillips curve under $\pi_* = 1.005$ and $\chi = 0.5$ are consistent with Japanese data in the high-inflation period.

Finally, we calibrate the rest of parameters so that the distributions of price changes in the model are consistent with that in Japanese data. First, the AR(1) parameter of idiosyncratic productivity shocks, $\rho_z = 0.6$, the standard deviation of idiosyncratic productivity shocks in a goods sector, $\sigma_{g,z} = 0.1$, and the probability for a positive menu cost, $\nu = 0.91$, are set to conventional values in the previous literature, including Vavra (2014). Then, given those conventional values, we choose other parameters by matching the moments of the distribution of price changes. Regrettably, we have just the category-level data for price changes rather than the product-level data. Therefore, we compute the distribution of price changes for each category of products. When computing the category-level distribution, we assume that the probability to get chances for price changes, ξ, is decomposed into the category-level friction, ξ_k, and the product-level friction, ξ_i. That is, we assume

$$\xi_k = \xi^{\iota} \text{ and } \xi_i = \xi^{1-\iota},$$

where $\iota \in [0, 1]$. Note that each firm has chances for price changes with probability ξ because $\xi_k \times \xi_i = \xi$. See Appendix for more details about how to compute the category-based distribution of price changes.

With the category-level distribution of price changes in each sector j (j-distribution, hereafter), we calibrate seven parameters $(\mu, \iota, \sigma_{s,z}, \kappa_{g,1}, \kappa_{g,2}, \kappa_{s,1}, \kappa_{s,2})$. While each moment of the j-distribution is not determined by a single parameter but depends on a composite of parameters, the rough mapping between the parameter value and the target moment is as follows: First, the probability for the arrival of idiosyncratic productivity shock, μ, is chosen by using the interquartile range of the g-distribution as a target, because a small μ leads to a dispersed distribution and vice versa. Then, the standard deviation of idiosyncratic productivity shocks for the services sector, $\sigma_{s,z}$, is chosen by using the interquartile range of the s-distribution as a target. We choose the weight between the category-level friction and the product-level friction as $\iota = 0.7$, so that the mass of firms at $\tilde{\pi}_i = 1$ (i.e., the mass of 0%-inflation firms) in the s-distribution is consistent with data. Finally, we choose the parameter for Gamma distribution of the menu cost $(\kappa_{g,1}, \kappa_{g,2}, \kappa_{s,1}, \kappa_{s,2})$. Considering the shape of Gamma distribution, we first set κ_2 to an arbitrary small number $(\kappa_{g,2} = \kappa_{s,2} = 0.03)$ and then choose $\kappa_{g,1} = 17$ by using the mass of firms at $\tilde{\pi}_i = 1$ in the g-distribution as a target. Then, we choose $\kappa_{s,1} = 8$ to be consistent with the change in the mass of firms at $\tilde{\pi}_i = 1$ in the s-distribution when the trend inflation π^* is changed from 2% to 0%. The change in the mass of 0%-inflation firms is closely related to the value of menu cost because the number of firms in the inaction area is basically determined by the menu cost.

5.2 Simulated Price-Change Distributions

Figure 8 shows simulated price-change distributions in goods and services sectors under 2% or 0% trend inflation. The figure indicates that while some moments for the distribution are used as the calibration targets, the distributions computed by the model can replicate the changes in the distribution in both sectors along with the decline in trend inflation in Japan. In the goods sector, as the trend inflation changes from 2% to 0%, the price-change distribution slides slightly leftward while keeping the weight in the vicinity of 0% unchanged, reflecting a low menu cost in the goods sector. In the services sector, the price-change distribution has more weight in the vicinity of 0% and its dispersion is narrower under 0% trend inflation than under 2% trend inflation, reflecting a high menu cost in the services sector.

Furthermore, consistent with the data, while the distribution in the services sector is highly skewed under 2% trend inflation, it is not skewed under 0% trend inflation. Under positive trend inflation, firms expect their relative price to continuously become lower. Hence, given the fact that it is costly to frequently change prices under a high menu cost, firms in the services sector lose incentive to cut prices under positive trend inflation because they know that their prices will eventually have to increase at some point in the future. Such a difference in the shape of the distribution under 0% and 2% trend inflation implies that examining price-change distributions provides fruitful information regarding a shift in trend inflation.

5.3 Slope of the Phillips Curves

Before discussing whether the multisector menu-cost model can replicate the observed flattening of the Phillips curve in both goods and services sectors, we first investigate via comparative statics the influence of declining trend inflation as well as an increasing share of services in total output on the slope of the Phillips curve. Figure 9 displays the simulated slope of the Phillips curve under the low, middle, and high trend inflation (i.e., 0%, 2%, and 4%) by sector, where the horizontal axis represents the ratio of services sector output to total output (i.e., 0–100%). On one hand, Figure 9 (3) shows that the Phillips curve in the services sector flattens as trend inflation shifts downward. On the other hand, Figure 9 (2) indicates that the Phillips curve in the goods sector also flattens significantly, even though the goods sector bears a much lower menu cost in the model. These results are consistent with the observed slope of the Phillips curve in the goods sector. On the influence of increasing the ratio of services sector output to total output, Figure 9 (2) and (3) show that the rise in share of services makes the Phillips curve flatter in both goods and services sectors.

Two points are worth noting about the mechanism behind these observations. First, declining trend inflation makes the services sector reduce the incentives of price changes due to the existence of the menu cost, leading to an increase in nominal price rigidity in the services sector. Second, firms in the goods sector set their prices while considering the relative price of services. Therefore, an increase in price rigidity in the services sector is likely to reduce the necessity of price changes in the goods sector, too. In this sense, price rigidity propagates from one sector to others through a relative price effect. The mechanism is consistent with the observation that under the 0% share of services, slopes of the Phillips curve on all items (Figure 9 (1)) are almost the same as those in the goods sector (Figure 9 (2)). These findings imply the importance of examining price-setting behaviors in the services sector as well as the goods sector to draw macroeconomic implications because price rigidity in one sector may have a significant effect on the whole economy.

Finally, we compare the simulated and observed slopes of the Phillips curve, taking into account the changes in both trend inflation and the share of services. Figure 10 provides a view of the development of the share of services in consumption. It shows that the share of services has increased by about 5–10% from the high-inflation period of 1982–1994 CY to the low-inflation period of 1995–2012 CY. Average inflation has also declined from 2% to 0% during the same period. The simulation based on our menu-cost model implies that both changes in trend inflation and share of services decrease the slope of the Phillips curve by approximately 0.15%, which coincides with the observed flattening of the Philips curve, as shown in Figure 4. These findings imply that, through the lens of the menu-cost model, the flattening of the Phillips curve observed in Japan can be explained by the decline in trend inflation as well as the rise in share of services. Therefore, if the Japanese economy returns to positive trend inflation, then the Phillips curve also would become steeper again. Or, if Japan experiences rises in the proportion of the share of services in the future, then the Phillips curve would flatten more.

6. Concluding Remarks

Studying Japan's experience during chronic deflation could be useful in drawing insight about the relationship between price rigidities and trend inflation. In this paper, we carried out both empirical and theoretical investigations by employing the menu-cost hypothesis. First, we tested plausibility of the menu-cost hypothesis by estimating the limited dependent variable model with two-sided thresholds after controlling for the other factors such as demand and supply shocks. As a result, we showed higher menu cost in the services sector than in the goods sector empirically. Second, we constructed a multisector menu-cost model in line with the empirical findings and showed that the model could replicate the shift in the price-change distributions and changes in the slope of the Phillips curve in both goods and services sectors. These findings verified that the menu-cost hypothesis could consistently explain the series of change in firms' price-setting behaviors and macroeconomic consequences on the slope of the Phillips curve during the deflationary period in Japan.

There are some possible research topics for future studies. First, a theoretical investigation on why the services sector faces higher menu costs is an important work to complement the analysis in this paper. While this paper empirically validates higher menu cost in the services sector and takes it as given to investigate a macroeconomic implication, it is worth investigating which feature in the services sector businesses entails such a high menu cost. Second, while this paper focuses only on Japan's experience, extending this analysis to other countries could be an interesting additional study. In particular, an increase in the share of services is commonly observed in other countries too. These can be interesting research topics, but we have left them to be explored in the future.

Appendix

In Appendix, we explain how to compute the distribution of price changes for each category of products. First, the optimal price change for firm i in sector j for the average level of macroeconomic condition is calculated by

$$\bar{\pi}_{j,t}(q_i, z_i) \equiv \frac{q_j^*(q_i, z_i; \bar{Y}, \bar{a})}{q_i} \pi(\bar{Y}, \bar{a}),$$

where $\bar{Y}$ and $\bar{a}$ are defined as $\bar{Y} = 1/T \sum_{t=1}^{T} Y_t$ and $\bar{a} = 1/T \sum_{t=1}^{T} a_t$ using the simulated path $\{Y_t, a_t\}_{t=1,\dots,T}$. Note that $q_j^*(\cdot)$ is the optimal choice of a relative price if the firm changes the price. Then, we construct the product-level distribution of price changes in sector j by randomly sampling a value of price change $\{\tilde{\pi}_{i,j}\}_{i=1,..,N}$ with a large number of N_i according to,

$$\tilde{\pi}_{i,j} = \begin{cases} \bar{\pi}_{j,t}(q_i, z_i) \;\; \textit{with prob.} \;\; \xi_i\left[\nu \Gamma_j^*(q_i, z_i; \bar{Y}, \bar{a}) + (1-\nu)\right] \times \bar{\Upsilon}_j(q_i, z_i) \\ 1 \qquad \textit{with prob.} \;\; 1 - \sum_{z_i} \sum_{q_i} \xi_i\left[\nu \Gamma_j^*(q_i, z_i; \bar{Y}, \bar{a}) + (1-\nu)\right] \times \bar{\Upsilon}_j(q_i, z_i), \end{cases}$$

where $\bar{\Upsilon}_j(q_i, z_i) \equiv 1/T \sum_{t=1}^{T} \Upsilon_{j,t}(q_i, z_i)$ is the average mass of firms for the individual state (q_i, z_i) in sector j on the simulated path for the mass of firms, $\{\Upsilon_{j,t}(q_i, z_i)\}_{t=1,\dots,T}$. Finally, under the assumption that each category consists of M products, the price change for category k in sector j is defined as

$$\tilde{\pi}_{k,j} = \begin{cases} \frac{1}{M} \sum_{i=1}^{M} \tilde{\pi}_{i,j} \qquad \textit{with prob.} \;\; \xi_k \\ 1 \qquad \textit{with prob.} \;\; 1 - \xi_k \;\; , \end{cases}$$

where $\{\tilde{\pi}_{i,j}\}_{i=1,..,M}$ is a value of price change that is randomly sampled from the product-level distribution of price changes, which is specified above. In the quantitative analysis, we choose $M = 20$ according to the procedure in Japan. Using the sample of $\{\tilde{\pi}_{k,j}\}_{k=1,..,N_k}$ with a large number of N_k, we can construct the category-level distribution of price changes in sector j.

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Table 1. Series Description in the Dataset

Category	Statistics		Classification
Corporate Activity	Indices of Industrial Production	Productions	by goods
		Shipments	by goods
		Inventories	by goods
		Inventory Ratio	by goods
		Utilization Ratio	by industry
	Indices of Tertiary Industry Activity		by industry
	Machinery Orders Statistics	Total Value of Machinery Order	by sectors
	Statistics on Building Construction Starts	Floor Area	by use types
		Planned Amount of Construction Costs	by use types
		Number of Buildings	by use types
	Monthly Bankruptcy Report	Number of Bankruptcy	
	Electricity Demand	Electricity Demand	by sectors
Price	Corporate Goods Price Index	Producer Price Index	by groups
		Export Price Index	by groups
		Import Price Index	by groups
	Services Producer Price Index		by groups
	Nikkei Commodity Price Index		by goods
	Oil Price	Brent Crude Oil Price	
Labor Market	Labor Statistics	Scheduled Cash Earnings	by industry
		Total Hours Worked	by industry
		Non-scheduled Hours Worked	by industry
		Number of Regular Employee	by industry
	Labor Force Survey	Number of Employed Persons	
		Number of Unemployed Persons	
	Report on Employment Service	Number of Job Offers and Job Seekers	
	Employment Insurance Statistics	Insured Workers	
Household	New Car Registration	Number of sales	by vehicle classification
	Family Income and Expenditure Survey	Consumption expenditure	by items
	Current Survey of Commerce	Sales value	by industry
Government	Integrated Statistics on Construction Works	Amount of public construction completed	
Trade	Trade Statistics	Export Volume Index	by goods
		Import Volume Index	by goods
		Terms of Trade Index	
Money and Financial Market	Money Stock	M2	
	Foreign Exchange	Nominal Effective Exchange Rate	
		Real Effective Exchange Rate	
	Stock Prices	Tokyo Stock Price Index	by scales
	Interest Rate	Overnight Call Rate	

Table 2. Estimation Results of the Friction Model (Consumer Price Index)

	CPI (All items, less fresh food and imputed rent)		CPI (Goods, less fresh food)		CPI (Services, less imputed rent)	
θ^-	1.52	(0.01) ***	0.40	(0.01) ***	3.54	(0.01) ***
θ^+	1.36	(0.01) ***	1.34	(0.01) ***	1.33	(0.01) ***
β_1	0.92	(0.00) ***	0.95	(0.00) ***	0.89	(0.01) ***
β_2	0.72	(0.01) ***	1.10	(0.01) ***	0.15	(0.01) ***
Consumption tax rate	0.64	(0.01) ***	0.39	(0.01) ***	0.96	(0.01) ***
σ	6.48	(0.05) ***	6.12	(0.07) ***	6.80	(0.08) ***
Observations	140,241		103,348		36,893	

Note: The standard errors for estimates are presented in parenthesis.
*** denotes significance at the 1% level.

Table 3. Estimation Results of the Friction Model (Retail Price Survey)

	RPS (Goods, less fresh food)		RPS (Services, less imputed rent)	
θ^-	12.65	(0.07) ***	18.37	(0.09) ***
θ^+	16.48	(0.07) ***	15.99	(0.08) ***
β_1	2.47	(0.04) ***	2.88	(0.05) ***
β_2	0.65	(0.07) ***	2.40	(0.07) ***
Consumption tax rate	2.76	(0.11) ***	0.96	(0.12) ***
σ	20.44	(0.26) ***	15.26	(0.46) ***
Observations	201,216		107,648	

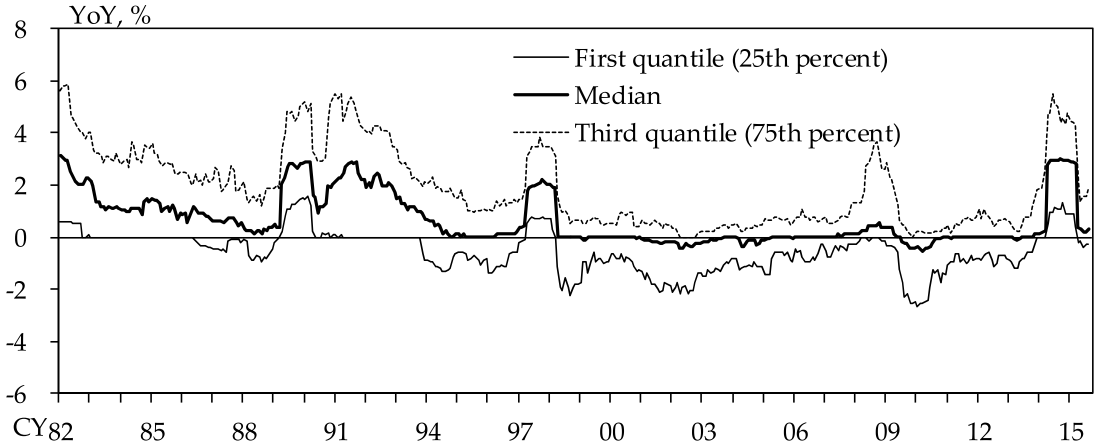
Note: The standard errors for estimates are presented in parenthesis.
*** denotes significance at the 1% level.

Table 4. Calibrated Values

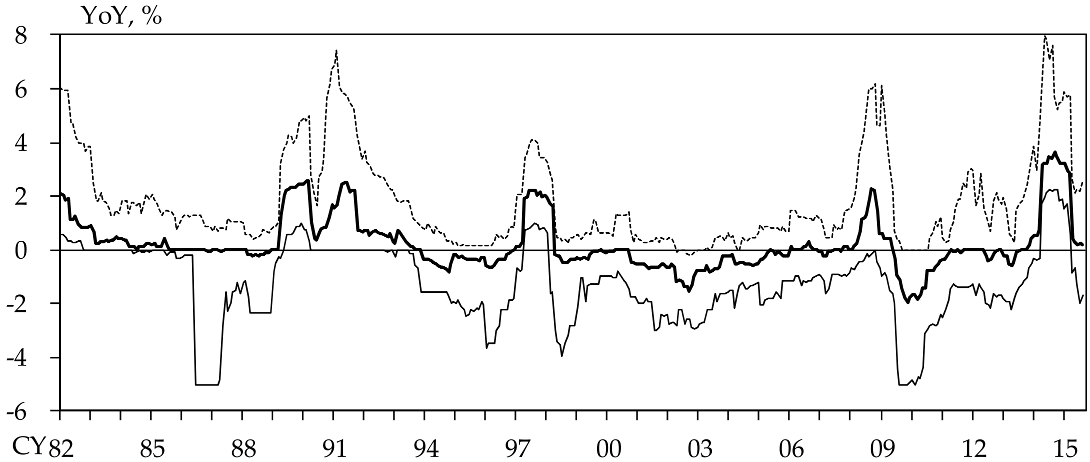
parameter	value
discount rate, β	$0.98^{\frac{1}{4}}$
elasticity of substitution, θ	6.0
responsiveness to inflation, ϕ_π	1.5
AR(1) parameter for z, ρ_z	0.6
standard deviation of z for goods, $\sigma_{g,z}$	0.1
standard deviation of z for services, $\sigma_{s,z}$	0.025
prob. for arrival of shock, μ	0.5
weight for nominal friction, ι	0.7
prob. for positive menu cost, ν	0.91
prob. for price changes, ξ	0.6
AR(1) parameter for a, ρ_a	0.75
standard deviation of a, σ_a	0.003
menu cost for goods, $(\kappa_{1,g}, \kappa_{2,g})$	(17, 0.03)
menu cost for services, $(\kappa_{1,s}, \kappa_{2,s})$	(8, 0.03)

Figure 1. Median and the First/Third Quantile Points of the Price-Change Distribution

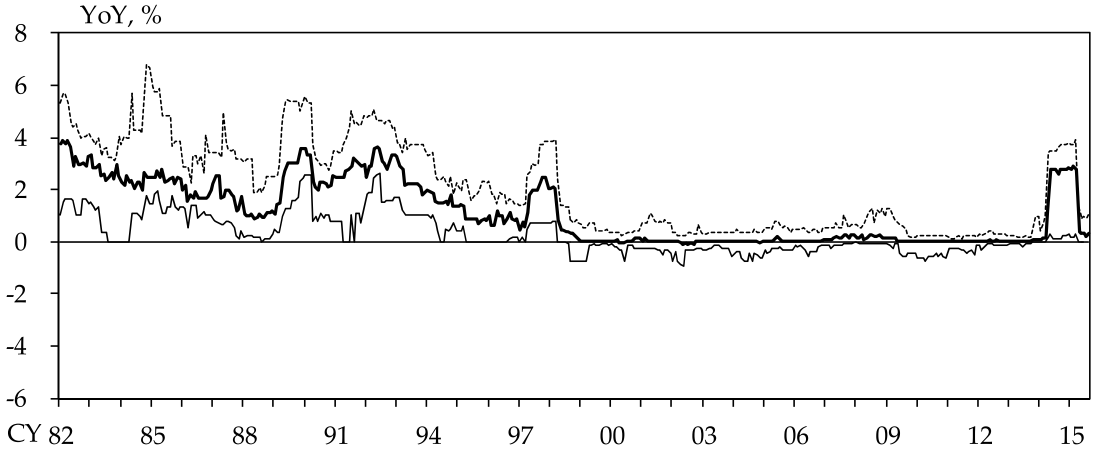
(1) CPI (All items, less fresh food and imputed rent)



(2) CPI (Goods, less fresh food)



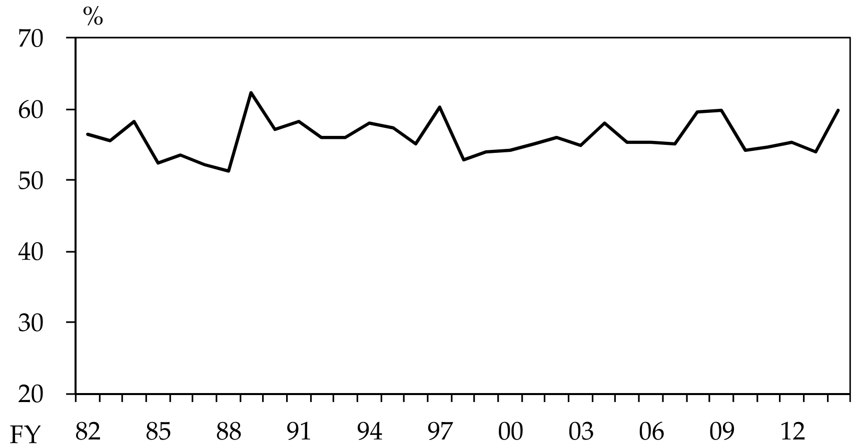
(3) CPI (Services, less imputed rent)



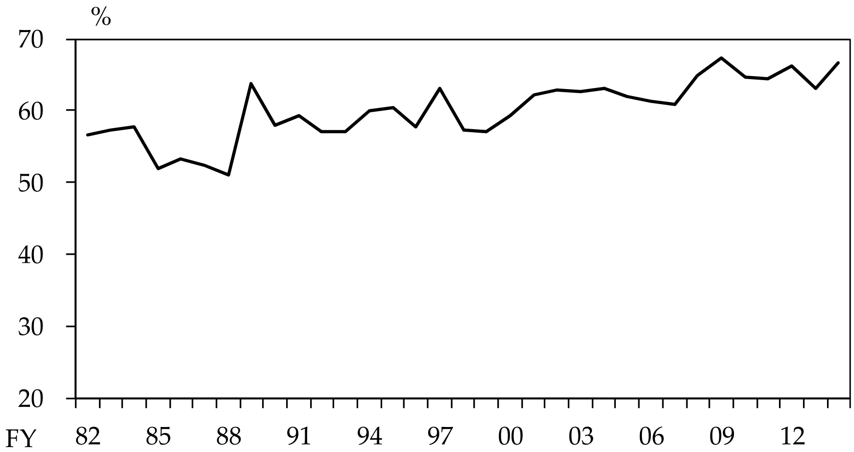
Note: All the series are averages weighted by the CPI weight.

Figure 2. Frequency of Price Adjustments

(1) CPI (All items, less fresh food and imputed rent)



(2) CPI (Goods, less fresh food)



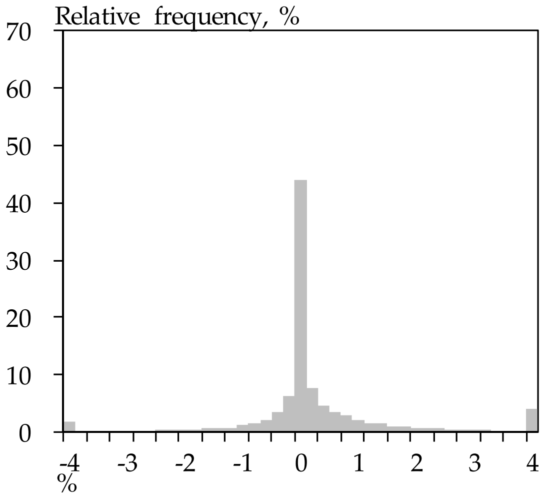
(3) CPI (Services, less imputed rent)

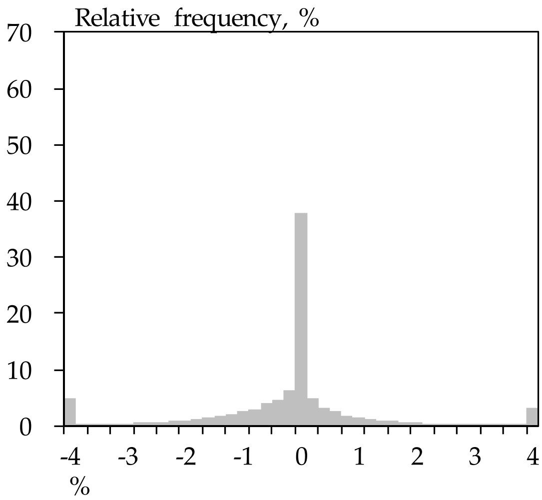
Note: "Price change" is defined as a quarterly change more than ±0.1% in the item level. Figures show yearly averages of monthly frequency, calculated by dividing the number of items whose prices change by the number of total items in each month.

Figure 3. Price-Change Distributions in the High- and Low-Inflation Periods

(1) CPI (Goods, less fresh food)

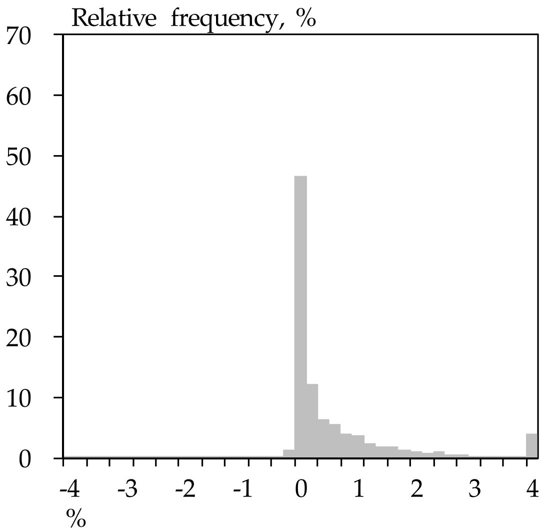
<High-inflation period (1982-94FY)> <Low-inflation period (1995-2012FY)>

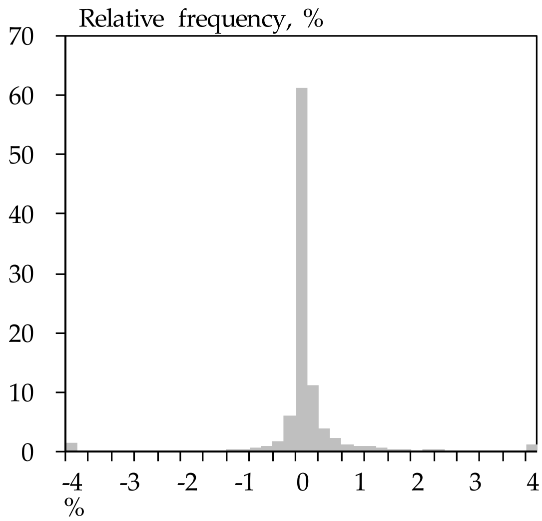




(2) CPI (Services, less imputed rent)

<High-inflation period (1982-94FY)> <Low-inflation period (1995-2012FY)>

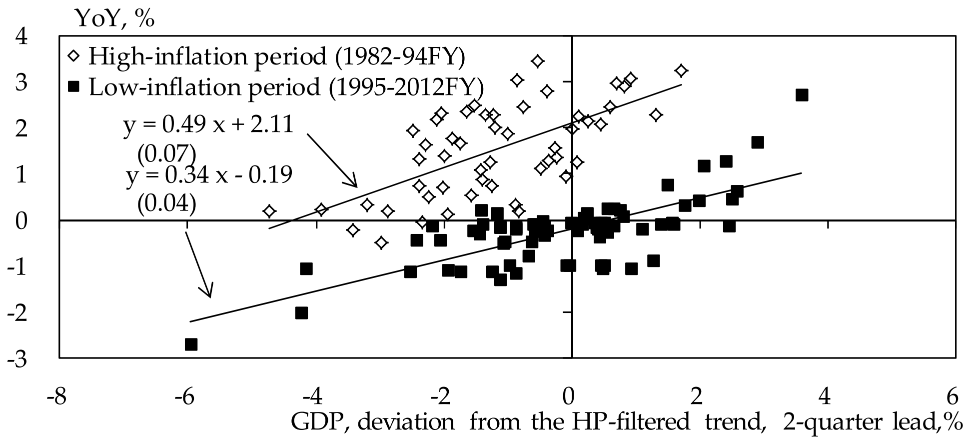




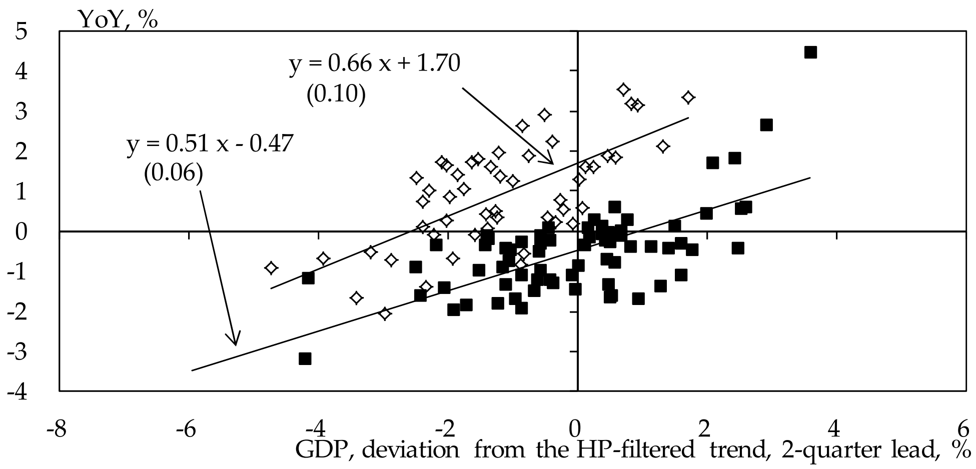
Note: Figures are calculated based on quarterly-based inflation rate.

Figure 4. Phillips Curve

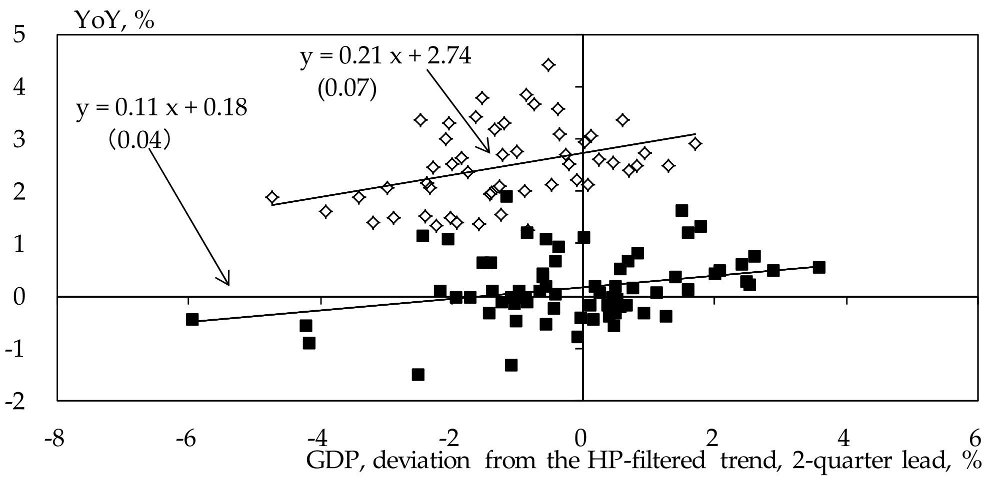
(1) CPI (All items, less fresh food and imputed rent)



(2) CPI (Goods, less fresh food)



(3) CPI (Services, less imputed rent)



Note: The standard errors for estimates are presented in the parenthesis.

For the Hodrick-Prescott filter, we set the smoothing parameter to 1600.

Figure 5. Median and the First/Third Quantile Points of the Distribution of Firm-level Wage Cost

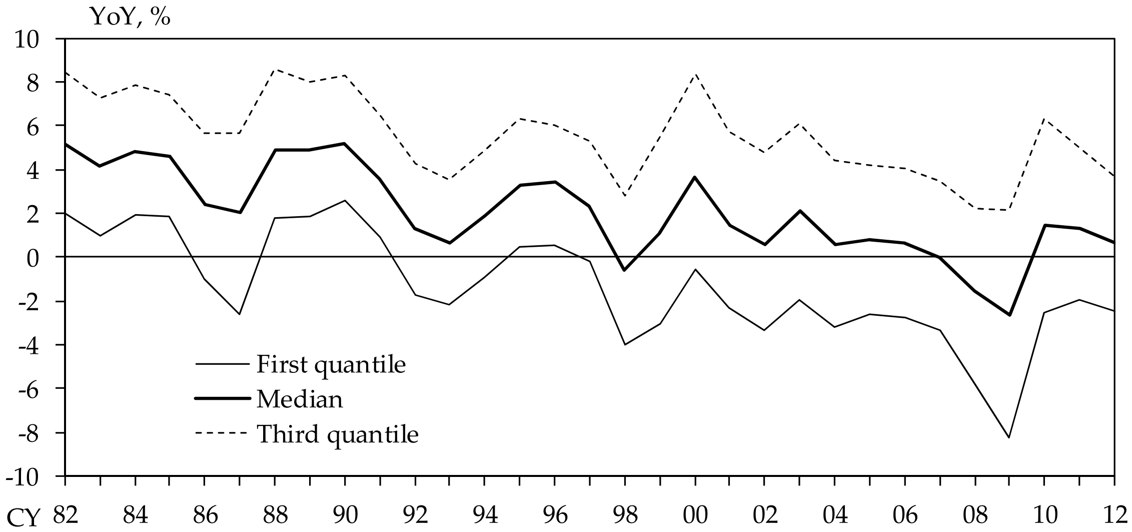


Figure 6. A Limited Dependent Variable Model with Two-sided Thresholds

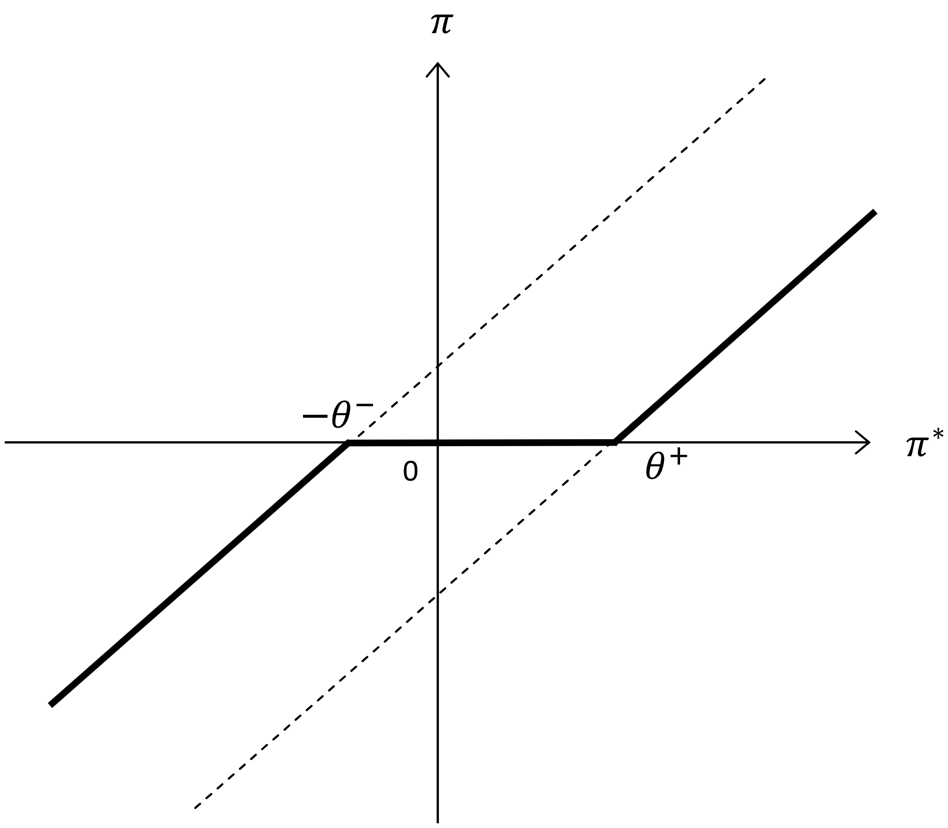
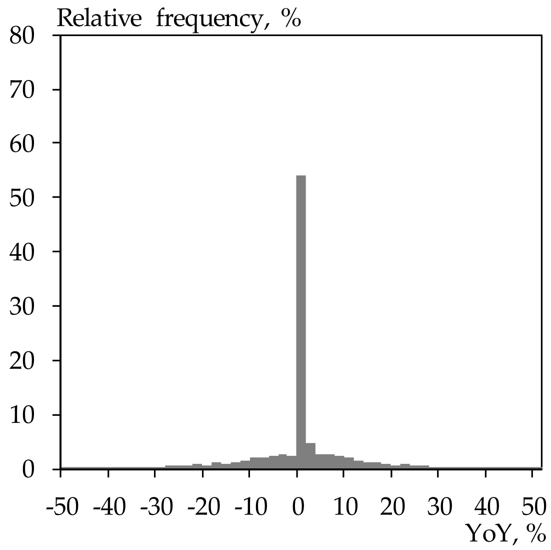


Figure 7. Price-Change Distributions Based on the Retail Price Survey

<Goods, less fresh food>



<Services>

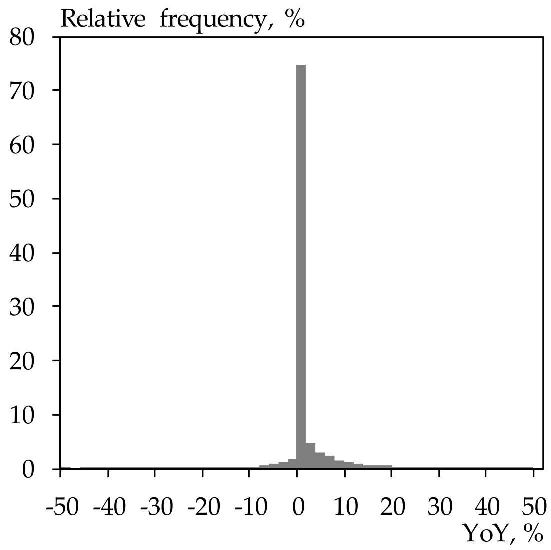
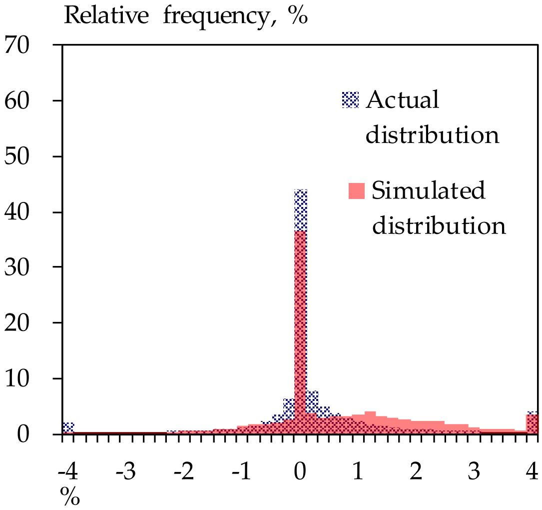


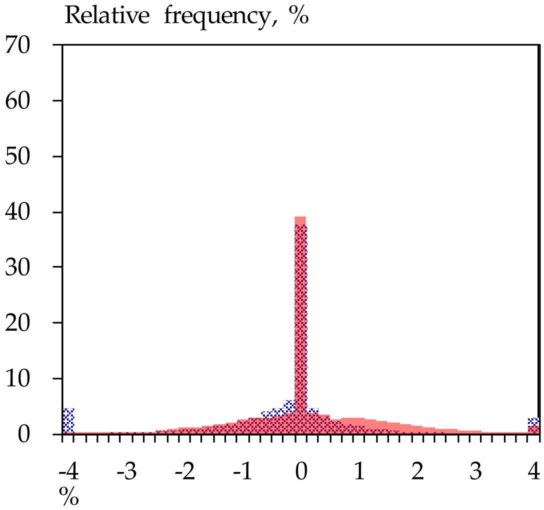
Figure 8. Simulated Distribution of Price Changes under 2% and 0% Trend Inflation

(1) Goods

<2% trend inflation>

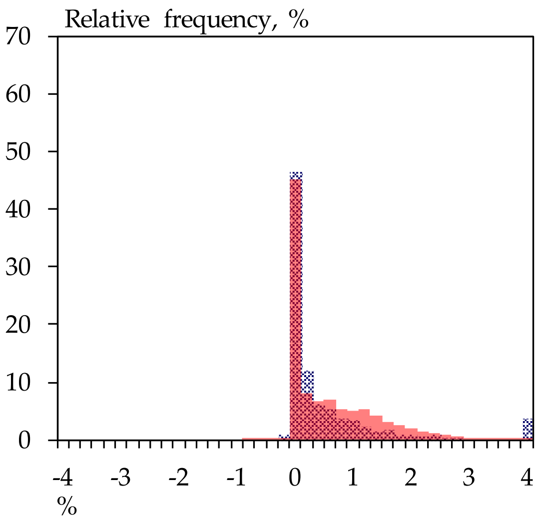


<0% trend inflation>

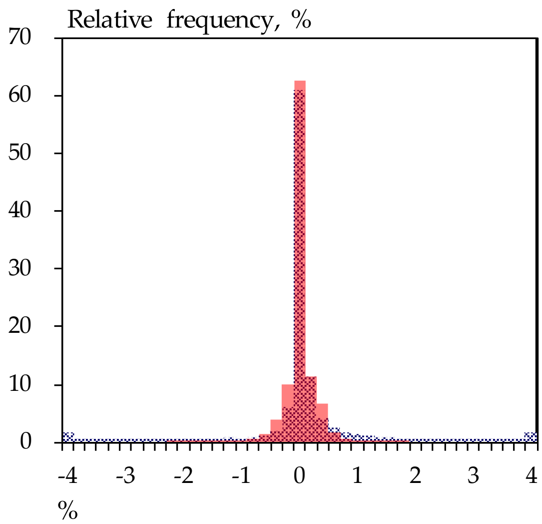


(2) Services

<2% trend inflation>



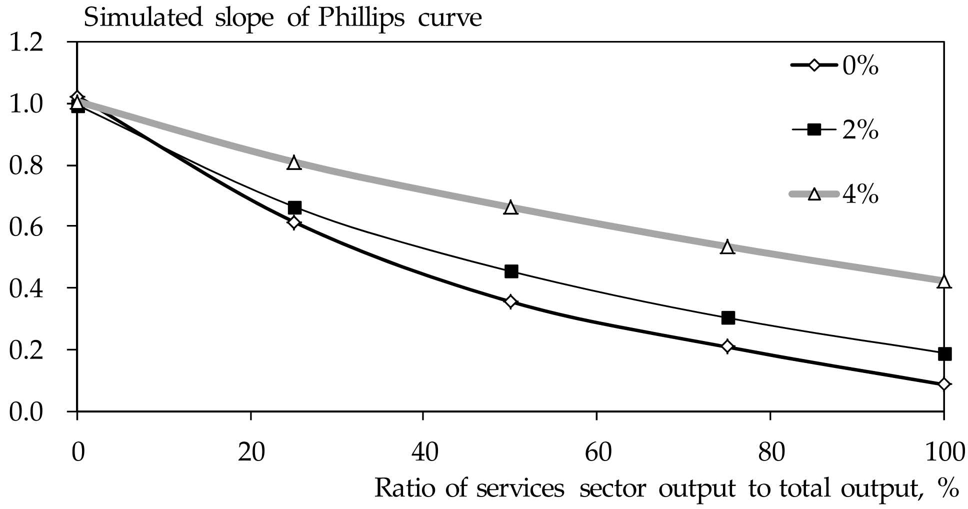
<0% trend inflation>



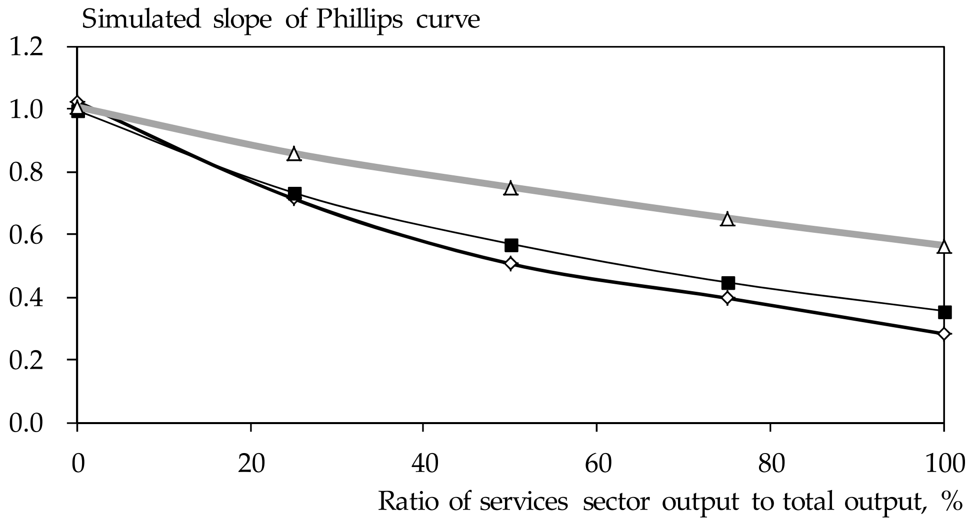
Note: Each actual distribution corresponds to distributions in the high- and low-inflation periods in Figure 3, respectively.

Figure 9. Changes in the Simulated Slope of the Phillips Curve in Different Conditions

(1) All Sectors



(2) Goods Sector



(3) Services Sector

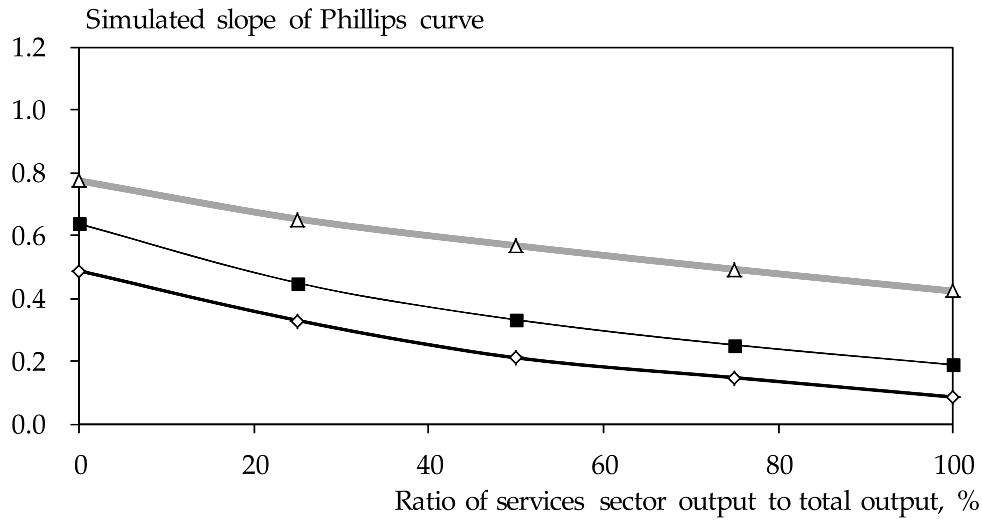
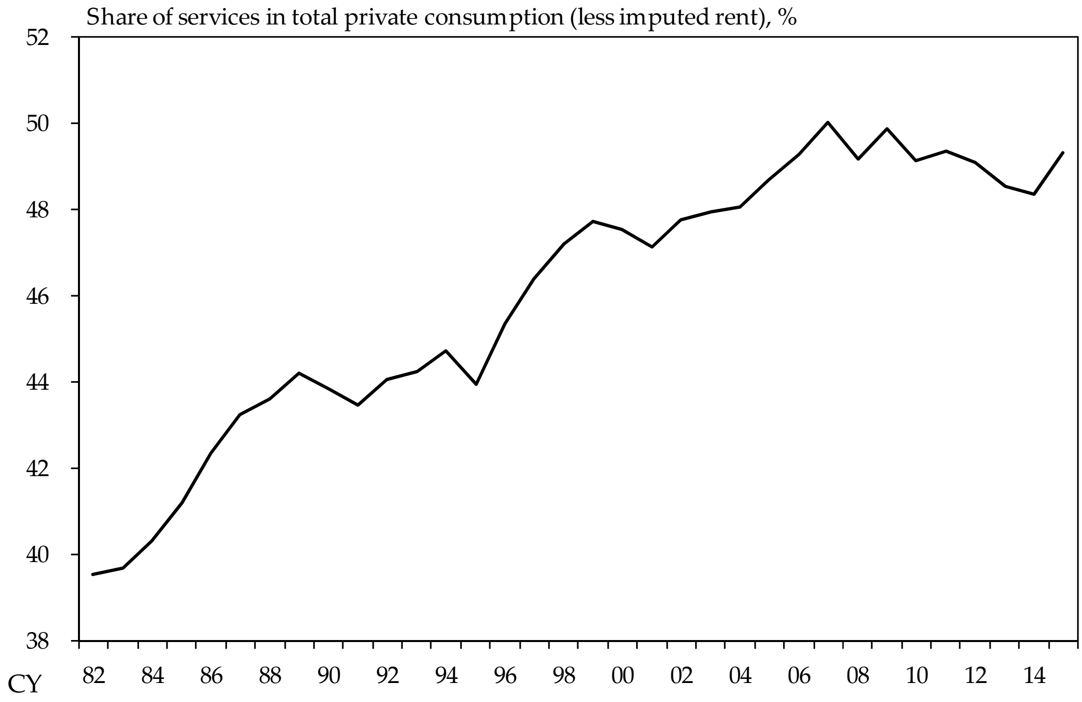


Figure 10. Share of Services in Consumption



Note: SNA basis.