Using the New Keynesian Phillips Curve to Understand Inflation Since the Great Recession

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ABSTRACT

The low inflation during the Great Recession despite expansionary monetary policy delays economic recovery and possibly the timing of increase in Federal Reserve's target rate. This paper studies the New Keynesian Phillips Curve before and after the recent recession to figure out what changes in the recent recession led to the slow recovery. It also provides predictions for inflation in the near future based on NKPC estimates. The paper first estimates the New Keynesian Phillips Curve, focusing on the shift of weights on backward-looking and forward-looking inflations and the influence of output gap. Then I use previous NKPC estimates to predict inflation rate in the future with various output gap predictions to justify the Federal Reserve's decision on increasing federal funds rate. Main findings include (1) expected inflation has been more influential on inflation since 2008 compared to earlier time period and (2) the output gap needs to close faster than currently for the inflation rate to stabilize around 2 percent in the long run. Results suggest that the public's confidence in Federal Reserve's ability to stabilize price level can explain the unresponsiveness of inflation. The liftoff reflects the Fed's confidence in the economic recovery.

During times when the economy is strong, the Federal Reserve aims to keep inflation stable around 2 percent. In the recent recession since 2008, however, the Federal Reserve attempted to boost inflation in order to depress real interest rate and stimulate economic growth. During normal times, the Fed can easily cut federal funds rate to lower real interest rate because of sticky prices, but the interest rate hitting Zero Lower Bound complicates the issue. With nominal rate sitting at lowest possible value, zero, the Fed had to implement unconventional expansionary policies, such as the quantitative easing, to raise inflation and in turn decrease real interest rate. Nevertheless, the effort did not pay off as expected. The inflation rate has remained stubbornly below 2 percent. This low inflation contributed to the slow recovery by Fed's keeping real interest rates relatively high. In past time period, monetary policy was effective in adjusting inflation, which makes us wonder what has changed during the Great Recession, and whether monetary policy can still affect inflation given current situation.

The Fed announced the liftoff in late 2015, after more than seven years since the onset of the Great Recession. In early 2015, various economic condition indicators suggested that the economy has improved enough for the Fed to increase inflation target from 0 to 25 basis points to 25 to 50 basis points. But the Fed finally announced the liftoff in December 2015, long after people's expectation. This delay left people wondering whether the hesitance was merely due to caution or slow economy.

During the Great Recession, even though the inflation was not as high as the Fed would like it to be, it was higher than the prediction from standard Phillips Curve using pre-crisis trend estimates. Since 2008, the output gap has been consistently negative, which should lower inflation significantly, but the inflation has been quite stable. Researchers and policymakers did not foresee such a small drop in inflation,

> The surprise [about inflation] is that it's fallen so little, given the depth and duration of the recent downturn. Based on the experience of past severe recessions, I would have expected inflation to fall by twice as much as it has (Williams 2010, p. 8).

The PCE core inflation dropped less than 2 percent in 2008 and 2009, and maintained positive since the onset of the recession. Nevertheless, several research papers show that the economy should have reached deflationary territory with minus 4 percent inflation rate during the Great Recession (Gordon, 2013). Therefore, economists have been finding solutions to this "missing deflation." Gordon (2013) conveys a contrary theory using the Triangle Model (Gordon, 1977, 1982). He suggests that there was no such "missing deflation", and the Phillips Curve can still predict inflation quite accurately (within half of a percentage for 2013:Q1).

Although some argue (Gordon, 2013, Ball and Sandeep, 2011) that the NKPC cannot fit the actual data very well since it relies largely on short lags of previous period inflation, this paper shows that the NKPC is still helpful in understanding dynamics of inflation. On one hand, the NKPC has changed quite significantly since the Great Recession, so that the pre-recession estimates cannot approximate the inflation well. On the other hand, the changes in estimated coefficients since 2008 reflect the behaviors that can shed light on monetary policy design and let economists uncover why the inflation has been stable during such a big recession.

The recent major change in inflation was the increase by 25 basis points in the Federal Reserve's target interest rate. Since the liftoff of Fed's target interest rate happened very recently, there are few published studies trying to understand and analyze this change in policy stance. This paper will contribute to the literature by attempting to understand the rationales for the liftoff decision after providing predictions of inflation rate according to different assumptions on the economic situation.

This paper first estimates the New Keynesian Phillips Curve to understand why inflation

has not been as low as expected and not responsive to the expansionary policies since the Great Recession. It explores changes of weights in the main factors influencing inflation. According to the New Keynesian Phillips Curve, lagged inflation, inflation expectation, and output/unemployment gap altogether determine inflation. I use responses from two surveys, Thomson Reuters/University of Michigan Surveys of Consumers and Survey of Professional Forecasters, as expected inflation. By estimating the difference in the weights on factors influencing inflation before and during the Great Recession, this paper can add to the literature in explaining this unusual period, reveal some reasons for the sluggish recovery and suggest ways for the Federal Reserve to design more effective policies in the future.

After getting reasonable estimates for the New Keynesian Phillips Curve, this paper uses the estimated model to solve for future inflation rates. The predictions of inflation in short or medium terms serve as a tool to provide insight on the Fed's decision of liftoff at the end of 2015.

I find that inflation expectation plays a bigger role relative to lagged inflation, across different survey data, in affecting inflation since the Great Recession, compared to previous time period. Regression results from time period before the Great Recession exhibit smaller coefficient on inflation expectation relative to lagged inflation, compared to time period since 2008. The result also suggests that the output gap does not have a significant influence on inflation despite of its large magnitude. Thus, the insignificance of output gap explains why the inflation has been higher than previously expected and remained positive. More importantly, the low expected inflation during the Great Recession seems to be a more influential factor than the low lagged inflation to the subdued inflation. As a result, the Fed may boost inflation by raising people's expectation of inflation using monetary policy tools.

Another major finding of this paper is that the inflation would end up negative based on the current closing trend of output gap, and that the output gap needs to close at a faster rate for the inflation to stabilize around 2 percent in the medium term.

The remainder of the paper proceeds as follows. Section I discusses the choice of using NKPC to explain the dynamics of inflation. Section II describes the estimation and prediction methods, and the surveys and relevant data used to get the results. Section III presents and interprets results. Section IV concludes findings and suggests improvements for future monetary policy during recessions.

I. Model

The dynamics of inflation are typically incorporated into a macroeconomic model, the Phillips Curve, either traditional or New Keynesian. Although some claim that the Phillips Curve fails to explain the inflation dynamics since 2008, Gordon (2013) argues that it is still effective in estimating inflation. The traditional Phillips Curve is more backward looking than New Keynesian Phillips Curve, expressed as

$$(1)\ \pi_t = E_{t-1}[\pi_t] + \phi(y_t - y_t^*) + \nu_t.$$

The dependent variable π_t is the current period inflation rate. The first independent variable $E_{t-1}[\pi_t]$ is last period's expectation of current period inflation, which is either adaptive expectation or rational expectation. The second right-hand-side variable $(y_t - y_t^*)$ is current period's output gap. Finally, ν_t represents an aggregate supply shock. This standard Phillips Curve estimates the inflation well when economy is strong and stable and inflation is variable, but it fails to approximate inflation dynamics well during the Great Recession.

On the other hand, the New Keynesian Phillips Curve describes the changes in inflation

more accurately for recent macroeconomic history. The NKPC is more forward looking since it include the effect of expected inflation for next time period in the equation. Moreover, the addition of the inflation expectation factor is useful for policy design because monetary policy can affect people's expectation for future economic performance.

The original New Keynesian Phillips Curve is

$$(2)\ \pi_t = \beta E_t[\pi_{t+1}] + \gamma x_t,$$

where the dependent variable is again inflation in the current period, and the independent variables are this period's expected inflation of next period and a real activity variable x_t. Economists mainly use output/unemployment gap or marginal cost as the real activity variable. The disadvantage of the marginal cost variable is that it cannot fit very well with real data and it is less informative to monetary policy than output/unemployment gap (Nason and Smith, 2008).

In order to better fit the data and provide more interpretation of the estimates, adding lagged inflation into the NKPC model can help. Galí and Gertler (1999) create a hybrid NKPC model including lagged inflation to allow for a fraction of backward looking price setters. Although they argue that the backward-looking inflation is statistically significant yet not quantitatively significant, my estimates show that the backward-looking inflation is significant in both contexts. Therefore, I use the following specification for New Keynesian Phillips Curve, similar to the hybrid NKPC in Galí and Gertler (1999),

$$(3)\ \pi_t = \beta_1 \pi_{t-1} + \beta_2 E_t[\pi_{t+1}] + \gamma(y_t - y_t^*) + \varepsilon_t.$$

The dependent variable is again inflation in current period. The independent variables include lagged inflation π_{t-1}, this period's expectation of next period's inflation $E_t[\pi_{t+1}]$, output gap of current period, and error term.

The NKPC is helpful in decomposing why the inflation has remained low despite

expansionary monetary policy and big output gap. There are several circumstances that can result in a low inflation but not deflation since 2008: (1) the coefficient on lagged inflation has been high during the Great Recession when inflation has been below 2 percent; (2) the coefficient on inflation expectation becomes higher in the recent recession and the inflation expectation has been the same as the Fed's mandate, 2 percent; (3) the measurement of output gap is not accurate or the output gap stops to affect inflation. This is not an exhaustive list of possibilities, but these cases are most relevant to policy design, because monetary policy can play a more important role when the effect of inflation expectation on inflation rate is bigger.

II. Method and Data

A. Method

For the first half of analysis, I use regression analysis to estimate coefficients on forward-looking and backward-looking inflation rates and output gap in the NKPC. I obtain the estimation using ordinary least squares (OLS). The NKPC models used in regression are specified as follows:

$$(4)\ \pi_t = \alpha + \beta_1 \pi_{t-1} + \beta_2 E_t[\pi_{t+1}] + \gamma(y_t - y_t^*) + \varepsilon_t, \text{ for SPF survey data,}$$

$$\text{and } (5)\ \pi_t = \alpha + \beta_1 \pi_{t-4} + \beta_2 E[\pi_{t+4}] + \gamma(y_t - y_t^*) + \varepsilon_t, \text{ for Michigan survey data.}$$

The notation is largely the same as the one I use for NKPC in section I, with α denoting the constant term in the regression equation. Since this paper is mainly interested in the changes in NKPC during the recent recession, I obtain estimates for coefficients separately for time periods before and after the onset of the Great Recession in 2008.

After running regression to estimate coefficients, I examine the predicted inflation since the Great Recession using estimated coefficients from pre-2008 regression. In order to examine

each component's effect on inflation, I decompose the predicted inflation by independent variables. I produce both static prediction using actual lagged inflation and dynamic prediction using predicted lagged inflation.[1]

The second half of the analysis consists of predictions of inflation produced from forward solution using lag operators. Assuming rational expectation, I can rewrite the NKPC as follows,

$$(6)\ \lambda_0(1-\lambda_1 L)(1-\lambda_2 L^{-1})\pi_t = \gamma(y_t - y_t^*) + \alpha.$$

Using the method described in Blanchard (1979), I have the following forward solution to inflation,

$$(7)\ (1-\lambda_2 L^{-1})^{-1}(y_t - y_t^*) = (1+ \lambda_2 L^{-1} + \lambda_2^2 L^{-2} + \lambda_2^3 L^{-3} + \dots)(y_t - y_t^*).$$

Substituting equation (7) into equation (6) and dropping the constant term[2], the inflation predictions with rational expectations render to

$$(8)\ \hat{\pi}_t = \lambda_1 \pi_{t-1} + (\gamma/\lambda_0)(1+ \lambda_2 L^{-1} + \lambda_2^2 L^{-2} + \lambda_2^3 L^{-3} + \dots)(y_t - y_t^*),$$

$$(9)\ \hat{\pi}_{t+1} = \lambda_1\ \hat{\pi}_t + (\gamma/\lambda_0)(1+ \lambda_2 L^{-1} + \lambda_2^2 L^{-2} + \lambda_2^3 L^{-3} + \dots)(y_{t+1} - y_{t+1}^*), \text{ etc.}$$

B. Data

Data used in the regression analysis include inflation, output gap, and expected inflation. I obtained all data from the Federal Reserve System, including Federal Reserve Economic Data and Federal Reserve Bank of Philadelphia, and performed simple transformation for some of the variables. In order to avoid interpolation between observations and still guarantee a decent

[1] I calculate the static prediction using $\hat{\pi}_t = \hat{\alpha} + \hat{\beta}_1 \pi_{t-1} + \hat{\beta}_2 E_t[\pi_{t+1}] + \hat{\gamma}(y_t - y_t^*)$, π_{t-1} is actual lagged CPI inflation in last period. The predicted lagged inflation in dynamic prediction comes from $\hat{\pi}_{t-1} = \alpha + \hat{\beta}_1 \pi_{t-2} + \hat{\beta}_2 E_{t-1}[\pi_t] + \hat{\gamma}(y_{t-1} - y_{t-1}^*)$, and then I feed this lagged inflation into $\hat{\pi}_t = \alpha + \hat{\beta}_1 \hat{\pi}_{t-1} + \hat{\beta}_2 E_t[\pi_{t+1}] + \hat{\gamma}(y_t - y_t^*)$ to get the prediction.

[2] I dropped constant α when deriving future inflation because α is the bias in expected inflation from survey data.

sample size for post-recession time period, I used all quarterly data. Furthermore, I transform the unit of all variables to percentage so that the regression result is easy to interpret.

In order to match up with two survey inflation expectation data, I obtained two kinds of price levels, CPI and PCE core, and transformed them into annualized quarterly inflation using percentage change from same period one year ago. Figure 1 shows the dynamics of inflations obtained from these two price levels. As CPI is more volatile and is sensitive to oil and food prices, the CPI inflation fluctuates a lot more than PCE core inflation. Moreover, CPI inflation rate temporarily went down below 0 in 2009 whereas PCE core inflation has always been positive. However, the medians of both measures of inflation rate are very close, around the Fed's mandate, 2 percent.

Finally, the inflation expectation data are from two surveys, Thomson Reuters/ University of Michigan Surveys of Consumers and Survey of Professional Forecasters. The Michigan survey asks consumers to predict inflation one year later, whereas the SPF asks professional forecasters to give predictions for one quarter to five quarters ahead CPI inflation. Figure 2 shows one-year-ahead Michigan survey expected inflation, one-year-ahead SPF expected CPI inflation, and one-quarter-ahead SPF expected CPI inflation. The one-year-ahead expectations are less volatile than the one-quarter-ahead inflation, and Michigan survey expected inflation is overall higher than the SPF expectations. Because of the low volatility, I use PCE core inflation with Michigan survey inflation expectation in regression. Since the SPF expected inflation is explicitly in terms of CPI, I pair the SPF expectation data with CPI in analysis.

III. Results

Across different survey data and inflation measures, the effect of inflation expectation on inflation increases relative to the effect of lagged inflation during the Great Recession. Table 1 and Table 2 show the main findings. In general, the NKPC approximates dynamics of inflation quite closely due to the inclusion of the lagged term.

The output gap turns out to be neither statistically significant nor quantitatively significant in determining inflation since the Great Recession across different survey data. Since inflation has not been very sensitive to the gap, the large negative output gap since 2008 was not able to lower inflation. But output gap influenced inflation differently across different survey data. On one hand, the Michigan survey data suggests that output gap was not a significant factor determining inflation even before 2008. On the other hand, the SPF survey data suggests that the output gap was an influential factor for inflation before 2008, with statistically significant yet small estimated coefficient on output gap, but the coefficient ceased to be significant since 2008, implying that the insignificance of output gap is one reason for inflation being higher than expected.

This difference is probably due to the difference in respondents of two surveys. Respondents of the Michigan survey are regular consumers who only have a rough guess of inflation, but respondents of the SPF survey are professionals in macroeconomic field following economic data closely. Therefore, the responses in the SPF survey can be better aligned with output gap because economists probably predict inflation using output gap data.

Although the effect of expectation increases relative to the effect of lagged inflation, the shift of weight is not one-to-one. Since the sum of the coefficients on backward-looking and forward-looking inflations is close to 1, I tested whether the two coefficients add up to 1 using both Wald's test and another regression that forces the two coefficients to add up to 1. Test

results using different expectation data are not consistent. The Michigan Survey data regression shows that the sum is unlikely to be 1, but the SPF data regression suggests that the two coefficients on lagged inflation and expected inflation are likely to sum up to 1. The regression summary tables also contain the exact test results.

Nevertheless, it is evident that inflation expectation plays a bigger role during the Great Recession compared to previous times, so that monetary policy is potentially more effective in affecting inflation through adjusting people's expectation of inflation. On the other hand, it is worth notice that the lagged inflation is still more influential than expected inflation in most estimation results.

Since surveys conducted on different respondents yield very different responses, I performed two sets of regression analyses using distinct inflation expectation survey data. Results in Tables 1, 2, and 3 show that the differences between the regression estimates are not only from the time span difference, but also the data itself.

After examining the performance of NKPC and realizing that it is a good fit for explaining the dynamics of inflation, I attempt to produce prediction for the inflation rate in the future. In order to have a more precise prediction, I use PCE core inflation and the expected inflation from the Michigan Survey, and fit the NKPC equation using data from the first quarter of 1978 to the third quarter of 2015. I stopped at the third quarter of 2015 mainly because I would like to use the prediction to interpret the Federal Reserve's announcement of a liftoff in the fourth quarter of 2015.

The predicted inflation suggests that the inflation will sit well below the 2 percent target if the output gap continues to close at its previous rate. From 2013 to 2015, the output gap decreases by a factor of 0.92 from one period to the next. Assuming that the output gap behaves

in a similar pattern in the future, the inflation would end up around -4 percent. In order to justify the Fed's liftoff, the output gap should decrease at a faster pace. Therefore, I tried various extrapolations of the output gap to determine how much the output gap should be so that the inflation would return to 2 percent. Results suggest that if the output gap would decrease by a factor of 0.6 to 0.7 starting from fourth quarter of 2015, the inflation rate would stabilize around 2 percent by the end of 2017 or 2018.

In parts A, B, and C of this section, I will analyze the regression results using two inflation expectations before and after the onset of the Great Recession separately. I first discuss the results for before 2008 time period. Then I present results for 2008 to 2014 and discuss them focusing on the changes from pre-recession period.

In parts D and E, I will analyze the inflation predictions using different trends of future output gap. I first show predictions calculated using the current trend of output gap. Then I provide alternative inflation predictions using various extrapolations of the output gap to investigate how much the output gap should be in order to have the inflation rate stabilize around 2 percent in the future.

A. Before 2008

Regression results show that in normal times, lagged inflation contributes more to the inflation than expected inflation do. The sum of estimated coefficients on these two inflations is close to 1 across different inflation expectation measures. The coefficient on output gap is small in magnitude, suggesting that inflation is not very responsive to the gap, but the coefficient is significant in the regression using SPF inflation expectation.

i. Michigan

Table 1 presents pre-recession regression results using Michigan survey data in the first two columns under "Before 2008" tab. Model (1) shows result from the following equation, $\pi_t = \alpha + \beta_1\pi_{t-4} + \beta_2 E[\pi_{t+4}] + \gamma(y_t - y_t^*) + \varepsilon_t$. The estimated coefficients on lagged inflation and expected inflation are 0.65 and 0.46 respectively, both of which are statistically significant. The sum of these two estimates is 1.11, close to 1. Therefore, I test whether the two coefficients add up to 1 using Wald's test and by construction. Model (2) reports result from the equation that forces the sum of two coefficients on lagged and expected inflations to be 1, written as $\pi_t = \alpha + (1-\beta_2)\pi_{t-4} + \beta_2 E[\pi_{t+4}] + \gamma(y_t - y_t^*) + \varepsilon_t$. The p-value from Wald's test is 0.00, meaning that the two coefficients probably do not add up to 1. Interestingly, the estimated coefficients from the restricted model do not vary much from the ones in the unrestricted model. After all, the true coefficients on lagged inflation and expected inflation probably do not sum to one, but the sum should be quite close to 1.

The output gap does not affect inflation significantly prior to the Great Recession, according to estimates using Michigan survey inflation expectation. The estimated coefficient is 0.02 with the standard error of 0.03, implying that the output gap cannot influence PCE core inflation significantly.

ii. SPF

Table 2 reports pre-recession regression results using SPF survey CPI inflation expectation in the first two columns under "Before 2008" tab. Model (3) obtains result from the following equation, $\pi_t = \alpha + \beta_1\pi_{t-1} + \beta_2 E[\pi_{t+1}] + \gamma(y_t - y_t^*) + \varepsilon_t$. The estimated coefficients on lagged inflation and expected inflation are 0.64 and 0.39 respectively, both of which are statistically significant. The magnitudes of the estimates are very similar to the ones discussed earlier from the regression using Michigan survey inflation expectation. Similarly, the sum of

these two estimates is 1.03, very close to 1 again. The restricted model, column (4), produces result from the following equation, $\pi_t = \alpha + (1-\beta_2)\pi_{t-1} + \beta_2 E[\pi_{t+1}] + \gamma(y_t - y_t^*) + \varepsilon_t$. The p-value from Wald's test is 0.27, suggesting that the probability of observing more extreme result is 27 percent if the two coefficients add up to 1, and that I cannot reject the null hypothesis. Echoing to the p-value, the estimated coefficients from the restricted model are very close to the ones in the unrestricted model. Therefore, the true coefficients on lagged inflation and expected inflation are likely to sum to one.

The estimated coefficient on output gap is, different from the results in part (i), significant during pre-2008 time period. The estimated coefficient is 0.06 with the standard error of 0.02, implying that the output gap can affect CPI inflation significantly. Admittedly, the magnitude of coefficient on output gap is small, but the gap can substantially influence inflation if the gap is large.

Table 3 also reports regression results using SPF survey CPI inflation expectation, but it uses the model $\pi_t = \alpha + \beta_1\pi_{t-4} + \beta_2 E[\pi_{t+4}] + \gamma(y_t - y_t^*) + \varepsilon_t$. The significance and shifts of weights on different factors influencing regression are generally the same as the regression results using 1 lag. Therefore, a detailed discussion on Table 3 will be omitted. But there is one important finding from results comparing results in Tables 1 and 3: the difference in estimates of NKPC in Tables1 and 2 is not only due to different time span but also due to the data itself.

B. Since 2008

Results suggest that the forward-looking inflation is more influential to the dynamics of inflation since the Great Recession. The inflation expectation has a bigger effect on inflation relative to lagged inflation since 2008, although the magnitude of its effect does not always

increase compared to pre-2008 period. Across different inflation expectation data sources, the output gap is not influential to inflation since 2008.

i. Michigan

The last two columns in Table 1 under "Since 2008" tab shows post-recession regression results using Michigan survey data. The estimated coefficients on lagged inflation and expected inflation are -0.01 and 0.29. The coefficient on lagged inflation decreases more than the coefficient on expected inflation does in recession period compared to normal period, meaning that the impact of expected inflation on inflation increases compared to the impact of lagged inflation since 2008. In addition, the lagged inflation is neither statistically significant nor substantially significant during the Great Recession, which suggests that inflation is mostly influenced by inflation expectation. The sum of these two estimates is 0.28, far from 1, and the Wald's test and restricted model results all imply that the true sum should probably not be 1. Nevertheless, the estimated coefficient on expected inflation in the restricted model increases compared to the restricted model estimate for pre-2008 period, which is consistent with the unrestricted model.

The output gap does not affect inflation significantly prior to the Great Recession, according to estimates using Michigan survey inflation expectation. The estimated coefficient in unrestricted model is 0.05 with the standard error of 0.04, implying that output gap is not an influential factor to inflation. In the restricted model, the estimated coefficient on output gap for pre-2008 period is negative, which is consistent with historical and theoretical estimate. In contrast, the estimated coefficient is positive for post-2008 period, suggesting that negative output gap would not depress inflation and if anything, it would actually raise inflation. All in

all, the negative big output gap could not drag inflation down much during the Great Recession, which explains the missing deflation puzzle.

In addition, the model (1) result needs to be interpreted with caution since the NKPC model does not fit very well for post-recession period. The R-squared value is relatively low for the estimation since the Great Recession, suggesting that the NKPC might not be a good model for explaining dynamics of inflation in this time period using Michigan survey inflation expectation.

ii. SPF

The last two columns in Table 2 under "Since 2008" tab shows post-2008 estimation results using SPF survey data. The estimated coefficients on lagged inflation and expected inflation are 0.70 and 0.57. The coefficients on both lagged inflation and inflation expectation increase, but the increase on the coefficient of inflation expectation is larger. The coefficient on expected inflation increases from 0.39 to 0.57 whereas the coefficient on lagged inflation increases from 0.64 to 0.70. Although both coefficients increase compared to pre-2008 period, the coefficient on expected inflation increases more in recession period compared to normal period. This result suggests that the impact of expected inflation on inflation increases since 2008 compared to the impact of lagged inflation, which is consistent with the change in Michigan survey result. The sum of these two estimates is 1.26, and the Wald's test and restricted model results all imply that the true sum is not very likely to be 1. The estimated coefficient on expected inflation in the restricted model increases compared to the restricted model estimate for pre-2008 period, which is consistent with results from the unrestricted model.

The output gap is, similar to the result from Michigan survey data, not very influential in

determining inflation since the Great Recession. The gap ceases to affect inflation since the Great Recession, contributing to the higher than expected inflation in this time period.

Table 3 shows the regression result with one-year-ahead SPF inflation expectation and four lags of CPI inflation. I conduct this regression to show that the different estimated coefficients in Tables 1 and 2 are not due to different lags but due to inherent difference in the data instead. The result is quite different from the ones in Table 1 and Table 2 quantitatively. The weight on expected inflation during post-recession period is more than 1, and the coefficient of output gap is bigger. Although the point estimates exceeds the theoretically mandated region, getting these estimates is not too abnormal given the small sample. The low R-squared values reflect that the NKPC model does not fit well, which is probably due to the high volatility of CPI inflation. CPI inflation fluctuates a lot since it includes oil and food prices, which are difficult to predict, so that a one-year-ahead expectation and four-period-lagged inflation cannot explain the current inflation. The result is, however, consistent with previous regression analysis qualitatively, suggesting that the inflation expectation is more influential to inflation since the Great Recession.

Anyway, the results agree on the increasing influence of expected inflation since the Great Recession, implying that the stable and low inflation expectation contributes to the low inflation and stable price levels. The estimated coefficients on expected inflation are higher during post-2008 period than during pre-2008 period with or without $\beta_1 + \beta_2 = 1$ restriction, and this result is consistent across different survey data regressions.

C. CPI Inflation Decomposition

Since the regression result is more significant using SPF inflation expectation with CPI inflation, it seems that New Keynesian Phillips Curve fits the SPF data better. Thus, I use pre-2008 estimates to obtain the predicted CPI inflation since 2008, and closely examine how each independent variable affects inflation. I calculate both dynamic prediction inflation and static prediction inflation since 2008, and Figure 3 illustrates both predictions and the actual CPI inflation. From the figure, the static prediction approximates the actual CPI inflation better than the dynamic prediction, but the two predictions are mostly lower than the actual inflation over the entire period.

Figure 4 shows the decomposition of dynamically predicted CPI inflation. Over the entire time period, output gap should have dragged the CPI down and maximum decrease due to the large and negative output gap should have been around 0.5. However, since the output gap becomes insignificant for post-2008 period, the actual inflation is higher than predicted. Figure 5 shows the decomposition of statically predicted CPI inflation, and the output gap exhibits the same behavior over this time period.

Moreover, Figure 4 visualizes that the stable inflation expectation contributes more to the dynamic prediction rate since 2008. The lagged CPI inflation, on the other hand, behaves a lot more volatile than expected inflation and contributes less to the inflation after 2008, especially since 2013:3. In Figure 4, the shift of contribution from lagged inflation to expected inflation remains evident whereas this shift is not as obvious in Figure 5.

The actual CPI inflation has been 0.5 to 1.0 percent higher than either dynamically or statically predicted inflations. The increase in the weight on inflation expectation since 2008 accounts for the higher than predicted actual CPI inflation.

D. Predictions of Inflation

Table 4 shows the NKPC estimation and the other coefficient estimates I use to calculate predicted inflation rates after the third quarter of 2015. Column (1) of Table 4 shows the estimates of NKPC without imposing any restriction. Even though the Wald's test does not reject the hypothesis that the coefficients for lagged inflation and expected inflation add up to 1, the decomposition to get $\lambda_0, \lambda_1,$ and λ_2 for the forward solution leads to complex numbers. Therefore, I imposed the restriction that the sum of coefficients on lagged inflation and expected inflation is 1 in order to get real numbers for $\lambda_0, \lambda_1,$ and λ_2. As a result, the inflation responds quite sensitively to the change in output gap because λ_2 is rather small, which is 0.48.

I calculate the output gap using potential GDP from CBO projection and real GDP data for all time periods before the third quarter of 2015. I express the output gap as the percentage change of real GDP from potential GDP in the current period. The output gap calculated as described above decreases by a relative constant factor, about 0.92, every quarter from 2013. I assume that GDP will catch up with the CBO's projection on potential GDP. Therefore, the output gap eventually diminishes to 0. So I simply multiply the gap in previous period by 0.92 to extrapolate the data further into future periods.

Figure 6 shows the PCE core inflation from 2008:4 to 2015:3 with the predicted inflation calculated using current trend of output gap from 2015:4 to 2025:4. The inflation would go up a little bit right after the third quarter of 2015 due to the construction of the prediction formula, and go down constantly until it settles around -3.84, suggesting that the output gap needs to close at a faster rate in order to have the inflation rate back at 2 percent in the long run.

E. Alternative Inflation Predictions Using Various Output Gap Extrapolations

Since the Fed's long term target for inflation is 2 percent, and it decided to raise the target interest rate in December 2015, it should expect a different path for future output gap. Figure 7 shows the output gap since 2008 and 5 potential paths of it in 10 years. All alternative predictions of output gap exhibit a constant factor of decrease from one period to the next. The original CBO output gap prediction path goes to zero in more than 10 years, and half of the gap diminishes after 2017:3. Alterative output gap extrapolations will have half of the gap diminish within two years from 2015:3, with the fastest recovery in two quarters.

Figure 8 shows different predictions of inflation corresponding to different paths of output gap closure. All predictions go up immediate after 2015:3 due to the dominating effect of lagged inflation at first and then go down and settle around some rate eventually. Predictions 4 and 5 in the graph stabilize around 2 percent in 2 to 3 years, corresponding to 0.7 and 0.6 as the constant decreasing factor. Therefore, the output gap should close in 3 or 2 years, corresponding to 0.7 and 0.6 respectively, in order to have the interest rate settle down around 2 percent eventually.

Findings suggest that the liftoff last December can only be justified if the Fed had an optimistic recovery path for the economy. Based on my predictions, the economy still needs to keep the zero inflation if the Fed wants inflation to go back to 2 percent. Therefore, the Fed must have an optimistic projection for the economy in the near future based on other economic indicators. It is also possible if the Fed has alternative stimulation policies in mind for a faster economic recovery.

IV. Conclusion

In recent years, inflation has mostly been positive and higher than previous trend prediction, but lower than what the Federal Reserve would like it to be since the Great Recession. Furthermore, the Federal Reserve announced the liftoff of the federal funds rate in the fourth quarter of 2015, which is later than people expected but earlier than the prediction using New Keynesian Phillips Cure. This research examines the dynamics of inflation by first estimating a hybrid New Keynesian Phillips Curve before and since the recent recession in 2008, and then produce various predictions of inflation in the medium term using NKPC. Two-period regression results using different survey data all suggest that the inflation expectation becomes more influential to inflation, and that the output gap stops to affect inflation significantly since 2008. Various predictions of inflation based on different output gap projections show that the output gap should close faster currently in order to reach the Fed's mandate of 2 percent inflation. I conclude that (1) the increasing influence of inflation expectation, which is stable around 2 percent, and the decreasing influence of output gap altogether explain the low but not deflating inflation rate since the Great Recession; (2) the output gap needs to close in 2 to 3 years for the inflation to stabilize around 2 percent in five years.

Admittedly, there are some caveats in this paper that one should consider while reading. For the New Keynesian Phillips Curve estimation, the small sample size for post-recession time period leads to imprecise and potentially unreliable estimates. Therefore, the conclusion is more relevant qualitatively than quantitatively. Nevertheless, even the qualitative result can shed light on the Federal Reserve's monetary policy.

From my comparison of NKPC estimates before and since the great recession, the Fed should consider forming higher expectation of inflation for general public in order to raise inflation and depress real interest rate. The announcement of liftoff at the end of 2015 suggests

that the Federal Reserve believes that the output gap will close at a faster rate and serves to increase people's confidence in economic recovery. But we still need time to see whether the inflation will return to 2 percent objective steadily as the Federal Reserve expects.

To do list:

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Table 1 – NKPC Estimations with Michigan Survey Data

Dependent variable: inflation rate π

Independent variable	Before 2008		Since 2008	
	(1)	(2)	(1)	(2)
Lagged inflation rate (β_1)	**0.65**	**0.59**	-0.01	**0.46**
	(0.04)	(0.04)	(0.13)	(0.11)
Expected inflation (β_2)	**0.46**	**0.41**	**0.29**	**0.54**
	(0.04)	(0.04)	(0.10)	(0.11)
$\beta_1 + \beta_2$	1.11	1.00	0.28	1.00
	(0.02)	(0.04)	(0.15)	(0.11)
Output gap (γ)	0.02	-0.03	0.05	0.00
	(0.03)	(0.03)	(0.04)	(0.05)
Constant (α)	**-0.57**	**-0.23**	0.83	**-0.96**
	0.09	(0.05)	(0.45)	(0.35)
R-squared	0.99	0.81	0.46	0.95
Adjusted R-squared	0.99	0.81	0.39	0.94
Wald's test p-value	0.00		0.00	
Observations (N)	120	120	28	28

Notes: Standard errors are given in parentheses.

The table reports estimated coefficients from an OLS regression on the following equations:

(1) $\pi_t = \alpha + \beta_1 \pi_{t-4} + \beta_2 E[\pi_{t+4}] + \gamma(y_t - y_t^*) + \varepsilon_t$

(2) $\pi_t = \alpha + (1-\beta_2)\pi_{t-4} + \beta_2 E[\pi_{t+4}] + \gamma(y_t - y_t^*) + \varepsilon_t$

Wald's test null hypothesis: $\beta_1 + \beta_2 = 1$

Before 2008 covers data from 1978:1 to 2007:4.

Since 2008 covers data from 2008:1 to 2014:4.

Inflation is measured by PCE core.

Table 2. – NKPC Estimations with Survey of Professional Forecasters Data, 1 lag
Dependent variable: inflation rate π

Independent variable	Before 2008		Since 2008	
	(3)	(4)	(3)	(4)
Lagged inflation rate (β_1)	**0.64**	**0.63**	**0.70**	**0.56**
	(0.04)	(0.04)	(0.10)	(0.06)
Expected inflation (β_2)	**0.39**	**0.37**	**0.57**	**0.44**
	(0.04)	(0.04)	(0.10)	(0.06)
$\beta_1 + \beta_2$	1.03	1.00	1.26	1.00
	(0.03)	(0.04)	(0.15)	(0.06)
Output gap (γ)	**0.06**	**0.05**	-0.03	0.08
	(0.02)	(0.02)	(0.10)	(0.08)
Constant (α)	-0.06	0.04	-0.62	0.34
	(0.11)	(0.05)	(0.66)	(0.38)
R-squared	0.93	0.72	0.82	0.76
Adjusted R-squared	0.92	0.72	0.70	0.74
Wald's test p-value	0.27		0.09	
Observations (N)	106	28	106	28

Notes: Standard errors are given in parentheses.
The table reports estimated coefficients from an OLS regression on the following equations:
(3) $\pi_t = \alpha + \beta_1\pi_{t-1} + \beta_2 E_t[\pi_{t+1}] + \gamma(y_t - y_t^*) + \varepsilon_t$
(4) $\pi_t = \alpha + (1-\beta_2)\pi_{t-1} + \beta_2 E_t[\pi_{t+1}] + \gamma(y_t - y_t^*) + \varepsilon_t$
Wald's test null hypothesis: $\beta_1 + \beta_2 = 1$
Before 2008 covers data from 1981:3 to 2007:4.
Since 2008 covers data from 2008:1 to 2014:4.
Inflation and inflation expectation are both in terms of CPI inflation rate.

Table 3. – NKPC Estimations with Survey of Professional Forecasters Data, 4 lags
Dependent variable: inflation rate π

Independent variable	Before 2008		Since 2008	
	(5)	(6)	(5)	(6)
Lagged inflation rate (β_1)	**0.32**	**0.33**	**-0.37**	**-0.34**
	(0.07)	(0.07)	(0.13)	(0.14)
Expected inflation (β_2)	**0.72**	**0.67**	**3.44**	**1.34**
	(0.11)	(0.07)	(0.92)	(0.14)
Output gap (γ)	**0.19**	**0.18**	0.14	0.33
	(0.05)	(0.05)	(0.14)	(0.13)
Constant (α)	-0.13	0.00	-3.55	**1.39**
	(0.27)	(0.09)	(0.20)	(0.60)
R-squared	0.70	0.20	0.59	0.38
Adjusted R-squared	0.69	0.19	0.74	0.33
Observations (N)	106	106	28	28

Notes: Standard errors are given in parentheses.
The table reports estimated coefficients from an OLS regression on the following equations:
(5) $\pi_t = \alpha + \beta_1\pi_{t-4} + \beta_2 E[\pi_{t+4}] + \gamma(y_t - y_t^*) + \varepsilon_t$
(6) $\pi_t = \alpha + (1-\beta_2)\pi_{t-4} + \beta_2 E[\pi_{t+4}] + \gamma(y_t - y_t^*) + \varepsilon_t$
Inflation and inflation expectation are both in terms of CPI.

Table 4 – NKPC Estimations with Michigan Survey Data

Dependent variable: inflation rate π

Independent variables	(1)	(2)
Lagged inflation rate (β_1)	**0.69**	**0.68**
	(0.02)	(0.03)
Expected inflation (β_2)	**0.42**	**0.32**
	(0.03)	(0.03)
$\beta_1 + \beta_2$	1.11	1.00
	(0.02)	(0.03)
Output gap (γ)	**0.06**	**0.07**
	(0.01)	(0.02)
Constant (α)	**-0.55**	**-0.15**
	(0.09)	(0.05)
R-squared	0.96	0.59
Adjusted R-squared	0.96	0.58
Wald's test p-value	0.00	
λ_0		0.68
λ_1		1
λ_2		0.48
Observations (N)	151	151

Notes: Standard errors are given in parentheses.

The table reports estimated coefficients from an OLS regression on the following equations:

(1) $\pi_t = \alpha + \beta_1\pi_{t-4} + \beta_2 E[\pi_{t+4}] + \gamma(y_t - y_t^*) + \varepsilon_t$

(2) $\pi_t = \alpha + (1-\beta_2)\pi_{t-4} + \beta_2 E[\pi_{t+4}] + \gamma(y_t - y_t^*) + \varepsilon_t$

Wald's test null hypothesis: $\beta_1 + \beta_2 = 1$

λ_0, λ_1, and λ_2 correspond to the symbols in equations (5) to (8) in section II.

Data from 1978:1 to 2015:3.

Inflation is measured by PCE core.

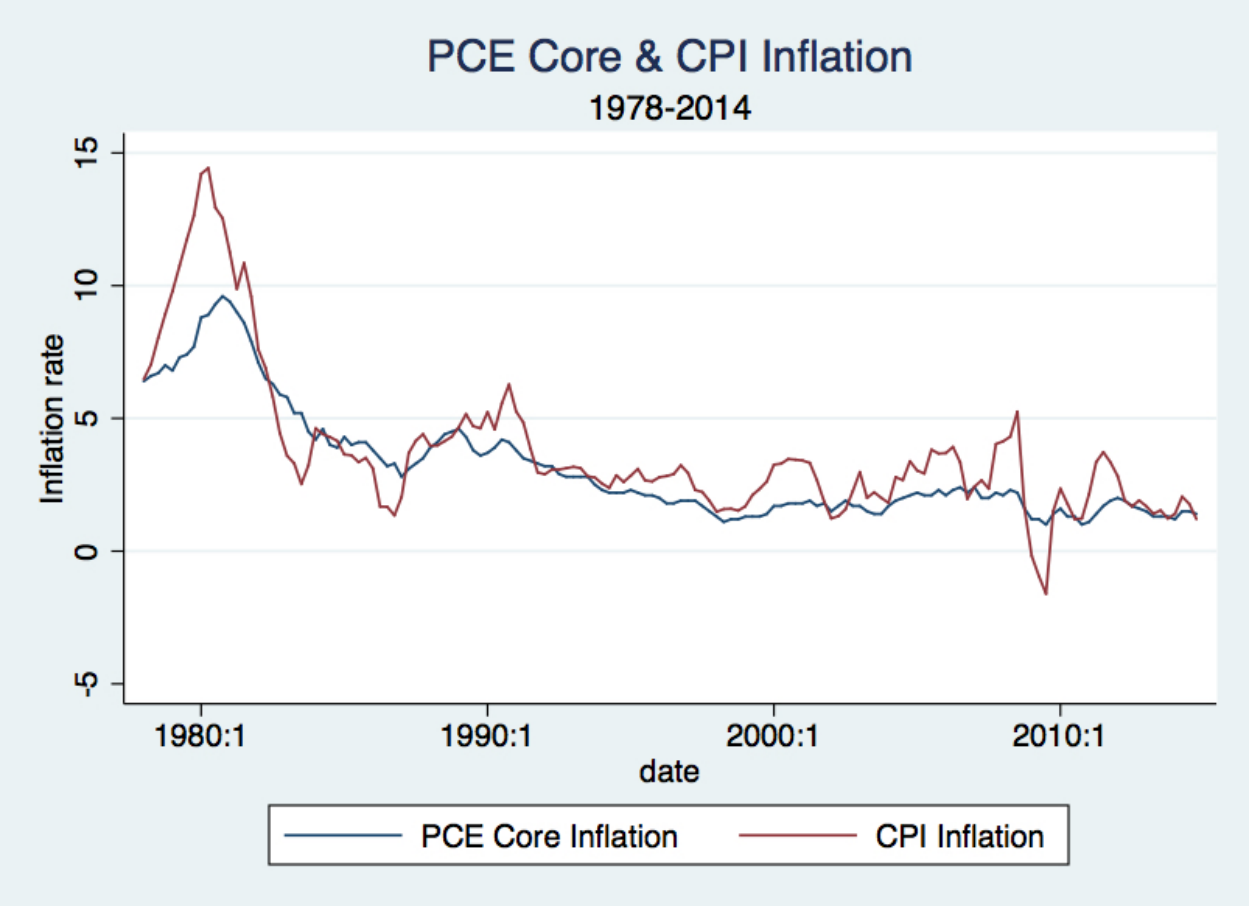

Figure 1

Notes:
The inflation rate is measured in percent, from 1978:1 to 2014:4.

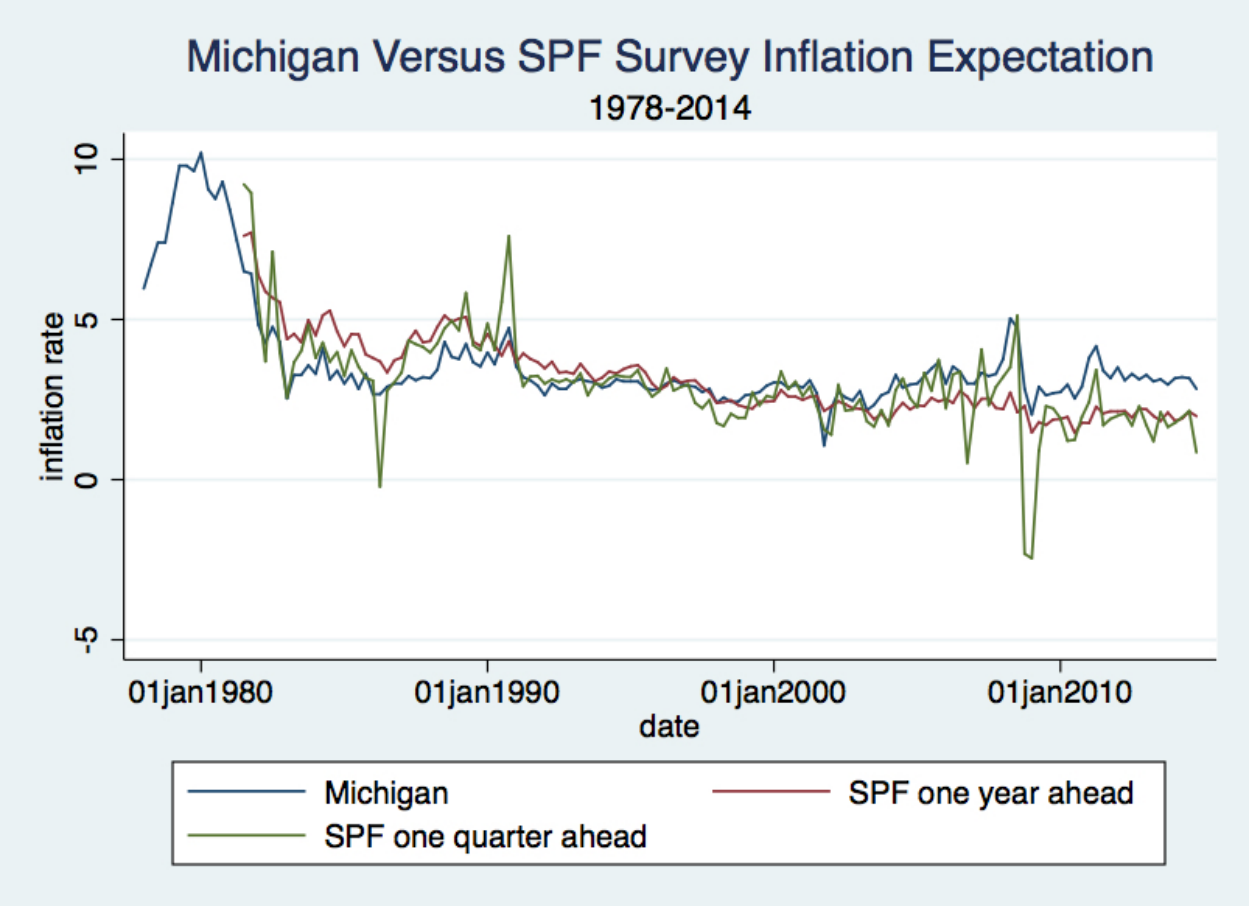

Figure 2

Notes:
Inflation measured in percent.
Michigan survey inflation expectation starts from 1978:1, while SPF forecast starts from 1981:3.
The SPF expectations are mean responses.

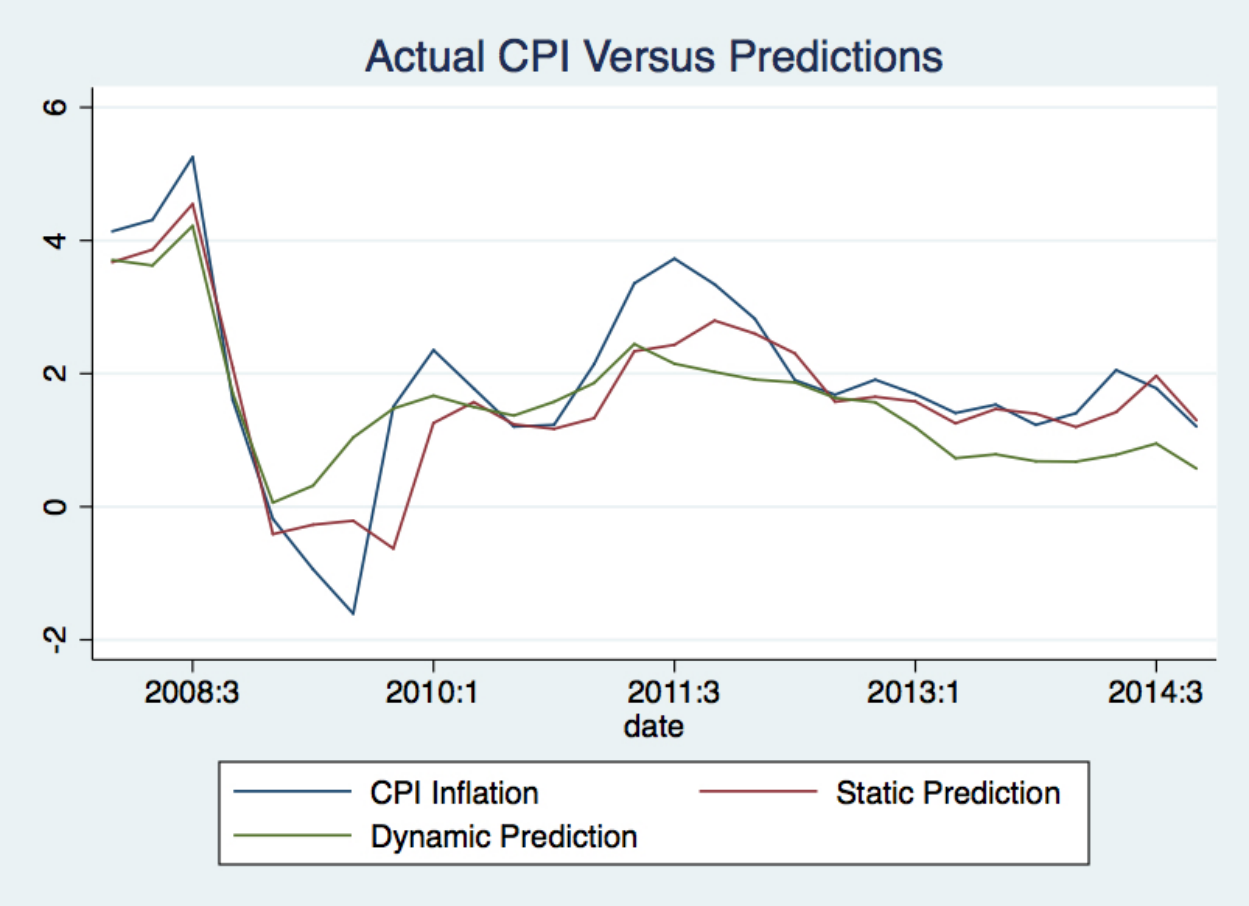

Figure 3

Notes:

Inflation measured in percent, from 2008:1 to 2014:4.

The static prediction is calculated as $\hat{\pi}_t = \hat{\alpha} + \hat{\beta}_1\pi_{t-1} + \hat{\beta}_2 E_t[\pi_{t+1}] + \hat{\gamma}(y_t - y_t^*)$, π_{t-1} is actual lagged CPI inflation in last period.

The predicted lagged inflation in dynamic prediction comes from $\hat{\pi}_{t-1} = \alpha + \hat{\beta}_1\pi_{t-2} + \hat{\beta}_2 E_{t-1}[\pi_t] + \hat{\gamma}(y_{t-1} - y_{t-1}^*)$, and then feeding this lagged inflation into $\hat{\pi}_t = \alpha + \hat{\beta}_1\hat{\pi}_{t-1} + \hat{\beta}_2 E_t[\pi_{t+1}] + \hat{\gamma}(y_t - y_t^*)$ to get the prediction.

Estimated coefficients used are from Table 2 column (3) under "Before 2008" tab.

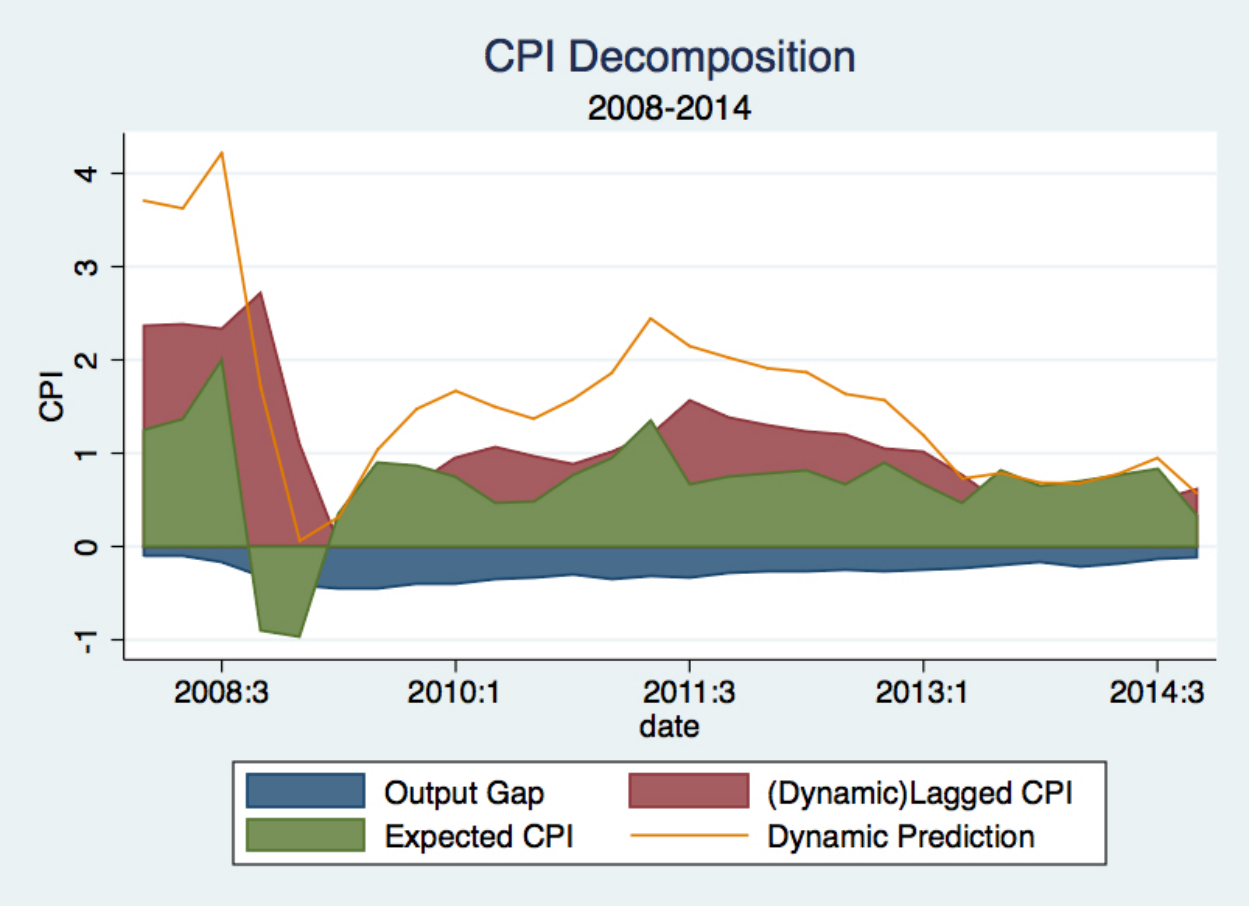

Figure 4

Notes:

This figure shows the decomposition of the dynamically predicted inflation since 2008, using pre-2008 estimates. The shaded areas correspond to different components in the predicted inflation. Adding up the shaded areas (negative sign included) would achieve the magnitude of prediction line.

The predicted lagged inflation in dynamic prediction comes from $\hat{\pi}_{t-1} = \alpha + \hat{\beta}_1\pi_{t-2} + \hat{\beta}_2 E_{t-1}[\pi_t] + \hat{\gamma}(y_{t-1} - y^*_{t-1})$, and then feeding this lagged inflation into $\hat{\pi}_t = \alpha + \hat{\beta}_1 \hat{\pi}_{t-1} + \hat{\beta}_2 E_t[\pi_{t+1}] + \hat{\gamma}(y_t - y^*_t)$ to get the prediction.

Estimated coefficients used are from Table 2 column (3) under "Before 2008" tab.

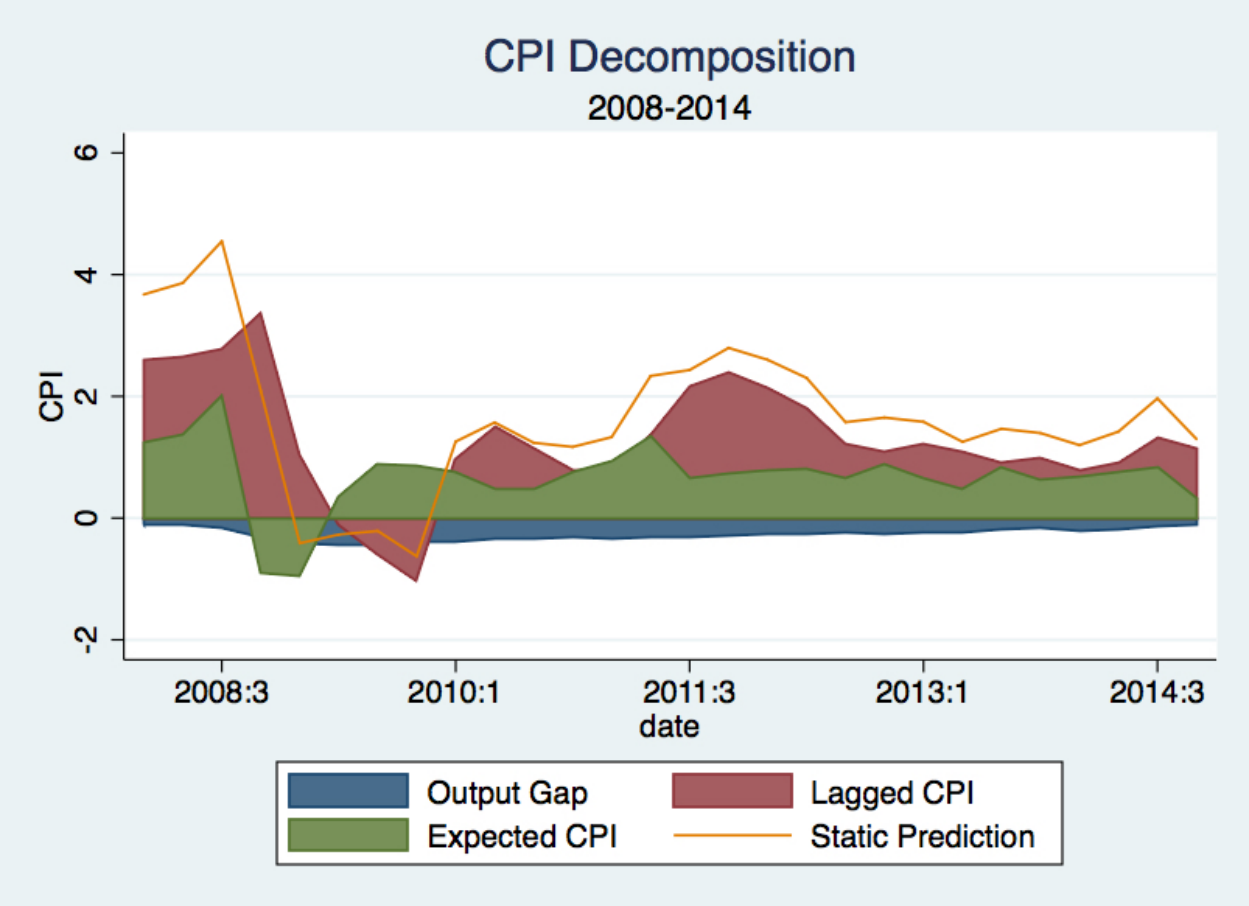

Figure 5

Notes:

This figure shows the decomposition of the statically predicted inflation since 2008, using pre-2008 estimates. The shaded areas correspond to different components in the predicted inflation. Adding up the shaded areas (negative sign included) would achieve the magnitude of prediction line.

The static prediction is calculated as $\hat{\pi}_t = \hat{\alpha} + \hat{\beta}_1 \pi_{t-1} + \hat{\beta}_2 E_t[\pi_{t+1}] + \hat{\gamma}(y_t - y_t^*)$, π_{t-1} is actual lagged CPI inflation in last period.

Estimated coefficients used are from Table 2 column (3) under "Before 2008" tab.

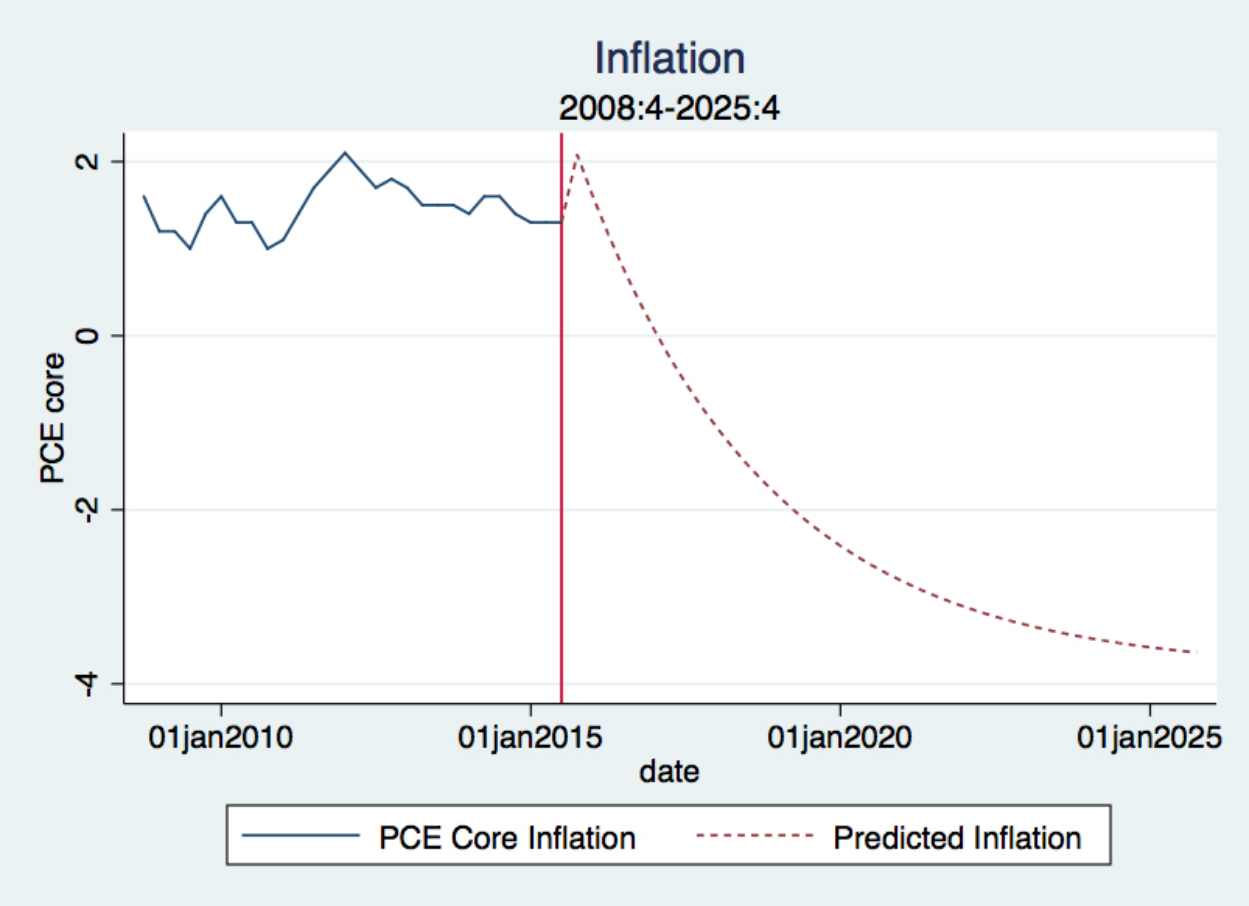

Figure 6

Notes:
Inflation is measured in percent. Predicted inflation starts from 2015:4 and settles down around 3.84 eventually.

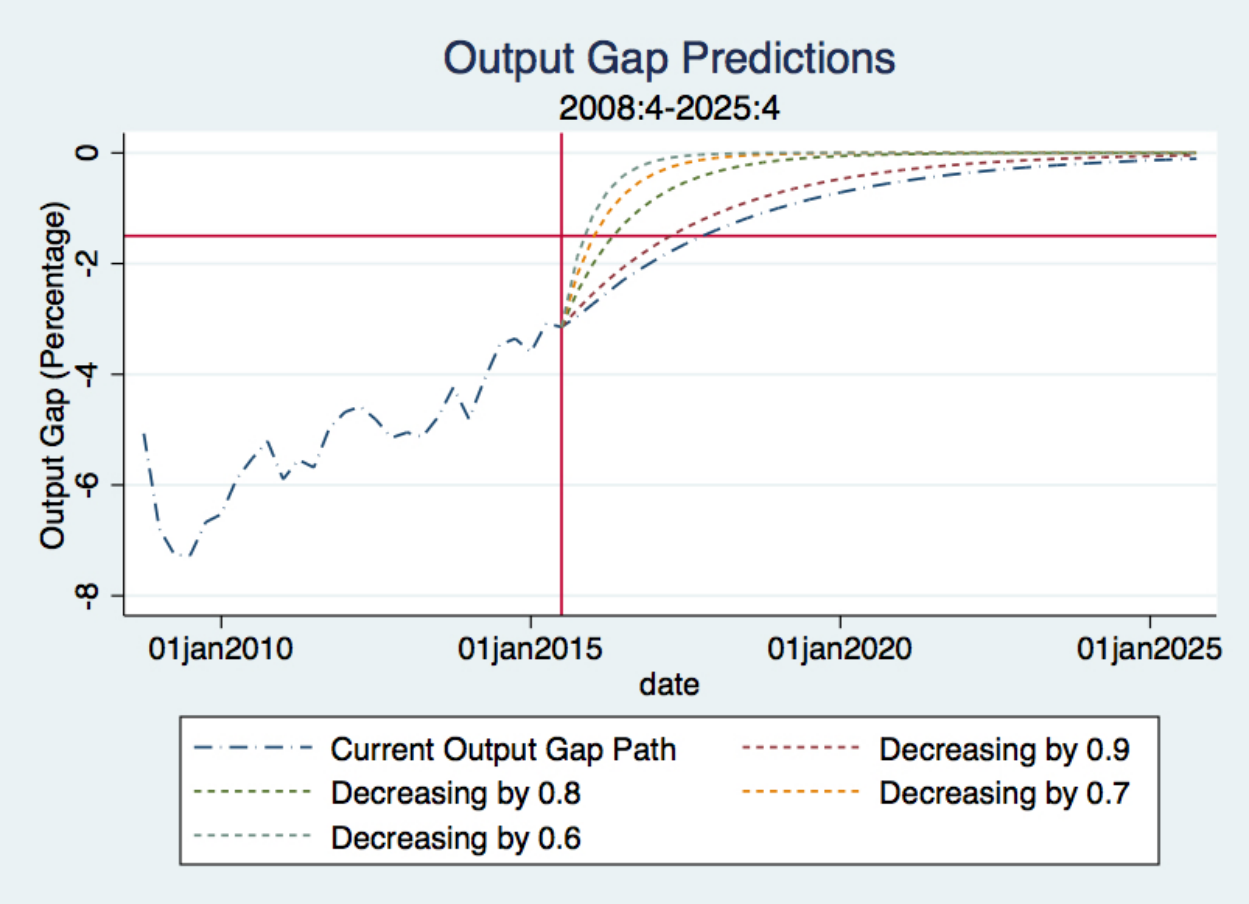

Figure 7

Notes:
Predictions of output gap start from 2015:4. The output gap using current recovery path decreases by a factor of 0.92 quarterly. The rest predictions decreases by the factors marked on the respective labels quarterly.
The horizontal line indicates when output gap is -1.5 percent, half of the current output gap.

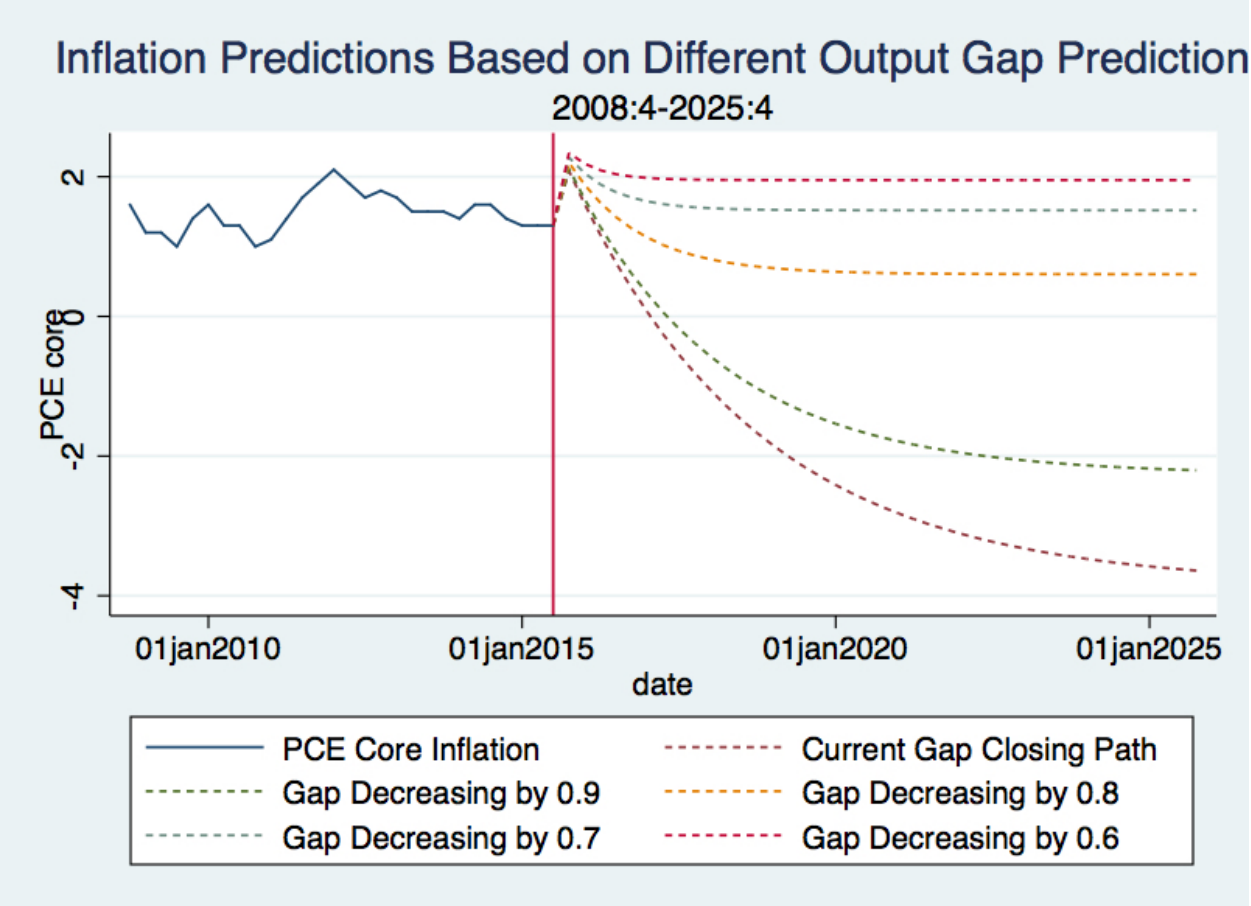

Figure 8

Notes:
Inflation is measured in percent. Predictions start from 2015:4.
Prediction with the output gap decreasing by a factor of 0.9 settles down to -2.27.
Prediction with the output gap decreasing by a factor of 0.8 settles down to 0.60.
Prediction with the output gap decreasing by a factor of 0.7 settles down to 1.52.
Prediction with the output gap decreasing by a factor of 0.6 settles down to 1.95.

Appendix

Data Sources:

Potential GDP:
GDPPOT on FRED, annual rate from US. Congressional Budget Office.

Real GDP:
GDPC1 on FRED, seasonally adjusted annual rate from US. Bureau of Economic Analysis.

Michigan Survey Inflation Expectation:
MICH on FRED, one year ahead inflation expectation, from Thomson Reuters/ University of Michigan Surveys of Consumers.

SPF Inflation Expectation:
From Philadelphia Fed, obtained mean one quarter ahead expected CPI inflation rate and one year ahead expected CPI inflation rate. Quarterly forecasts are annualized quarter-over-quarter percent changes. Annual forecasts are fourth-quarter over fourth-quarter percent changes. The CPI core, PCE, and PCE core inflation rate forecast were not gathered until 2007.