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Essays on Macroeconomics

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by

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ABSTRACT OF THE DISSERTATION

Essays on Macroeconomics

by

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University of California, Los Angeles, 2024
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This dissertation studies the effects macroeconomic policies and events on economic outcomes and welfare, using a combination of empirical analysis and quantitative modeling. The first chapter examines the effects of negative interest rate policies implemented by central banks in the aftermath of the Great Recession. The second chapter studies the timing of the Industrial Revolution and the sources of business cycle fluctuations prior to the Great Depression. Both chapters contribute to our understanding of how economic policies and events impact economic welfare.

The first chapter studies the impact of negative interest rate policies on bank lending, investment, and employment, taking into account the role of capital-labor substitution in production. Using matched firm-bank data from seven euro area countries and employing a difference-in-differences approach, I find that following the introduction of these policies, firms linked to banks with higher deposit ratios receive less credit relative to their counterparts associated with banks with lower deposit ratios. These firms also invest less but tend to hire more employees, especially in industries with high capital-labor

substitutability. These findings highlight the role of capital-labor substitution in shaping the effects of negative interest rate policies. To further analyze these findings in a general equilibrium framework and to quantify the aggregate effects of these policies, I use a DSGE model that incorporates bank lending and a CES production function. I find that negative interest rate policies increase lending, investment, employment, and welfare in consumption equivalent units. This model also reveals that higher capital-labor substitutability surprisingly leads to larger declines in output and bank equity following a negative capital productivity shock. Based on this insight, I show that welfare gains from implementing negative interest rate policies increase with capital-labor substitution, and even slight variations in capital-labor substitution elasticity can have significant implications for both the economy and banks.

The second chapter provides quantitative analyses of two striking historical episodes, the timing of the Industrial Revolution in England, and the sources of U.S. economic fluctuations between 1889-1929. Applying data from 1245-1845 within the "Malthus to Solow" framework shows that the timing of the Industrial Revolution reflects a subtle interplay between large changes in TFP and deaths from plagues. We find that U.S. economic fluctuations, including the Panics of 1893 and 1907, were driven primarily by volatile TFP, and that growth during the "Roaring Twenties" should have been even stronger, reflecting a large labor wedge that emerged around World War I.

The dissertation of Fatih Ozturk is approved.

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To my mother, for her unconditional support and eternal encouragement.

To my father and brother, for their unfailing support.

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CHAPTER 1

Capital-Labor Substitution, Negative Interest Rates, and Bank Lending: Theory and Evidence from the Euro Area

1.1 Introduction

Several central banks, including the European Central Bank, implemented negative interest rate policies to stimulate their economies following the weak recovery from the Great Financial Crisis. These policies involve imposing a fee on banks' excess reserves, effectively resulting in a negative interest rate on these funds. The objective was to motivate banks to channel their excess liquidity into the economy through loans, rather than letting them remain idle at central banks. However, the effects of such policies remain debated, with literature showing mixed results regarding their impact on stimulating economies (Heider, Saidi, & Schepens, 2021; Balloch, Koby, & Ulate, 2022).

A critical factor that is overlooked in this debate is related to how substitutable capital and labor are in production. This substitutability plays a pivotal role in determining the extent of the decrease in output after capital productivity shocks. Consequently, when the central bank aims to stimulate the economy, the magnitude of interest rate adjustments, including the decision to implement negative rates, is closely tied to this substitutability. Understanding this relationship is essential for central banks in their interest rate decisions. This is particularly true for the European Central Bank, which manages monetary policy for the Euro area. However, the Euro area is diverse, and its member countries might exhibit varying elasticities of substitution between capital and labor, stemming from differences in technologies and institutions (Knoblach & Stöckl, 2020).

In this paper, I provide both empirical and theoretical analyses to examine the impact of negative interest rate policies on bank lending, investment, and employment. I emphasize the role of capital-labor substitution in production in shaping the effects of these policies and extend the existing literature by underscoring its influence. I construct matched firm-bank data based on firms' banking relationships from seven euro area countries to identify the effects of these policies and how capital-labor substitution shapes them. To situate these empirical findings within a general equilibrium framework, I use my empirical estimates within a general equilibrium model to inform its production block. Through this model, I quantify the aggregate and welfare effects of negative interest rate policies and examine how capital-labor substitution influences these effects.

In my empirical analysis, I utilize matched firm-bank data that I construct from seven euro area countries. I employ a difference-in-differences approach in which I exploit banks' ex-ante heterogeneous exposure to these policies to causally identify the effects. Negative interest rate policies affect banks differently based on the extent to which they fund themselves through deposits (Heider, Saidi, & Schepens, 2019). Banks with higher deposit-to-asset ratios are more affected than those with lower ratios because the deposit interest rate remains at zero while the non-deposit interest rate becomes negative. As a result, banks with higher deposit ratios experience a smaller decrease in their funding costs and are, therefore, expected to lend less. The richness of my data allows me to control the demand for bank credit using four-digit-industry-country-year fixed effects. I assume that firms operating within narrowly defined industries exhibit similar credit demands. My key empirical findings are twofold.

First, banks that are more exposed to negative interest rate policies supply less credit to firms. Following the introduction of these policies, a one-standard deviation increase in the deposit-to-asset ratio leads to a 1% decrease in lending growth. This decrease is both statistically and economically significant, given that the average credit growth between the periods before and after the policies is 1.4%. While the magnitude of my estimates is smaller than those of other studies that also report negative effects on bank lending, this highlights the importance of my approach in controlling the demand for bank credit and the significance of my data, which consists of more representative firms in Europe.

Second, the decrease in lending translates into a reduction in firm investment: A one-standard deviation increase in the deposit-to-asset ratio leads to a 50 basis points decrease in investment. This decrease is also both statistically and economically significant, considering that the average change in investment between the periods before and after the policies is 3%. However, I find that firms linked to banks with higher deposit ratios often maintain or even increase employment, compared to firms linked to banks with lower deposit ratios, especially in industries with high capital-labor substitution. These observations underscore the potential influence of capital-labor substitution on the effects of negative interest rate policies.

In my theoretical analysis, I draw upon my empirical findings and consider the potential role of capital-labor substitution. I incorporate these empirical estimates into a dynamic stochastic general equilibrium (DSGE) model, which features bank lending and a normalized constant elasticity of substitution (CES) production function. Using this model, I assess the aggregate effects of negative interest rate policies, conduct a welfare analysis, and explore how the elasticity of substitution between capital and labor impacts both the aggregate effects of these policies and the welfare analysis. I have two main theoretical conclusions.

First, I find that a higher elasticity of substitution between capital and labor in production leads to a larger drop in output and bank equity following a negative shock to capital productivity. At first glance, it might seem that higher elasticity would help mitigate the economic downturn. This is because firms could more easily substitute capital with labor, potentially leading to a smaller decrease in employment and the marginal product of capital. However, this perspective overlooks the household response to the negative capital productivity shock. Households anticipate that, with a higher elasticity of substitution, the return on their savings will yield much less. This is because the return on capital drops more sharply due to a more pronounced drop in the demand for capital. Consequently, households choose to reduce their savings by more and decrease their consumption by less, as their intertemporal optimality condition suggests. As a result, they enjoy leisure more and supply less labor when the elasticity of substitution is higher.

I show that this finding has significant implications for banks. In particular, it suggests that a higher elasticity of substitution between capital and labor in production function amplifies banks' vulnerability following a negative shock to capital productivity. The return on bank loan is tied to the marginal product of capital. With a higher elasticity of substitution, the marginal product of capital decreases by more since employment drops by more. As a result, banks absorb bigger losses on their loans which hurts their equity much more. For instance, in response to the same negative shock to capital productivity, banks in an economy with the elasticity of substitution of 1.25 experience an additional 26 basis points drop in their capital ratio compared to banks in an economy with the elasticity of substitution of 1. This additional decrease in the capital ratio suggests, based on estimates from Berger & Bouwman (2013), that the default probability increases by 11%. Utilizing findings from Laeven, Ratnovski, & Tong (2016), such a decrease translates into an increase in loan losses of nearly $1 billion for a bank with total assets of $100 billion. Furthermore, this decline corresponds to a decrease in banks' quarterly stock return by 14.3 basis points, based on estimates from Demirgunc-Kunt, Detragiache, & Merrouche (2013).

I then inform the production block of my model using my cross-sectional estimates, which are well-identified macro moments, in the moment matching exercise (Nakamura & Steinsson, 2018). Specifically, I calibrate the elasticity of substitution parameter in the production function of the model to match the cross-sectional identified bank lending effects in the Euro area.

Second, using the calibrated model that features the elasticity of substitution between capital and labor in production of 1.25, I find that negative interest rate policies effectively stimulate the economy in response to a negative shock to capital productivity. This elasticity value aligns with the estimates of Karabarbounis & Neiman (2014), who found it to be 1.25 using cross-country data, and with Hubmer (2023), who estimated it at 1.35 based on US data.

In the model, comparing on-impact responses of a scenario where central banks implement negative interest rate policies to a counterfactual one where they do not, I find that bank lending is 1.33% higher with the policies in place. Concurrently, the spread between the bank loan rate and the policy rate is 65 basis points lower. Furthermore, investment is 2.52% higher when these policies are adopted. Output and employment are also higher, with increases of 44 basis points and 66 basis points, respectively, under negative interest rate policies. Welfare gains from implementing negative interest rate policies are 0.02%. This means that households would be willing to give up 0.02% of their initial consumption at the steady state in favor of negative interest rate policies.

1.1.1 Related literature

This paper is related to the literature that studies the effects of negative interest rate policies. It makes two distinct contributions to the literature.

First, it contributes to the scant literature that explores the effects of negative interest rate policies theoretically. Balloch et al. (2022) offer an insightful survey of this literature. While Eggertsson, Juelsrud, Summers, & Wold (2023) and Abadi, Brunnermeier, & Koby (2023) suggest that negative interest rates can be detrimental, research from Ulate (2021), Onofri, Peersman, & Smets (2023), and de Groot & Haas (2023) indicate that interest rate cuts in negative territory, though less effective than those in positive territory, still stimulate the economy.

In comparison to the existing literature, this paper explores the role of the substitutability of capital and labor in production when analyzing the effects of negative interest rate policies on bank lending, as well as firm investment and employment. I find that a higher elasticity of substitution between capital and labor leads to larger declines in output and bank equity following a negative capital productivity shock. Consequently, the benefits of implementing negative interest rate policies rise with this elasticity. Even minor changes in the elasticity can have profound effects on the economy and the stability of banks. This finding holds significant implications for central banks.

Second, it contributes to the large body of empirical literature that examines the effects of negative interest rates on banks and the economy. These studies vary in their empirical methodologies, as discussed in Balloch et al. (2022), which offers an excellent survey of the literature. Studies using high-frequency identification (Ampudia & Van den Heuvel, 2022) find that unexpected policy rate cuts in negative territory decrease bank equity values and have negative effects on bank stock prices. A prevalent method compares banks with different exposure levels to these policies. Studies by Amzallag, Calza, Georgarakos, & Sousa (2019) for Italy, Eggertsson et al. (2023) for Sweden, Kwan, Ulate, & Voutilainen (2023) for Finland, Balloch & Koby (2019) for Japan, and Heider et al. (2019) for the euro area indicates that more exposed banks tend to reduce lending and raise interest rates post-policy. Conversely, studies by Demiralp, Eisenschmidt, & Vlassopoulos (2021) for the euro area, Grandi & Guille (2023) and Girotti, Horny, & Sahuc (2022) for France, Basten & Mariathasan (2018) and Schelling & Towbin (2022) for Switzerland, Hong & Kandrac (2022) for Japan, and Bottero, Minoiu, Peydró, Polo, Presbitero, & Sette (2022) for Italy report opposing findings.

Compared to the existing literature, this paper constructs a matched firm-bank level dataset from seven euro area countries, enabling more precise identification of the effects of negative interest rate policies. The richness of my data allows me to control the demand for bank credit using four-digit-industry-country-year fixed effects. Furthermore, firms in the dataset come from a diverse cross-section of various industries and are highly representative of average European firms, which are unable to switch from bank credit.

The remainder of the paper is organized as follows: Section 1.2 introduces the data and outlines the empirical strategy. Section 1.3 presents the empirical results. Section 1.4 introduces the model. Section 1.5 presents the calibration of the parameter for the elasticity of substitution in production, provides results from numerical simulations, and discusses them. Section 1.6 concludes the paper.

1.2 Data and identification strategy

In this section, I first describe the data and the matching procedure used in the paper. I then turn to the identification strategy used to causally identify the effects of negative interest rate policies.

1.2.1 Data and matching

I use the Orbis dataset to construct a novel matched firm-bank dataset for the years 2011 to 2019 from seven euro area countries that implement negative interest rate policies.

1.2.1.1 Data

Orbis is the largest cross-country firm-level database, and it is frequently used in literature because it offers granular and harmonized data at both the firm and bank levels across countries. Orbis has detailed balance sheet and income statement information on millions of firms worldwide, and it covers all industries in the economy and includes both private and public firms. Furthermore, firms in Orbis report their associated banks. This information is crucial for me to construct a novel matched firm-bank level dataset.

The Orbis dataset captures a diverse cross-section of firms from various industries and is highly representative of an average European firm. Firms with fewer than 250 employees constitute a significant portion of the dataset. Such firms typically cannot switch to alternative funding sources. This sharpens my identification of the effects of bank funding on them, aligning well with my primary objective: to quantify the impact of bank credit supply on firms and their respective reactions. Some studies primarily focus on firms with access to syndicated loans, limiting their analysis to a sample dominated by very large firms.

1.2.1.2 Matching firm- and bank-level data

I match firms with their respective banks to causally identify how negative interest rate policies affect the banks' credit supply to firms and the subsequent responses of these firms.

Although firms in my data report their banks' names, linking the reported bank name to its corresponding name in Orbis is not straightforward, as there is no standardized procedure to match them. I address this challenge by employing fuzzy name matching techniques in Python to match the reported bank names with bank balance sheet data. My matching procedure achieves a matching rate of over 95%.

Kalemli-Özcan, Laeven, & Moreno (2022) employ a similar matching approach within the Orbis dataset to study the relationship between weak bank balance sheets and firm-level investment following the Great Financial Crisis. This matching technique is also used in other studies, such as Giannetti & Ongena (2012) and Ongena, Peydro, & Horen (2015), which examine the role of foreign banks in transmitting crises.

1.2.1.3 Sample

In constructing and cleaning my dataset, I follow the methodology outlined in Kalemli-Ozcan, Sorensen, Villegas-Sanchez, Volosovych, & Yesiltas (2015).

The sample covers the period from 2011 to 2019. This includes 3 years before the introduction of negative interest rate policies in 2014 and 6 years following their implementation, allowing for an analysis of both short-term and long-term effects. I exclude 2020 from the sample due to the Covid-19 crisis and the significant policy responses to it.

I restrict my sample to the non-financial sector, which includes firms with NACE Rev. 2 codes ranging from 01 to 98, with the exception of codes 64 through 66[1]. I use firms from 7 euro area countries: Austria, France, Germany, Greece, the Netherlands, Portugal, and Spain. Firms in Italy do not report their bankers, and therefore Italy is excluded from the sample.

Firms in Orbis report their outstanding short- and long-term liabilities without breaking down individual bank debts. Therefore, to identify credit supply effects, I exclude firms that borrow from multiple banks and retain only those with a single bank affiliation. While 99% of firms in France report a single bank, 60% of firms in Portugal do the same. It is common for many European firms to have a lending relationship with only one bank. Using 15 credit registries from Europe, Altavilla, Boucinha, Peydró, & Smets (2020) found that the share of firms with a single bank ranges from 54% to 90%, depending on the country.

I use unconsolidated accounts to avoid double counting when both the parent and subsidiary companies are in my dataset. In addition to the country and sector restrictions, I limit my sample to firm-year observations that consistently report key financial variables, which are assets, liabilities, bank credit, sales, and cash and cash equivalents, over a span of 9 consecutive years.

As a result, my constructed sample, covering the period from 2011 to 2019, has over 1 million observations, with 180k unique firms from 7 European countries, spanning 700 different industries and working with over 1000 different banks. Table 1.1 presents de-

[1]NACE Rev. 2 codes 64-66 refers to Financial and insurance activities.

scriptive statistics for the main regression variables, both before and after the introduction of negative interest rate policies.

1.2.2 Identification strategy

In this section, I describe the identification strategy used to causally identify the effects of negative interest rate policies on bank lending, investment, and employment, and how capital-labor substitution influences these effects.

1.2.2.1 Setting

During the Great Recession, many central banks lowered their rates to zero or very close to zero in order to provide monetary accommodation to their economies. This led them to reach the lower bound of conventional monetary policy. However, the recovery after the crisis, especially in Europe, was subdued. Consequently, several central banks in Europe, including the European Central Bank in 2014, started implementing negative interest rate policies to stimulate economic growth in their countries. Moving into negative territory is unusual, but understanding its impact on the banking sector, especially regarding their funding sources, is crucial.

Negative interest rate policies affect banks differently based on the extent to which they fund themselves through deposits. Specifically, banks with higher deposit-to-asset ratios are more affected than those with lower ratios. Both interest rates on deposits and on other funding sources follow the policy rate when it is non-negative. However, when the policy interest rate becomes negative, non-deposit interest rates follow the policy rate and also become negative, while the deposit rate remains at zero.

Banks are hesitant to transmit negative rates to their deposits (Eisenschmidt & Smets, 2019; Lopez, Rose, & Spiegel, 2020). As a result, banks with higher deposit-to-asset ratios

Table 1.1: Descriptive statistics.

Panel A:	Before, 2012-2013					
Variable	Mean	SD	p25	p50	p75	N
Asset	14.014	1.757	12.908	13.841	14.972	327579
Leverage	0.621	0.359	0.386	0.603	0.807	327579
As Annual growth $\Delta \ln(.)$						
Bank credit	-0.068	1.028	-0.357	-0.076	0.157	239159
Interest rate	0.006	1.388	-0.355	0.013	0.381	212000
Cash	-0.008	1.223	-0.487	0	0.46	321858
Net investment	-0.037	0.498	-0.219	-0.069	0.045	311041
Employment	-0.019	0.265	-0.071	0	0.022	198238
Employee expenses	-0.007	0.255	-0.078	0.004	0.078	306467
Sales	-0.017	0.336	-0.117	-0.008	0.093	327579
Material expenses	-0.027	0.505	-0.164	-0.011	0.130	276245
Panel B:	After, 2014-2019					
Variable	Mean	SD	p25	p50	p75	N
Asset	14.062	1.782	12.948	13.896	15.036	845468
Leverage	0.59	0.379	0.336	0.557	0.776	845468
As Annual growth $\Delta \ln(.)$						
Bank credit	-0.057	1.009	-0.335	-0.062	0.172	599514
Interest rate	-0.038	1.392	-0.394	-0.024	0.330	467655
Cash	0.055	1.155	-0.377	0.046	0.479	832195
Net investment	-0.007	0.506	-0.194	-0.051	0.08	795683
Employment	0.013	0.238	0	0	0.067	609433
Employee expenses	0.016	0.228	-0.048	0.015	0.091	699270
Sales	0.012	0.299	-0.068	0.010	0.105	845468
Material expenses	0.003	0.476	-0.119	0.010	0.145	632348

Notes: Based on an unbalanced sample of firms that are matched to their banks. Panel A presents descriptive statistics for the period 2012-2013. Panel B presents descriptive statistics for the period 2012-2013. Asset refers to the natural logarithm of total assets. Leverage is computed total liabilities to total assets. Bank credit is the sum of both long- and short-term financial debt. Interest rate is calculated as interest expenses to bank credit. Cash refers to cash and cash equivalent. Net investment is tangible fixed assets. Employment is the number of employees. Employee expenses refer to employees' costs (including pension costs). Sales are net sales. Material expenses are material costs. Source: My own calculations based on Orbis.

experience a decline in net interest margins, seeing a smaller reduction in their funding costs when the policy rate turns negative. Consequently, these banks are expected to lend less following the introduction of negative interest rate policies, compared to those with lower ratios.

1.2.2.2 Identification

I employ a difference-in-differences identification strategy in which I exploit banks' ex-ante heterogeneous exposure to these policies to determine how negative interest rate policies affect bank lending and how changes in bank lending translate into firm performance in terms of investment and employment.

I control for the demand for bank credit from firms using four-digit-industry-country-year fixed effects. The underlying identifying assumption is that firms within the same four-digit-industry-country-year classification experience similar demand shocks. This allows me to disentangle the effect of firms' credit demand from the banks' credit supply following the introduction of negative interest rate policies, as monetary policy reacts to macroeconomic conditions. This approach is similar to that of Degryse, De Jonghe, Jakovljević, Mulier, & Schepens (2019), which utilize the Belgian credit registry and use industry-location-size-time fixed effects to control for credit demand when firms have a single bank. I also include firm and bank fixed effects to control for the effect of their existing relationship.

I note that I capture the relative cross-sectional effects, not the overall aggregate effects. This is due to the time fixed effects in my comprehensive fixed effect structure, which absorb the aggregate impacts of negative interest rate policies. As a result, the estimates from my regressions do not directly measure the effect of negative interest rate policies on aggregate variables. However, these estimates are well-identified macro moments and will be used in a moment-matching exercise to inform the production function block of my general equilibrium model. This approach is similar to Nakamura & Steinsson (2018). To assess the impact of negative interest rate policies on the broader economy, such as their effect on total lending, as well as to conduct a welfare analysis, I use a general equilibrium model in Section 1.4.

1.2.2.3 Empirical specifications

In this section, I present the empirical specification to causally identify the effects of the policies on the variables of interest.

Effect on credit supply

To causally identify the effects of negative interest rate policies on the credit supply, I employ the following specification

$$\text{Loan growth}_{isct} = \beta \text{Deposit ratio}_b \times \text{Post}_t + \alpha_b + \delta_{sct} + \gamma' X_{isct-1} + \epsilon_{isct} \tag{1.1}$$

where Loan growth$_{isct}$ denotes loan growth at of firm i in sector s in country c in year t, and is calculated as the difference in the natural logarithm of credit between periods t and $t-1$. Deposit ratio corresponds to firm i's bank b's deposits to assets at the end of 2013. Post is a dummy variable equal to one for the years $t = \{2014, \ldots, 2019\}$ and equal to zero for the years $t = \{2012, 2013\}$. α_b is bank fixed effects, accounting for both observable and unobservable bank-specific factors. It also controls for the effect of the existing relationship between bank b and firm i. δ_{sct} is sector-country-year fixed effects. They control for time-varying sector-country fixed effects. X refers to firm-level controls. I control for leverage, which is defined as the ratio of total liabilities to total assets; sales growth, defined as the annual change in the natural logarithm of sales; cash, defined as the ratio of cash and cash equivalents to total assets; and size, determined as the logarithm of total assets. Highly leveraged firms are less likely to obtain bank credit due to their elevated default rates. Sales growth controls for firms' growth opportunities, with those exhibiting high sales growth typically expected to invest and borrow more. Holding cash reduces a firm's dependence on external financing, including bank credit. Firm size is a significant determinant of leverage, and consequently, of access to bank credit.

The estimate of β captures the causal impact of negative rates on bank lending. As previously mentioned, I expect β to be negative. This coefficient measures how much banks with higher deposit ratios, compared to those with lower deposit ratios, reduce their lending following negative interest rate policies.

I note that the inclusion of sector-country-year fixed effects, δ_{sct}, means that I cannot estimate the coefficient on Post. Similarly, including either firm fixed effect, α_i, or bank fixed effect, α_b, prevents me from estimating the coefficient on Deposit ratio.

My difference-in-differences methodology requires that firms linked to banks with higher deposit ratios and those associated with banks with lower deposit ratios should have the same loan growth trend before the introduction of negative interest rate policies. This *parallel trend assumption* is foundational to the difference-in-differences approach. To bolster the validity of my empirical strategy, I investigate whether this assumption holds true. I address this by conducting the following regression. It is an event study difference-in-differences with the time-varying regression coefficients, showing the differential evolution of loan growth between firms associated with banks with higher deposit ratios and those linked to banks with lower deposit ratios over the years.

$$\text{Loan growth}_{isct} = \sum_{t=2012}^{2019} \beta_t D_{Year=t} \times \text{Deposit ratio}_b + \alpha_b + \delta_{sct} + \gamma' X_{isct-1} + \epsilon_{isct} \tag{1.2}$$

The variable $D_{Year=t}$ is a dummy variable taking the value one if the year is equal to t, where $t = \{2012, \ldots, 2019\}$. I pick 2013 as the reference year, which is the year right before the introduction of negative interest rate policies in 2014.

The time-varying regression coefficient, β_t, captures the differential evolution of loan growth over the years between firms associated with banks with higher deposit ratios and those linked to banks with lower deposit ratios. If the coefficients for the pre-period years of 2012 and 2013 are around zero, this bolsters the *parallel trend assumption,* indicating that these firms experienced similar credit growth prior to the introduction of negative interest rate policies. I will also use the same regression framework for other variables of interest.

Effect on interest rate

I also use my baseline specification to estimate the effect on interest rate, using interest rate growth as the dependent variable in the regression. It is calculated as the difference in the natural logarithm of interest rate between periods t and $t-1$. Interest rate refers to the ratio of interest expenses to the sum of both long- and short-term financial debt as recorded in Orbis.

In this regression, where the dependent variable is interest rate growth, I expect β to be positive. This is because banks with higher deposit ratios tend to experience a decrease in profitability compared to those with lower deposit ratios, due to the mechanism mentioned above. Consequently, to boost their profits, banks with higher deposit ratios charge higher interest rates following negative interest rate policies than those with lower deposit ratios.

Effect on other financial variables

I also examine the effects on other firm-level financial variables. I check whether firms with banks more exposed to these policies switch to other funding sources. This is to verify whether my results truly stem from banks more exposed to negative interest rate policies supplying less credit to firms, compared to their peers less exposed to these policies. Consequently, I estimate the following regression, which is identical to Equation

(1.5), but with a different dependent variable.

$$\text{Firm other financial}_{isct} = \beta \text{Deposit ratio}_b \times \text{Post}_t + \alpha_b + \delta_{sct} + \gamma' X_{isct-1} + \epsilon_{isct} \quad (1.3)$$

Firm other financial is (i) leverage, calculated as the ratio of total liabilities (excluding equity) to total assets in period t and (ii) cash growth, measured as the difference in the natural logarithm of cash and cash equivalent between periods t and $t-1$.

In the regression, where the dependent variable is leverage, I expect β to be negative. This is because firms associated with banks with higher deposit ratios experience a reduction in bank credit and they cannot switch to alternative funding sources. As a result, I expect their leverage to be lower than that of firms linked to banks with lower deposit ratios. Conversely, in the regression, where the dependent variable is cash growth, I expect β to be positive. Following the credit reduction, firms associated with banks with higher deposit ratios are expected to increase their cash holding. This can be attributed to the self-financing motive (Almeida, Campello, Laranjeira, & Weisbenner, 2012).

Effect on risk taking

I also examine the effects of negative interest rate policies on bank risk-taking through bank lending. I employ my baseline specification detailed in Equation (1.1) and split the sample into safe and risky firms.

My ex-ante risk measure is based on firms' ex-ante return on asset volatility (expressed as a standard deviation) between 2011 and 2013, a period before the introduction of negative interest rate policies (Heider et al., 2019). The return on assets is calculated using the sum of operating profit and financial profits before tax, divided by assets.

I define risky firms as those with a standard deviation of their return on assets above the median of the distribution in their country, while safe firms are those with volatility below the median of that distribution.

The sign of the coefficient β depends on whether *the risk-bearing channel* or *the reaching for yield channel* is more important. According to *the risk-bearing channel*, banks tend to take less risk following a decline in their profitability. This is because they have less capital to absorb losses and to meet regulatory capital requirements. In contrast, *the reaching for yield channel* operates in the opposite direction. It posits that a decrease in bank profitability encourages banks to take on more risk by lending to riskier firms.

Effect on investment and employment

I also investigate how a change in bank lending translates into investment and employment in firms that borrow from banks more exposed to negative interest rate policies. My goal is to quantify the real effects of these policies through bank lending to firms. Consequently, I estimate the following regression, which is identical to Equation (1.1), but with a different dependent variable.

$$\text{Firm outcome growth}_{isct} = \beta \text{Deposit ratio}_b \times \text{Post}_t + \alpha_b + \delta_{sct} + \gamma' X_{isct-1} + \epsilon_{isct} \tag{1.4}$$

Firm outcome growth is (i) net investment, calculated as the difference in the natural logarithm of tangible fixed assets between periods t and $t-1$ and (ii) employment growth, defined as the difference in the natural logarithm of number of employees between periods t and $t-1$.

In the regression, where the dependent variable is net investment, I expect β to be negative. Firms associated with banks with higher deposit ratios are more likely to invest less compared to those linked to banks with lower deposit ratios. This is because capital becomes more expensive for them as their banks lend less and charge higher interest rates.

In the regression, where the dependent variable is employment, the sign of the coefficient β depends on how easily firms can substitute capital with labor. If capital and labor are complements, I expect β to be negative. However, if capital and labor are substitutes, I expect β to be positive.

Effect of elasticity of substitution on investment and employment

I examine the effects of the elasticity of substitution between capital and labor in production on investment and employment. Drawing on previous work, Herrendorf, Herrington, & Valentinyi (2015) estimate the elasticity of substitution between capital and labor by sector for the United States. They find that the primary[2] and secondary sectors[3] exhibit a higher elasticity of substitution than the tertiary[4] sector. In essence, capital and labor are less substitutable in the tertiary sector compared to other sectors. Similarly, Kopecna, Scasny, & Recka (2020) arrive at the same conclusion for the European Union.

Given these insights, for my analysis, I use the baseline specification detailed in Equation (1.1). I then divide the sample into two groups based on their sectorial elasticities: firms in sectors with higher elasticity, from the primary and secondary sectors, and those in sectors with lower elasticity, from the tertiary sectors.

In the regression, where the dependent variable is net investment, I expect β to be negative for both sectors. Firms associated with banks with higher deposit ratios are more likely to invest less compared to those linked to banks with lower deposit ratios. This is because capital becomes more expensive for them as their banks lend less and charge higher interest rates. I expect this to hold true for firms in sectors with both lower and higher elasticity.

[2]The primary sectors encompass Agriculture, Forestry and Fishing, and Mining and Quarrying.

[3]The secondary sectors cover Manufacturing; Electricity, Gas, Steam, and Air Conditioning Supply; Water Supply, Sewerage, Waste Management, and Remediation Activities; and Construction.

[4]The tertiary sectors comprise Wholesale and Retail Trade; Repair of Motor Vehicles and Motorcycles; Transport and Storage; Accommodation and Food Service Activities; Information and Communication; Real Estate Activities; Professional, Scientific, and Technical Activities; Administrative and Support Service Activities; Public Administration and Defence; Compulsory Social Security; Education; Human Health and Social Work Activities; Arts, Entertainment and Recreation; and Other Service Activities.

In contrast, in the regression, where the dependent variable is employment, the sign of the coefficient β depends on how easily firms can substitute capital with labor. If capital and labor are less substitutable (more complementary), as seen in the tertiary sector, I expect β to be negative. Conversely, if capital and labor are more substitutable (more like substitutes), as observed in the primary and secondary sectors, I expect β to be positive.

1.3 Empirical results

In this section, I present in five steps my results for the estimations outlined in the previous section. First, I document the effect of negative interest rate policies on bank lending and the lending rate. Second, I show the effects on other financial variables, leverage and cash holdings, to strengthen my lending results. Third, I present the effects on firm performance in terms of investment and employment and emphasize the role of capital-labor substitution in shaping these effects. Fourth, To provide further evidence supporting my empirical approach, I examine whether the *parallel trend assumption* is satisfied. Fifth, I investigate whether there is an increase in risk taking.

1.3.1 Lending and lending rate

Table 1.2 reports lending results.

The estimated coefficient on the interaction term, β, shown in Columns (1) to (4) of Table 1.2, is negative and highly significant. This suggests that firms with banks more exposed to negative interest rate policies receive less bank credit compared to firms with less exposed banks following the introduction of these policies.

Based on the estimate in Column (1), in terms of economic significance, a one-standard deviation increase in the deposit-to-asset ratio leads to a 1% decrease in lending growth. This decrease is relevant and economically significant, especially considering that the

Table 1.2: Negative Interest Rates and Bank Credit Supply

Dependent variable:	Loan growth			
	(1)	(2)	(3)	(4)
Deposit ratio × Post	-0.0594**	-0.0598**		
(%)	(0.0252)	(0.0251)		
Deposit ratio × Post			-0.0209***	-0.0208***
(0/1)			(0.00777)	(0.00770)
Firm Control	No	Yes	No	Yes
Bank FE	Yes	Yes	Yes	Yes
Country-Industry-Time FE	Yes	Yes	Yes	Yes
Observations	735780	735780	735780	735780
R^2	0.0273	0.0280	0.0273	0.0280

Notes: The table presents OLS estimates of the following model at the bank-firm level.

$$\text{Loan growth}_{isct} = \beta \text{Deposit ratio}_b \times \text{Post}_t + \alpha_b + \delta_{sct} + \gamma' X_{isct-1} + \epsilon_{isct}$$

The dependent variable is loan growth at the firm-bank level and is calculated as the difference in the natural logarithm of credit between periods t and $t-1$. Credit refers to the sum of long- and short-term financial debt recorded in Orbis. The deposit ratio, presented in Columns (1) and (2), denotes the ratio of deposits over total assets (in %) for the year 2013. In Columns (3) and (4), the deposit ratio is assigned a value of one if the ratio of deposits to total assets in 2013 is above the median of its respective country's distribution. Post is a dummy variable representing the period from 2014 onward. The set of firm control variables (not reported) includes i) size, measured as the logarithm of total assets, ii) leverage, defined as the ratio of total liabilities to total assets, iii) sales growth, measured as the annual change in the natural logarithm of sales, iv) cash, defined as the ratio of cash and cash equivalents to total assets. Bank fixed effects are included. Country-Industry-Time fixed effects are based on four-digit NACE Rev.2 codes. Robust standard errors, clustered at the bank level, are in parentheses. ***, **, and * indicate significance at 1%, 5%, and 10%, respectively.

average credit growth between the periods before and after the policies is 1.4%.

The result is robust when adding firm-level variables in Column (2) to control for observable determinants of credit demand. In Columns (3) and (4), I modify the exposure measure, the main independent variable, from continuous to binary. This new independent variable takes a value of one if the deposit-to-asset ratio is above the median within its country's deposit-to-asset distribution. The coefficient on the interaction term is negative and statistically significant. This suggests that banks more exposed to policies, relative to their less exposed counterparts, supply less credit. The resulting decrease in lending growth is equal to 2%.

My findings align with prior research that reports negative effects on bank lending. However, the magnitude of the effects that I have identified is notably smaller than that found in some other studies. For instance, Heider et al. (2019) find a decrease of 13% following a one-standard deviation increase in the deposit-to-asset ratio, while Eggertsson et al. (2023) report a decline of 2.6%. In contrast, my research suggests a more moderate decrease of 1%. One potential reason for this difference might be the unique strengths and precision of my dataset. Firstly, firms in my dataset, representative of an average European business, predominantly rely on bank credit, making it an ideal sample to study lending effects with greater accuracy. Secondly, I comprehensively control bank credit demand using four-digit-industry-country-year fixed effects spanning 708 industries across 7 countries over an 8-year period, with the assumption that firms within specific industries have similar credit needs.

Moving to the interest rate results in Table 1.3, I note that the coefficients in Columns (1) to (4) are positive and statistically significant. This implies that banks more exposed to negative interest rate policies charge higher interest rates than their less exposed counterparts. This approach aligns with their aim to boost their profitability.

Based on the estimate in Column (1), in terms of the economic significance, a one-

Table 1.3: Negative Interest Rates and Loan Interest Rate

Dependent variable:	Interest rate growth			
	(1)	(2)	(3)	(4)
Deposit ratio × Post	0.0716**	0.0727**		
(%)	(0.0364)	(0.0365)		
Deposit ratio × Post			0.0209*	0.0211*
(0/1)			(0.0111)	(0.0111)
Firm Control	No	Yes	No	Yes
Bank FE	Yes	Yes	Yes	Yes
Country-Industry-Time FE	Yes	Yes	Yes	Yes
Observations	580228	580228	580228	580228
R^2	0.0325	0.0328	0.0325	0.0328

Notes: The table presents OLS estimates of the following model at the bank-firm level.

$$\text{Interest rate growth}_{isct} = \beta \text{Deposit ratio}_b \times \text{Post}_t + \alpha_b + \delta_{sct} + \gamma' X_{isct-1} + \epsilon_{isct}$$

The dependent variable is interest rate growth at the firm-bank level and is calculated as the difference in the natural logarithm of interest rate between periods t and $t-1$. Interest rate refers to the ratio of interest expenses to the sum of long- and short-term financial debt as recorded in Orbis. The deposit ratio, presented in Columns (1) and (2), denotes the ratio of deposits over total assets (in %) for the year 2013. In Columns (3) and (4), the deposit ratio is assigned a value of one if the ratio of deposits to total assets in 2013 is above the median of its respective country's distribution. Post is a dummy variable representing the period from 2014 onward. The set of firm control variables (not reported) includes i) size, measured as the logarithm of total assets, ii) leverage, defined as the ratio of total liabilities to total assets, iii) sales growth, measured as the annual change in the natural logarithm of sales, iv) cash, defined as the ratio of cash and cash equivalents to total assets. Bank fixed effects are included. Country-Industry-Time fixed effects are based on four-digit NACE Rev.2 codes. Robust standard errors, clustered at the bank level, are in parentheses. ***, **, and * indicate significance at 1%, 5%, and 10%, respectively.

standard deviation increase in the deposit-to-asset ratio leads to a 11 basis points increase in interest rate. This increase is both relevant and economically significant, especially when considering that the cost associated with the inability to pass on negative rates to depositors stands at around 25 basis points, given the average deposit-to-asset ratio of 50%.

1.3.2 Leverage and cash holding

Table 1.4 reports the effects on other financial variables, leverage and cash holdings.

Beginning with the leverage results, I observe that the coefficients in Columns (1) and (2) are positive and statistically significant at the 1 percent level. This suggests that firms with more exposed banks cannot substitute the decrease in bank credit with other funding sources, resulting in a reduction of their leverage ratio.

Turning to the cash holdings results, I observe that the coefficients in Columns (3) and (4) are positive and statistically significant. This indicates that firms associated with banks more exposed to negative interest rate policies increase their cash holdings more than their counterparts linked to less exposed banks, following the introduction of these policies. Such behavior is consistent with their self-financing motive.

The result is robust to adding firm level variables to control for observable determinants of credit demand and changing the main dependent variable from continuous to binary.

These results verify my results truly stem from banks more exposed to negative interest rate policies supplying less credit to firms, compared to their peers less exposed to these policies.

Table 1.4: Negative Interest Rates and Other Firm Financial Variables

Dependent variable:	Leverage		Cash growth	
	(1)	(2)	(3)	(4)
Deposit ratio × Post	-0.00687***		0.0610**	
(%)	(0.00214)		(0.0252)	
Deposit ratio × Post		-0.00275***		0.0119**
(0/1)		(0.000689)		(0.00599)
Firm Control	Yes	Yes	Yes	Yes
Firm FE	Yes	Yes	Yes	Yes
Bank FE	Yes	Yes	Yes	Yes
Country-Industry-Time FE	Yes	Yes	Yes	Yes
Observations	1016143	1016143	997570	997570
R^2	0.914	0.914	0.205	0.205

Notes: The table presents OLS estimates of the following model at the bank-firm level.

$$\text{Leverage}_{isct} = \beta \text{Deposit ratio}_b \times \text{Post}_t + \alpha_i + \delta_{sct} + \gamma' X_{isct-1} + \epsilon_{isct}$$
$$\text{Cash growth}_{isct} = \beta \text{Deposit ratio}_b \times \text{Post}_t + \alpha_i + \delta_{sct} + \gamma' X_{isct-1} + \epsilon_{isct}$$

The dependent variable in Columns (1) and (2) is leverage at the firm level and is calculated as the ratio of total liabilities to total assets in period t. The dependent variable in Columns (3) and (4) is cash growth at the firm level and is calculated as the difference in the natural logarithm of cash and cash equivalent between periods t and $t-1$. The deposit ratio, presented in Columns (1) and (3), denotes the ratio of deposits over total assets (in %) for the year 2013. In Columns (2) and (4), the deposit ratio is assigned a value of one if the ratio of deposits to total assets in 2013 is above the median of its respective country's distribution. Post is a dummy variable representing the period from 2014 onward. The set of firm control variables (not reported) includes i) size, measured as the logarithm of total assets, ii) leverage, defined as the ratio of total liabilities to total assets, iii) sales growth, measured as the annual change in the natural logarithm of sales, iv) cash, defined as the ratio of cash and cash equivalents to total assets. Bank fixed effects are included. Country-Industry-Time fixed effects are based on four-digit NACE Rev.2 codes. Robust standard errors, clustered at the bank level, are in parentheses. ***, **, and * indicate significance at 1%, 5%, and 10%, respectively.

1.3.3 Investment and employment

My lending results show that banks more exposed to negative interest rate policies reduce their credit supply to firms borrowing from them, relative to banks that are less exposed, after these policies are implemented. In this section, I study how a decrease in bank lending translates into investment and employment in firms that borrow from banks more exposed to negative interest rate policies and how capital-labor substitution shapes these effects.

Table 1.5 reports the effects on real firm outcomes, investment and employment.

Beginning with the investment results, the estimated coefficient on the interaction term, β, shown in Columns (1) to (4) of Table 1.5, is negative and highly significant. This suggests that firms with banks more exposed to negative interest rate policies invest less compared to firms with less exposed banks following the introduction of these policies.

Based on the estimate in Column (1), in terms of the economic significance, a one-standard deviation increase in the deposit-to-asset ratio leads to an approximately 50 basis points decrease in investment. This decrease is relevant and economically significant, especially considering that the average change investment between the periods before and after the policies is 3%.

The result is robust when adding firm-level variables in Column (2) to control for observable determinants of investment.

In Columns (3) and (4), I modify the exposure measure, the main independent variable, from continuous to binary. This new independent variable takes a value of one if the deposit-to-asset ratio is above the median within its country's deposit-to-asset distribution. The coefficient on the interaction term is negative and statistically significant. This suggests that banks more exposed to policies, compared to their less exposed counterparts, supply less credit. The resulting decrease in lending growth is equal to 60 basis

Table 1.5: Negative Interest Rates and Investment

Dependent variable:	Net investment			
	(1)	(2)	(3)	(4)
Deposit ratio × Post	-0.0274***	-0.0261***		
(%)	(0.00994)	(0.00993)		
Deposit ratio × Post			-0.00591*	-0.00590**
(0/1)			(0.00306)	(0.00301)
Firm Control	No	Yes	No	Yes
Firm FE	Yes	Yes	Yes	Yes
Country-Industry-Time FE	Yes	Yes	Yes	Yes
Observations	955772	955772	955772	955772
R^2	0.199	0.211	0.199	0.211

Notes: The table presents OLS estimates of the following model at the bank-firm level.

$$\text{Net investment}_{isct} = \beta \text{Deposit ratio}_b \times \text{Post}_t + \alpha_i + \delta_{sct} + \gamma' X_{isct-1} + \epsilon_{isct}$$

The dependent variable is net investment at the firm level and is calculated as the difference in the natural logarithm of tangible fixed assets between periods t and $t-1$. The deposit ratio, presented in Columns (1) and (2), denotes the ratio of deposits over total assets (in %) for the year 2013. In Columns (3) and (4), the deposit ratio is assigned a value of one if the ratio of deposits to total assets in 2013 is above the median of its respective country's distribution. Post is a dummy variable representing the period from 2014 onward. The set of firm control variables (not reported) includes i) size, measured as the logarithm of total assets, ii) leverage, defined as the ratio of total liabilities to total assets, iii) sales growth, measured as the annual change in the natural logarithm of sales, iv) cash, defined as the ratio of cash and cash equivalents to total assets. Bank fixed effects are included. Country-Industry-Time fixed effects are based on four-digit NACE Rev.2 codes. Robust standard errors, clustered at the bank level, are in parentheses. ***, **, and * indicate significance at 1%, 5%, and 10%, respectively.

points.

These findings contrast with the conclusions of Bittner, Bonfim, Heider, Saidi, Schepens, & Soares (2022), Bottero et al. (2022), and Altavilla, Burlon, Giannetti, & Holton (2022), who find increase in investment in firms associated with banks more exposed to policies. The divergence arises because, while they observe positive effects on bank lending, I identify negative effects. Less credit translates into less investment, as capital financing becomes more costly for firms associated with banks that are more exposed to negative interest rate policies.

Moving to the employment results in Table 1.6, I observe that the coefficients in Columns (1) and (2) are positive, but they are not statistically significant and do not differ from zero. This suggests that firms associated with banks more exposed to negative interest rate policies might attempt to substitute capital with labor, as capital becomes more expensive due to their banks charging higher rates. Such behavior hints that capital and labor could be gross substitutes in production. To assess the robustness of this result, I change the dependent variable to payroll expenses in Columns (3) and (4). Consistent with the initial result, the coefficient associated with the interaction term remains positive, but is not statistically significant.

In Table 1.10 in Appendix 1.7.2, to further support my argument that firms associated with more exposed banks increase their employment compared to those linked to less exposed banks, I examine the effects on output growth, defined as the annual change in the natural logarithm of output, and on intermediate input growth in production, defined as the annual change in the natural logarithm of materials. I find that the coefficients on the interaction term in both the output regression and the intermediate input regression are positive, though not statistically significant.

The coefficient on the interaction term suggests there is no significant difference in output growth between firms associated with more exposed banks and those linked to

Table 1.6: Negative Interest Rates and Employment

Dependent variable:	Employment growth		Employee expenses growth	
	(1)	(2)	(3)	(4)
Deposit ratio × Post	0.00489		0.00234	
(%)	(0.00901)		(0.00525)	
Deposit ratio × Post		0.00133		0.00169
(0/1)		(0.00179)		(0.00164)
Firm Control	Yes	Yes	Yes	Yes
Firm FE	Yes	Yes	Yes	Yes
Country-Industry-Time FE	Yes	Yes	Yes	Yes
Observations	701950	701950	861511	861511
R^2	0.187	0.187	0.223	0.223

Notes: The table presents OLS estimates of the following model at the bank-firm level.

$$\text{Employment growth}_{isct} = \beta \text{Deposit ratio}_b \times \text{Post}_t + \alpha_i + \delta_{sct} + \gamma' X_{isct-1} + \epsilon_{isct}$$
$$\text{Employee expenses growth}_{isct} = \beta \text{Deposit ratio}_b \times \text{Post}_t + \alpha_i + \delta_{sct} + \gamma' X_{isct-1} + \epsilon_{isct}$$

The dependent variable in Columns (1) and (2) is employment growth at the firm level and is calculated as the difference in the natural logarithm of number of employees between periods t and $t-1$. The dependent variable in Columns (3) and (4) is employee expenses growth at the firm level and is calculated as the difference in the natural logarithm of employee expenses between periods t and $t-1$. Employee expenses refer to the employees costs of the company (including pension costs) in Orbis. The deposit ratio, presented in Columns (1) and (3), denotes the ratio of deposits over total assets (in %) for the year 2013. In Columns (2) and (4), the deposit ratio is assigned a value of one if the ratio of deposits to total assets in 2013 is above the median of its respective country's distribution. Post is a dummy variable representing the period from 2014 onward. The set of firm control variables (not reported) includes i) size, measured as the logarithm of total assets, ii) leverage, defined as the ratio of total liabilities to total assets, iii) sales growth, measured as the annual change in the natural logarithm of sales, iv) cash, defined as the ratio of cash and cash equivalents to total assets. Bank fixed effects are included. Country-Industry-Time fixed effects are based on four-digit NACE Rev.2 codes. Robust standard errors, clustered at the bank level, are in parentheses. ***, **, and * indicate significance at 1%, 5%, and 10%, respectively.

less exposed banks. However, given that firms with more exposed banks experience reduced capital yet maintain similar output levels, it is logical to infer that these firms have increased their labor to compensate for the decreased capital, especially considering that intermediate inputs remain consistent across both types of firms.

1.3.3.1 Effect of elasticity of substitution on investment and employment

Table 1.7 reports the effects of the elasticity of substitution on both investment and employment for sectors with higher and lower elasticity of substitution.

Starting with the investment results, the estimated coefficient on the interaction term, β, shown in Columns (1) to (2) of Table 1.7, is negative. This observation is consistent and appears unrelated to the sector's elasticity of substitution. This is because firms associated with banks with higher deposit ratios charge higher interest rates on their loans, making capital more expensive.

Turning to the employment results, the coefficient in Column (3) is positive and statistically significant. This underscores that firms in sectors with higher elasticity of substitution increase their employment. Conversely, the coefficient in Column (4) is negative, but not statistically significant, and does not differ from zero. This suggests that firms operating in sectors with production technology characterized by lower elasticity of substitution did not increase their employment.

These employment findings indicate that firms linked to banks more exposed to negative interest rate policies increase their employment compared to firms with less exposed banks, but this is mostly observed in sectors that feature a higher elasticity of substitution after the introduction of these policies. This observation aligns with the findings of Laeven, McAdam, & Popov (2023) who draw a similar conclusion when studying the effects of the credit crunch on Spanish firms in the aftermath of the Great Financial Crisis.

Table 1.7: Negative Interest Rates and Elasticity of Substitution

Dependent variable:	Net investment		Employment growth	
	(1)	(2)	(3)	(4)
Sample:	Primary & Secondary	Tertiary	Primary & Secondary	Tertiary
Deposit ratio × Post	-0.0188	-0.0305***	0.0278**	-0.00801
(%)	(0.0161)	(0.0116)	(0.0125)	(0.0107)
Firm Control	Yes	Yes	Yes	Yes
Firm FE	Yes	Yes	Yes	Yes
Country-Industry-Time FE	Yes	Yes	Yes	Yes
Observations	346739	609033	243474	458476
R^2	0.215	0.209	0.183	0.180

Notes: The table presents OLS estimates of the following model at the bank-firm level.

$$\text{Net investment}_{isct} = \beta \text{Deposit ratio}_b \times \text{Post}_t + \alpha_i + \delta_{sct} + \gamma' X_{isct-1} + \epsilon_{isct}$$
$$\text{Employment growth}_{isct} = \beta \text{Deposit ratio}_b \times \text{Post}_t + \alpha_i + \delta_{sct} + \gamma' X_{isct-1} + \epsilon_{isct}$$

The dependent variable in Columns (1) and (2) is net investment at the firm level and is calculated as the difference in the natural logarithm of tangible fixed assets between periods t and $t-1$. The sample is restricted to firms in Primary (agriculture and mining) and Secondary (manufacturing, electricity and water supply, and construction) sectors in Column (1) and firms in Tertiary (wholesale trade, transportation, accommodation, information and communication, real estate, professional services, education, health) sector in Column (2). The dependent variable in Columns (3) and (4) is employment growth at the firm level and is calculated as the difference in the natural logarithm of number of employees between periods t and $t-1$. The sample is restricted to firms in Primary (agriculture and mining) and Secondary (manufacturing, electricity and water supply, and construction) sectors in Column (3) and firms in Tertiary (wholesale trade, transportation, accommodation, information and communication, real estate, professional services, education, health) sector in Column (4). The deposit ratio denotes the ratio of deposits over total assets (in %) for the year 2013. Post is a dummy variable representing the period from 2014 onward. The set of firm control variables (not reported) includes i) size, measured as the logarithm of total assets, ii) leverage, defined as the ratio of total liabilities to total assets, iii) sales growth, measured as the annual change in the natural logarithm of sales, iv) cash, defined as the ratio of cash and cash equivalents to total assets. Bank fixed effects are included. Country-Industry-Time fixed effects are based on four-digit NACE Rev.2 codes. Robust standard errors, clustered at the bank level, are in parentheses. ***, **, and * indicate significance at 1%, 5%, and 10%, respectively.

1.3.4 Checking parallel trend assumption

Figure 1.1 displays the time-varying regression coefficients of the model relative to the year 2013, using loan growth as the dependent variable, with the confidence intervals of a 90% confidence level. The coefficient is not statistically different from zero for the pre-period years of 2012 and 2013, but it becomes negative and significant at the 10 percent level from 2014 through 2019. This provides further support for the causal interpretation of my results.

In Appendix 1.7.1, I present figures for leverage (see Figure 1.6), cash holdings (see Figure 1.7), and investment (see Figure 1.8), similar to the previous one on credit growth, to assess whether a trend exists before the introduction of the policy. The results remain consistent: the coefficients are not statistically different from zero for the pre-policy years of 2012 and 2013. Following the policy's introduction in 2014, they become significant.

1.3.5 Risk-taking

Table 1.8 reports the effects of negative interest rate policies on risk-taking through bank lending, splitting the sample into safe and risky firms. In Columns (1) and (2), the risk measure is based on the sum of operating and financial profits over assets. In Columns (3) and (4), the risk measure uses EBITDA, which is defined as the sum of operating profits and depreciation, over sales.

The estimated coefficient for the interaction term of safe firms in Column (1) is negative, but not statistically significant. In contrast, the coefficient for risky firms in Column (2) is negative and is statistically significant, with a much larger magnitude than in Column (1). Moving to the estimated coefficients in Columns (3) and (4), I find that the decrease in bank credit for safe firms is smaller than that for risky firms. These results suggest that banks with higher deposit ratios supply less credit to risky firms than to safe

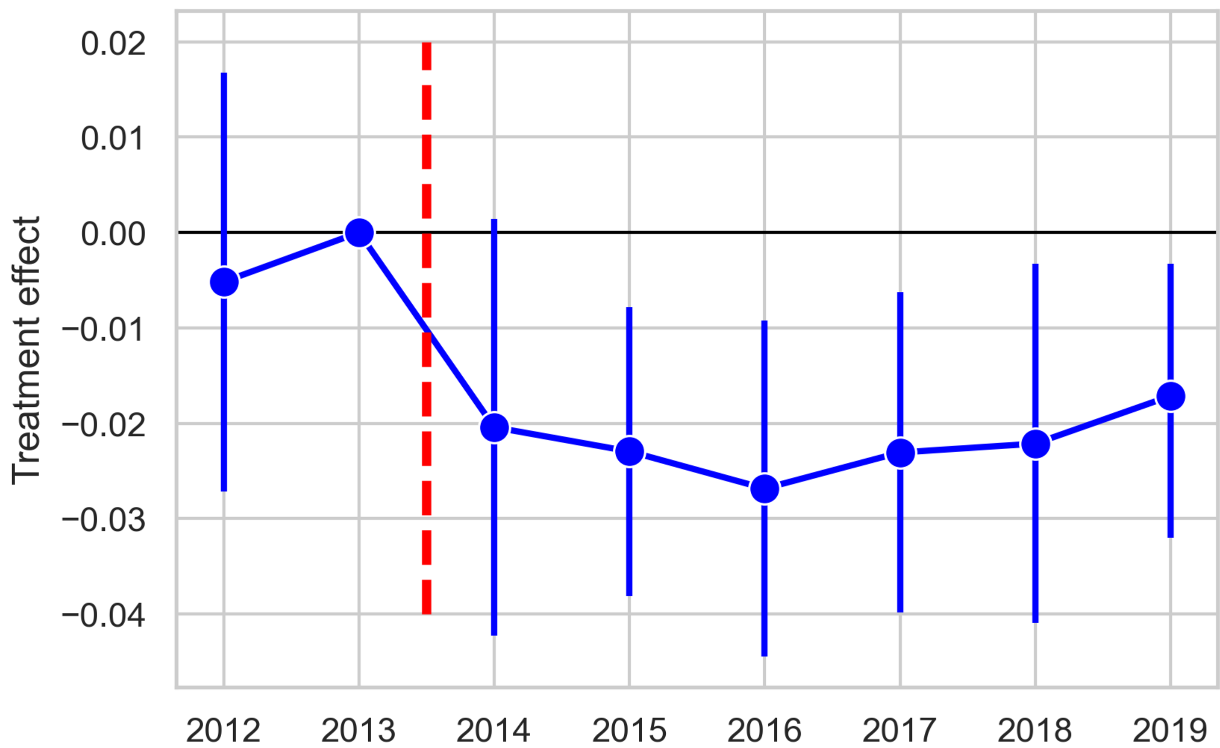

Figure 1.1: Impact of negative interest rate policies on bank credit supply.

Note: This figure plots the coefficient estimates $\hat{\beta}_t$ of the following model at the bank-firm level:

$$\text{Loan growth}_{isct} = \sum_{t=2012}^{2019} \beta_t D_{\text{Year}=t} \times \text{Deposit ratio}_b + \alpha_b + \delta_{sct} + \gamma' X_{isct-1} + \epsilon_{isct}$$

$\hat{\beta}_t$ is time-varying treatment effect of negative rates on loan growth. Vertical bars correspond to 90% confidence intervals. $D_{Year=t}$ is dummy variable taking the value one if the year is equal to t, where $t = \{2012, \ldots, 2019\}$. The year 2013 is the reference year. The dependent variable is loan growth at the firm-bank level and is calculated as the difference in the natural logarithm of credit between periods t and $t-1$. Credit refers to the sum of both long- and short-term financial debt as recorded in Orbis. The deposit ratio denotes the ratio of deposits over total assets (in %) for the year 2013. The set of firm control variables (not reported) includes i) size, measured as the logarithm of total assets, ii) leverage, defined as the ratio of total liabilities to total assets, iii) sales growth, measured as the annual change in the natural logarithm of sales, iv) cash, defined as the ratio of cash and cash equivalents to total assets. Bank fixed effects are included. Country-Industry-Time fixed effects are based on four-digit NACE Rev.2 codes. Robust standard errors are clustered at the bank level.

Table 1.8: Negative Interest Rates and Risk Taking

Dependent Variable	Loan growth			
	(1)	(2)	(3)	(4)
Sample:	Safe	Risky	Safe	Risky
Deposit ratio × Post	-0.0290	-0.0955***	-0.0487*	-0.0698*
	(0.0277)	(0.0353)	(0.0283)	(0.0358)
Firm Control	Yes	Yes	Yes	Yes
Bank FE	Yes	Yes	Yes	Yes
Country-Industry-Time FE	Yes	Yes	Yes	Yes
Observations	354462	314136	346068	317820
R^2	0.0392	0.0424	0.0394	0.0403

Notes: The table presents OLS estimates of the following model at the bank-firm level.

$$\text{Loan growth}_{isct} = \beta \text{Deposit ratio}_b \times \text{Post}_t + \alpha_b + \delta_{sct} + \gamma' X_{isct-1} + \epsilon_{isct}$$

The dependent variable is loan growth at the firm-bank level and is calculated as the difference in the natural logarithm of credit between periods t and $t-1$. Credit refers to the sum of both long- and short-term financial debt as recorded in Orbis. The sample is restricted to safe firms in Columns (1) and (3). The sample is restricted to risky firms in Columns (2) and (4). In Columns (1) and (2), a firm is assumed to be safe when the standard deviation of its return on assets (using the sum of operating profit and financial profits before tax) before 2014 is below the median of the distribution in its country, while risky firms are those whose standard deviation of its return on assets is above the median of that distribution. In Columns (3) and (4), a firm is assumed to be safe when the standard deviation of its return on sales (using the sum of operating profit and depreciation) before 2014 is below the median of the distribution in its country, while risky firms are those whose standard deviation of its return on assets is above the median of that distribution. The deposit ratio denotes the ratio of deposits over total assets (in %) for the year 2013. Post is a dummy variable representing the period from 2014 onward. The set of firm control variables (not reported) includes i) size, measured as the logarithm of total assets, ii) leverage, defined as the ratio of total liabilities to total assets, iii) sales growth, measured as the annual change in the natural logarithm of sales, iv) cash, defined as the ratio of cash and cash equivalents to total assets. Bank fixed effects are included. Country-Industry-Time fixed effects are based on four-digit NACE Rev.2 codes. Robust standard errors, clustered at the bank level, are in parentheses. ***, **, and * indicate significance at 1%, 5%, and 10%, respectively.

firms following negative interest rate policies.

This evidence is consistent with *the risk-bearing channel*. According to this channel, following a decline in bank profitability, banks tend to take less risk. This is because they have less capital to absorb losses and to meet regulatory capital requirements. This channel operates in the opposite direction of *the reaching for yield channel*, which posits that a decrease in bank profitability encourages banks to take on more risk by lending to riskier firms.

This result aligns with the findings of Arce, Garcia-Posada, Mayordomo, & Ongena (2021), who find that more exposed banks provide less credit to risky firms compared to their safer counterparts, and of Boungou (2020), who finds that banks taking less risks in countries after negative interest rates have been introduced.

1.4 Model

In this section, I present the model that I will use to study the aggregate effects of negative interest rate policies and to understand the role of capital-labor substitution in shaping these effects. This model will then be used for the numerical simulations in Section 1.5.

I utilize a New Keynesian DSGE model based on Ulate (2021), which extends Gertler & Karadi (2011) with monopolistic banks a la Gerali, Neri, Sessa, & Signoretti (2010). While Ulate (2021) employs a Cobb Douglas production function, I use a normalized CES production function, which nests the Cobb Douglas production function. The novelty of my model is that it considers the role of capital-labor substitution in shaping the effects of negative interest rate policies, drawing from my empirical findings. Specifically, I consider different substitution elasticities between capital and labor in production—a critical but overlooked factor in debates about negative interest rate policies. As I discuss in subsequent sections, even minor variations in this elasticity of substitution between capital and labor in production have considerable implications for the economy, banks, and welfare.

The model consists of households, intermediate goods producers, capital producers, retailers, banks, government, and central bank. Households work, consume, and save through bank deposits. Intermediate goods firms use capital and labor to produce intermediate inputs. Retailers transform these inputs into retail goods, which are then used to produce final consumption goods. Capital producers produce new capital. Banks collect deposits from households, lend to intermediate goods firms, and invest in central bank reserves. The central bank conducts monetary policy through a Taylor rule and can set negative interest rates on reserves.

In addition, households exhibit habit formation, and capital producers face investment adjustment costs. These features help capture business cycles in a more realistic manner. They are essential for quantifying the role of capital-labor substitution in shaping the effects of negative interest rates and for welfare analysis

1.4.1 Households block

The economy is populated by a continuum of households of mass one. Households consume, C_t, supply labor, N_t, and save in bank deposits, D_t. Bank deposits are one-period contracts that yield nominal gross interest return $1 + i^d_{t-1}$ from period $t-1$ to t.

In the utility function below, β represents households' discount factor, h denotes their habit formation behavior, χ is labor utility weight, and η stands for the Frisch elasticity of labor supply.

Households maximize their expected lifetime discounted utility:

$$\max_{C_t, D_t} E_0 \sum_{t=0}^{\infty} \beta^t \left[\ln(C_t - hC_{t-1}) - \chi \frac{N_t^{1+\frac{1}{\eta}}}{1+\frac{1}{\eta}} \right], \tag{1.5}$$

subject to their budget constraint:

$$P_t C_t + D_t = W_t N_t + \Pi_t - T_t + (1 + i^d_{t-1}) D_{t-1}, \tag{1.6}$$

where P_t is price level, W_t is nominal wage, Π_t is nominal profits to households from ownership of banks and firms, T_t is nominal lump sum taxes.

The first order conditions are as follows with respect to labor supply, bank deposits, and consumption.

$$\chi N_t^{\frac{1}{\eta}} = \phi_t \frac{W_t}{P_t} \tag{1.7}$$

$$1 = E_t \left[\beta \Lambda_{t,t+1} (1 + i^d_t) \frac{P_t}{P_{t+1}} \right] \tag{1.8}$$

$$\phi_t = (C_t - hC_{t-1})^{-1} - \beta h E_t (C_{t+1} - hC_t)^{-1} \tag{1.9}$$

$$\Lambda_{t,t+1} = \frac{\phi_{t+1}}{\phi_t}, \tag{1.10}$$

where $\Lambda_{t,t+1}$ is the stochastic discount factor.

1.4.2 Firms block

There are three firms in this block: intermediate goods producers, capital producing firms, and retailers.

1.4.2.1 Intermediate goods producers

Intermediate goods producers produce intermediate inputs using capital and labor following the normalized CES production function.

I choose to work with the normalized CES production function for two reasons. First, the empirical results presented in the previous section suggest a potential departure from the Cobb Douglas production function concerning its elasticity of substitution between capital and labor. Given this, I aim to understand how responses to negative interest rate policies, as captured by the impulse response functions, vary when the elasticity differs from what the Cobb Douglas production function implies. Second, Cantore & Levine (2012) and others[5] argue that normalization of CES production function is essential when compare economies that are distinguished solely by their substitution parameters because using non-normalized CES production not only obscures calibration results but could also affect dynamic responses to shocks as the elasticity of output with respect to production inputs can change at different steady state. Without normalization, a meaningful and consistent comparison would be unattainable.

At the end of period $t-1$, intermediate good producers borrow an amount of capital K_t from their banks to use in the next period t in their production. After the production, they return the capital to their banks. And there are no capital adjustment costs at intermediate good producers.

The firm produces intermediate output Y_t^m according to the normalized CES production function relating their output (Y_t^m) to capital (K_t) and labor (N_t):

$$Y_t^m = Y_0 A_t \left[\alpha_0 \left(\frac{K_t}{K_0} \xi_t \right)^{\frac{\sigma-1}{\sigma}} + (1-\alpha_0) \left(\frac{N_t}{N_0} \right)^{\frac{\sigma-1}{\sigma}} \right]^{\frac{\sigma}{\sigma-1}}, \tag{1.11}$$

where σ is the elasticity of substitution between capital and labor, α_0 is capital share, and Y_0, K_0, N_0 are the steady-state values resulting from the normalization associated with the normalized CES production function. A_t denotes total factor productivity and ξ_t denotes the quality of capital.

Let P_t^m be the price of intermediate goods output. Then the firm chooses its labor

[5] The other papers using the normalized CES production function are de la Grandville & Solow (2009); León-Ledesma, McAdam, & Willman (2010); Klump, McAdam, & Willman (2012); Cantore & Levine (2012); Cantore, Leon-Ledesma, McAdam, & Willman (2014).

demand as follows:

$$P_t^m(1-\alpha_0)\left(\frac{Y_0^m}{N_0}A_t\right)^{\frac{\sigma-1}{\sigma}}\left(\frac{Y_t^m}{N_t}\right)^{\frac{1}{\sigma}} = W_t. \tag{1.12}$$

And given that the firm earns zero profit, the stochastic nominal gross return for banks is given by

$$1+i_{t+1}^l = \frac{Q_{t+1}\xi_{t+1}(1-\delta) + P_{t+1}^m\alpha_0\left(\frac{Y_0^m}{K_0}A_{t+1}\xi_{t+1}\right)^{\frac{\sigma-1}{\sigma}}\left(\frac{Y_{t+1}^m}{K_{t+1}}\right)^{\frac{1}{\sigma}}}{Q_t} \tag{1.13}$$

Intermediate goods producers face no financial frictions when obtaining capital from banks. Consequently, they are able to transfer all their residual stochastic returns to their banks. In a manner akin to Gertler & Karadi (2011), these producers effectively offer their banks a perfectly state-contingent security.

1.4.2.2 Capital producers

Capital producing firms produce new capital. However, when adjusting their investment, I_t, they face adjustment costs, which I denote with $f(\cdot)$. The evolution of capital is:

$$K_{t+1} = (1-\delta)\xi_t K_t + I_t. \tag{1.14}$$

Capital producing firms maximize discounted real profits:

$$\max_{I_\tau} E_t \sum_{\tau=t}^{\infty} \beta^{\tau-t}\Lambda_{t,\tau}\left\{\left(\frac{Q_\tau}{P_\tau}-1\right)I_\tau - f\left(\frac{I_\tau}{I_{\tau-1}}\right)I_\tau\right\}, \tag{1.15}$$

where $\Lambda_{t,\tau}$ denotes households stochastic discount factor between periods t and τ, as given in Equation 1.10.

The first order condition with respect to investment gives the real price of capital, $\frac{Q_t}{P_t}$:

$$\frac{Q_t}{P_t} = 1 + f\left(\frac{I_t}{I_{t-1}}\right) + f'\left(\frac{I_t}{I_{t-1}}\right)\frac{I_t}{I_{t-1}} - E_t\beta\Lambda_{t,t+1}f'\left(\frac{I_{t+1}}{I_t}\right)\left(\frac{I_{t+1}}{I_t}\right)^2. \tag{1.16}$$

1.4.2.3 Retailers

Each retail firm s uses intermediate inputs and costlessly transforms them into a differentiated variety of a retail good, $Y_t(s)$. And final output, Y_t, is a CES composite of a continuum of mass unity of differentiated retail firms.

$$Y_t = \left(\int_0^1 Y_t(s)^{\frac{\theta-1}{\theta}} ds\right)^{\frac{\theta}{\theta-1}}. \tag{1.17}$$

From the cost minimization of final good producer:

$$Y_t(s) = \left(\frac{P_t(s)}{P_t}\right)^{-\theta} Y_t \tag{1.18}$$

$$P_t = \left(\int_0^1 P_t(s)^{1-\theta} ds\right)^{\frac{1}{1-\theta}} \tag{1.19}$$

And the retail firm s is able to freely adjust its prices with probability $1-\gamma$ and choose the optimal price $P_t^*(s)$ to solve

$$\max E_t \sum_{r=0}^{\infty} \gamma^r \beta^r \Lambda_{t,t+r} \frac{P_t}{P_{t+r}} [P_t^*(s) - P_{t+r}^m] Y_{t+r}(s). \tag{1.20}$$

The first-order condition related to price setting is:

$$1 = (1-\gamma)\left(\frac{P_t^*}{P_t}\right)^{1-\theta} + \gamma\left(\frac{P_{t-1}}{P_t}\right)^{1-\theta}. \tag{1.21}$$

The evolution of prices and dispersion of prices are as follows:

$$\Gamma_t^1 = \phi_t \varphi_t \frac{P_t^m}{P_t} Y_t + \gamma\beta E_t \left(\frac{P_t}{P_{t+1}}\right)^{-\theta} \Gamma_{t+1}^1 \tag{1.22}$$

$$\Gamma_t^2 = \phi_t \varphi_t \frac{P_t^*}{P_t} Y_t + \gamma\beta E_t \frac{P_t^*}{P_{t+1}^*} \left(\frac{P_t}{P_{t+1}}\right)^{-\theta} \Gamma_{t+1}^2 \tag{1.23}$$

where $\theta\Gamma_t^1 = (\theta - 1)\Gamma_t^2$. The relationship between final and intermediate outputs is:

$$Y_t^m = Y_t \nu_t^p, \tag{1.24}$$

where $\nu_t^p = \gamma \left(\frac{P_{t-1}}{P_t}\right)^{-\theta} \nu_{t-1}^p + (1-\gamma)\left(\frac{P_t^*}{P_t}\right)^{-\theta}$.

1.4.3 Banks block

Banks are from Ulate (2021), so I will keep the description of this bank block brief. There is a continuum of banks $j \in [0, 1]$. Each bank operates under a monopolistic framework, exerting its influence both in deposit and loan markets. Let ϵ^l denote the loan elasticity of substitution and ϵ^d denote the deposit elasticity of substitution. Since all banks behave identically in equilibrium, I drop the subscript j in what follows.

Banks have equity F_t and determine the interest rate they charge on loans, denoted as i_t^l, the amount they lend, L_t, the interest rate they pay on deposits i_t^d, the amount of deposits they accept, D_t, and the amount of reserves they hold in the central bank, H_t, which earns the policy rate i_t. Consequently, banks have the following balance sheet identity (in real terms):

$$\frac{L_t}{P_t} + \frac{H_t}{P_t} = \frac{F_t}{P_t} + \frac{D_t}{P_t} \tag{1.25}$$

Banks maximize the presented discounted value of the dividends, DIV_{t+1}, that return to households.

$$\max E_t \sum_{s=0}^{\infty} \beta^{s+1} \Lambda_{t,t+s+1} DIV_{j,t+s+1} \tag{1.26}$$

where $\Lambda_{t,t+s+1}$ denotes households stochastic discount factor between period t and $t+s+1$. Banks pay a $1-\omega$ fraction of their total profits, denoted by X_t, as dividends. The remaining fraction ω of X_t will remain inside the bank to accumulate bank equity F_t, such that:

$$F_{t+1} = F_t(1-\zeta)(1+\pi_{t+1}) + \omega X_{t+1} \tag{1.27}$$

where ζ is the fraction of nominal bank equity used for bank managerial costs. Total profits net of managerial costs, and inclusive of an adjustment for inflation, X_t is:

$$X_{t+1} = i_t F_t + (i^l_{t+1} - \mu^l_t - i_t)L_t + (i_t + \mu^d_t - i^d_t)D_t - \Psi\left(\frac{L_t}{F_t}; \kappa, \nu\right)F_t - F_t(1-\zeta)\pi_{t+1} \tag{1.28}$$

where $\Psi(\cdot)$ represents costs associated with deviation from target loan-to-equity ratio, ν, (Gerali et al., 2010)[6]. μ^d_t represents benefits of issuing deposit and μ^l_t denotes cost of issuing loans (Ulate, 2021).

The first order conditions are as follows for deposit and loan rates, respectively.

$$1 + i^d_t = \frac{\epsilon^d}{\epsilon^d - 1}(1 + i_t + \mu^d_t) \tag{1.29}$$

$$E_t(1 + i^l_{t+1}) = \frac{\epsilon^l}{\epsilon^l - 1}(1 + i_t + \mu^l_t) + \kappa\nu\frac{\epsilon^l}{\epsilon^l - 1}\left(\ln\frac{L_t}{F_t} - \ln\nu\right) \tag{1.30}$$

[6]The costs associated with deviating from the target ratio are approximately quadratic cost, which is parameterized by coefficient κ. Using a quadratic cost is a modeling shortcut that captures the importance of bank capital in a tractable manner.

1.4.4 Monetary policy and aggregate resource constraint

Output is divided between consumption, investment, government consumption, G_t, and adjustment costs. The economy-wide resource constraint is thus given by

$$Y_t = C_t + I_t + G_t + f\left(\frac{I_t}{I_{t-1}}\right)I_t + \mu_t^l \frac{L_{t-1}}{P_t} - \mu_t^d \frac{D_{t-1}}{P_t} + \zeta \frac{F_{t-1}}{P_t} + \Psi\left(\frac{L_{t-1}}{F_{t-1}}; \kappa, \nu\right)\frac{F_{t-1}}{P_t}, \tag{1.31}$$

And total loans equal to value of capital:

$$L_t = Q_t K_{t+1} \tag{1.32}$$

The monetary policy is characterized by the following Taylor rule with interest-rate smoothing. Let i_t be the net nominal interest rate and $\bar{\iota}$ is the steady state nominal rate.

$$i_t = (1 - \rho_i)(\bar{\iota} + \Psi_\pi(\pi_t - \bar{\pi})) + \rho_i i_{t-1} + \epsilon_t^i \tag{1.33}$$

where ρ_i is smoothing parameter and ϵ_t^i denotes exogenous shock to monetary policy. The processes for the shocks (technology and government) are standard in the model. The lump sum transfers from government to households are given by: $T_t = H_t - (1 + i_{t-1})H_{t-1} - P_t G_t$.

1.5 Numerical simulations

I simulate the model using the Guerrieri & Iacoviello (2015) toolkit and their piece-wise second-order perturbation approach to account for the occasionally binding constraints.

My crisis experiment is a shock to capital quality a la Gertler & Karadi (2011). The capital productivity declines by 2.5 percent on-impact, with an autocorrelation of 0.90. The fall in real bank equity due to the shock is similar to what the banks in Europe experienced after the Great Financial Crisis (Kalemli-Ozcan, Sorensen, & Yesiltas, 2012). I compare the results obtained under three different scenarios.

1. Benchmark ZLB scenario: Deposit rate is constrained to be non-negative and policy rate can be negative but cannot pass –50 basis points. This scenario assumes that banks cannot pass negative interest rates onto their deposit rates, mirroring the real-world practice[7].

2. Counterfactual ZLB scenario: Both deposit rate and policy rate can be negative but they cannot pass –50 basis points. This scenario provides a theoretical alternative to the current real-world bank behavior.

3. Traditional ZLB scenario: Both deposit rate and policy are constrained to be non-negative. This scenario provides a theoretical alternative if the central bank does not opt for a negative interest rate policy.

I first focus on the Benchmark ZLB scenario with the Counterfactual ZLB scenario. Within these models, I compare their lending responses. My objective is to quantify the additional credit that banks would extend if they either passed on negative rates to depositors or diversified their funding sources. This conclusion is drawn from my causally identified empirical estimates. The difference in lending between these scenarios plays a crucial role in my calibration, which aims to determine the elasticity of substitution in the production function. Specifically, I will use the difference in lending between these scenarios to determine the elasticity of substitution between capital and labor in the production function, employing a moment-matching exercise in line with Nakamura & Steinsson (2018).

After determining the elasticity parameter, I will then assess the aggregate effects of negative interest rate policies using the calibrated model. Subsequently, I compare responses of the Benchmark ZLB scenario to the Traditional ZLB scenario. My goal is to

[7] The lowest interest rate set by the ECB is –50 basis points.

study the aggregate effects of negative interest rate policies because my empirical estimates do not capture these effects due to the time fixed effects present in my rich fixed effect structure.

I examine the impact of the elasticity of substitution between capital and labor in the production function on the economy under the Benchmark ZLB scenario. I consider various levels of elasticity parameters that are from the literature while maintaining both the size of the shock and its persistence the same.

Table 1.9: Model Parameters

Parameter	Definition	Value	Parameter	Definition	Value
β	Discount factor	0.9937	ω	Fraction staying in bank	1/9
h	Habit parameter	0.815	ζ	Bank managerial cost	0.01
χ	Utility weight of labor	3.409	ν	Loan-to-equity ratio target	9
η	Frisch elasticity	1	κ	Cost of deviating from target	0.0012
α	Capital share	0.33	ϵ^d	Deposits elasticity of substitution	-268
δ	Depreciation rate	0.025	ϵ^l	Loans elasticity of substitution	203
υ	Inverse elasticity of investment	1.728	μ^d	Benefits of issuing deposits	0.25%
θ	Elasticity of substitution among goods	6	μ^l	Cost of issuing loans	0.25%
γ	Probability of keeping prices fixed	0.75	$\bar{H}/\bar{F}$	Reserves-to-equity ratio	2
ψ_π	Inflation coefficient, Taylor rule	3.5			
ρ_i	Smoothing parameter, Taylor rule	0.8			
g	Steady state G/Y	0.2			

Notes: Parameters used in the model. The substitution elasticity σ between capital and labor in the CES production is calibrated using the cross-sectional estimates within the model.

1.5.1 Calibrating the elasticity of substitution between capital and labor in the production

In this section, I calibrate the parameter for the elasticity of substitution between capital and labor in the normalized CES production function of the model. I follow a calibration strategy similar to Nakamura & Steinsson (2018). I use estimates from my bank lending regressions. These estimates serve as well-identified macro moments suitable for moment-matching exercise, thus providing target moments for the theoretical model.

I choose a target moment based on my cross-sectional estimate of bank lending. This target moment quantifies the additional bank credit that might have been provided if banks were not subject to the zero lower bound on their deposits. In the theoretical model, I compare the differences in bank lending under two scenarios: the Benchmark ZLB, where banks cannot pass on negative rates, and the Counterfactual ZLB, where they can. This comparison quantifies the additional credit banks would extend if they either passed on negative rates to depositors or diversified their funding sources. I then choose the elasticity of substitution between capital and labor in the production function so that the lending difference matches the target.

My empirical coefficient estimate indicates a 1.30 percent increase in lending in response to a 22 percent decrease in the deposit-to-asset ratio following the implementation of negative interest rate policies.

$$0.013 \approx -0.0594 \times -0.22 \tag{1.34}$$

A 22% decrease in the deposit-to-asset ratio corresponds to the difference in the mean deposit-to-asset ratio between high-deposit banks (those with a deposit-to-asset ratio above the median in the distribution) and low-deposit banks. Therefore, the 22% difference in the deposit-to-asset ratio between high-deposit and low-deposit banks helps us understand and quantify the magnitude of extra credit that low-deposit banks might provide relative to high-deposit banks. Essentially, I am allowing every bank in my sample to utilize more wholesale funding, thereby reducing the pressure due to the zero lower bound constraint on deposit rates.[8]

The figure above represents annual growth. Since my model is based on quarters, I need to convert this to quarterly growth. This conversion can be approximated by dividing the annual growth by 4.

$$0.0032 \approx -0.0594 \times -0.22 \times \frac{1}{4} \tag{1.35}$$

Hence, in my model, I aim to capture this change in credit growth, amounting to 32 basis points, between the Benchmark ZLB scenario and the Counterfactual ZLB scenario.

In my model, in the Benchmark ZLB scenario, banks cannot pass on negative rates to their depositors. However, in the Counterfactual ZLB scenario, they can. By comparing lending responses between these scenarios, I aim to quantify the additional credit that banks would extend if they were to pass on negative rates to depositors or if they diversified their funding sources. Alternative funding sources, such as wholesale funding, bonds, or interbank loans, do not face the same zero lower bound challenges as traditional deposit accounts do.

Figure 1.2 illustrates the on-impact difference in the percentage deviation of lending from its steady-state level between the Benchmark scenario and the Counterfactual scenario, plotted as a function of the elasticity of substitution between capital and labor. From the figure, it is evident that when the elasticity of substitution parameter is set to 1.25, the difference in lending responses between the two scenarios matches the empirical estimate from my regression, which amounts to 32 basis points. This elasticity value aligns with the estimates of Karabarbounis & Neiman (2014), who found it to be 1.25 using

[8] One can observe similar changes in the deposit-to-asset ratio by examining the differences between high-deposit and low-deposit banks at the 5th, 25th, 50th, 75th, and 95th percentiles.

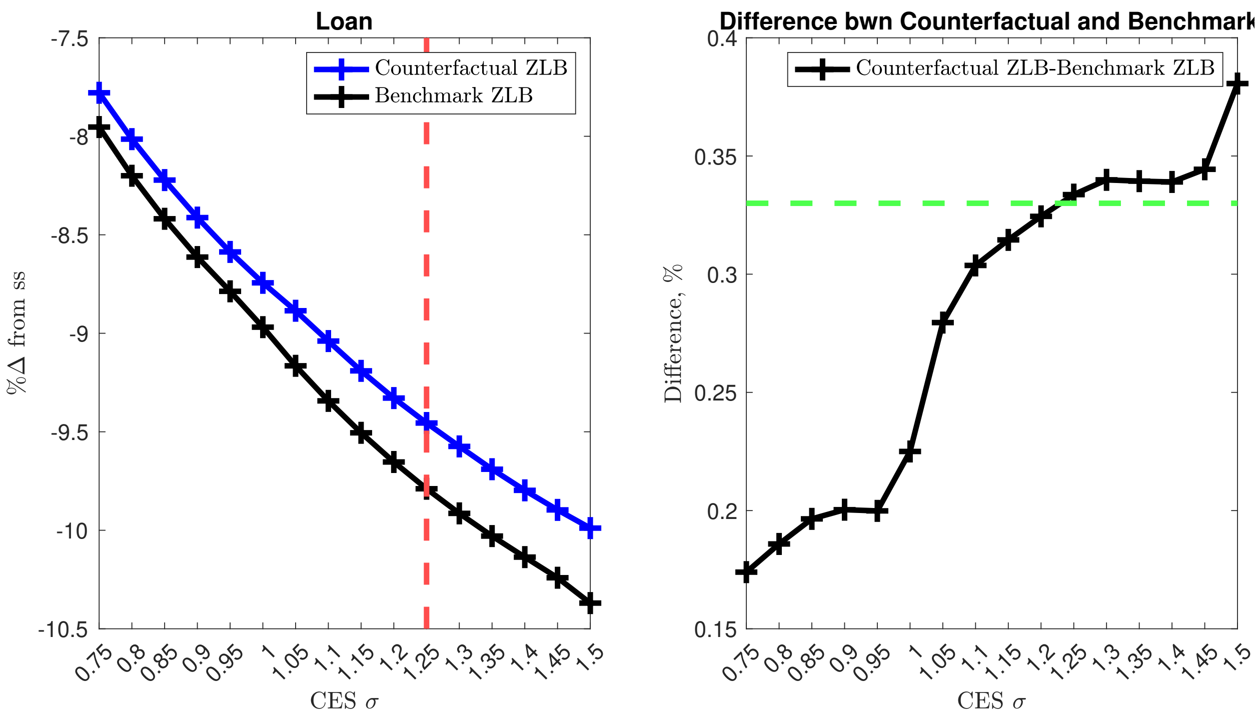

Figure 1.2: Calibrating CES σ to match the empirical estimates based on lending.

Notes: The figure on the left depicts the on-impact percentage deviation of lending from its steady-state level for both the Benchmark scenario (in black line) and the Counterfactual scenario (in blue line), plotted as a function of the elasticity of substitution between capital and labor. The figure on the right depicts the on-impact difference between these two lines as a function of the elasticity of substitution between capital and labor.

cross-country data, and with Hubmer (2023), who estimated it at 1.35 based on US data.

For robustness, I follow the same steps and procedures as in my previous analysis. However, this time, my objective is to match the differences in interest rates rather than lending. The results derived from this alternative approach align with my earlier findings, further validating the reliability of my calibrated elasticity of substitution parameter. As depicted in Figure 1.9 in Appendix 1.7.3, when the elasticity of substitution parameter is set at 1.25, the difference in interest rate outcomes between the two scenarios aligns with the empirical finding from my regression, amounting to 39 basis points.

1.5.2 Evaluating negative interest rate policies

In this section, I evaluate the aggregate effects of negative interest rate policies and conduct a welfare analysis using the calibrated model. Subsequently, I compare the responses of the Benchmark ZLB scenario to the Traditional ZLB scenario.

Figure 1.3 shows the impulse response functions of the most important variables in the model to the shock to capital productivity under two scenarios. The Benchmark ZLB scenario is plotted in the blue line and the Traditional ZLB scenario is plotted in the red line. The impulse response function for the policy rate, the deposit rate, and the loan spread defined as the spread between the expected loan rate and the policy rate are plotted in annualized levels in percentage points. The rest of the impulse response functions are plotted as percent deviations from their steady states.

Figure 1.3 shows that in the Benchmark ZLB scenario, the policy rate is stuck at its limit of –50 basis points, while in the Traditional ZLB scenario, it remains at the zero lower bound. Due to this, output in the Benchmark ZLB scenario drops less than in the Traditional ZLB scenario because the central bank stimulates the economy by reducing the policy rate. Although the consumption response between these two scenarios does not show a vast difference like in the output, it is worth noting that consumption is slightly

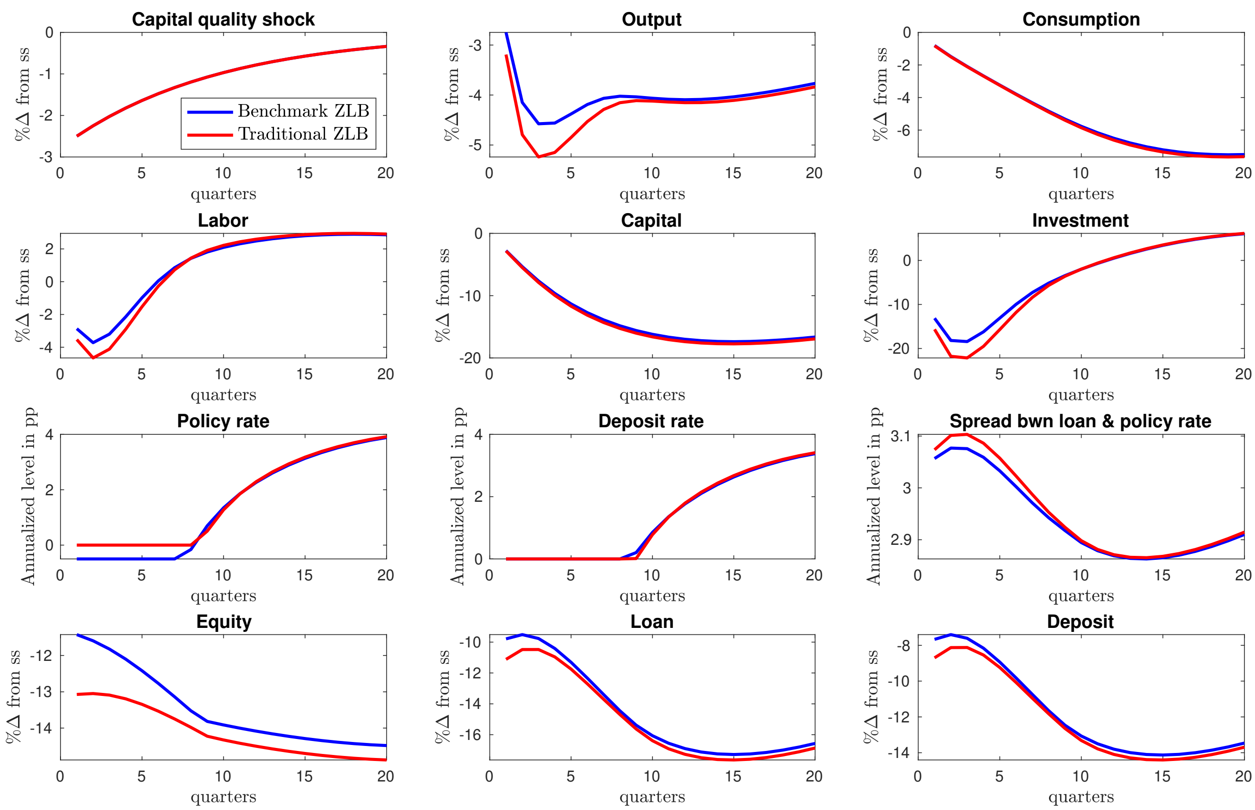

Figure 1.3: IRFs to capital quality shock.

Notes: The figure depicts the IRFs of some of the main variables in the model to a capital productivity shock under the Benchmark ZLB scenario (in blue line) and the Traditional ZLB scenario (in red line) with the calibrated model where CES $\sigma = 1.25$. The x–axis is in quarters and y–axis is percent deviation from the steady state for capital quality shock, output, consumption, labor, capital, equity, loan, and deposit, and in annualized percentage points for policy rate, deposit, and spread between loan rate and policy rate.

lower in the Traditional ZLB scenario.

When examining bank results, it is observed that bank equity declines more significantly in the Traditional ZLB scenario. The extra decrease is approximately equal to 1.5 percent. This is due to banks charging higher loan spreads, resulting in decreased lending. Consequently, their profitability suffers, leading to reduced equity.

1.5.2.1 Welfare implications

I evaluate the welfare implications of two scenarios in terms of consumption equivalent units, relative to steady-state allocations. These allocations correspond to a situation where there is no shock to capital productivity in the first quarter.

I calculate λ_j, which represents the percent deviation from consumption without the shock, where $j \in \{\textit{Benchmark ZLB}, \textit{Traditional ZLB}\}$.

$$\text{Welfare}_j = \sum_{t=0}^{\infty} \beta^t \left[\ln((1-\lambda_j)C_{ss} - (1-\lambda_j)hC_{ss}) - \chi \frac{N_{ss}^{1+\frac{1}{\eta}}}{1+\frac{1}{\eta}} \right] \tag{1.36}$$

where C_{ss} (N_{ss}) is the consumption (labor) at steady-state.

$$\text{Welfare}_j = \sum_{t=0}^{\infty} \beta^t \left[\ln(C_{j,t} - hC_{j,t-1}) - \chi \frac{N_{j,t}^{1+\frac{1}{\eta}}}{1+\frac{1}{\eta}} \right] \tag{1.37}$$

where $C_{j,t}$ ($N_{j,t}$) is the consumption (labor) in scenario j at period t.

I find that $\lambda_{\textit{Benchmark ZLB}} = 2.43\%$ and $\lambda_{\textit{Traditional ZLB}} = 2.45\%$. The difference between these two is equal to 0.2 basis points.

I also conduct a welfare analysis in util terms, expressing the results as percent deviation relative to a situation without the shock. I find that the deviation is 101.7 basis points under the Traditional ZLB scenario, while it is 100 basis points in the Benchmark

ZLB scenario.

Based on the welfare analysis, both in terms of consumption equivalent and utils measures, it is evident that negative interest rate policies result in a smaller drop in welfare. While the difference is not substantial, this still underscores the effectiveness of negative interest rate policies as a tool for central banks, leading to notable welfare improvements.

1.5.3 Role of elasticity of substitution between capital and labor in production

In this section, I examine how the elasticity of substitution between capital and labor in the production function impacts the economy under the Benchmark ZLB scenario, considering various levels of elasticity parameters. I keep the size of the shock and its persistence as in the previous section.

Figure 1.4 below presents the impulse response functions of key variables in the model, responding to the shock to capital productivity, across three different elasticity parameters. CES σ takes the following three values: $\sigma \in \{0.75, 1.00, 1.25\}$. The first case, CES $\sigma = 0.75$, indicates that capital and labor are gross complements. The second corresponds to a Cobb Douglas production function. The third represents my estimate, which served as the benchmark used in the previous section, and in this case, capital and labor are gross substitutes.

1.5.3.1 Results and mechanism behind them

Figure 1.4 shows that when there is a negative shock to capital quality, making capital less productive, a higher elasticity of substitution between capital and labor magnifies labor market outcomes in equilibrium. Specifically, this higher elasticity leads to a more pronounced decline in labor and a correspondingly higher wage rate at equilibrium. This amplified response arises due to two key reasons. First, when there is an increased elasticity of substitution, the marginal product of capital decreases more substantially. This

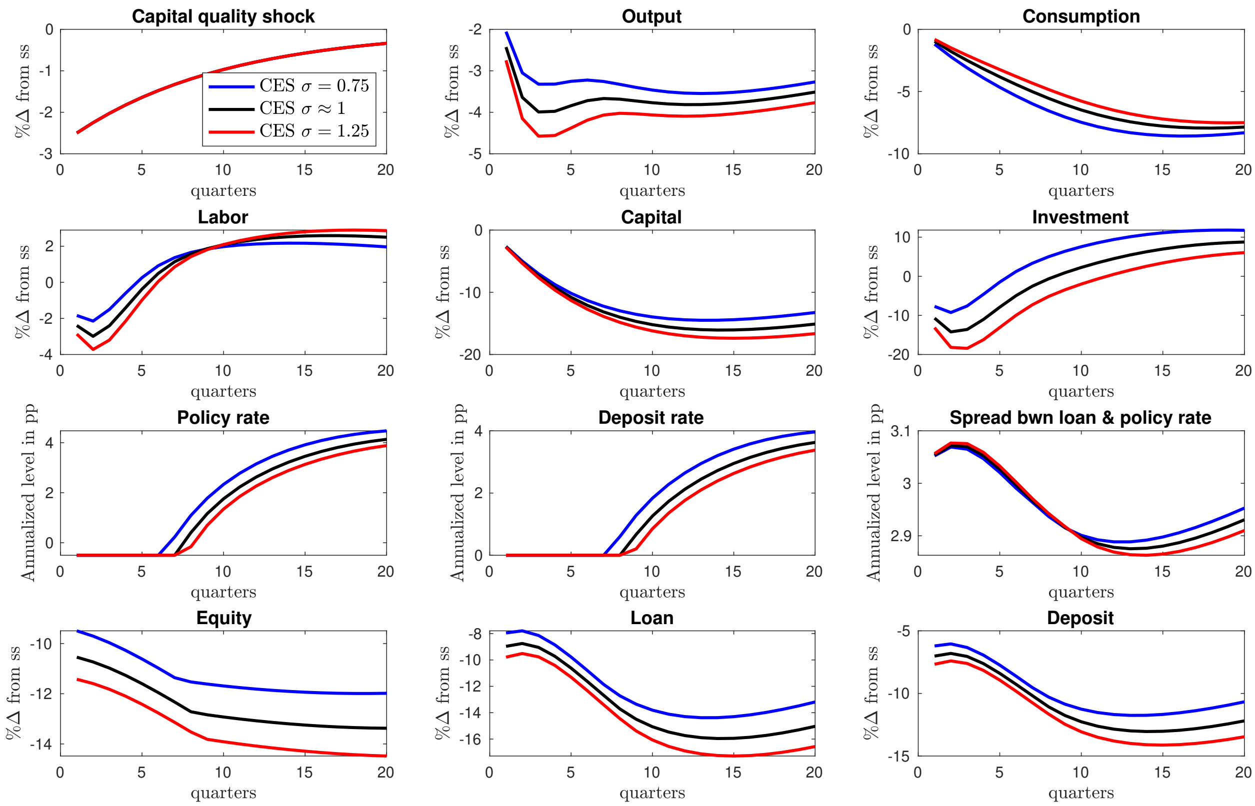

Figure 1.4: IRFs to capital productivity shock with different substitution elasticity.

Notes: The figure depicts the IRFs of some of the main variables in the model to a capital productivity shock under the Benchmark ZLB scenario for when CES σ = 0.75 (in blue line), CES σ ≈ 1.00 (in black line), and CES σ = 1.25 (in red line). The *x*–axis is in quarters and *y*–axis is percent deviation from the steady state for capital quality shock, output, consumption, labor, capital, equity, loan, and deposit, and in annualized percentage points for policy rate, deposit, and spread between loan rate and policy rate.

affects households' intertemporal decisions between current consumption and savings. As the return on capital drops more sharply (and savings yield less), households choose to consume more and save less. This decision leads to a more pronounced decrease in labor supply with a higher elasticity of substitution, as households work fewer hours. Second, an increase in the elasticity of substitution allows firms to more easily substitute labor for capital. This leads to a lesser decrease in the marginal product of labor, resulting in a less significant reduction in labor demand.

A higher elasticity of substitution results in a more pronounced drop in both labor and investment, which subsequently leads to a more pronounced decrease in output.

After a negative shock to capital productivity, the marginal product of capital declines more sharply if the elasticity of substitution is high. This is because firms can more easily substitute capital with labor under these conditions. The return on bank loans, which are stochastic and tied to the marginal product of capital, also faces a more pronounced drop. This results in banks experiencing a steeper decrease in their profitability. In turn, this leads to a more substantial decrease in bank equity and a larger deviation from its steady state.

In essence, a higher elasticity of substitution in the production function amplifies banks' vulnerability. This stems from firms' ability to easily switch between capital and labor, leading to a more pronounced reduction in capital demand and, consequently, a decreased demand for bank loans when there is a negative shock to capital productivity.

Shocks to capital productivity are highly persistent, with an autocorrelation of 0.90. This means that capital remains less productive for a prolonged period compared to its steady state level. Consequently, the demand for capital remains lower over an extended period. As a result, the gap in bank equity between a model with high elasticity and one with low elasticity remains significant and elevated.

With high elasticity, bank equity and, consequently, profitability drop more significantly. In response to this, banks increase their loan spread, charging firms higher loan rates to regain some of their equity losses. This leads to a more pronounced decrease in the amount of loans banks provide when elasticity is high. Additionally, banks collect fewer deposits because they offer lower rates on these deposits. This results in a more pronounced decrease in the volume of deposits banks collect when elasticity is high.

In Figure 1.5, I highlight the effect of elasticity on the on-impact (the effect in the first quarter) rather than over all 20 quarters in the impulse response function. This is shown using various sigma values, $\sigma \in \{0.75, \ldots, 1.00, \ldots, 1.50\}$.

1.5.3.2 Effects of elasticity of substitution between capital and labor in production on banks

In this section, I aim to explore the implications of different elasticity of substitution parameters on banks. Specifically, I will compare CES $\sigma = 1$, which corresponds to Cobb Douglas production function prevalent in the literature, against CES $\sigma = 1.25$, the estimate derived from my empirical work using a moment-matching exercise consistent with the methodology of Nakamura & Steinsson (2018).

Figure 1.10 in Appendix 1.7.3 plots the bank leverage following the shock to capital productivity. In response to the same negative shock to capital productivity, banks in an economy with the elasticity of substitution of 1.25 experience an additional 26 basis points drop in their capital ratio compared to banks in an economy with the elasticity of substitution of 1. While this finding is based on the model, I will now explore its broader implications using external estimates outside of the model to offer a more tangible interpretation of the results.

Using Berger & Bouwman (2013) estimates, this additional decrease in capital ratio (or increase in leverage) significantly amplifies the probability of default across various economic situations—an 8.15% surge during a banking crisis, 11.38% during a market crisis,

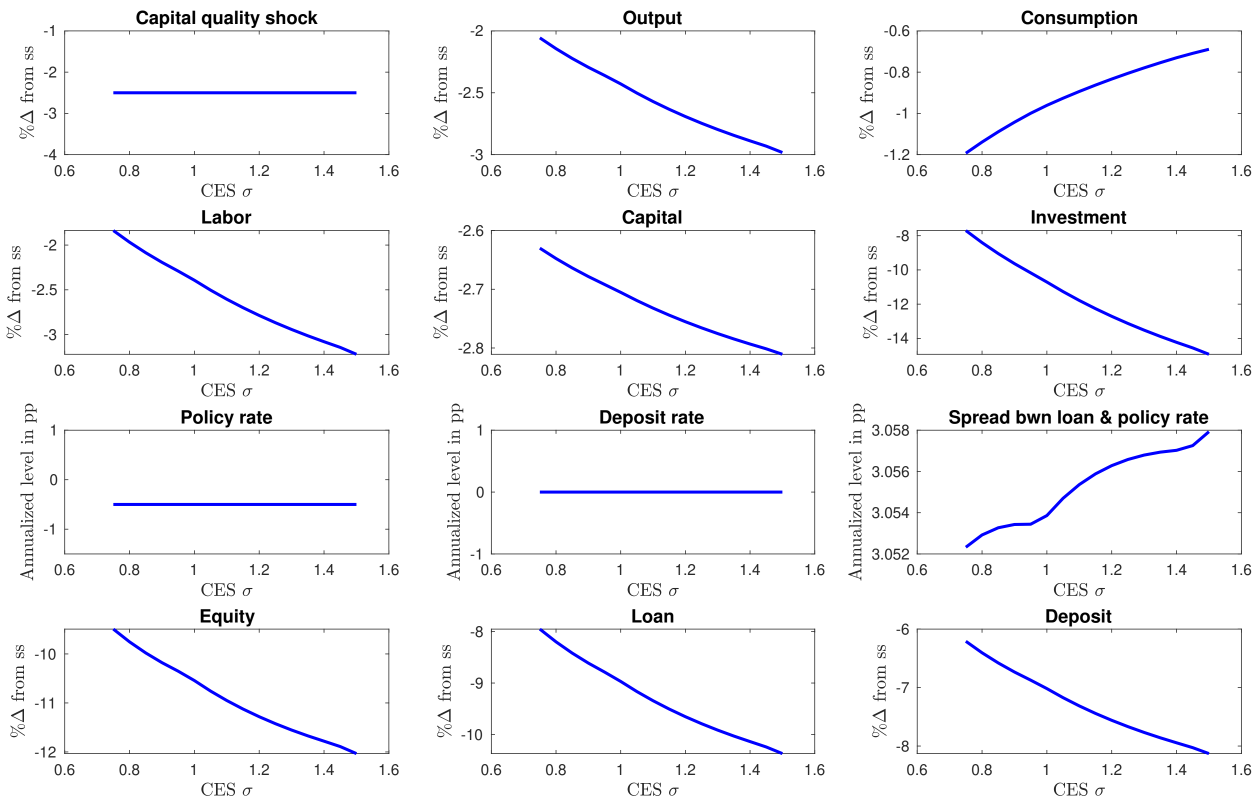

Figure 1.5: On-impact responses to capital productivity shock with different substitution elasticity.

Notes: The figure depicts the on-impact response of some of the main variables in the model to a capital productivity shock under the Benchmark ZLB scenario for CES $\sigma \in \{0.75, \ldots, 1.00, \ldots, 1.50\}$. The x–axis is in quarters and y–axis is percent deviation from the steady state for capital quality shock, output, consumption, labor, capital, equity, loan, and deposit, and in annualized percentage points for policy rate, deposit, and spread between loan rate and policy rate.

and 10.72% in normal times. Additionally, drawing insights from Laeven et al. (2016), the leverage increase also increases the dollar value of bank losses during crises. It amounts to an increase of US$0.91 billion for a bank with total assets of $100 billion. Lastly, when examining the effect on bank stock returns according to the findings of Demirgunc-Kunt et al. (2013), there is an additional decrease of 14.3 basis points in stock returns each quarter. This corresponds to roughly 3% of the median quarterly decrease of 4.7% observed during crisis periods. These sizable bank effects underscore that even slight deviations from the prevailing assumption in the production function, like the one presented in my paper, can lead to substantial consequences with important implications for both banks and central banks.

1.5.3.3 Effects of elasticity of substitution between capital and labor in production on welfare

Figure 1.11 in Appendix 1.7.3 plots the deviation in consumption relative to the case without the shock to capital productivity for the Benchmark ZLB scenario (in blue line) and the Traditional ZLB scenario (in red line), as a function of the elasticity of substitution between capital and labor. This is similar to the exercise in Section 1.5.2.1. The figure shows that welfare gains from implementing negative interest rate policies, measured as the difference between the Benchmark ZLB scenario and the Traditional ZLB scenario increases in CES σ because the economic downturn is larger when the substitution between capital and labor in production is higher.

1.6 Conclusion

In this paper, I present both empirical evidence and theoretical analyses on the effects of negative interest rate policies. Using matched firm-bank level data that I construct from seven euro area countries, I document that banks with higher deposit ratios supply less credit to firms relative to those with lower deposit ratios after the introduction of these policies. The dataset enables more precise identification of the effects compared to other studies. This precision arises because I can construct four-digit-industry-country-year and firm fixed effects, which allow for more comprehensive control of the demand for bank credit. I then show that, while firms linked to banks with higher deposit ratios invest less in response to lending contractions, they tend to hire more relative to firms associated with banks with lower deposit ratios, especially in industries with high capital-labor substitution.

Motivated by my empirical analysis, I utilize my cross-sectional estimates, serving as well-identified macro moments, in a moment-matching exercise to inform the production block of the DSGE model. I then use this model to examine the impact of negative interest rate policies on aggregate variables and welfare over time. My analysis underscores that negative interest rate policies are effective in stimulating the economy. Additionally, my findings indicate that higher capital-labor substitution in production surprisingly leads to a larger economic downturn when there is a negative shock to capital productivity. Furthermore, my findings emphasize that even minor variations in the elasticity of substitution can have significant implications for the economy, banks, and welfare.

1.7 Appendix

1.7.1 Checking parallel trends

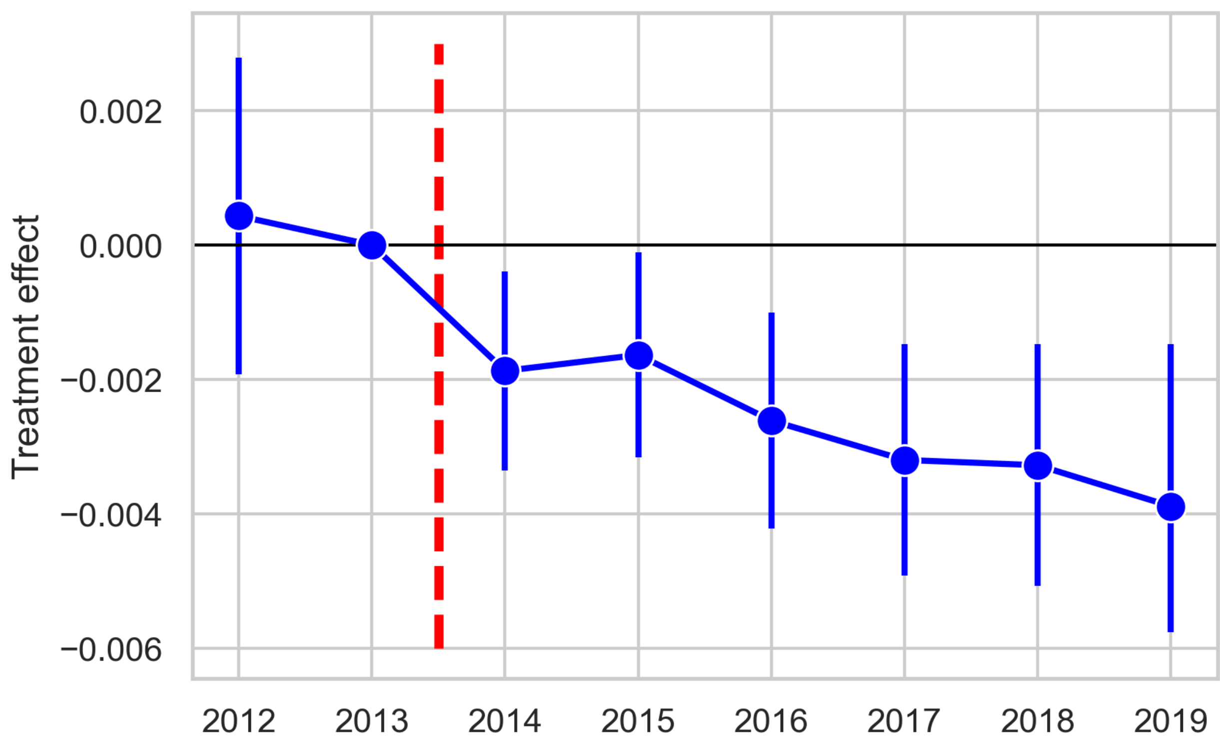

Figure 1.6: Impact of negative interest rate policies on firm leverage.

Note: This figure plots the coefficient estimates $\hat{\beta}_t$ of the following model at the bank-firm level.

$$\text{Leverage}_{isct} = \sum_{t=2012}^{2019} \beta_t D_{Year=t} \times \text{Deposit ratio}_b + \alpha_b + \delta_{sct} + \gamma' X_{isct-1} + \epsilon_{isct}$$

$\hat{\beta}_t$ is time-varying treatment effect of negative rates on loan growth. Vertical bars correspond to 90% confidence intervals. $D_{Year=t}$ is dummy variable taking the value one if the year is equal to t, where $t = \{2012, \ldots, 2019\}$. The year 2013 is the reference year. The dependent variable is leverage at the firm level and is calculated as the ratio of total liabilities to total assets in period t. The deposit ratio denotes the ratio of deposits over total assets (in %) for the year 2013. The set of firm control variables (not reported) includes i) size, measured as the logarithm of total assets, ii) leverage, defined as the ratio of total liabilities to total assets, iii) sales growth, measured as the annual change in the natural logarithm of sales, iv) cash, defined as the ratio of cash and cash equivalents to total assets. Bank fixed effects are included. Country-Industry-Time fixed effects are based on four-digit NACE Rev.2 codes. Robust standard errors are clustered at the bank level.

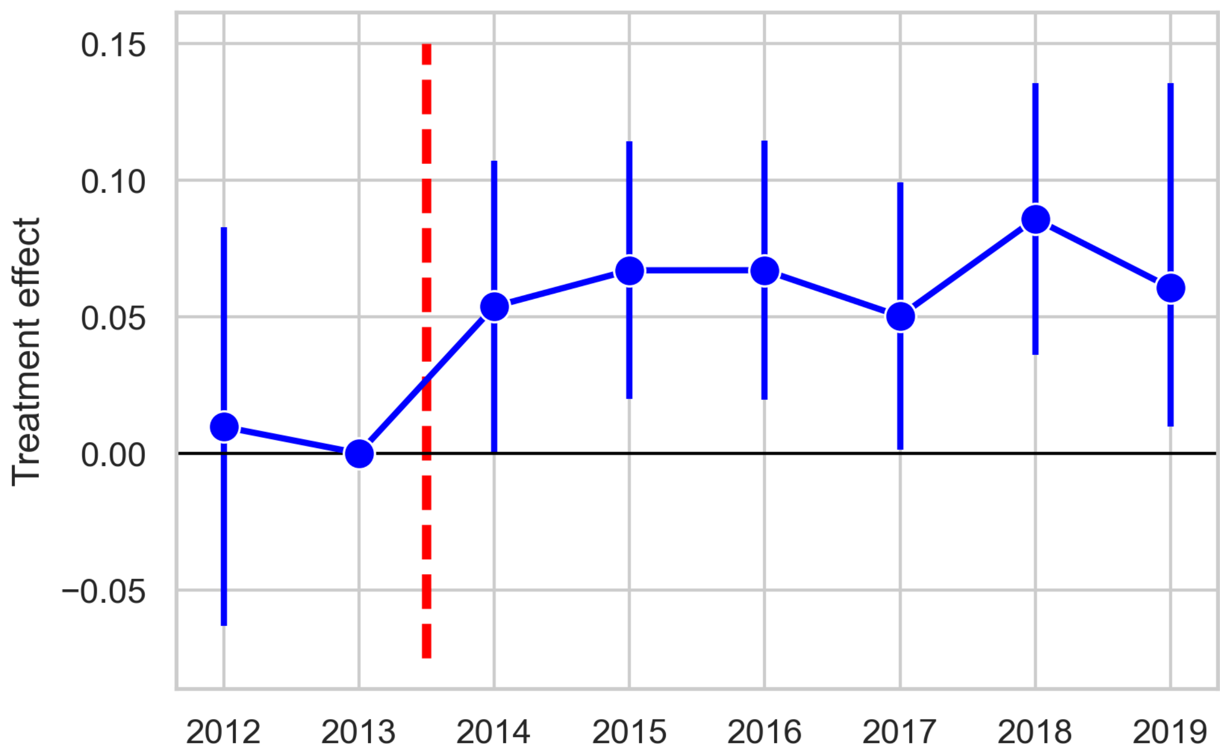

Figure 1.7: Impact of negative interest rate policies on firm cash holdings.

Note: This figure plots the coefficient estimates $\hat{\beta}_t$ of the following model at the bank-firm level.

$$\text{Cash growth}_{isct} = \sum_{t=2012}^{2019} \beta_t D_{Year=t} \times \text{Deposit ratio}_b + \alpha_b + \delta_{sct} + \gamma' X_{isct-1} + \epsilon_{isct}$$

$\hat{\beta}_t$ is time-varying treatment effect of negative rates on loan growth. Vertical bars correspond to 90% confidence intervals. $D_{Year=t}$ is dummy variable taking the value one if the year is equal to t, where $t = \{2012, \ldots, 2019\}$. The year 2013 is the reference year. The dependent variable is cash growth at the firm level and is calculated as the difference in the natural logarithm of cash and cash equivalent between periods t and $t-1$. The deposit ratio denotes the ratio of deposits over total assets (in %) for the year 2013. The set of firm control variables (not reported) includes i) size, measured as the logarithm of total assets, ii) leverage, defined as the ratio of total liabilities to total assets, iii) sales growth, measured as the annual change in the natural logarithm of sales, iv) cash, defined as the ratio of cash and cash equivalents to total assets. Bank fixed effects are included. Country-Industry-Time fixed effects are based on four-digit NACE Rev.2 codes. Robust standard errors are clustered at the bank level.

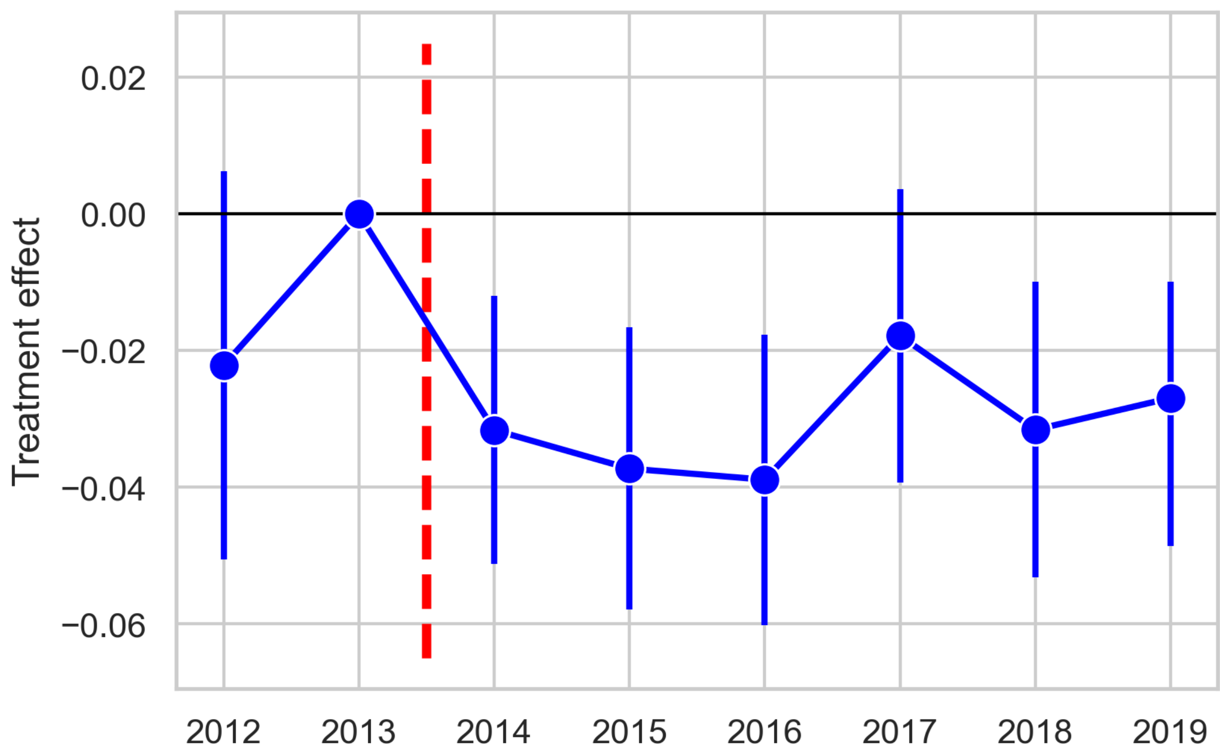

Figure 1.8: Impact of negative interest rate policies on firm investment.

Note: This figure plots the coefficient estimates $\hat{\beta}_t$ of the following model at the bank-firm level.

$$\text{Net investment}_{isct} = \sum_{t=2012}^{2019} \beta_t D_{Year=t} \times \text{Deposit ratio}_b + \alpha_b + \delta_{sct} + \gamma' X_{isct-1} + \epsilon_{isct}$$

$\hat{\beta}_t$ is time-varying treatment effect of negative rates on loan growth. Vertical bars correspond to 90% confidence intervals. $D_{Year=t}$ is dummy variable taking the value one if the year is equal to t, where $t = \{2012, \ldots, 2019\}$. The year 2013 is the reference year. The dependent variable is net investment at the firm level and is calculated as the difference in the natural logarithm of tangible fixed assets between periods t and $t-1$. The deposit ratio denotes the ratio of deposits over total assets (in %) for the year 2013. The set of firm control variables (not reported) includes i) size, measured as the logarithm of total assets, ii) leverage, defined as the ratio of total liabilities to total assets, iii) sales growth, measured as the annual change in the natural logarithm of sales, iv) cash, defined as the ratio of cash and cash equivalents to total assets. Bank fixed effects are included. Country-Industry-Time fixed effects are based on four-digit NACE Rev.2 codes. Robust standard errors are clustered at the bank level.

1.7.2 Robustness

Table 1.10: Negative Interest Rates and Output

Dependent variable:	Material expenses growth		Sales growth	
	(1)	(2)	(3)	(4)
Deposit ratio × Post	0.000885		0.00170	
(%)	(0.00899)		(0.00589)	
Deposit ratio × Post		0.000382		0.000551
(0/1)		(0.00319)		(0.00219)
Firm Control	Yes	Yes	Yes	Yes
Firm FE	Yes	Yes	Yes	Yes
Country-Industry-Time FE	Yes	Yes	Yes	Yes
Observations	776848	776848	969229	969229
R^2	0.179	0.179	0.243	0.243

Notes: The table presents OLS estimates of the following model at the bank-firm level.

$$\text{Material expenses growth}_{isct} = \beta \text{Deposit ratio}_b \times \text{Post}_t + \alpha_i + \delta_{sct} + \gamma' X_{isct-1} + \epsilon_{isct}$$
$$\text{Sales growth}_{isct} = \beta \text{Deposit ratio}_b \times \text{Post}_t + \alpha_i + \delta_{sct} + \gamma' X_{isct-1} + \epsilon_{isct}$$

The dependent variable in Columns (1) and (2) is material expenses growth at the firm level and is calculated as the difference in the natural logarithm of material expenses between periods t and $t-1$. The dependent variable in Columns (3) and (4) is sales growth at the firm level and is calculated as the difference in the natural logarithm of sales between periods t and $t-1$. The deposit ratio, presented in Columns (1) and (3), denotes the ratio of deposits over total assets (in %) for the year 2013. In Columns (2) and (4), the deposit ratio is assigned a value of one if the ratio of deposits to total assets in 2013 is above the median of its respective country's distribution. Post is a dummy variable representing the period from 2014 onward. The set of firm control variables (not reported) includes i) size, measured as the logarithm of total assets, ii) leverage, defined as the ratio of total liabilities to total assets, iii) sales growth, measured as the annual change in the natural logarithm of sales, iv) cash, defined as the ratio of cash and cash equivalents to total assets. Bank fixed effects are included. Country-Industry-Time fixed effects are based on four-digit NACE Rev.2 codes. Robust standard errors, clustered at the bank level, are in parentheses. ***, **, and * indicate significance at 1%, 5%, and 10%, respectively.

Table 1.11: Negative Interest Rates and Small and Large Firms - Loan Growth

Dependent variable:	Loan growth			
	(1)	(2)	(3)	(4)
Sample:	Small to large firms		Very large firms	
Deposit ratio × Post	-0.0537**		-0.0193	
(%)	(0.0253)		(0.119)	
Deposit ratio × Post		-0.0192**		-0.0336
(0/1)		(0.00764)		(0.0503)
Firm Control	Yes	Yes	Yes	Yes
Bank FE	Yes	Yes	Yes	Yes
Country-Industry-Time FE	Yes	Yes	Yes	Yes
Observations	713065	713065	19489	19489
R^2	0.0279	0.0279	0.197	0.197

Notes: The table presents OLS estimates of the following model at the bank-firm level.

$$\text{Loan growth}_{isct} = \beta \text{Deposit ratio}_b \times \text{Post}_t + \alpha_b + \delta_{sct} + \gamma' X_{isct-1} + \epsilon_{isct}$$

The dependent variable is loan growth at the firm-bank level and is calculated as the difference in the natural logarithm of credit between periods t and $t-1$. The sample is restricted to small, medium-sized, and large firms in Columns (1) and (2). The sample is restricted to very large firms in Columns (3) and (4). Credit refers to the sum of long- and short-term financial debt recorded in Orbis. The deposit ratio, presented in Columns (1) and (2), denotes the ratio of deposits over total assets (in %) for the year 2013. In Columns (3) and (4), the deposit ratio is assigned a value of one if the ratio of deposits to total assets in 2013 is above the median of its respective country's distribution. Post is a dummy variable representing the period from 2014 onward. The set of firm control variables (not reported) includes i) size, measured as the logarithm of total assets, ii) leverage, defined as the ratio of total liabilities to total assets, iii) sales growth, measured as the annual change in the natural logarithm of sales, iv) cash, defined as the ratio of cash and cash equivalents to total assets. Bank fixed effects are included. Country-Industry-Time fixed effects are based on four-digit NACE Rev.2 codes. Robust standard errors, clustered at the bank level, are in parentheses. ***, **, and * indicate significance at 1%, 5%, and 10%, respectively.

Table 1.12: Negative Interest Rates and Small and Large Firms - Interest Rate Growth

Dependent variable:	Interest rate growth			
	(1)	(2)	(3)	(4)
Sample:	Small to large firms		Very large firms	
Deposit ratio × Post	0.0853**		-0.276*	
(%)	(0.0354)		(0.154)	
Deposit ratio × Post		0.0241**		-0.0611
(0/1)		(0.0102)		(0.0720)
Firm Control	Yes	Yes	Yes	Yes
Bank FE	Yes	Yes	Yes	Yes
Country-Industry-Time FE	Yes	Yes	Yes	Yes
Observations	558844	558844	18447	18447
R^2	0.0305	0.0305	0.209	0.209

Notes: The table presents OLS estimates of the following model at the bank-firm level.

$$\text{Interest rate growth}_{isct} = \beta \text{Deposit ratio}_b \times \text{Post}_t + \alpha_b + \delta_{sct} + \gamma' X_{isct-1} + \epsilon_{isct}$$

The dependent variable is interest rate growth at the firm-bank level and is calculated as the difference in the natural logarithm of interest rate between periods t and $t-1$. Interest rate refers the ratio of interest expenses to the sum of both long- and short-term financial debt as recorded in Orbis. The sample is restricted to small, medium-sized, and large firms in Columns (1) and (2). The sample is restricted to very large firms in Columns (3) and (4). Credit refers to the sum of long- and short-term financial debt recorded in Orbis. The deposit ratio, presented in Columns (1) and (2), denotes the ratio of deposits over total assets (in %) for the year 2013. In Columns (3) and (4), the deposit ratio is assigned a value of one if the ratio of deposits to total assets in 2013 is above the median of its respective country's distribution. Post is a dummy variable representing the period from 2014 onward. The set of firm control variables (not reported) includes i) size, measured as the logarithm of total assets, ii) leverage, defined as the ratio of total liabilities to total assets, iii) sales growth, measured as the annual change in the natural logarithm of sales, iv) cash, defined as the ratio of cash and cash equivalents to total assets. Bank fixed effects are included. Country-Industry-Time fixed effects are based on four-digit NACE Rev.2 codes. Robust standard errors, clustered at the bank level, are in parentheses. ***, **, and * indicate significance at 1%, 5%, and 10%, respectively.

Table 1.13: Negative Interest Rates and Small and Large Firms - Investment

Dependent variable:	Net investment			
	(1)	(2)	(3)	(4)
Sample:	Small to large firms		Very large firms	
Deposit ratio × Post	-0.0264***		0.0170	
(%)	(0.0101)		(0.0421)	
Deposit ratio × Post		-0.00619**		0.0213
(0/1)		(0.00304)		(0.0165)
Firm Control	Yes	Yes	Yes	Yes
Firm FE	Yes	Yes	Yes	Yes
Country-Industry-Time FE	Yes	Yes	Yes	Yes
Observations	927521	927521	24435	24435
R^2	0.211	0.211	0.329	0.330

Notes: The table presents OLS estimates of the following model at the bank-firm level.

$$\text{Net investment}_{isct} = \beta \text{Deposit ratio}_b \times \text{Post}_t + \alpha_i + \delta_{sct} + \gamma' X_{isct-1} + \epsilon_{isct}$$

The dependent variable is net investment at the firm level and is calculated as the difference in the natural logarithm of tangible fixed assets between periods t and $t-1$. The sample is restricted to small, medium-sized, and large firms in Columns (1) and (2). The sample is restricted to very large firms in Columns (3) and (4). The deposit ratio, presented in Columns (1) and (2), denotes the ratio of deposits over total assets (in %) for the year 2013. In Columns (3) and (4), the deposit ratio is assigned a value of one if the ratio of deposits to total assets in 2013 is above the median of its respective country's distribution. Post is a dummy variable representing the period from 2014 onward. The set of firm control variables (not reported) includes i) size, measured as the logarithm of total assets, ii) leverage, defined as the ratio of total liabilities to total assets, iii) sales growth, measured as the annual change in the natural logarithm of sales, iv) cash, defined as the ratio of cash and cash equivalents to total assets. Bank fixed effects are included. Country-Industry-Time fixed effects are based on four-digit NACE Rev.2 codes. Robust standard errors, clustered at the bank level, are in parentheses. ***, **, and * indicate significance at 1%, 5%, and 10%, respectively.

Table 1.14: Negative Interest Rates and Small and Large Firms - Employment

Dependent variable:	Employment growth		Employee expenses growth	
	(1)	(2)	(3)	(4)
Sample:	Small to large	Very large	Small to large	Very large
Deposit ratio × Post	0.00224	-0.0163	0.00332	-0.0261
(%)	(0.00783)	(0.0355)	(0.00571)	(0.0234)
Firm Control	Yes	Yes	Yes	Yes
Firm FE	Yes	Yes	Yes	Yes
Country-Industry-Time FE	Yes	Yes	Yes	Yes
Observations	679484	19008	834027	24084
R^2	0.187	0.358	0.223	0.324

Notes: The table presents OLS estimates of the following model at the bank-firm level.

$$\text{Employment growth}_{isct} = \beta \text{Deposit ratio}_b \times \text{Post}_t + \alpha_i + \delta_{sct} + \gamma' X_{isct-1} + \epsilon_{isct}$$
$$\text{Employee expenses growth}_{isct} = \beta \text{Deposit ratio}_b \times \text{Post}_t + \alpha_i + \delta_{sct} + \gamma' X_{isct-1} + \epsilon_{isct}$$

The dependent variable in Columns (1) and (2) is employment growth at the firm level and is calculated as the difference in the natural logarithm of number of employees between periods t and $t-1$. The sample is restricted to small, medium-sized, and large firms in Columns (1) and (3). The sample is restricted to very large firms in Columns (2) and (4). The dependent variable in Columns (3) and (4) is employee expenses growth at the firm level and is calculated as the difference in the natural logarithm of employee expenses between periods t and $t-1$. Employee expenses refer to the employees costs of the company (including pension costs) in Orbis. The deposit ratio denotes the ratio of deposits over total assets (in %) for the year 2013. Post is a dummy variable representing the period from 2014 onward. The set of firm control variables (not reported) includes i) size, measured as the logarithm of total assets, ii) leverage, defined as the ratio of total liabilities to total assets, iii) sales growth, measured as the annual change in the natural logarithm of sales, iv) cash, defined as the ratio of cash and cash equivalents to total assets. Bank fixed effects are included. Country-Industry-Time fixed effects are based on four-digit NACE Rev.2 codes. Robust standard errors, clustered at the bank level, are in parentheses. ***, **, and * indicate significance at 1%, 5%, and 10%, respectively.

Table 1.15: Negative Interest Rates and France

Dependent Variable:	Loan growth	
	(1)	(2)
Sample:	Firms in France	
Deposit ratio × Post	-0.0631**	-0.0639**
(%)	(0.0308)	(0.0308)
Firm Control	No	Yes
Bank FE	Yes	Yes
Industry-Time FE	Yes	Yes
Observations	308422	308422
R^2	0.0156	0.0166

Notes: The table presents OLS estimates of the following model at the bank-firm level.

$$\text{Loan growth}_{isct} = \beta \text{Deposit ratio}_b \times \text{Post}_t + \alpha_b + \delta_{sct} + \gamma' X_{isct-1} + \epsilon_{isct}$$

The dependent variable is loan growth at the firm-bank level and is calculated as the difference in the natural logarithm of credit between periods t and $t-1$. Credit refers to the sum of long- and short-term financial debt recorded in Orbis. The sample is restricted to firms in France. The deposit ratio, presented in Columns (1) and (2), denotes the ratio of deposits over total assets (in %) for the year 2013. Post is a dummy variable representing the period from 2014 onward. The set of firm control variables (not reported) includes i) size, measured as the logarithm of total assets, ii) leverage, defined as the ratio of total liabilities to total assets, iii) sales growth, measured as the annual change in the natural logarithm of sales, iv) cash, defined as the ratio of cash and cash equivalents to total assets. Bank fixed effects are included. Industry-Time fixed effects are based on four-digit NACE Rev.2 codes. Robust standard errors, clustered at the bank level, are in parentheses. ***, **, and * indicate significance at 1%, 5%, and 10%, respectively.

Table 1.16: Negative Interest Rates and Other Loan Growth Measures

Dependent Variable	ln Loan		Loan-to-Asset	
	(1)	(2)	(3)	(4)
Deposit ratio × Post	-0.0600**		-0.00985**	
(%)	(0.0290)		(0.00427)	
Deposit ratio × Post		-0.0164*		-0.00322***
(0/1)		(0.00954)		(0.00103)
Firm Control	Yes	Yes	Yes	Yes
Bank FE	Yes	Yes	Yes	Yes
Country-Industry-Time FE	Yes	Yes	Yes	Yes
Observations	780287	780287	1020109	1020109
R^2	0.484	0.484	0.343	0.343

Notes: The table presents OLS estimates of the following model at the bank-firm level.

$$\ln \text{Loan}_{isct} = \beta \text{Deposit ratio}_b \times \text{Post}_t + \alpha_b + \delta_{sct} + \gamma' X_{isct-1} + \epsilon_{isct}$$
$$\text{Loan-to-Asset}_{isct} = \beta \text{Deposit ratio}_b \times \text{Post}_t + \alpha_b + \delta_{sct} + \gamma' X_{isct-1} + \epsilon_{isct}$$

The dependent variable in Columns (1) and (2) is the natural logarithm of credit at the firm-bank level in period t. The dependent variable in Columns (3) and (4) is the ratio of credit-to-asset at the firm-bank level in period t. Credit refers to the sum of long- and short-term financial debt recorded in Orbis. The deposit ratio, presented in Columns (1) and (3), denotes the ratio of deposits over total assets (in %) for the year 2013. In Columns (2) and (4), the deposit ratio is assigned a value of one if the ratio of deposits to total assets in 2013 is above the median of its respective country's distribution. Post is a dummy variable representing the period from 2014 onward. The set of firm control variables (not reported) includes i) size, measured as the logarithm of total assets, ii) leverage, defined as the ratio of total liabilities to total assets, iii) sales growth, measured as the annual change in the natural logarithm of sales, iv) cash, defined as the ratio of cash and cash equivalents to total assets. Bank fixed effects are included. Country-Industry-Time fixed effects are based on four-digit NACE Rev.2 codes. Robust standard errors, clustered at the bank level, are in parentheses. ***, **, and * indicate significance at 1%, 5%, and 10%, respectively.

1.7.3 Additional figures

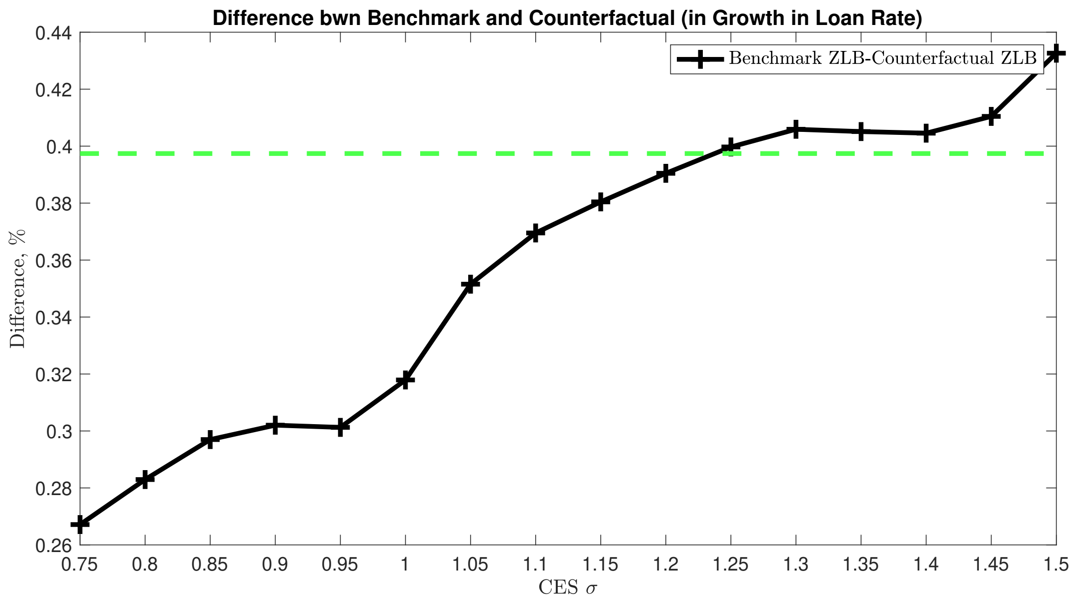

Figure 1.9: Calibrating CES σ to match the empirical estimates based on the interest rate.

Notes: The figure depicts the on-impact difference as percentage deviation of interest rate from its steady-state level between the Benchmark scenario and the Counterfactual scenario, plotted as a function of the elasticity of substitution between capital and labor.

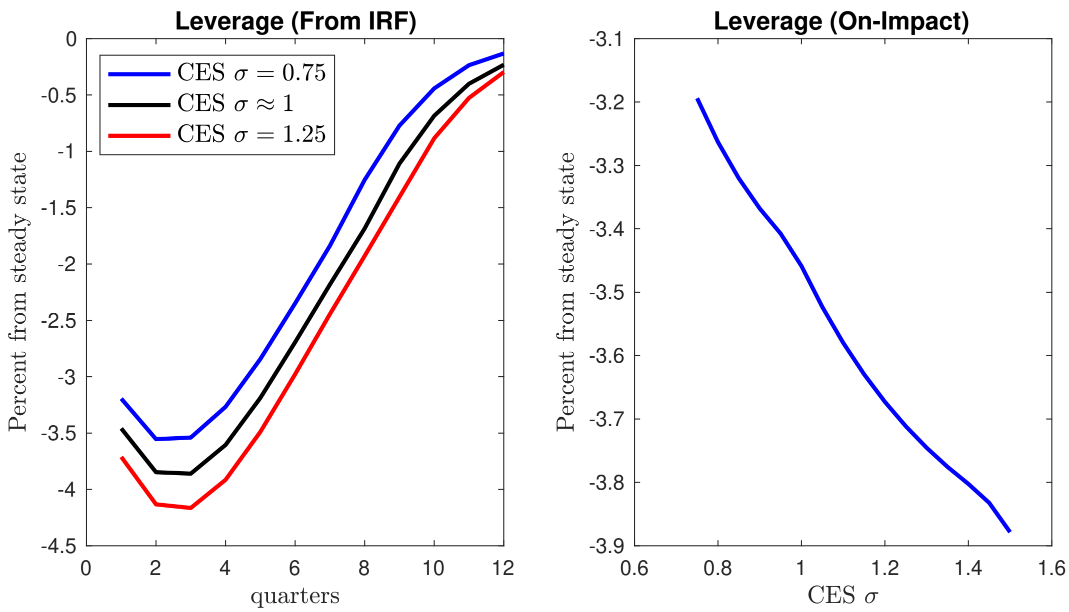

Figure 1.10: Bank leverage to response to capital productivity shock.

Notes: The figure on the left depicts the IRFs of bank leverage in the model to a capital productivity shock under the Benchmark ZLB scenario for CES $\sigma \in \{0.75, 1.00, 1.25\}$. The figure on the right is the on-impact percentage deviation of bank leverage from its steady state level for CES $\sigma \in \{0.75, \ldots, 1.00, \ldots, 1.50\}$.

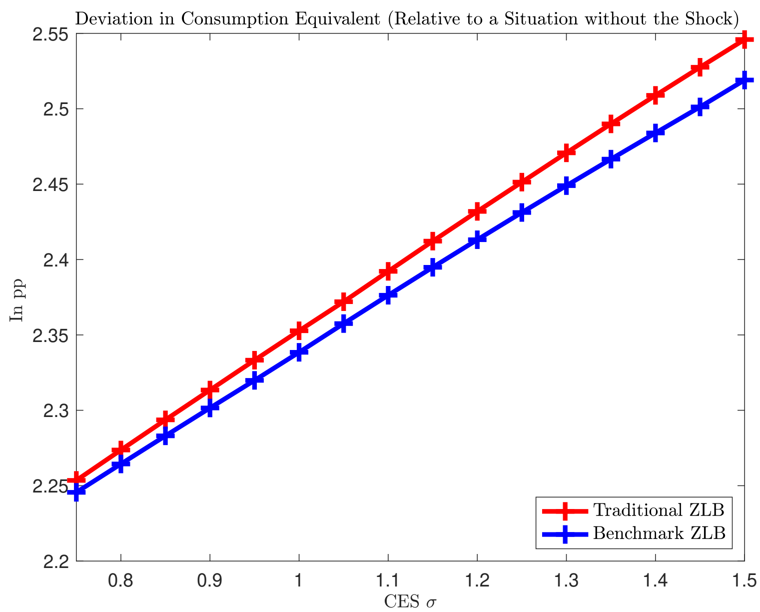

Figure 1.11: Deviation in consumption equivalent terms relative to situation without shock to capital productivity.

Notes: The figure depicts the percent deviation from consumption without shock to capital productivity for the Benchmark ZLB scenario (in blue line) and the Traditional ZLN scenario (in red line), plotted as a function of the elasticity of substitution between capital and labor.

CHAPTER 2

Dynamic General Equilibrium Modeling of Long and Short-Run Historical Events

(with Gary Hansen and Lee Ohanian)

2.1 Introduction

Macroeconomists have increasingly been studying historical events using quantitative general equilibrium tools, with a focus on important historical episodes that previously had been studied using traditional historical methods (see for example Ohanian (1997), Cole & Ohanian (1999, 2004), Kehoe & Prescott (2007), McGrattan (2012)). The application of general equilibrium analysis is shedding new light on important historical episodes by using diagnostic methods that help identify potential classes of models for evaluating these events, and by quantifying the impact of different shocks on macroeconomic activity during historical periods within fully articulated general equilibrium models.

The recent integration of macroeconomics with economic history involves the practice of combining general equilibrium analytical methods and historical narratives with existing and recently constructed historical datasets. This is creating new insights about long-run growth and cyclical fluctuations.

This chapter advances the use of quantitative general equilibrium tools within the field of historical economics to study two important and very different historical episodes that have received little attention using general equilibrium macroeconomic growth models.

The first is the Industrial Revolution, which captures the transition of Western economies from the Malthusian era, in which there was little, if any growth in per-capita income, to that of the era of Modern Economic Growth, which has featured persistent, long-run per capita growth and rising living standards, all of which took place around the middle of the 18th century. This analysis uses Hansen & Prescott (2002) model of the Industrial Revolution to analyze newly constructed data from Britain that dates back to 1245 (Clark, 2010).

Clark's data include total factor productivity (TFP), real output, population, factor prices, and capital stocks, among other variables, which allow us to provide the first quantitative-theoretic analysis of the transition from the Malthusian era to the modern growth era. Our main finding advances our quantitative understanding of the timing of the transition to modern economic growth that occurred in the 1700s.

We find that this transition realistically could never have occurred much before that time, as the productivity of the the Malthusian sector peaked around 15th century, virtually guaranteeing that the nascent capital-intensive technologies of that time would not be close to being competitive. Instead, a 300 year stagnation of the Malthusian sector implicitly allowed the newer capital-intensive production methods to catch up, become viable alternatives to the Malthusian technology, and ultimately dominate the labor and land-intensive Malthusian technologies. Moreover, we find that the timing of this catchup is robust to plausible amounts of historical TFP mismeasurement.

The second episode studied is the U.S. economy from 1889-1929. This is a particularly striking period in the history of the U.S., involving World War I, two major financial panics, the diffusion of several important new technologies, including electricity and the internal combustion engine, and the "Roaring Twenties", one of the most rapid growth decades in U.S. history, and the period which immediately preceded the Great Depression. This section uses variants of Business Cycle Accounting (Cole & Ohanian, 2002; Chari, Kehoe, & McGrattan, 2007; Brinca, Chari, Kehoe, & McGrattan, 2016), a general equilibrium diagnostic tool, to study this period in its entirety, and well as analyze individual events, including World War I and the Panics of 1893 and 1907, and the "Roaring Twenties". One main finding is that technology shocks are remarkably important drivers of economic activity between 1889 and 1916, including the Panics of 1893 and 1907. This finding stands in sharp contrast to the perception that technology shocks today are quantitatively unimportant. Our second main finding is that labor is substantially depressed during World War I, and this labor depression continues through the 1920s, one of the highest growth decades in U.S. history. We find that a large labor wedge is the key factor depressing growth during the 1920s, and that output per capita should have been about 15 percent higher by 1929 in the absence of the increased labor wedge. We find that standard factors, such as tax rates, do not account for the post-1916 labor wedge, and that future research should study this decade to gain a better understanding of the specific factors that created this wedge.

The chapter is organized as follows. Section 2.2 presents the analysis of the Industrial Revolution. Section 2.3 presents the analysis of the U.S. economy between 1889-1929. Section 2.4 concludes.

2.2 Growth in the Very Long Run

In this section, we use the model studied in Hansen & Prescott (2002) to interpret data from Clark (2010). In particular, this model features an endogenous transition from Malthusian stagnation to sustained growth. Malthusian stagnation is the result of firms choosing to use a production process where land's share of income is positive, and hence there are decreasing returns to capital and labor. Another important feature required for Malthusian stagnation is that the population growth rate is an increasing function of living standards. Sustained growth begins when a production process is employed that exhibits constant returns to capital and labor.

Perhaps the most important feature of this model is that both production process are available throughout history and the choice to employ one or both processes is made by firms in response to the total factor productivity associated with each of these processes. In the early stages of development, when TFP for the second production process is low, only the land intensive technology is used. Eventually, if TFP associated with the second production process grows over time, that process will inevitably begin to be employed. At this point an "industrial revolution" occurs and the economy converges to a standard Solow type balanced growth path.

The approach followed by Hansen & Prescott (2002) differs from other contributions to the literature using dynamic general equilibrium models to understand the industrial revolution in two respects. First, Hansen & Prescott (2002) study the consequences of technological progress while papers such as Galor & Weil (2000) or Lucas (2018) aim to explain technological progress itself. Second, the transition to sustained growth happens in the Malthus to Solow model when a production process with a lower land share becomes profitable and is adopted. In the other two papers, sustained growth results from an increase in the rate of return to human capital that leads to a demographic transition resulting from endogenous fertility decisions of the sort modeled in Becker & Barro (1988). Doepke (2004) develops a model that aims to unify these two approaches.

2.2.1 The "Malthus to Solow" Model

The model of Hansen & Prescott (2002) is a version of the Diamond (1965) overlapping generations growth model. Households live for two periods. They earn labor income when young which is used to finance consumption, investment in physical capital and land. In the second period of life, households are the owners of capital and land and finance consumption from renting these assets to firms, who use them along with labor as inputs in production. At the end of the period, old households sell their land to the young, which also helps finance their consumption. An additional important feature of the model is that population growth is a function of living standards as is generally assumed in a Malthusian growth model.

2.2.1.1 Technology

This is a one-good economy in which the single consumption good can be produced from two available production processes that are assumed to be accessible throughout time. The first is called the Malthus process and requires capital, labor and land (K_M, N_M, and$L$) to produce output according to the following Cobb-Douglas technology:

$$Y_{Mt} = A_{Mt} K_{Mt}^{\phi} N_{Mt}^{\mu} L_M^{1-\phi-\mu} \tag{2.1}$$

The second production process uses only capital and labor (K_S and N_S):

$$Y_{St} = A_{St} K_{St}^{\theta} N_{St}^{1-\theta} \tag{2.2}$$

Given that these two processes are always available and that Y_M and Y_S are the same good, the aggregate production function can be described as follows:

$$Y = F(K, N, L) = \max_{K_M, K_S, N_M, N_S} \left\{ A_M K_M^{\phi} N_M^{\mu} L^{1-\phi-\mu} + A_S K_S^{\theta} N_S^{1-\theta} \right\} \tag{2.3}$$

$$\text{subject to } K_M + K_S \leq K$$
$$N_M + N_S \leq N$$

Here, A_M is total factor productivity specific to the Malthus production process and A_S is total factor productivity specific to the Solow process.

Land is in fixed supply, it can't be produced and does not depreciate. Its only use is for production employing the Malthus process. Hence we normalize this to be one ($L_M = L = 1$).

Total output, $Y_t = Y_{Mt} + Y_{St}$, can be consumed or invested to produce capital productive the following period. Capital depreciates fully in the period it is used in production. Hence, the resource constraint is

$$C_t + K_{t+1} = Y_{Mt} + Y_{St} \tag{2.4}$$

One way of decentralizing this economy is to assume that one firm, called the Malthus firm, operates the Malthus production process (2.1) and another operates the Solow process (2.2).[1] Let w be the wage rate, r_K be the capital rental rate and $r_L$be the rental rate for land. Given these factor rental prices and values for A_M and A_S, each firm maximizes profit,

$$\max_{N_j,K_j,L_J} \left\{ Y_j - wN_j - r_K K_j - r_L L_j \right\}, \ j = M, S \tag{2.5}$$

2.2.1.2 Households

We assume that N_t households are born in period t live for two periods. A household born in period t consumes c_{1t} units of consumption in the first period of his life and $c_{2,t+1}$ units in the second. His utility is given by

$$U(c_{1t}, c_{2,t+1}) = \log c_{1t} + \beta \log c_{2,t+1} \tag{2.6}$$

The number of new households born in a given period is assumed to grow at rate that is a function of living standards. Living standards at date t are assumed to be given by c_{1t}

[1] Given constant returns to scale, the number of firms does not matter.

and N_t evolves as follows:

$$N_{t+1} = g(c_{1t})N_t \tag{2.7}$$

The initial old at date t_0 are assumed to be endowed equally with land ($\frac{1}{N_{t_0-1}}$ units) and capital ($\frac{K_{t_0}}{N_{t_0-1}}$ units). In addition, each young household is endowed with one unit of labor that is supplied inelastically. Old households are assumed to rent land and capital to firms and then sell their land to the young at the end of the period. This finances consumption in the second period of life, c_2. The young supply labor and earn labor income which is used to finance c_1, investment (k_{t+1}), and the purchase of land from the old. The price of land is denoted by q. Hence, a household born in period t will choose consumption, investment and land purchase to maximize (2.6) subject to the following budget constraints:

$$c_{1t} + k_{t+1} + q_t l_{t+1} = w_t \tag{2.8}$$

$$c_{2,t+1} = r_{K,t+1}k_{t+1} + (r_{L,t+1} + q_{t+1})l_{t+1} \tag{2.9}$$

2.2.1.3 Competitive Equilibrium

Given N_{t_0}, N_{t_0-1} and K_{t_0}, as well as a sequence of sector specific total factor productivities $\{A_{Mt}, A_{St}\}_{t=t_0}^{\infty}$, a competitive equilibrium consists of sequences of prices $\left\{q_t, w_t, r_{Kt}, r_{Lt}\right\}_{t=t_0}^{\infty}$, firm allocations $\{K_{Mt}, K_{St}, N_{Mt}, N_{St}, Y_{Mt}, Y_{St}\}_{t=t_0}^{\infty}$, and household allocations $\left\{c_{1t}, c_{2t}, k_{t+1}, l_{t+1}\right\}_{t=t_0}^{\infty}$ such that

- Given the sequence of prices, the firm allocations solve the problems specified in equation (2.5).
- Given the sequence of prices, the household allocation maximizes (2.6) subject to (2.8) and (2.9). Recall that the old in period t_0 are endowed with $\frac{1}{N_{t_0-1}}$ units of land and $\frac{K_{t_0}}{N_{t_0-1}}$ units of capital.

- Markets clear:
  - $K_{Mt} + K_{St} = N_{t-1}k_t$
  - $N_{Mt} + N_{St} = N_t$
  - $N_{t-1}l_t = 1$
  - $Y_{Mt} + Y_{St} = N_t c_{1t} + N_{t-1}c_{2t} + N_t k_{t+1}$
- $N_{t+1} = g(c_{1t})N_t$

2.2.1.4 Characterizing the Equilibrium

Here we briefly summarize how we solve for an equilibrium sequence of prices and quantities. More details are provided in Hansen & Prescott (2002) and Greenwood (2020). The key results show that the Malthus sector will always operate, but the Solow sector will only operate if A_S is sufficiently large. In particular, the papers cited establish the following results:

1. For any w_t and r_{Kt}, the Malthus sector will operate. That is, $Y_{Mt} > 0$ for all t.
2. Given values for w_t and r_{Kt}, maximized profit per unit of output in the Solow sector is positive if and only if
$$A_{St} > \left(\frac{r_{Kt}}{\theta}\right)^{\theta}\left(\frac{w_t}{1-\theta}\right)^{1-\theta} \tag{2.10}$$
   Profits are zero if equation (2.10) holds with equality. Hence, the Solow firm will only produce output ($Y_{St} > 0$) if A_{St} is greater than or equal to the right hand side of (2.10).

Given values for A_{Mt}, A_{St}, K_t and N_t for some t, define w_t^M and r_{Kt}^M as follows:

$$w_t^M \equiv \mu A_{Mt} K_t^{\phi} N_t^{\mu-1} \tag{2.11}$$

$$r_{Kt}^M \equiv \phi A_{Mt} K_t^{\phi-1} N_t^{\mu} \tag{2.12}$$

Our solution procedure involves first evaluating the right hand side of equation (2.10) at w_t^M and r_{Kt}^M each period. If A_{St} is less than or equal to this value, only the Malthus sector will operate. In this case, in equilibrium $w_t = w_t^M$, $r_{Kt} = r_{Kt}^M$ and $r_{Lt} = (1-\phi-\mu)A_{Mt}K_t^{\phi}N_t^{u}$. If A_{St} is greater than this value, both sectors will operate and the marginal product of labor and capital will be equated across sectors (see problem (2.3)). Hence, the equilibrium rental rates are as follows:

$$w_t = \begin{cases} w_t^M & \text{if } A_{st} \leq \left(\frac{r_{Kt}^M}{\theta}\right)^{\theta} \left(\frac{w_t^M}{1-\theta}\right)^{1-\theta} \\ \mu A_{Mt} K_{Mt}^{\theta} N_{Mt}^{\mu-1} = (1-\theta) A_{St} K_{St}^{\theta} N_{St}^{-\theta} & \text{if } A_{St} > \left(\frac{r_{Kt}^M}{\theta}\right)^{\theta} \left(\frac{w_t^M}{1-\theta}\right)^{1-\theta} \end{cases} \tag{2.13}$$

$$r_{Kt} = \begin{cases} r_{Kt}^M & \text{if } A_{st} \leq \left(\frac{r_{Kt}^M}{\theta}\right)^{\theta} \left(\frac{w_t^M}{1-\theta}\right)^{1-\theta} \\ \phi A_{Mt} K_{Mt}^{\phi-1} N_{Mt}^{\mu} = \theta A_{St} K_{St}^{\theta-1} N_{St}^{1-\theta} & \text{if } A_{St} > \left(\frac{r_{Kt}^M}{\theta}\right)^{\theta} \left(\frac{w_t^M}{1-\theta}\right)^{1-\theta} \end{cases} \tag{2.14}$$

$$r_{Lt} = (1-\phi-\mu) A_{Mt} K_{Mt}^{\phi} N_{Mt}^{u} \tag{2.15}$$

The first order conditions for choosing k_{t+1} and l_{t+1} in the household's problem can be written

$$c_{1t} = \frac{w_t}{1+\beta} \tag{2.16}$$

$$q_{t+1} = q_t r_{K,t+1} - r_{L,t+1} \tag{2.17}$$

Finally, the budget constraints and market clearing conditions imply that

$$K_{t+1} = N_t(w_t - c_{1t}) - q_t \tag{2.18}$$

Given a value for q_{t_0}, $\{A_{Mt}, A_{St}\}_{t=t_0}^{\infty}$, K_{t_0} and N_{t_0}, the equations (2.3), (2.7) and (2.13) - (2.18) determine the equilibrium sequence of prices and quantities,

$$\left\{Y_t, w_t, r_{Kt}, r_{Lt}, c_{1t}, q_{t+1}, K_{t+1}, N_{t+1}\right\}_{t=t_0}^{\infty} .$$

The initial price of land, q_{t_0}, is not given but is also determined by the equilibrium conditions of the model. In particular, q_{t_0} turns out be uniquely determined by the requirement that iterations on equation (2.17) do not cause q_t to eventually become negative or K_{t+1} (determined by equation 2.18) to become negative. We use a numerical shooting algorithm to find this value of q_{t_0}.

2.2.1.5 Calibration of Population Growth Function

In the application carried out here, we interpret one model time period to be 25 years. We use the same population growth function, $g(c_{1t})$, as in Hansen & Prescott (2002). This function, which was based on data from Lucas (1988) on population growth rates and per capita income, has the following properties: (1) the population growth rate increases linearly in living standards until population doubles every 35 years or 1.64 periods; (2) at the point where population doubles every 35 years, living standards are twice the Malthusian level; (3) the population growth rate decreases linearly from this point until living standards are 18 times the Malthusian level at which point the growth rate of population is zero; and (4) population is constant as living standards continue to rise. Here, c_{1M} is the Malthusian steady state level of c_{1t} and γ_M is the growth factor of A_{Mt} in a Malthusian steady state. This will be characterized fully in the next subsection.

$$g(c_{1t}) = \begin{cases} \gamma_M^{1/(1-\mu-\phi)} \left(2 - \frac{c_{1t}}{c_{1M}}\right) + 1.64 \left(\frac{c_{1t}}{c_{1M}} - 1\right) & \text{for } c_{1t} < 2c_{1M} \\ 1.64 - 0.64 \frac{c_{1t}-2c_{1M}}{16c_{1M}} & \text{for } 2c_{1M} \leq c_{1t} \leq 18c_{1M} \\ 1 & \text{for } c_{1t} > 18c_{1M} \end{cases} \tag{2.19}$$

2.2.1.6 The Malthusian Steady State

As in Hansen & Prescott (2002), we will assume that this economy begins in a Malthusian steady state, which is the asymptotic growth path for a version of the model with only the Malthus production process available or where A_S is sufficiently low for all t that equation (2.10) is never satisfied. Also, prior to period t_0, A_M is assumed to grow at a constant rate equal to $\gamma_M - 1$, $c_{1t} < 2c_{1M}$, and the population growth rate is determined according to the first segment of the function g in equation (2.19). In this case, the Malthusian steady state growth rate of population will be $g_N = \gamma_M^{1/(1-\mu-\phi)}$. Both the price of land and the stock of capital will also grow at this same rate on this steady state growth path.

It will be useful for our empirical exercise if we choose a value for steady state income per capita, call it y_M, and compute the rest of the steady state to be consistent with that value. From steady state versions of equations (2.11) and (2.16), we can compute c_{1M} as

$$c_{1M} = \frac{w_M}{1+\beta} = \frac{\mu}{1+\beta} y_M \,. \tag{2.20}$$

Next, the following three equations, which are steady state versions of equations (2.14), (2.17) and (2.18), can be solved to obtain the rental rate of capital, $r_{K,M}$, the steady state capital to labor ratio, $\hat{k}_M$, and the steady state land price to labor ratio, $\hat{q}_M$:

$$r_{K,M} = \phi \frac{\hat{y}}{\hat{k}} \tag{2.21}$$

$$\left(\frac{r_{K,M}}{g_N} - 1 \right) \hat{q} = (1 - \mu - \phi) \hat{y} \tag{2.22}$$

$$g_N \hat{k} = \left(\mu - \frac{\mu}{1+\beta} \right) \hat{y} - \hat{q} \tag{2.23}$$

2.2.2 Quantitative Exercise: England from 1245 to 1845

The model presented in the last subsection is now used to interpret time series taken from Clark (2010).[2] Clark uses a variety of sources to construct data that can be used in a quantitative general equilibrium model, including TFP, national income, the capital stock, and payments to capital and labor. This allows us to study the Industrial Revolution in much more quantitative detail than previously possible.

Given that one model time period is interpreted to be 25 years, we use 25 year averages of annual data on total factor productivity, output per capita, and population constructed by Clark using the methodology described in Clark (2010). In particular, data for a given year, say 1845, is actually an average constructed from annual data from 1845 to 1870.[3]

Figure 2.1 shows Clark's total factor productivity series from 1245 to 1845. The series is extended to 2020 by allowing it to grow from 1845 according to the value we assign to the parameter γ_M. Twenty five year averages of Clark's estimate of England's population from 1245 to 1845 is shown in Figure 2.15 in Appendix 2.5 and his estimate for real per capita income is in Figure 2.16 in Appendix 2.5.

2.2.2.1 Model Calibration

The model parameter values we used were $\mu = 0.65$ and $\phi = 0.1$ for the Malthus production process and $\theta = .35$ for the Solow process. These values imply that labor's share of income is the same (0.65) for both production processes, following Hansen & Prescott

[2]Clark (2010) provides data at ten year intervals on a variety of macroeconomic aggregates. The data we actually use was received from the author and includes annual data that enabled us to compute 25 year averages.

[3]Specifically, total factor productivity is from the third column of Table 33 in Clark (2010), which was constructed using a price index of domestic expenditures. An alternative measure is provided using the price of net domestic output. Similarly, we chose to measure per capita output using real national income that was also constructed using domestic expenditure prices. This series is contained in Table 28 of Clark (2010). The population series we use is from Table 7 of that paper.

Figure 2.1: Malthusian TFP (A_M).

(2002). Land's share in the Malthus process is 0.25. The growth factor for Malthus total factor productivity prior to 1245 and after 1845, when our measured data series ends, is given by $\gamma_M = 1.0074$. This was set to match the average population growth rate from 1245 to 1745 and characterizes our Malthusian steady state. Similarly, the growth factor for Solow total factor productivity beginning in 1895 is $\gamma_S = 1.27$. This implies an asymptotic growth rate of real output per capita equal to 1.5 percent per year. The value of the discount factor, β, was set equal to one following Hansen and Prescott.

The value of y_M used is equal to 55. The movements in per capita income exhibited by our model economy are both the direct result of TFP movements and the Malthusian dynamics associated with the economy converging back to steady state following a given change in TFP. We chose y_M by simply trying different values above and below the mean of per capita income from 1245 to 1745 and taking the one that allowed our model to best fit the time series on per capita income during that period.

The final calibration issue to be resolved, other than initial conditions K_{t_0} and N_{t_o}, is a time series for A_S prior to 1895. Recall that the Solow production process will be employed only when A_S satisfies equation (2.10). We construct our A_S time series so that this happens for the first time in the year 1745. Prior to that, the value of A_S is perhaps growing at a slow rate, but is irrelevant to the computation of an equilibrium. We set $A_{S,1745}$ equal to 25, which is the smallest integer value that satisfies equation (2.10). Following that,A_S grows 10 percent each period until 1870. This value was chosen so that a demographic transition would not occur until at least this date given that the rate of population in our data sample continues to raise with living standards. That is, we chose this value so that the population growth rate would continue to be determined by the first branch of equation (2.19).

Figure 2.2 is a plot of our assumed A_S series from 1745 to 1845.

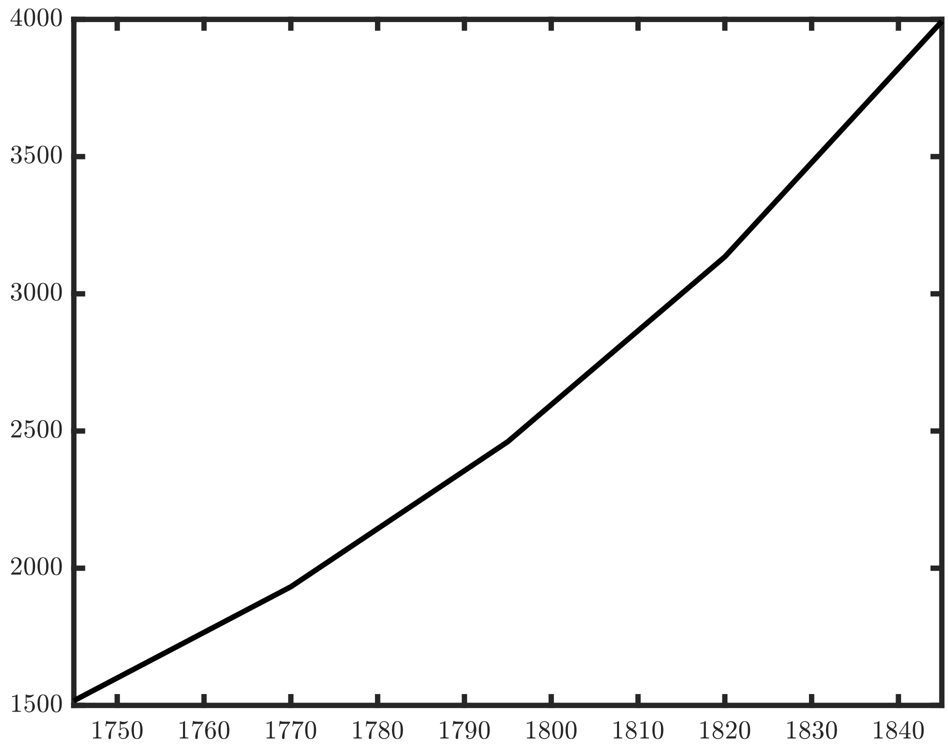

Figure 2.2: Solow TFP (A_S).

2.2.2.2 Benchmark Simulation

We assume that the economy was in a Malthusian steady state at date $t_0 - 1 = 1220$. Given $y_M = 55$ and $N_{t_0-1} = 5$, we obtain $K_{t_0-1} = \hat{k}N_{t_0-1}$. Also, so that $y_{1220} = y_M$, we set $A_{M,1220} = A_{M,1245}$ and normalize the A_M sequence so that $y_{t_0-1} = Y_M = A_{M,t_0-1}K^{\phi}_{t_0-1}N^{\mu-1}_{t_0-1}$. In this case, our initial conditions for 1245 are $N_{t_0} = g_N N_{t_0-1}$ and $K_{t_0} = \hat{k}N_{t_0}$.

We also add an additional element in our benchmark simulation that is not part of the model described so far. In particular, England suffered from a series of plagues that decimated its population for three centuries from 1345 (the Black Death) to 1645 (the Great Plague of London). In particular, there is a downward sloping portion in Figure 2.15 in Appendix 2.5 that shows that population was declining from 1320 to 1470.[4] We capture this by replacing equation (2.7) with

$$N_{t+1} = P_t g(c_{1t}) N_t \,, \tag{2.24}$$

where P_t, which we interpret as a "plague shock", is equal to one for all t except for $t = 1295 - 1445$. For these dates, we set $P_t = 0.8$.

Figure 2.3 shows that our benchmark simulation successfully captures the decline in population from 1295 to 1445. After that, England's actual population increased more rapidly than in the model economy. This is particularly true after 1750. Figure 2.4 shows that the model economy captures the fluctuations in per capita income quite well.

The transition from employing all inputs in the Malthus production process to having almost all of the capital and labor assigned to the Solow process is shown in Figure 2.5. In particular, in the first period of the industrial revolution, 1745, 31 percent of capital and 12 percent of labor is employed in the Solow process. The fraction of inputs employed in Solow production increases over time and exceeds 95 percent in 1895 for labor and in 1870

[4]We will discuss how the model would respond to the plagues beyond 1470 in subsequent experiment.

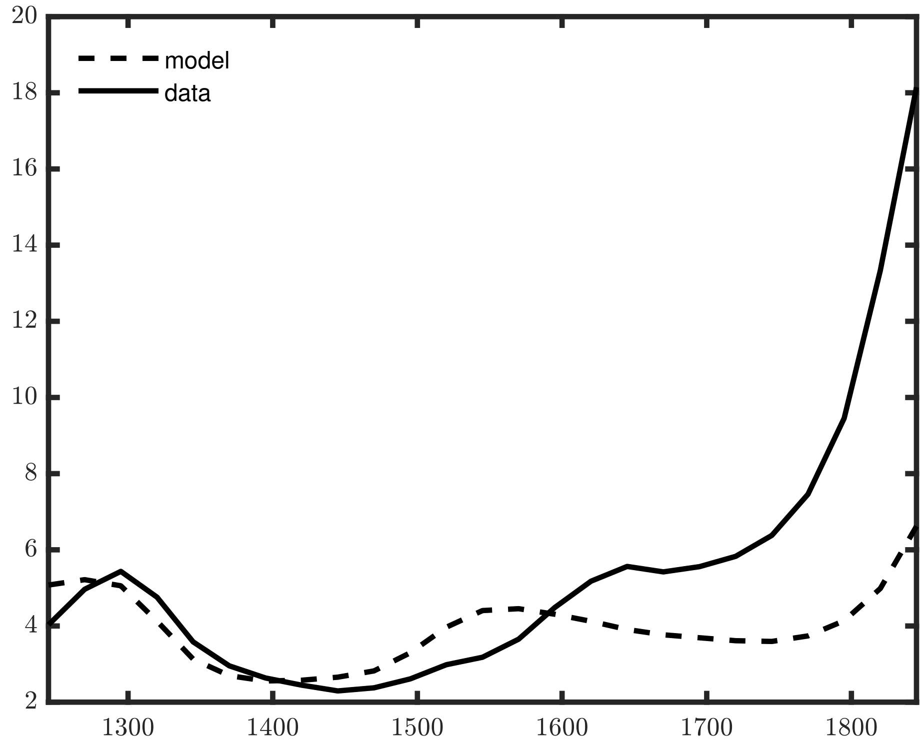

Figure 2.3: Population from Benchmark experiment.

for capital. At this point, the economy has come close to converging to a standard neoclassical steady state growth path where real output per capita is growing by 1.5 percent per year.

2.2.2.3 No Plagues

As a counterfactual experiment, we recompute the benchmark under the assumption that $P_t = 1$ for all t. In this case, as shown in Figure 2.17 in Appendix 2.5, model population is as much as three times larger than in the actual data during the period of plagues from 1345 to 1645. Similarly, Figure 2.18 in Appendix 2.5 shows that per capita income in our model is significantly lower than in the actual data during this period due to population in the model economy being so high.

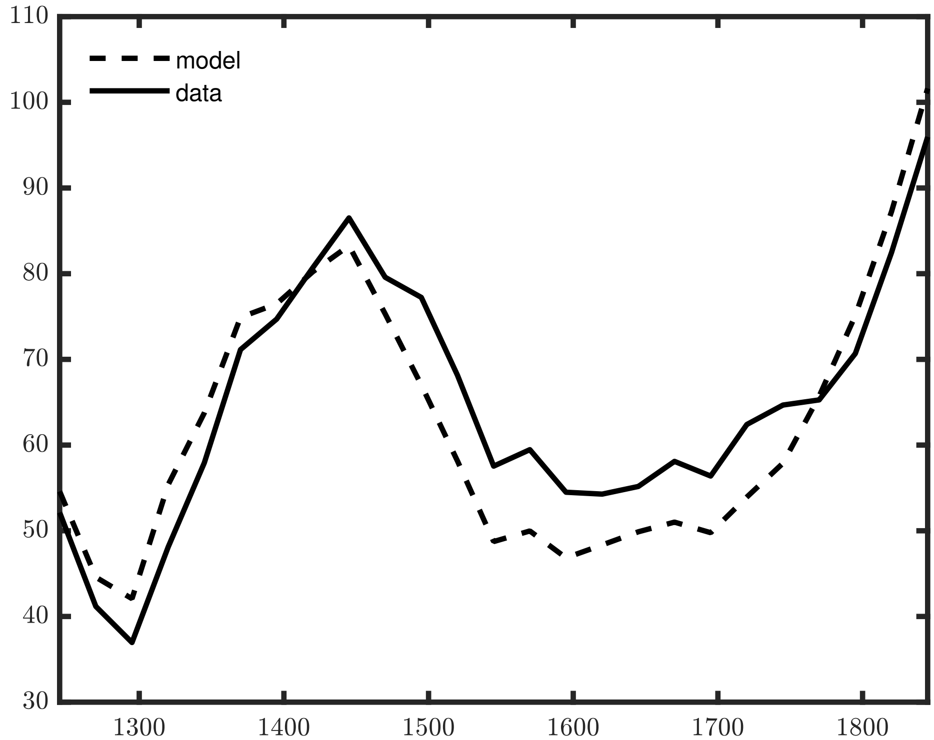

Figure 2.4: Output per capita from Benchmark experiment.

2.2.2.4 More Plagues

As mentioned previously, England suffered plagues pretty continuously from 1245 to 1645. In this experiment, we set $P_t = 0.8$ for $t = 1295 - 1620$. As shown in Figure 2.19 in Appendix 2.5, this leads to model population being as much as a third of what is observed in the actual data from 1550 to 1750. This result is simply a more extreme version of what is observed with population in the benchmark simulation. Model and data series for per capita income look fairly similar in this experiment as shown in Figure 2.20 in Appendix 2.5. Clearly, there is something happening with population during the period 1550-1750 that is not captured solely by plagues and Malthusian dynamics.

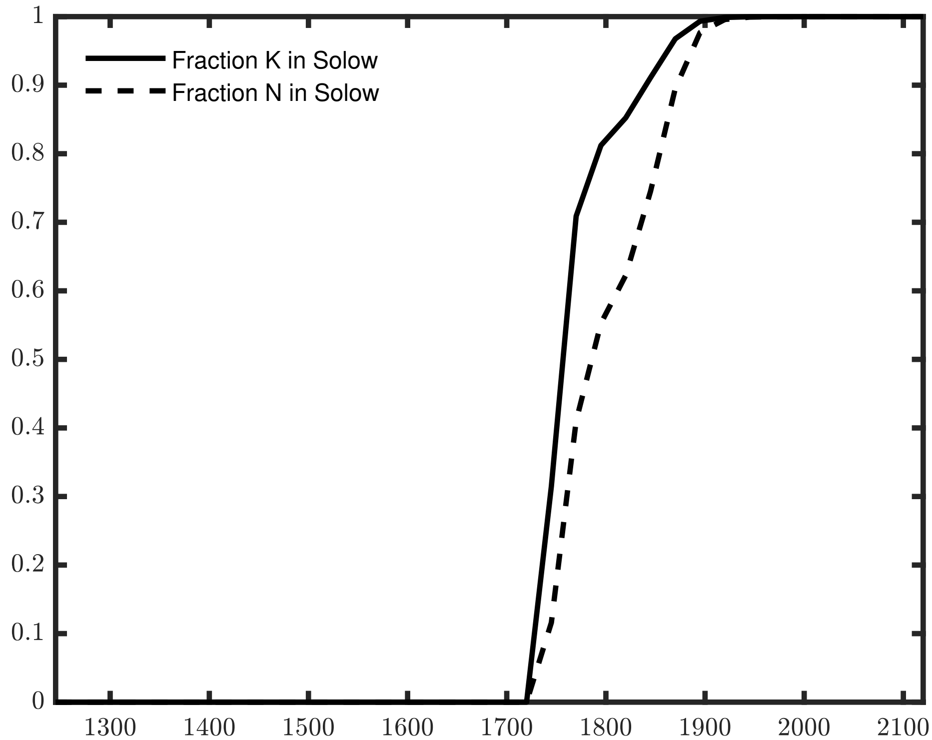

Figure 2.5: Fraction of inputs employed in Solow.

2.2.2.5 Timing of the Industrial Revolution

In the experiments done so far, we constructed the A_S sequence so that the Solow production process is initially adopted in 1745. Note that in Figure 2.21 in Appendix 2.5, A_M (the solid line) reaches a peak in 1445 and then drops significantly.

In this counterfactual experiment, we assume this drop never occurred and that A_M simply grew at rate $\gamma_M - 1$ after 1445 (see dotted line in Figure 2.21 in Appendix 2.5). Will this relative success of the Malthusian production process, given the same sequence for A_S as in the benchmark, cause the Industrial Revolution to happen at a later date? Turns out that the adoption of the Solow process begins at exactly the same date as in the benchmark (1745). Figure 2.6 shows the right hand side of equation (2.10) for both the benchmark and this counterfactual case from 1245 to 1745. We see that while this threshold is very high when A_M reached its peak in 1450 in both cases, the threshold falls very quickly in the benchmark due to declines in A_M. In the counterfactual, however, Malthusian dynamics dominate. As A_M continues to grow, population also grows (see Figure 2.22 in Appendix 2.5). This causes income per capita to decline as it converges to the Malthusian steady state of y_M = 55 (see Figure 2.7). These same dynamics cause the Solow threshold to decline and, as it turns out, it is still profitable to adopt the Solow process in 1745 when A_S is equal to 25.

The key here is that in the Malthusian steady state, the right hand side of equation (2.10) is a constant. This threshold might deviate from this steady state due to short run fluctuations in A_M, but over time will converge back to this constant. Hence, while we chose the A_S sequence in the benchmark so that the Solow production process would be adopted in 1745, this result turns out to be robust in the absence of significant upward movements in the A_M process in the period near 1745.

Figure 2.6: Solow threshold from "Timing of Industrial Revolution" and Benchmark experiments.

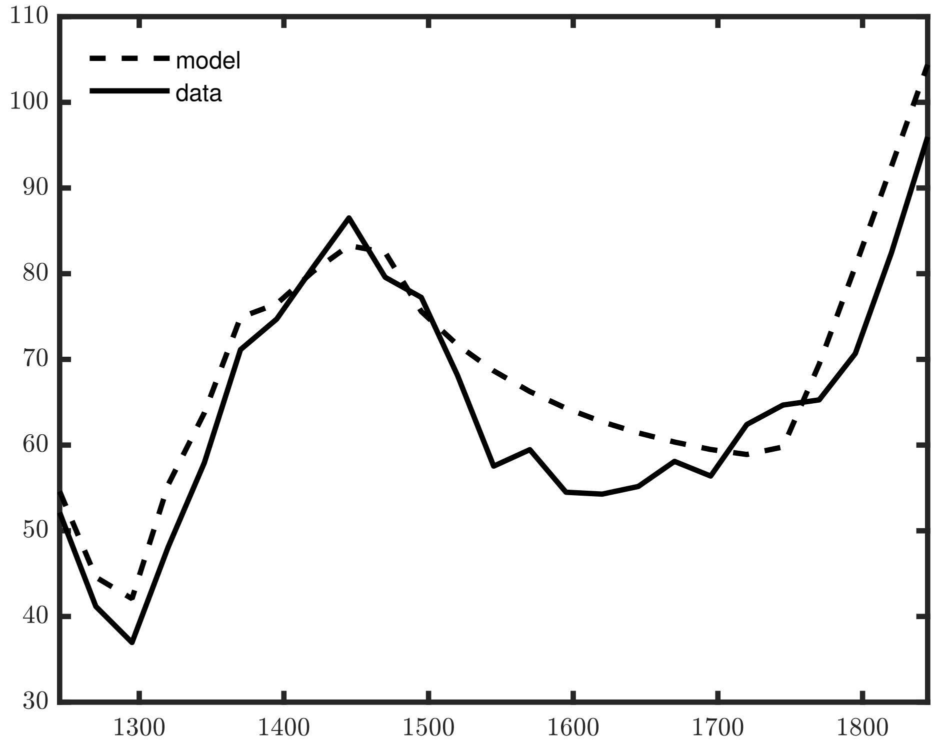

Figure 2.7: Output per capita from "Timing of Industrial Revolution" experiment.

2.3 Business Cycle Accounting of the 1889-1929 U.S. Economy

To apply Business Cycle Accounting (BCA) for this period, we use data constructed by John Kendrick (1961). Kendrick constructed data from 1869-1957 for the U.S. economy using NIPA principles. These data include real measures of consumption, private and government fixed investment, inventories, government consumption, and exports and imports. The data also have consistent measures of labor and capital input that are aggregated from sectoral measures of these variables. These data are considered to be high quality and the best available for this time period. The data are decennial from 1869-1889, and are annual from 1889 onwards, which leads us to begin in 1889.

The period from 1889-1929 is striking from a macroeconomic perspective because of a number of short-run events and also because of it its importance in the long-run evolution of the American economy. This period includes the "Roaring Twenties", well-known for its high economic growth rate and as the runup to the Great Depression. It also includes World War I, in which government consumption rose enormously, taking away resources from the private sector. There were also two very famous financial panics, the Panic of 1893 and the Panic of 1907.

More broadly, 1889-1929 is a period of enormous technological change, including the diffusion of electrification and the expansion of the internal combustion engine, which transformed production methods (electrification) and transportation (internal combustion engine). 1889-1929 also includes the heyday of American monopolies, including the famous Standard Oil trust and John D. Rockefeller, and Andrew Carnegie's U.S. Steel trust, both of which motivated the passage of the country's major antitrust acts, the Sherman Act in 1890 and the Clayton Act in 1914.

To our knowledge, neither this period in its totality, nor any of the individuals events within the period, have been analyzed using quantitative general equilibrium tools. This chapter thus provides the first such evaluation of this remarkable period. BCA, first used in Cole & Ohanian (2002), and Chari, Kehoe, & McGrattan (2002), and then developed further in Chari et al. (2007), and Brinca et al. (2016), henceforth BCKM, is ideally suited for investigating this period, because it is the leading diagnostic general equilibrium framework for identifying a set of possible factors affecting macroeconomic performance and for measuring the quantitative importance of these factors for output, consumption, investment, and hours worked. Moreover, we show that BCA is not only useful for analyzing fluctuations at the business cycle frequency (e.g. four years), but also is useful for studying lower frequency phenomena that evolve over a decade or more.

1889-1929 represents a period of unique long-run economic evolutions that are overlayered with several large short-run fluctuations that are of interest in their own right. As we show below, BCA highlights a number of key factors that are striking and surprising relative to the literature, and surprising relative to findings from postwar business cycles and the Great Recession. They also will suggest specific theoretical classes of models for understanding this important episode.

We summarize BCA and its application protocol here, and refer the reader to BCKM for details. BCA begins with a standard optimal growth model. Each period t, a random event s_t is realized. Let $s^t = (s_0, \ldots, s_t)$ denote the history of events up through and including period t and $\pi_t(s^t)$ be the probability of history s^t being realized at period t. Preferences are defined over expected sequences of consumption and leisure. There is a standard Cobb-Douglas constant returns to scale production function with labor-augmenting technological change. Output is divided between consumption, investment, and government consumption. There is a standard law of motion for capital, and the household time endowment is normalized to unity:

$$\max E_0 \sum_{t=0}^{\infty} \sum_{s^t} \beta^t \pi_t(s^t) U(C_t(s^t)/N_t, 1 - l_t(s^t))$$

subject to:

$$F(K_t(s^{t-1}), (1+\gamma)^t N_t l_t(s^t)) \geq C_t(s^t) + X_t(s^t) + G_t(s^t)$$

and the capital accumulation law:

$$K_{t+1}(s^t) = X_t(s^t) + (1-\delta) K_t(s^{t-1})$$

All variables except for time allocated to market production are then divided by technological progress $(1+\gamma)^t$ and population $N_t = (1+\gamma_n)^t$ to induce stationarity, and the transformed variables are denoted by lower case letters. The optimality conditions for this problem (assuming that transversality is satisfied) are given by[5]:

$$U_{lt}(s^t) = U_{ct}(s^t) f_{lt}$$

[5] We will be using log utility, therefore β^* denotes $\beta(1+\gamma_n)$.

$$U_{ct}(s^t)(1+\gamma) = \beta^* \sum_{s^{t+1}} \pi_t(s^{t+1}|s^t) U_{ct+1}(s^{t+1})\{f_{kt+1} + 1 - \delta\}$$

$$f(k_t(s^{t-1}), l_t(s^t)) \geq c_t(s^t) + k_{t+1}(s^t)(1+\gamma)(1+\gamma_n) - (1-\delta)k_t(s^{t-1}) + g_t(s^t)$$

To use this model for diagnostic purposes, we first augment these optimality conditions with multiplicative terms known as "wedges", that are functions of state s^t. The wedges will allow this model to completely account for the data. As you will see below, several of the wedges appear to be tax rates, though we do not give the wedges structural interpretations at this stage of analysis. The augmented first order conditions are below:

$$U_{lt}(s^t) = U_{ct}(s^t)[1 - \tau_{lt}(s^t)]A_t(s^t)f_{lt}$$

$$A_t(s^t)f(k_t(s^{t-1}), l_t(s^t)) \geq c_t(s^t) + k_{t+1}(s^t)(1+\gamma)(1+\gamma_n) - (1-\delta)k_t(s^{t-1}) + g_t(s^t)$$

$$U_{ct}(s^t)(1+\gamma)[1+\tau_{xt}(s^t)] = \beta^* \sum_{s^{t+1}} \pi_t(s^{t+1}|s^t) U_{ct+1}(s^{t+1})\{A_{t+1}(s^{t+1})f_{kt+1} + (1-\delta)[1+\tau_{xt+1}(s^{t+1})]\}$$

We begin with the wedge $A_t(s^t)$, which multiplies the production function. This wedge is observationally equivalent to the Solow Residual, and thus accounts for movements in output not due to movements in capital and labor. This is called an *efficiency wedge*. Next, consider the first order condition for allocating time between market work and leisure. The wedge here is denoted as $1 - \tau_{lt}(s^t)$, and is written in this way because it is observationally equivalent to a tax on labor income. This is called the *labor wedge*, and as noted above, is not given a structural interpretation at this stage. The economy's intertemporal condition is augmented with a wedge denoted as $1/[1 + \tau_{xt}(s^t)]$, and is written in this way because it is similar to a tax on investment. It is called the *investment wedge*. The last wedge is called the *government consumption wedge,* which accounts for the sum of government consumption and net exports. With a Markovian implementation there is one to one and onto mapping from the event s_t to the wedges $(A_t, \tau_{lt}, \tau_{xt}, g_t)$.

The stochastic process for the event $s_t = (A_t(s^t), \tau_{lt}(s^t), \tau_{xt}(s^t), g_t(s^t))$ is governed by a first-order VAR:

$$s_{t+1} = P_0 + Ps_t + \varepsilon_{t+1},\ E(\varepsilon\varepsilon') = V$$

in which P_0 and P are matrices of autoregressive coefficients to be estimated, ε is a vector of innovations, and V is the variance-covariance matrix of the innovations. As BCKM show, it is straightforward to estimate the coefficients and the elements of the variance-covariance matrix using maximum likelihood after log-linearizing the model, setting it up in state space form, and using the Kalman Filter.

With these wedges, which equal the number of endogenous variables, the augmented model fits the data perfectly, and therefore the model is used as an *accounting device.* To do this, we first measure the wedges as realizations from their stochastic process, and we then use the wedges within the linearized model to conduct various experiments, including quantifying the contribution of one or more wedges in accounting for the endogenous variables. We then use the results from these experiments to evaluate different classes of structural models. Below, we report some very surprising findings from this analysis in comparison from findings from postwar analyses, and from the perspective of narrative historical studies about this period.

2.3.1 Business Cycle Accounting Findings

Real GNP and its components, and labor input, measured as hours worked, are from Kendrick (1961). Following standard practice, all variables are first divided by the population, 16 years old and over[6]. As is standard practice, we divide all growing variables by a common trend, in which we use 1.6 percent annually. We divide government spending into government consumption and government investment, in which the latter is put in the investment category, and following BCKM and Hansen & Ohanian (2016), we add net exports to government consumption.

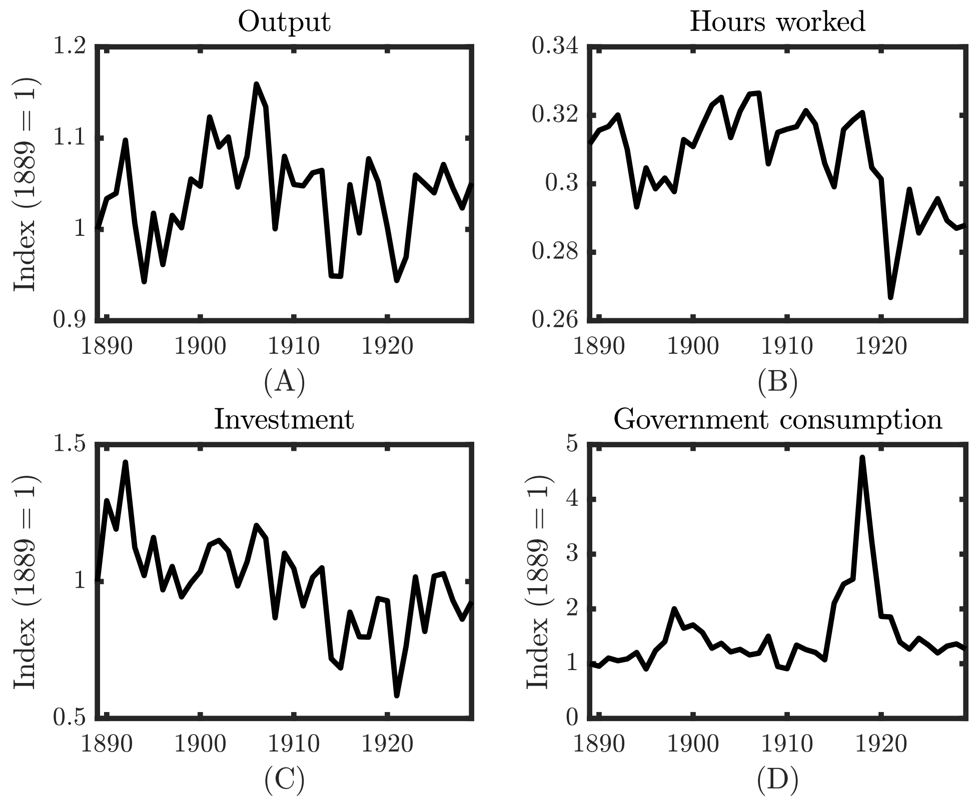

Figure 2.8: Detrended macro aggregates.

Figure 2.8 shows these data. There are several noteworthy features. One is the very large increase in government consumption during World War I, which suggests potentially large effects of the war on the economy. Ohanian (1997) and McGrattan & Ohanian (2010) quantitatively analyze how well a neoclassical model can account for the World War II economy, and how much government fiscal policy affected output, labor input, invest-

[6]The data are available from 1900 to 1929. Linear interpolation is used to construct the data from 1889 to 1899 using the data on the population 15 years old and over. Details are available upon request.

ment and consumption. Applying BCA to this period will provide an assessment of the neoclassical model for the World War I economy which will be a natural complement to the existing World War II studies.

Another notable feature is the behavior of the economy around the two major financial panics, the Panic of 1893 and the Panic of 1907. Both episodes feature above-normal economic growth for some years prior to the panic, followed by a drop in real GDP and hours worked, then followed by a rapid rebound in economic activity.

But perhaps the most striking feature of these data is the pattern of hours worked. These average around 1/3 of the households time endowment from the mid-1890s up to the mid-teens, but then hours drop around the end of World War I and remain at that low level through the booming 1920s. This raises an important question: Why do hours worked remain so low during an economic boom with sharply rising investment and productivity? Standard theory indicates that hours should be higher than average during the 1920s, not lower than average.

To quantitatively evaluate these three issues, we log-linearize the model, set it up in state space form, and estimate the parameters of the wedge stochastic process using maximum likelihood via the Kalman Filter. To model the stochastic process for the wedges, we use a VAR. We use one lag for the VAR because the data are annual.

Figure 2.9 reports the four wedges between 1889-1929. Panel A shows the efficiency wedge over time. This shows large and stationary movements until World War I, then it rises substantially through the 1920s, likely reflecting the rapid diffusion of electricity and the internal combustion engine. Given the large literature on 1920s productivity growth and innovation diffusions, we refer to the efficiency wedge during this period as productivity growth.

The investment wedge shows a large trend decline, which is observationally equivalent to a continuously declining tax on investment goods. It also features temporary

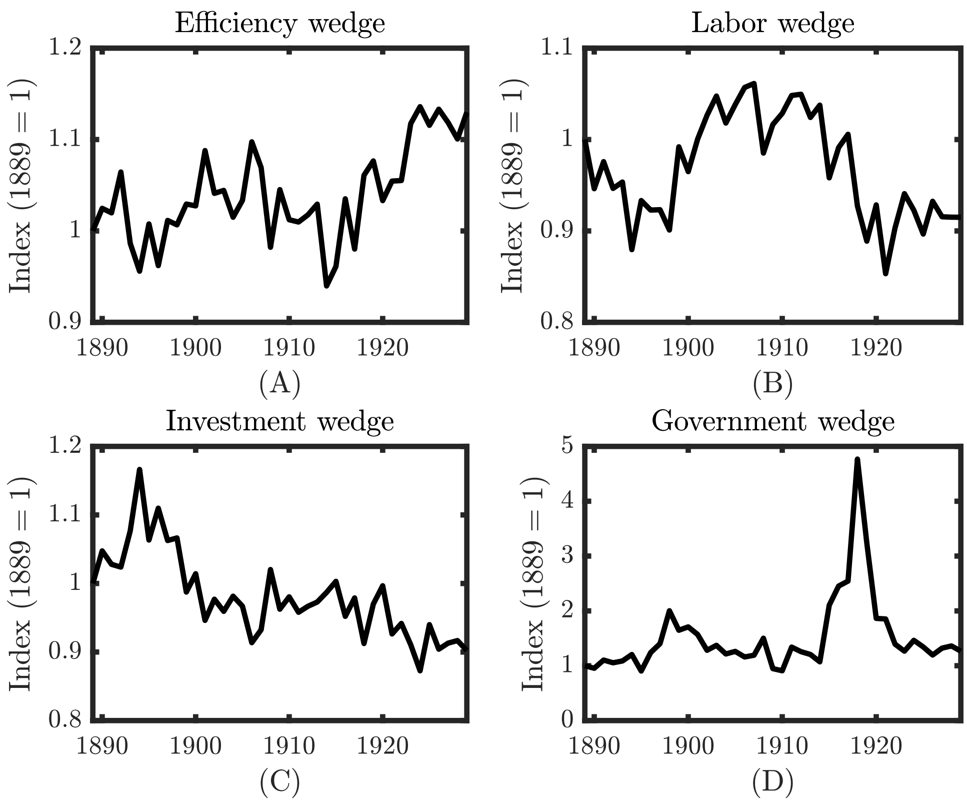

Figure 2.9: Estimated wedges.

increases around the times of the Panics of 1893 and 1907. The World War I spending increases dwarfs all other movements in the government wedge, as government spending rises by about a factor of four during the war. The labor wedge declines in the early teens, which is equivalent to a higher labor income tax. This higher labor wedge continues through World War I and the 1920s.

2.3.1.1 Contribution of the Wedges

Figure 2.10 shows the contribution of the efficiency wedge to output, hours worked, and investment. This is the model prediction for these variables over time with only the efficiency wedge included, and the other wedges set to their steady state values. We have split the graph between the period 1889-1916 and 1917-1929. We do this because the findings are so remarkably different between these two periods, and these large differences are economically very interesting.

Note that between 1889 and 1916, the efficiency wedge accounts very closely for output fluctuations which is just before the U.S. entered World War I in 1917. The figure shows this very close relationship between data and the model, in which the detrended model economy is driven just by stationary productivity shocks. Table 1 provides complementary information on goodness of fit by presenting what is analogous to an R^2 statistic for this procedure. Known as the "ϕ-statistic" within the literature, this R^2-type measure is

Table 2.1: ϕ-statistics for Output, Labor, and Investment

Samples	Output				Labor				Investment			
	ϕ_A^Y	$\phi_{\tau_l}^Y$	$\phi_{\tau_x}^Y$	$\phi_{\tau_g}^Y$	ϕ_A^L	$\phi_{\tau_l}^L$	$\phi_{\tau_x}^L$	$\phi_{\tau_g}^L$	ϕ_A^X	$\phi_{\tau_l}^X$	$\phi_{\tau_x}^X$	$\phi_{\tau_g}^X$
1889-1916	0.83	0.07	0.04	0.06	0.46	0.22	0.05	0.27	0.26	0.27	0.10	0.37
1917-1929	0.09	0.19	0.18	0.54	0.02	0.75	0.16	0.07	0.02	0.29	0.13	0.56
1889-1929	0.29	0.25	0.16	0.30	0.09	0.56	0.12	0.23	0.07	0.32	0.12	0.49

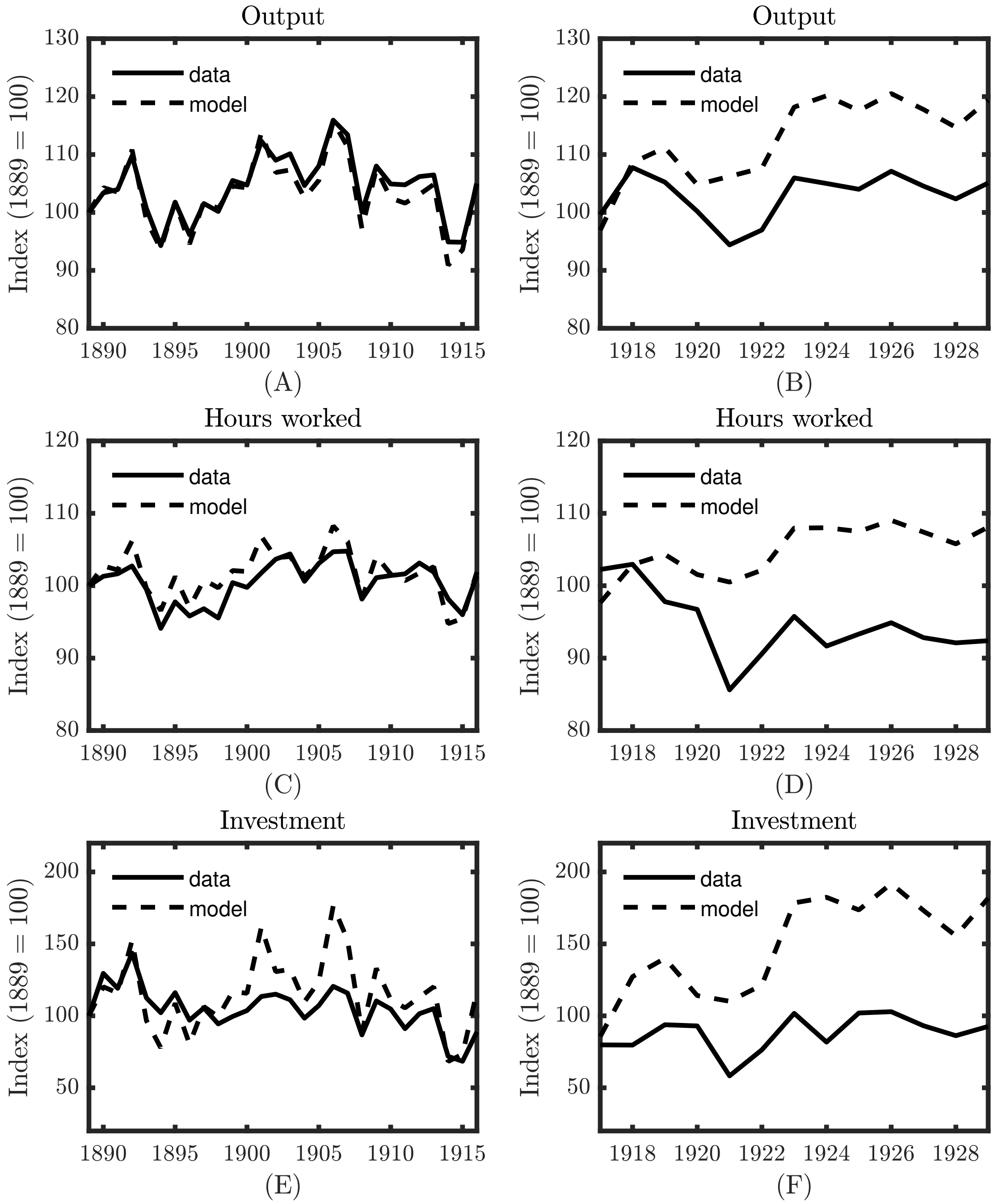

Figure 2.10: Efficiency wedge only economy.

given by:

$$\phi_i^Y = \frac{1/\sum_t (y_t - y_{it})^2}{\sum_j (1/\sum_t (y_t - y_{jt})^2)},$$

where ϕ_i^Y is the percentage of variable y accounted for by wedge $i = (A, \tau_l, \tau_x, g)$. In the numerator, y is the individual variable, i is the wedge individually driving the system, and y_{it} is the model prediction of variable y at date t using wedge i. In the denominator, the summation over j indicates that all wedges are included, which delivers a perfect fit of the model net of approximation error. The statistic lies between 0 and 1, in which a perfect fit is 1.

The efficiency wedge accounts for 83 percent of the squared model deviations from trend (see Table 1). This is high when compared to similar calculations made for different episodes and across countries. BCKM calculate this statistic for the Great Recession across 25 countries, including the U.S., and find an average of 64 percent. For the U.S, it was just 16 percent during the Great Recession.

After that, however, there is a significant disconnect between efficiency variations and output variations, as the efficiency wedge accounts for much less of output. Throughout the 1920s, the efficiency wedge is rising (see Figure 2.10), and by 1929, these large increases in the efficiency wedge alone drive output about 19 percent above its trend growth path within the model. This stands in sharp contrast to actual output, which is about 4 percent above its trend growth path in 1929.

These findings are striking when viewed within the context of the literature on twentieth century economic growth and the context of BCA. There is a broad consensus that the 1920s was one of the most striking decades of U.S. economic growth in its history, and that this growth was fostered by an unusual wave of technological advances, including the diffusion of electrification, which transformed production methods, and the internal combustion engine, which revolutionized transportation. The BCA efficiency wedge only economy result presented here indicates that the famous 1920s economic boom is much weaker than it should have been relative to the technological improvements that took place.

As a related point, we are unaware of any other period, in the U.S. or in other countries, in which the efficiency wedge accounts for so much of output (83 percent), and is then followed by an immediate and large change in this accuracy, in which the efficiency wedge accounts for so little of output. Note that the efficiency wedge accounts for only about 10 percent of output following 1916.

The post-1916 figure and the associated ϕ-statistic indicate that some other factor changed substantially around this time, and it persistently depressed the economy relative to what it could have achieved with the measured, positive efficiency wedge realizations. The figure also shows the accounting of labor and investment using just the efficiency wedge, and these patterns reveal more about the pre and post-1916 economy.

Note that the efficiency wedge's accuracy in accounting for hours is also very different between these two sub-periods. Table 2.1 shows that the efficiency wedge accounts for about 46 percent of hours worked between 1889 and 1916, which is very high relative to similar calculations in the real business cycle literature. In particular, much of the criticism of real business cycle models is that productivity shocks account for very little of hours worked in post-1983 data (Kehoe, Midrigan, & Pastorino, 2018).

The fraction of hours worked that the model accounts for declines from 46 percent to about two percent, in which the large positive efficiency wedge changes of the 1920s generate much higher labor than what actually occurs. This predicted large rise in labor reflects increases in both labor demand and in labor supply, both of which are driven by higher efficiency which raises worker productivity.

The pattern for investment (bottom Figure 2.10 panels) is qualitatively similar to that of hours, in that the model with just the efficiency wedge generates much higher investment than observed. Quantitatively, the deviation between model and data is much larger. By

1929, the model driven just by the efficiency wedge predicts investment that is about 70 percent above trend, compared to the actual value which is modestly above trend.

Figure 2.11 provides complementary information about the impact of the efficiency wedge by plotting the model predictions including all wedges *except* the efficiency wedge. Note that the prediction of the model with all other wedges is far from the data for output, and surprisingly, also for labor through the 1916 period. This latter finding is particularly noteworthy given that the labor wedge is included in making this prediction.

The post-1916 deviations present a consistent pathology about the 1920s. Rapidly growing efficiency should have led to higher labor input, which in turn should have led to much higher investment, given the complementarity between capital and labor in production. The fact that the post-1916 prediction errors are so large and of a consistent pattern suggests that a quantitatively important factor emerged around this time to simultaneously depress labor, investment, and output, and that was sufficiently large to negatively offset much of the expansionary effect of higher efficiency.

Simulating the model in response to just the labor wedge provides important information about this factor. Figure 2.12 shows that the labor wedge captures nearly all of the movement in labor after 1916. Recall that Figure 17 Panel B showed that the labor wedge, which is observationally equivalent to a labor income tax, becomes larger (more negative) around the time of World War I through the 1920s. Driven by just the labor wedge alone, the model predicts that the 1920s would have been one of the *worst* growth decades for the U.S. economy, with output remaining about six percent below trend through the decade, and with labor averaging about seven percent below trend through the decade.

This indicates the key reason why output was low was because labor was low, and while the labor wedge alone doesn't account for the fluctuations in investment, it does accurately predict that investment was depressed below its normal level during the 1920s. Since the labor wedge creates a wedge between the marginal rate of substitution between consumption and leisure, and high productivity, this suggests that the economic factor(s)

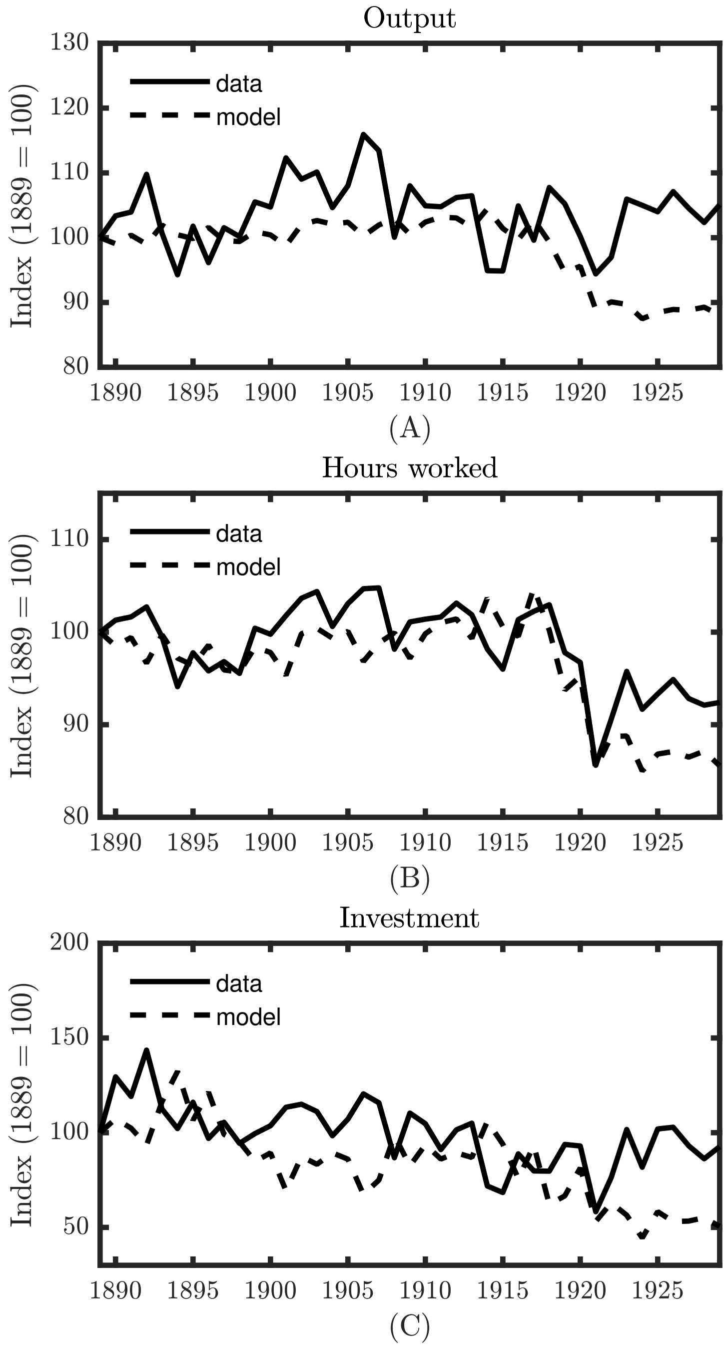

Figure 2.11: All wedges except efficiency wedge economy.

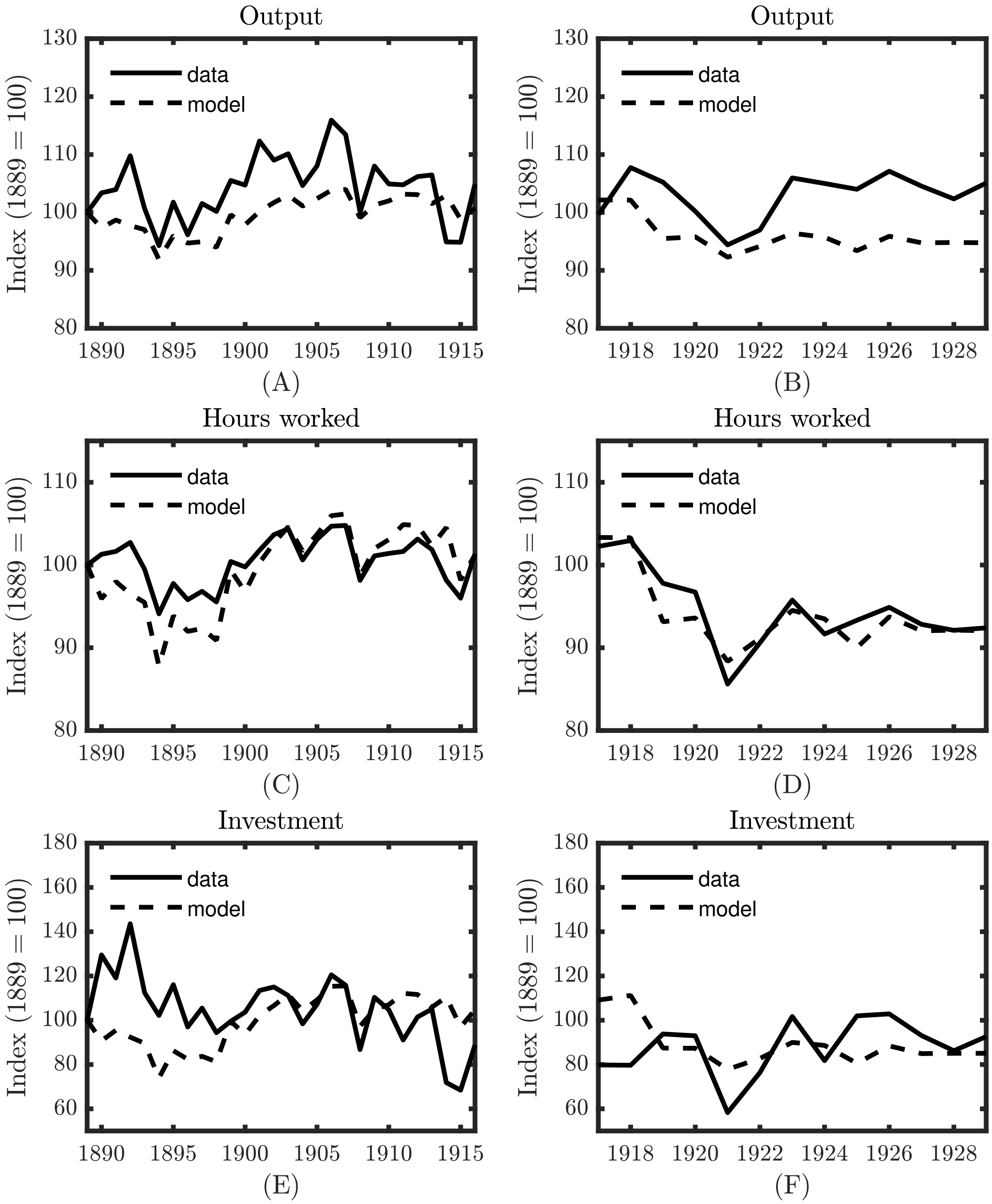

Figure 2.12: Labor wedge only economy.

behind the rising importance of the labor wedge during this period depressed either the incentives and/or the opportunities for individuals and firms to trade labor services.

Figures 2.23 and 2.24 in Appendix 2.5 show the model's ability to account for output, labor, and investment from the investment wedge individually, and the government wedge individually. The figures suggest that neither of these wedges are broadly important for understanding output, labor, or investment over the full period. The ϕ-statistics indicate that government accounts for more than 50 percent of output and investment after 1916, but that largely reflects the very large increase in government spending in 1917-19. Ohanian (1997) and McGrattan & Ohanian (2010) show that neoclassical models driven by large fiscal shocks closely account for the World War II economy. The World War I fiscal shock generates higher hours worked, higher output, and lower investment, all of which are qualitatively similar to the actual World War I economy. The model is not as quantitatively accurate for World War I as World War II, which likely reflects the fact that the World War I shock is not nearly as large as the World War II shock.

2.3.2 Business Cycle Accounting and the Panics of 1893 and 1907

The years 1889-1912 occurred under the National Banking Era, a monetary and financial system created by the National Banking Act of 1863. As a precursor to the Federal Reserve system, the National Banking Era featured nationally chartered banks that were under the oversight of the Comptroller of the currency. The goal was to create a de facto national currency in which national chartered banks would accept each other's currency. The system had flaws, however, and panics occurred frequently.

The Panics of 1893 and 1907 were two of the most severe panics in the history of the U.S. Previous research by Jalil (2015) as well as earlier studies of these panics, dates them consistently, with the Panic of 1893 occurring around the middle of the year, and the Panic of 1907 beginning around October of 1907. This section uses BCA to study these episodes and compares them to the most recent findings within the historical literature. BCA findings show that these two episodes differ regarding the importance of wedges, particularly regarding the labor market, and we find very different contributions of the panics on economic activity relative to the literature.

2.3.2.1 The Panic of 1893

The Panic of 1893 features large declines in output, hours worked, and investment, which began declining before the panic. Other authors have noted in higher frequency data that the economic decline began before the run on banks, and this makes it in principle difficult to evaluate how much of the panic was a symptom of economic weakness compared to its potential depressing effect on the economy by disrupting the financial system.

A recent assessment of the National Banking era panics by Jalil finds very large and persistent effects. He fits a VAR to Davis's (2004) constructed industrial production series, along with indicator variables that are based on how the financial press of that time viewed the panic. By reading the financial newspapers at that time, he grades a panic on a 1-3 scale as to the extent that the panic was an independent event, or whether it was more a symptom of the downturn. He constructs another indicator variable regarding the state of the economy at the time of the panic, also on a 1-3 scale, depending on its underlying strength. He finds that a panic has very large and persistent effects on industrial production during this period, with a one-unit change in the financial indicator variable leading to a 10 percent change in industrial production, and that the impact of the shock persists roughly unchanged for at least 3 years.

BCA provides a different, and complementary analysis to Jalil's VAR study. We find the efficiency wedge plays a very important role in the 1893 panic. The left panel of Figure 2.13 shows the predicted movements from the efficiency wedge alone from 1889 to 1905. The figure shows a close correspondence between predicted and actual changes, particularly

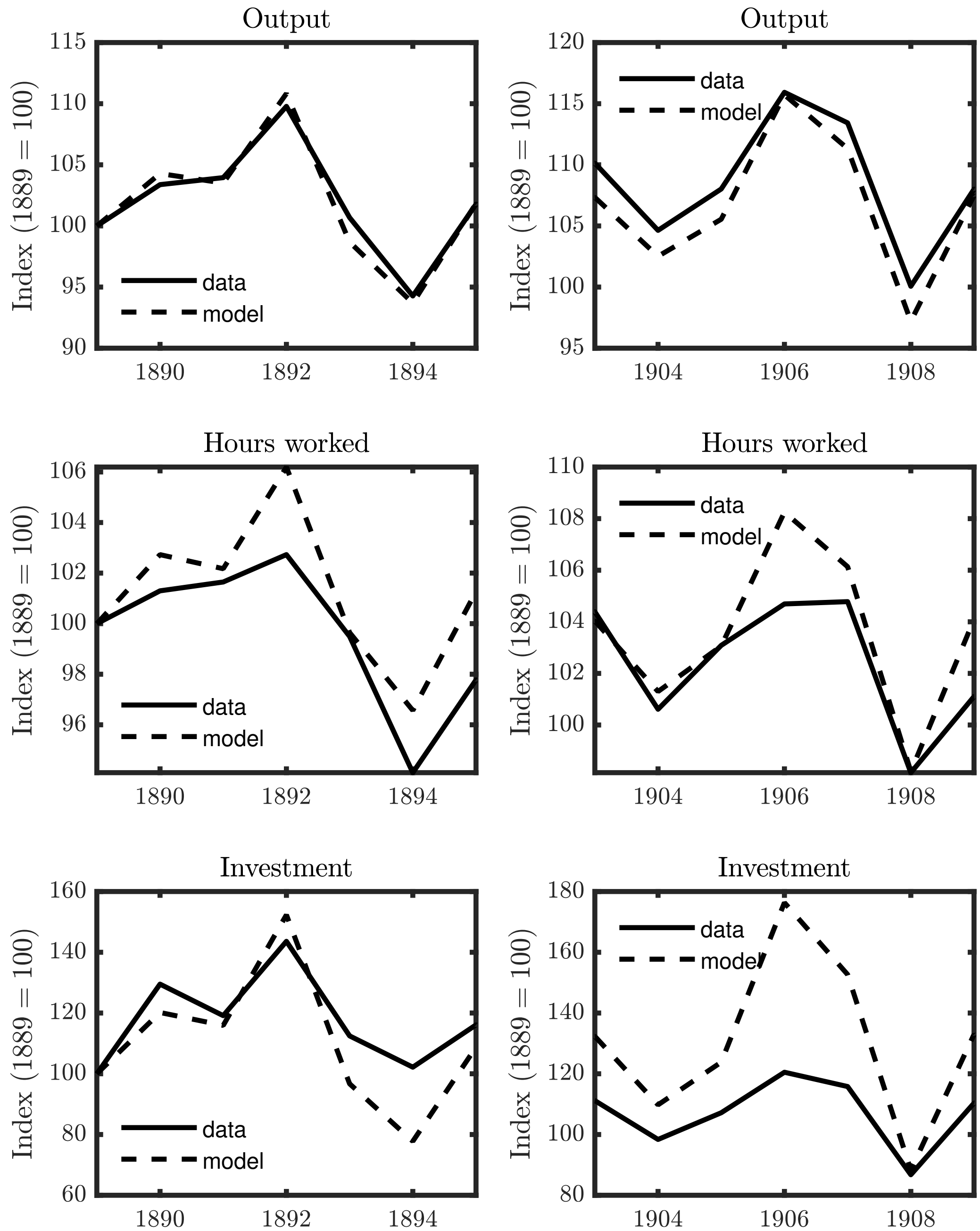

Figure 2.13: Efficiency wedge only economy in the Panics of 1893 and 1907.

for output, which fits nearly perfectly.

The efficiency wedge also captures the qualitative features of labor and investment movements. For labor, it predicts a somewhat smaller increase before the panic, but predicts an overall decline in labor over the downturn in percentage terms that is very close to the actual decline. Table 2.2 shows the ϕ-statistics for the efficiency wedge, which accounts for 92%, 51%, and 66% of the movements, respectively. This episode looks like it was generated largely by a classic real business cycle model, as the efficiency wedge substantially accounts for changes in output, labor, and investment.

This real business cycle interpretation of the Panic of 1893 is consistent with some earlier research. Sprague (1910) presents evidence of declining economic activity prior to the panic, including slowing investment in railroad expansion and building construction, and in silver production (see Figure 2.25 in Appendix 2.5). Davis (2004) shows that a broader-based index of industrial production declined in 1893 (see Figure 2.26 in Appendix 2.5). Moreover, the real investment to output ratio did not drop in 1893, which stands in contrast to what should have occurred if an impaired financial system was substantially impacting the economy. These data support the view that the Panic of 1893 was more of a symptom of the downturn, rather than a primary contributing factor, and that the downturn partially reflects a natural slowing of business following a boom.

Table 2.2: ϕ-statistics for the Panic of 1893

	Output			Labor			Investment		
Samples	ϕ_A^Y	$\phi_{\tau_l}^Y$	$\phi_{\tau_x}^Y$	ϕ_A^L	$\phi_{\tau_l}^L$	$\phi_{\tau_x}^L$	ϕ_A^X	$\phi_{\tau_l}^X$	$\phi_{\tau_x}^X$
1889-1890	0.65	0.01	0.30	0.42	0.03	0.25	0.47	0.03	0.46
1989-1891	0.86	0.01	0.09	0.47	0.03	0.31	0.57	0.03	0.36
1889-1892	0.95	0.01	0.02	0.22	0.04	0.52	0.83	0.03	0.10
1889-1893	0.88	0.02	0.05	0.41	0.06	0.14	0.72	0.05	0.14
1989-1894	0.92	0.02	0.02	0.61	0.10	0.03	0.65	0.11	0.06
1889-1895	0.92	0.02	0.02	0.51	0.11	0.04	0.66	0.10	0.06

2.3.2.2 The Panic of 1907

The Panic of 1907 is similar in that the efficiency wedge accounts largely for output, but differs in that it doesn't account as closely for labor or investment. The right panel of Figure 2.13 shows the predicted movements from the efficiency wedge alone from 1903 to 1909. Table 2.3 shows the ϕ-statistics for the Panic of 1907. It shows that the labor wedge plays a central role in the Panic of 1907 (see also Figure 2.14). The labor wedge accounts for 73% and 82% of the movements in labor and investment, respectively, while the efficiency wedge accounts for 73% of the movements in output.

A hint about the factors that generated the rising labor wedge during the Panic of 1907 may lie in the labor market and a failure for wages to adjust to slowing economic conditions at this time. Figure 2.27 in Appendix 2.5 shows an index of composite wages from 1889 to 1909. The figure shows that wages decline considerably around the 1893 downturn, but decline much less around the time of the 1907 downturn. This suggests that labor market imperfections around that time that slowed nominal wage adjustment may have significantly depressed employment during 1907.

The fact that we find a significant labor wedge in the Panic of 1907 is intriguing because this makes it similar to the Great Recession, in which a large labor wedge is also quantitatively important (see Ohanian (2010) and Brinca et al. (2016)). This comparison also

Table 2.3: ϕ-statistics for the Panic of 1907

	Output			Labor			Investment		
Samples	ϕ^Y_A	$\phi^Y_{\tau_l}$	$\phi^Y_{\tau_x}$	ϕ^L_A	$\phi^L_{\tau_l}$	$\phi^L_{\tau_x}$	ϕ^X_A	$\phi^X_{\tau_l}$	$\phi^X_{\tau_x}$
1903-1904	0.73	0.14	0.05	0.65	0.31	0.01	0.05	0.78	0.03
1903-1905	0.73	0.14	0.05	0.71	0.27	0.01	0.04	0.83	0.02
1903-1906	0.87	0.06	0.02	0.18	0.75	0.01	0.02	0.90	0.01
1903-1907	0.88	0.06	0.02	0.24	0.69	0.01	0.01	0.92	0.01
1903-1908	0.85	0.08	0.02	0.25	0.69	0.01	0.03	0.83	0.02
1903-1909	0.86	0.07	0.02	0.18	0.73	0.01	0.03	0.82	0.02

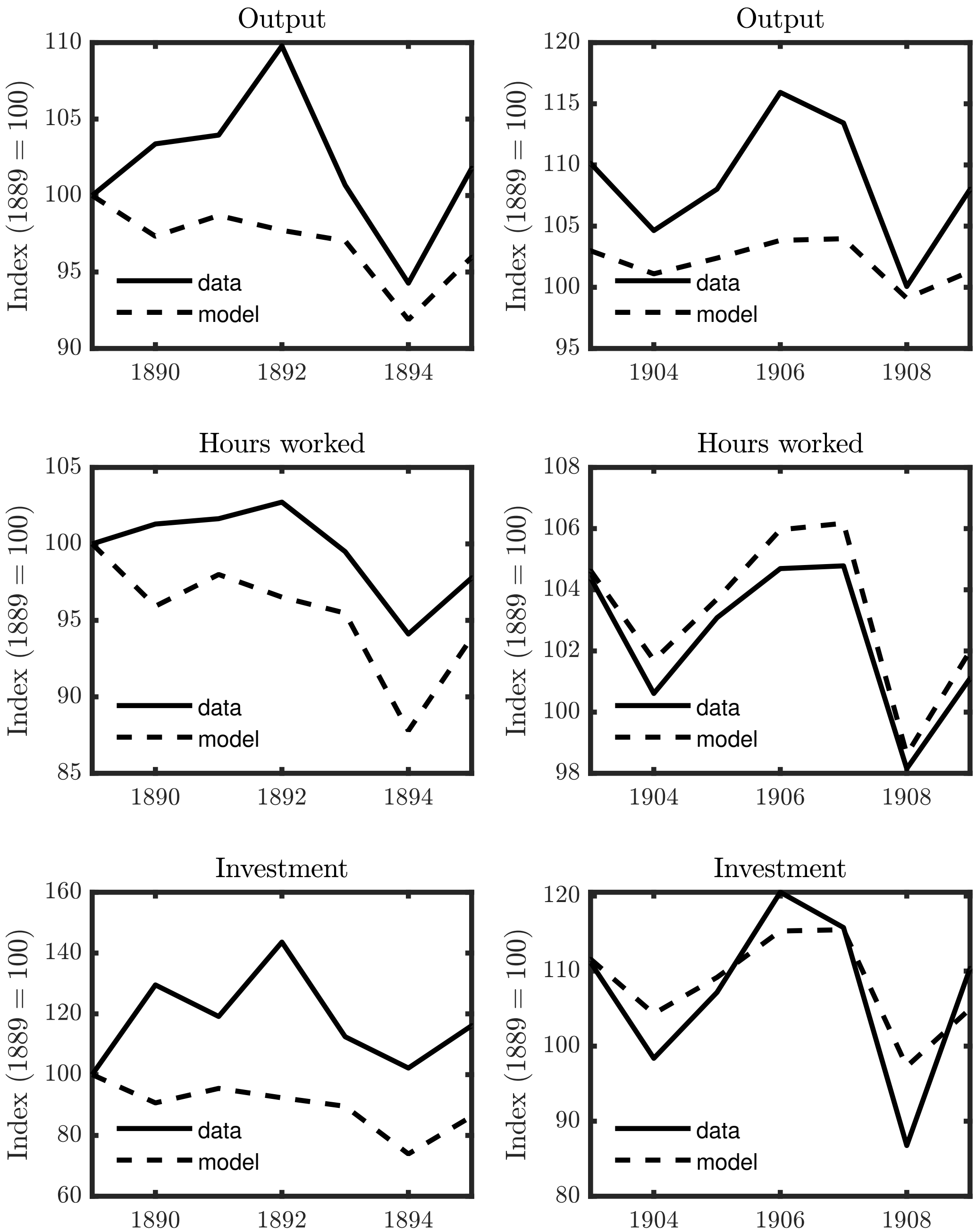

Figure 2.14: Labor wedge only economy in the Panics of 1893 and 1907.

emerges among economic historians comparing the two periods, including Bernanke (2013) and Tallman (2013). They argue that the Panic of 1907 is similar to the Great Recession from the perspective of lightly regulated financial intermediaries. For example, one can think of trust companies in 1907, which were relatively less regulated, and not part of the New York Clearinghouse, like shadow banks during the Great Recession, which were also less regulated and did not have immediate access to the Federal Reserve System.

2.3.3 Potential Interpretations of the 1920s BCA Findings

The BCA results after 1916 indicate very large changes in either the shocks hitting the economy relative to the pre-1916 period, and/or how these shocks affected the economy. The findings stand in sharp contrast to the literature, which focuses on relatively rapid 1920s economic growth that was driven by the increased diffusion of new technologies, specifically electricity and the internal combustion engine. The BCA findings show that technology did rise rapidly during this period, but that its large and positive contribution was substantially attenuated by some factor(s) creating a labor wedge that is observationally equivalent to a rising labor income tax distortion. This section considers some possibilities that may have created the large increase in the labor wedge.

The post-1916 findings regarding rapidly rising productivity in conjunction with a sizable labor market imperfection are similar to findings from studies that have analyzed why the recovery from the Great Depression was not stronger. Cole & Ohanian (1999) showed that the efficiency wedge rose rapidly after 1933, which should have promoted strong growth and returned hours worked back to normal after a few years. However, similar to 1917-1929, hours worked remained depressed as productivity increased. Cole and Ohanian analyzed a number of possible factors that could have depressed hours worked, including labor and capital income taxes, and financial market stability and monetary policy. They concluded that neither monetary policy, which eliminated deflation, nor financial markets, which were stabilized by new legislation, were at fault. They found that modestly higher labor and capital income taxes were minor factors. This led them (Cole & Ohanian, 2004) in subsequent research to study how much industry-labor cartel policies depressed hours worked, and found that it accounted for most of continuation of low hours worked. Chari et al. (2007) found that a very large labor wedge was responsible for the continuation of depressed hours, and also cited industry-labor cartels.

We now apply a similar approach as used in Cole & Ohanian (1999) to evaluate potential factors that could have kept labor depressed after 1917. Regarding tax rates, statutory tax rates declined substantially after World War I, which would motivate higher hours worked, ceteris paribus. Average tax rates were low, and did not change much over the period. Barro & Sahasakul (1983) construct average tax rates and find an average tax rate of about 0.5 percent in 1916, which rises to about two percent during the war, and then declines to about one to 1.5 percent during the 1920s. These data indicate that changes in taxes were quantitatively unimportant in accounting for the 1920s labor wedge.

Immigration slowed in the 1920s, as the population rose about 15 percent in the decade compared to about 21 percent in the two decades before that. This is frequently discussed in the literature on the 1920s as an important factor (Smiley, 1994). However, a relative decline in the labor force should motivate *higher* hours per worker, because hours per worker are a substitute for workers. A relative decline in labor should also lead to higher wages, ceteris paribus. Smiley notes that manufacturing wages for men rose 5.3 percent for semi-skilled males to 8.7 percent for unskilled males, but manufacturing output per hour worked rose 29 percent this same period. These data indicate that reduced immigration is not a promising candidate in accounting for the labor wedge.

The data on real manufacturing wages, and real manufacturing output per hour, suggest another issue within the labor market, and one that may be related to the 1920s labor wedge. The standard model of labor supply and demand predicts that the real wage will move closely with worker productivity. This is not the case in the 1920s, with manufacturing output per hour rising 29 percent, but real wages rising only between 5.3 and 8.7

percent. Why didn't competitive pressure increase wages? Why didn't comparatively low wages stimulate more hiring?

These observations about the 1920s labor market reveal dysfunction that is more difficult to identify than that of the Great Depression. During the 1930s, wages were far above trend, while labor was far below trend. This naturally suggested excess supply, in which labor market policies prevented the wage from falling and clearing the labor market. In this case, both the relative price of labor and the quantity of labor hired are below trend, despite the fact that productivity was high. Given these findings, future research should consider addressing these important questions about the 1920s.

2.4 Conclusion

This chapter provides quantitative general equilibrium analyses of the Industrial Revolution and the period of 1889-1929 in the United States. These episodes were selected because of their importance and interest, the lack of existing quantitative general equilibrium studies of these episodes, and the simplicity of applying quantitative general equilibrium models and methods.

Previous discussions about the Industrial Revolution have focused on inventions such as the steam engine and the Spinning Jenny. But this analysis shows that these developments are only half of the story. These new, capital intensive technologies were substitutes for the older, less capital-intensive technologies. The new technologies, which improved over time, would only be implemented if they were competitive with the alternatives. Given TFP data from that time, there was no chance that the Industrial Revolution could have taken place in the 1500s, or before, as the productivity of the Malthusian technologies were temporarily high around that time. After that, the Malthusian productivity stagnated, which meant that it was only a matter of time before the Solow technologies ultimately caught up and became profitable to adopt over the alternative, land-intensive

Malthusian technologies.

In addition, our analysis of the period from 1245 to 1845 reveals some puzzling issues concerning population movements during this period that deserve additional study.

Moving from the very long-run to a shorter horizon, we studied the remarkable 1889-1929 period in the U.S., one of the most important episodes in American economic history. In particular, the decade of the 1920s is known as perhaps the greatest peacetime growth decade. The research presented here shows that growth could easily have been much higher, given the remarkable productivity growth of the decade.

Instead, puzzlingly low labor input depressed the economy by a cumulative 15 percent relative to predicted model output driven by just productivity shocks. The decade reveals a large labor wedge, and we find that the labor wedge does not have an obvious interpretation. The coincidence of a large labor wedge, low labor input, and low wages suggest a labor market puzzle more challenging to identify that the labor market dysfunction that occurred just a decade later. What factor depressed employment in such a booming economy? Why didn't wages grow at nearly the same rate as productivity? Why didn't firms hire more labor, given its low relative price? These are open and important questions for future research.

2.5 Appendix

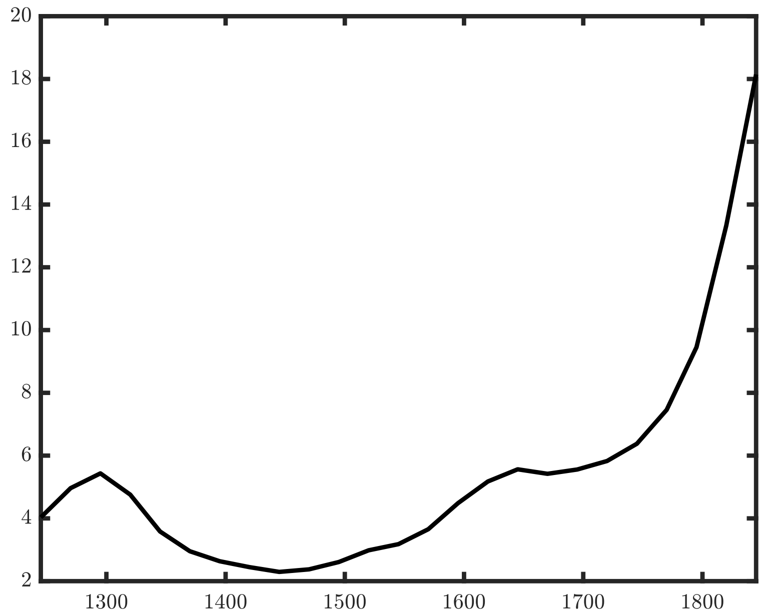

Figure 2.15: Population of England, 1245-1845 (millions of people).

Figure 2.16: Real national income per capita of England, 1245-1845 (average from 1860-69 = 100).

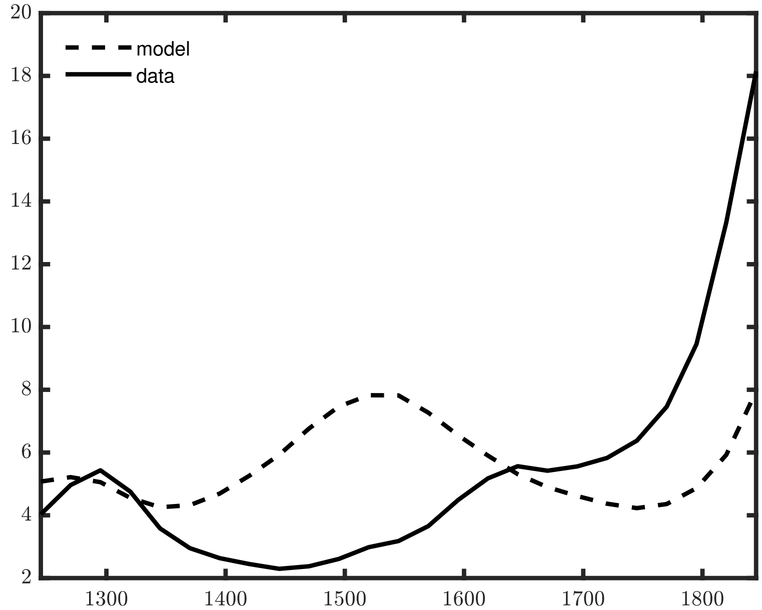

Figure 2.17: Population from “No Plagues” experiment.

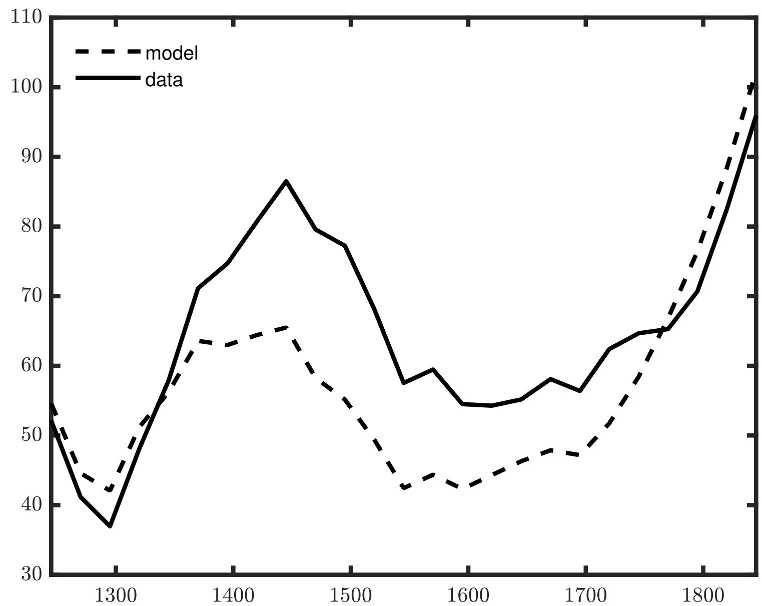

Figure 2.18: Output per capita from “No Plagues” experiment.

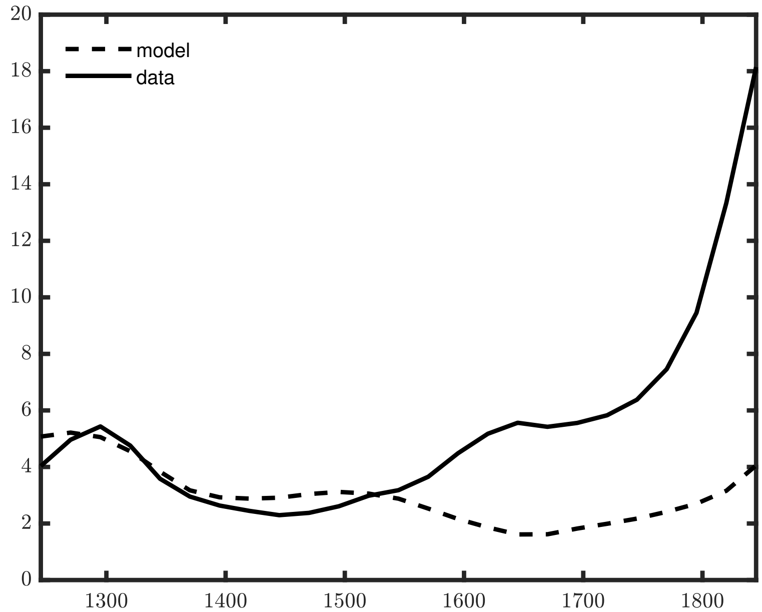

Figure 2.19: Population from “More Plagues” experiment.

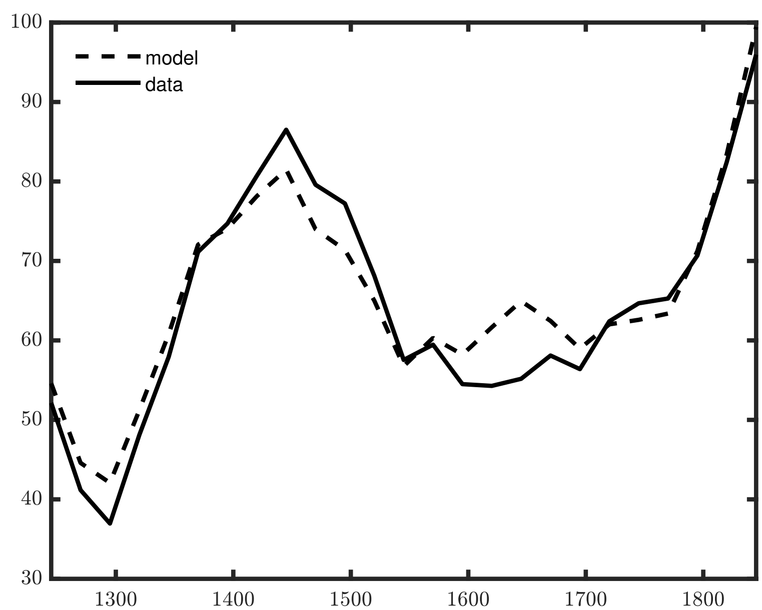

Figure 2.20: Output per capita from “More Plagues” experiment.

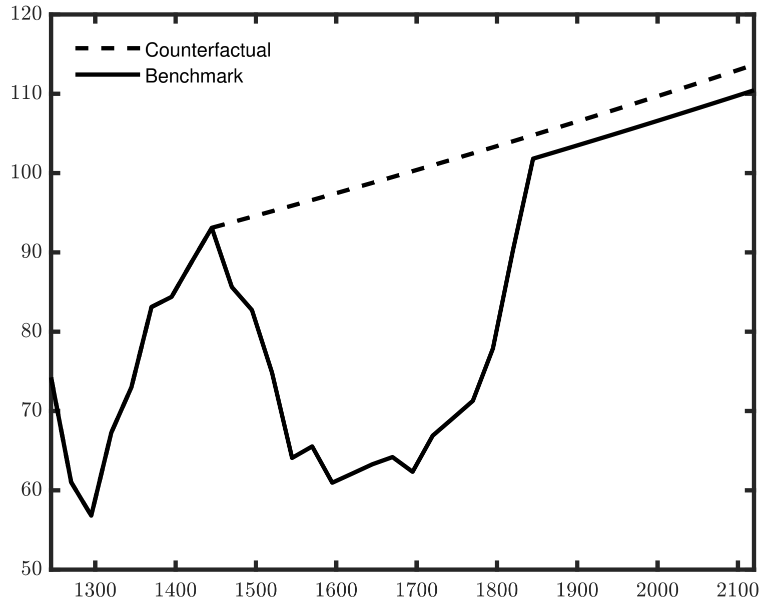

Figure 2.21: A_M for "Timing of Industrial Revolution" and Benchmark experiments.

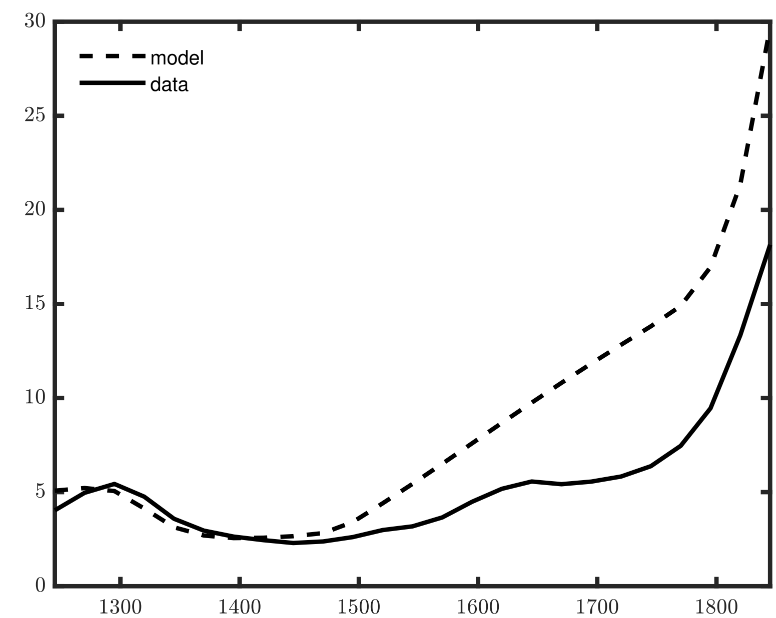

Figure 2.22: Population from "Timing of Industrial Revolution" experiment.

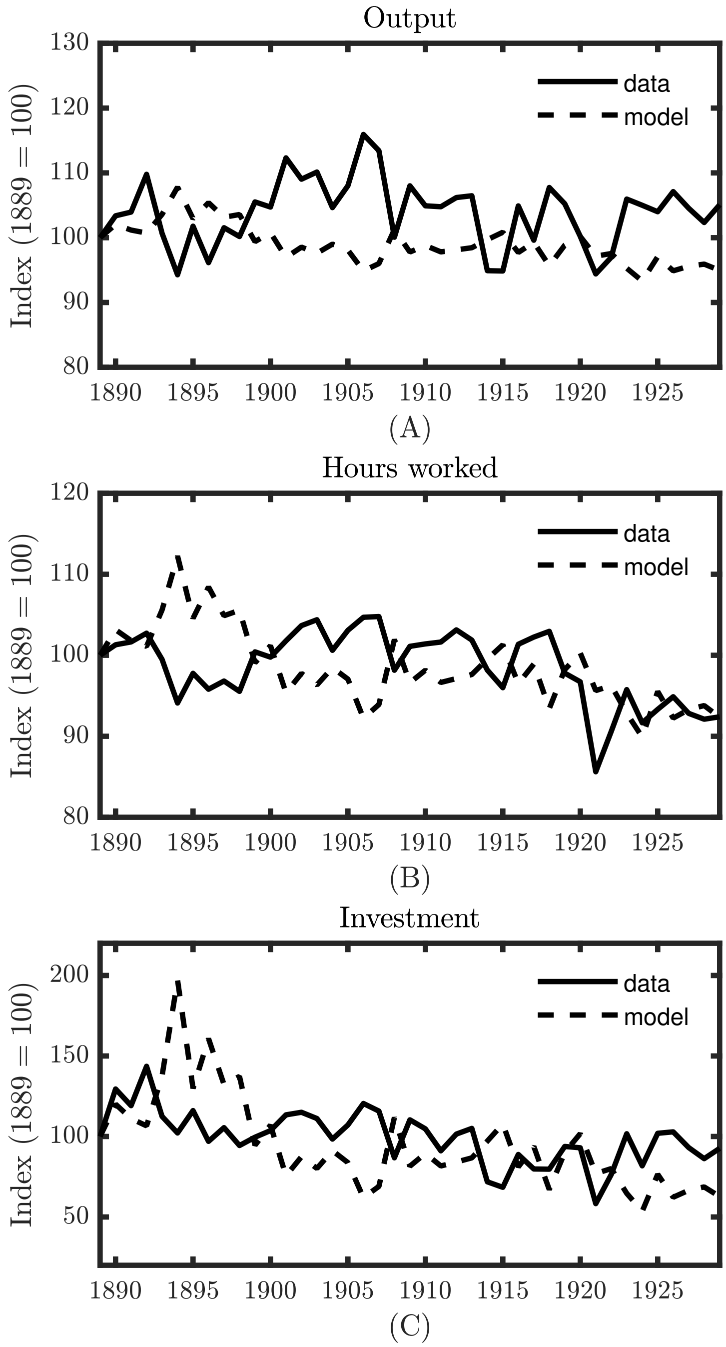

Figure 2.23: Investment wedge only economy.

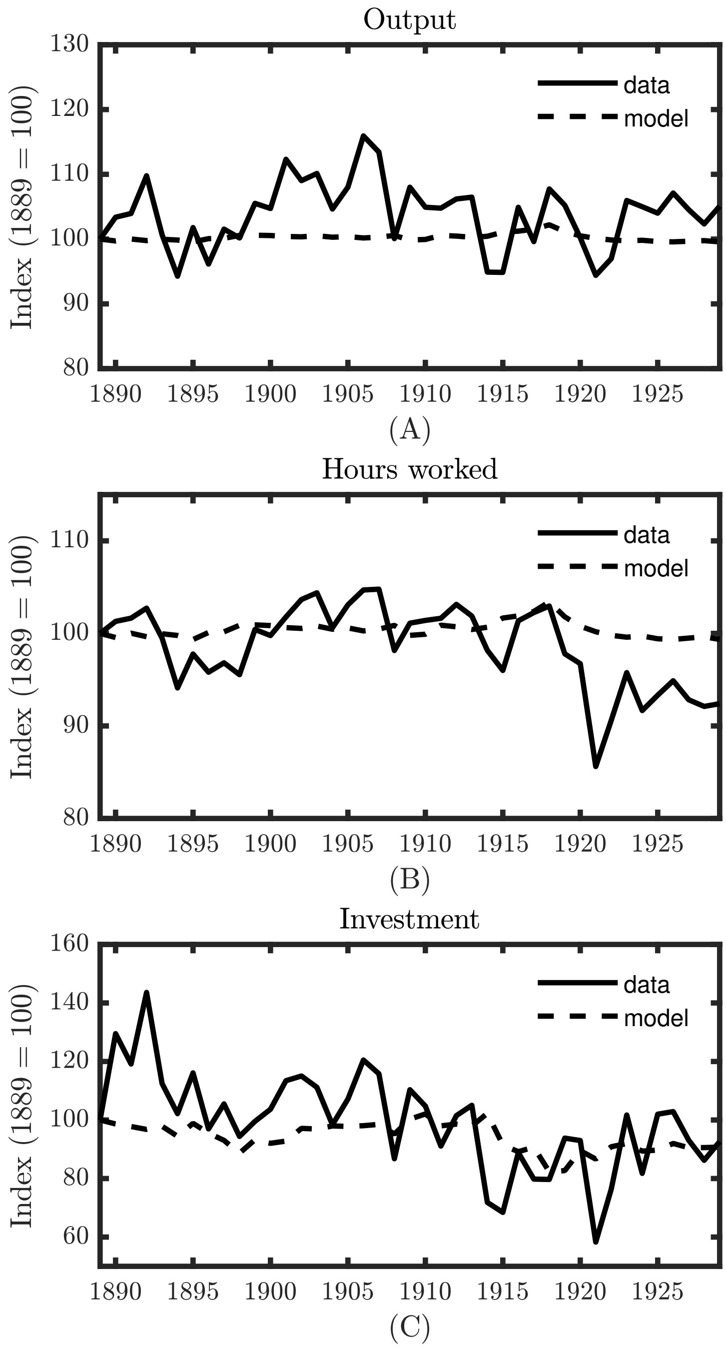

Figure 2.24: Government wedge only economy.

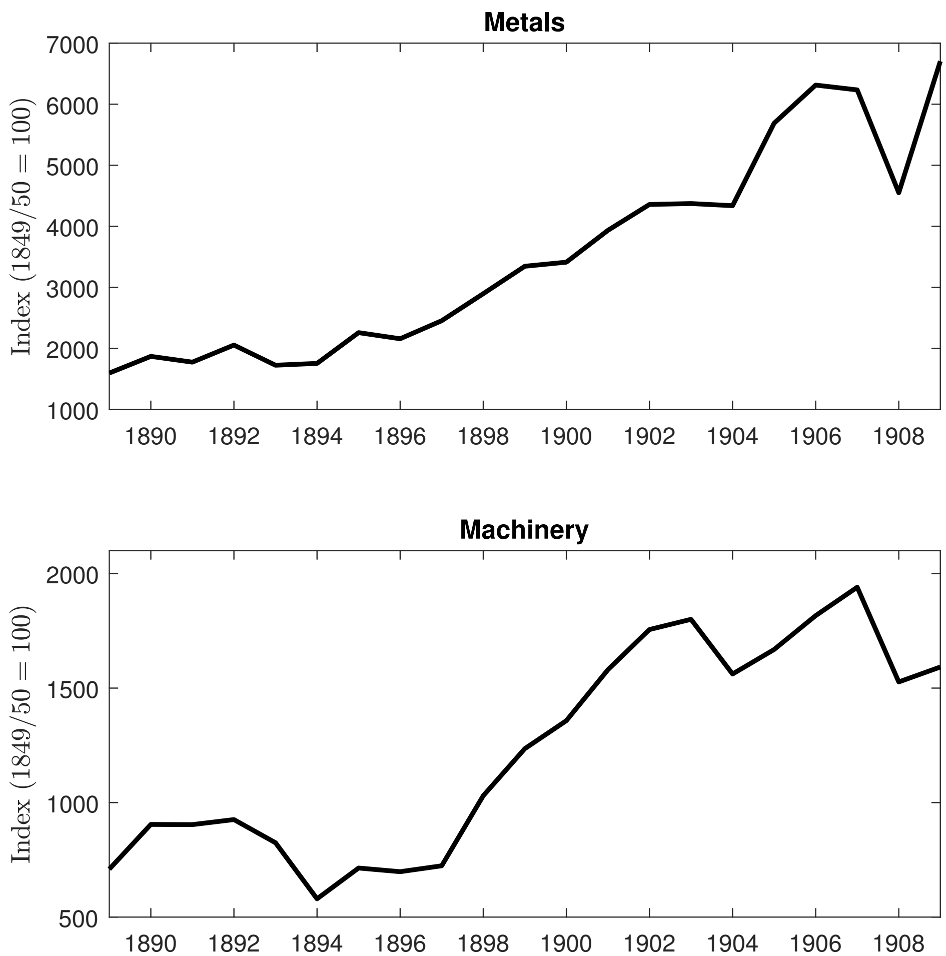

Figure 2.25: Industrial production of metals and machinery for United States, 1889-1909.

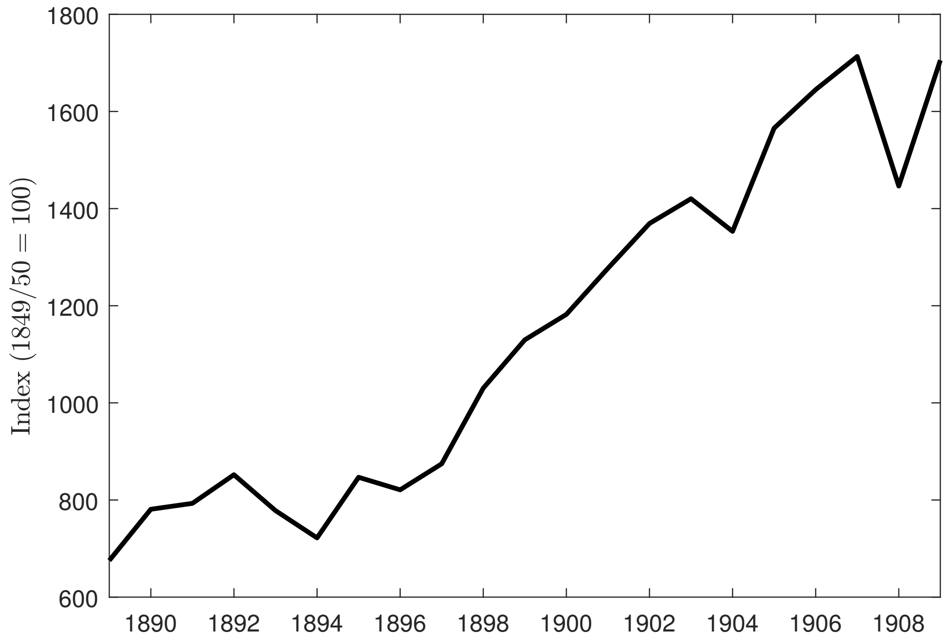

Figure 2.26: Index of industrial production for United States, 1889-1909.

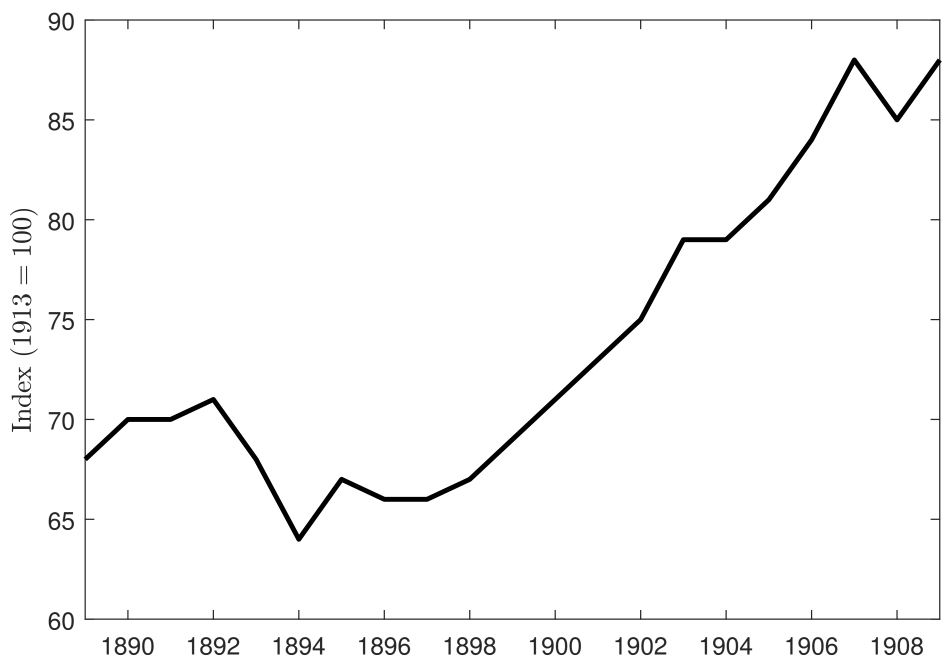

Figure 2.27: Index of composite wages for United States, 1889-1909.

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